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ACADEMIC DISSERTATION

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Abstract

This dissertation examines the main instrument of the European Union climate policy, the emissions trading scheme (EU ETS) during its first years. Emission trading provides a cost-efficient way to reduce emissions. It creates a price on carbon dioxide and thereby incentives for cleaner production. The four empirical studies in this dissertation provide new information on the price determination in the emissions trading market, market efficiency and market interactions with the electricity markets. This information is useful for many purposes. It benefits the market participants who make choice between trading of emission allowances in the market and abatement of emissions. For the authorities and policy planners the price signal and the efficiency of the markets reveal unique real-time information on marginal abatement costs, impacts of policy decisions and impacts of institutional design of this policy instrument.

To be a well-functioning policy instrument the EU ETS should create a credible price signal and efficient markets for trading allowances. The objective of this dissertation is to analyze the EU ETS markets and the price of the European Union emissions allowance, EUA, with econometric time series models. A large data set on market fundamentals is used to analyze the price series. The results of this dissertation reveal that EU ETS is functions well. Carbon has a price that reflects to a large extent the market fundamentals in the study period. The markets are maturing even if not fully informational efficient yet. Interactions with electricity markets are close. The impact of price of carbon on the price of electricity is positive but spatially uneven. In the long run, also climate change affects the electricity bill.

The first study of this dissertation investigates the price determination in the market. The empirical results based on years 2005–2011 show that the price of the EUA is largely determined by the market fundamentals. Especially the price of coal, gas, oil and the price of German electricity are reflected in the price of EUA. In the second study we build up forecasting models and use a trading simulation to study the informational efficiency of the market. Results reveal that the market is not fully efficient but maturing. There might have been possibilities to make economic profit during the second period in the EU ETS market.

The last two papers focus on the interaction of emissions trading with electricity markets. The third study looks at the impact of EUA price on the integrating European electricity markets. The electricity markets are integrating but the positive impact of carbon price on the electricity price is uneven depending on the fuel mix in regional electricity markets. The last study analyses the impact of increasing mean temperature due to climate change and the EUA price on the electricity bill in the EU. Warming climate affect the electricity bill unevenly: in the southern European countries the bill is expected to increase due to the increased demand for cooling, whereas the northern and central parts of the continent may face decreasing costs as the winters get warmer.

Key words: Climate change, EU ETS, price determination, market efficiency, electricity market, time series econometrics

Hinta hiilelle – ekonometrisia esseitä Euroopan unionin päästökaupasta ja sen vaikutuksista

Piia Aatola

Tiivistelmä

Väitöskirjassa tutkitaan Euroopan unionin ilmastopolitiikan keskeisen ohjauskeinon, päästöoikeuskaupan toimintaa ekonometrisin menetelmin. Päästökauppa on kustannustehokas tapa vähentää päästöjä. Se luo hiilidioksidille hinnan ja kannustaa siirtymään puhtaampiin tuotantomuotoihin. Väitöskirja tuottaa uutta tietoa päästökauppamarkkinoiden toiminnasta ja tehokkuudesta. Päästökaupan toiminnan tunteminen ja markkinoiden tehokkuuden arvioiminen on tärkeää. Se auttaa markkinatoimijoita valitsemaan päästöoikeuksien ostamisen ja oman tuotannon päästöjen puhdistamisen välillä. Viranomaisille ja ympäristöpolitiikan säätäjille se paljastaa ainutkertaista informaatiota puhdistamisen rajakustannuksista, joka muutoin on yritysten yksityistä tietoa.

Jotta päästökauppa toimisi halutulla tavalla, markkinoiden tuottaman hintasignaalin tulee olla luotettava ja markkinoiden tehokkaat. Väitöskirjan tulokset osoittavat, että tutkimusperiodin 2005–2011 aikana EU:n päästökauppamarkkinat toimivat hyvin. Ensimmäisessä esseessä tarkastellaan hinnan määräytymistä markkinoilla. Työssä osoitetaan, että päästöoikeuden hinta heijastelee markkinafundamentteja. Empiiriset tulokset vuosilta 2005–2011 osoittavat, että fundamenttitekijät, kuten sähkön ja polttoaineiden hinnat selittävät merkittävän osan päästöoikeuden hinnan vaihteluista. Toisessa esseessä tutkitaan päästöoikeusmarkkinoiden tehokkuutta kaupankäyntisimulaation avulla. Tulokset osoittavat, että päästöoikeusmarkkinoilla olisi ollut mahdollista tehdä taloudellista voittoa

toisella kauppakaudella. Tämä viittaa siihen, että kehittyvät päästökauppa-markkinat eivät olisi vielä toimineet täysin informaatiotehokkaasti.

Kolmannessa esseessä keskitytään tarkastelemaan eurooppalaisten sähkömarkkinoiden integraatiota ja arvioimaan, kuinka päästökaupan mukaantulo on vaikuttanut siihen. Hintasarjojen integroituvuutta tutkimalla todetaan, että alueellisten sähkön hintojen välille löytyy pitkän aikavälin tasapainorelaatioita eli yhtenäisten sähkömarkkinoiden luominen on kehittynyt. Päästökaupan vaikutus sähkömarkkinoihin kuitenkin vaihtelee. Pääasiallinen vaikutus päästökaupasta sähkön hintaan tulee sähköntuotannon hiilidioksidipitoisuuden kautta: mitä hiili-intensiivisempää tuotanto on, sen suurempi on päästöoikeuden hinnan vaikutus myös sähkön hintaan. Päästökaupan mukaantulo voi siten aluksi jopa eriyttää sähkönhintoja.

Ilmastonmuutoksen myötä sähkönkulutuksessa tapahtuu alueellisia muutoksia ja sähkön kysyntä muuttuu niin ilmastoinnin kuin lämmitystarpeenkin osalta. Työn viimeisessä osajulkaisussa osoitetaan, että ottamalla huomioon ilmastonmuutos-skenaarioiden mukainen ilmaston lämpeneminen sekä päästökaupan vaikutus sähkön hintaan, sähkölasku tulisi nousemaan Etelä-Euroopassa kun taas Pohjois-Eurooppa voisi säästää leudontuvien talvien ansiosta lämmityskuluissa, jos viilennystarve ei nouse liian suureksi.

Asiasanat: Ilmastonmuutos, päästökauppa, markkinoiden tehokkuus, sähkömarkkinat, ekonometria

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Helsinki, February 2013

Piia Aatola

List of original publications

This thesis is based on the original papers listed below, which are referred to in the text by their Roman numerals. Papers I and IV are reprinted with the kind permission of the publishers.

I Aatola, P., Ollikainen, M. and Toppinen, A. 2013. Price Determination in the EU ETS market: Theory and Econometric Analysis with Market Fundamentals. Energy Economics, 36, 380-395. http://dx.doi.org/10.1016/j.eneco.2012.09.009

II Aatola, P., Ollikka, K. and Ollikainen, M. 2013. Informational Efficiency of the EU ETS market – a Study of Price Predictability and Profitable Trading. Manuscript.

III Aatola, P., Ollikainen, M. and Toppinen, A. 2013. Impact of the Carbon Price on the Integrating European Electricity Markets. Manuscript.

IV Pilli-Sihvola, K., Aatola, P., Ollikainen, M. and Tuomenvirta, H. 2010. Climate change and electricity consumption - witnessing increasing or decreasing use and costs? Energy Policy. 5, 2409-2419. http://dx.doi.org/10.1016/j.enpol.2009.12.033

Putting a Price on Carbon –
Econometric Essays on the European Union Emissions Trading Scheme and its Impacts

Contents

1. Introduction

The European Union Emissions Trading Scheme (EU ETS) is the main instrument in EU climate policy. In global perspective, it is an ambitious and genuinely large-scale trading program. For instance, it is ten times larger in number of participants than the largest program in the U.S., the SO_2 trading program. Emissions trading was included in the toolbox of EU policy instruments after the signing of the Kyoto Protocol in 1997. Trading started officially in 2005 with a three-year trading period (2005–2007). The following year marked the beginning of the Kyoto period, which brought internationally binding emissions reduction targets; this period ended in 2012. The EU Commission has already made decisions on the arrangements for the third trading period (2013–2020). Thanks to its country-specific data on initial allocations, annually reported emissions, continuous data on forward prices and increasingly available data on spot prices, the EU ETS provides a very interesting object of research on environmental policies.

The theoretical background of emissions trading lies in the economic theory of internalizing externalities and achieving the socially optimal quality of the environment. Pigou (1932) introduced the idea of levying a tax on emissions to make polluters bear the full social cost. In contrast to Pigou, Coase (1960) emphasized that when all the property rights are well defined, the Pareto optimum solution can be found without governmental intervention by allowing the participants to bargain. As an instrument, emissions trading combines the best aspects of both approaches: society retains the property rights to a clean environment and sells permits to polluters at a price that reflects the social cost of pollution. In doing so the instrument implements the reduction in a cost-efficient way.

The roots of the literature on tradable property rights lie in the work of Dales (1968) and Crocker (1966), who, following Coase (1960), proposed that society has the right to clean air and a social planner can allocate permits for pollution. Montgomery (1972**)** demonstrated analytically that the system of tradable permits is cost-efficient, as it equalizes the marginal abatement costs between polluters. Montgomery's findings are based on perfect competition in the permit market. These first contributions spawned an extensive literature on tradable property rights that went on to examine the implications of imperfections, transaction costs, as well as monitoring and enforcement.[1] The first experiences

[1] Hahn (1984) examined the role of a dominant firm in the permit market. Misiolek and Elder (1989) focused on the case where firms have market power both in the permit and end product market. Innes et al. (1991) and von der Fehr (1993) extended the discussion to oligopolistic settings. Both cases threaten the cost-efficiency properties of a trading system. Stavins (1995) was the first to examine the role of transaction costs and he was followed by Gangadharan (2000) and Liski (2001). The role of uncertainty

of emissions trading are from the US, where authorities have run many trading programs since the 1970s.[2] Europe's turn came 30 years later. Today, the EU ETS is a large-scale trading program even in global terms.

The flexibility of permit trading created by the free trading of allowances and the reduction in the asymmetric information between the actors and the policy planner has increased the popularity of the system. The most important long-term feature of permit trading is that it creates a price for pollution. One prerequisite for a credible price signal is a well-defined institutional framework: a standardized commodity, trading rules and trading platforms. The auditing and supervision of the system must also be sufficient in order to establish credibility. The price signal is important for many agents and for several reasons. For installation operators, or the polluters, the price facilitates both short-term optimizing decisions on abatement and long-term investment decisions. For policy makers, it reveals unique private information on marginal costs. For the social planner, it provides information that indicates the stringency of the policy and may suggest adjustments in it.

Despite the promises of permit trading, there are many challenges in the emerging market for CO_2 emissions in the EU ETS. Thus far, the EU ETS has created a price and market for carbon as well as incentives for emissions reductions. The system is a liquid market that has grown rapidly in its first years but one that is still maturing and new. There are, however, many challenges related to the nature of price determination, market efficiency and the interaction of the system with other markets.

I examine these issues by combining analytical models with empirical econometric models on time series data from the first years of the ETS. The main research questions of this thesis are:

- Is the permit price determined by the market fundamentals?
- Is the EU ETS market mature? That is, can it be regarded as informational efficient?
- How do the common EU ETS market and the price of carbon impact the regional and integrating electricity markets? That is, do we witness convergence or divergence in electricity prices in the presence of a carbon market?

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has been examined in many forms. Montero (1998) combined the effect of both uncertainty and transaction costs. Monitoring and enforcement have been analyzed by Malik (1992) and Ben-David et al. (2000). Finally, various issues related to design have been examined in Böhringer and Lange (2005a, 2005b); Cason and Gangadharan (2003).

[2] SO2 trading program, Title IV of the Clean Air Act 1993 California's RECLAIM (Regional Clean Air Incentives Market), See the Environmental Protection Agency, EPA, 2012 http://www.epa.gov/airmarkt/progsregs/index.html

- How does the changing climate and carbon market affect the demand for electricity and on the electricity bill in Europe?

This thesis contributes to the growing literature that examines empirically the EU ETS during its first years. The studies in the theses shed light and provide new information on this policy instrument. The results are interested for both actors in the market and for the policy planners. As the tendency in the international climate policy is also towards more global carbon trade and the markets are getting linked to each other, the experience and research on the functioning of the EU ETS is provides valuable insights.

In a set of four essays, I examine these questions analytically and empirically using large data sets. The main objectives of the theses can be summed up as follows. The first essay focuses on the main price drivers and determinants of an EU ETS permit, or EU allowance (EUA). This work builds on that by Alberola et al. (2008), Chevallier (2009), Christiansen et al. (2005) and Hintermann (2010). Based on a robust statistical analysis, we test theory-driven hypotheses on the impact of market fundamentals on changes the price of an EUA. We conclude that the German baseload electricity price and gas and coal prices are the main and statistically significant fundamentals of the price of EUA. In the second essay, we examine the informational efficiency of the ETS market through a trading simulation. The work on market efficiency is closest to that of Daskalakis et al. (2008) and Montagnoli and de Vries et al. (2010). Showing signs of price predictability and profitable trading possibilities during the second trading period the results support the hypotheses of lacking informational efficiency in this emerging market.

The third paper looks at the interactions between Europe's integrating electricity markets and the ETS market. Bosco et al. (2010) and Zachmann (2008), among others, have studied the integration of the European electricity markets. In the interactions with the EU ETS market and the electricity market, reference is made to the research of Mansanet-Bataller et al. (2007) and Fezzi and Bunn (2009). These approaches are combined in studying the impact carbon market on the integrating electricity market. The overlap of the two harmonizing internal markets should lead to increased efficiency. However, the price of carbon affects regional electricity prices unevenly due to the differences in energy mixes and the merit order of power plants. This might, in the short run, disperse the electricity prices despite the trend towards integration driven by the increasing transmission capacities on the continent. The last essay examines the impact of the carbon market on the changing demand for electricity and on the EU's electricity bill. The changing climate and electricity production have spatially varying impacts on that bill. The results show that in the southern European countries the bill is expected to increase due to the increased demand for cooling, whereas the northern and central parts of the continent may face decreasing costs as the winters get warmer.

All in all, the results of this thesis suggest that the price of an EUA reflects the market fundamentals and that the ETS market is liquid and operationally efficient but shows signs of informational inefficiency. In addition, the ETS is shown to be closely linked to the electricity markets: the price of an EUA has a positive but uneven impact on the integrating electricity market prices on the continent. Depending on the energy mix and emission factor of the marginal power plant, the impact of the price of an EUA on the price of electricity varies.

2. Literature review

The EU ETS provides an excellent object for empirical studies on the impacts of environmental policies; it is no wonder that the literature is already extensive. Given the focus of this thesis, this literature is presented under two main headings: Price determination and emissions reductions and market efficiency and market interactions. The first encompasses price determination and the second market efficiency and impacts on other markets.

2.1 Price determination and emissions reductions

Market price is an indicator of scarcity and it reveals a great deal of information. For the participants in the ETS market, the price creates incentives to reduce emissions and avoid the costs of permits and, optionally, sell for profit any extra permits they may have acquired. For the authorities, the market price serves as a signal of the success of the policy and possible needs for adjustments in the system. The reliability and validity of the price is thus crucial for the very existence of the incentive mechanism of the instrument. If uncertainty makes the market price too volatile or if market power is used to manipulate the price, the credibility of the price signal suffers and might hinder participants from taking actions they might otherwise take. The market price should thus be stable enough to be a reliable signal for emission reduction and investment decisions. Accordingly, the price determination and the driving forces behind the market price are well-motivated questions, ones that have been studied in the previous literature. Christiansen et al. (2005) describe and identify the possible price determinants as being policy and regulatory issues as well as market fundamentals, including the emissions-to-cap ratio, fuel-switching, weather, and production levels. Alberola et al. (2008), Mansanet-Bataller et al. (2007) were the first to analyze these relationships econometrically. Delarue and D'haeseleer (2007) highlighted the importance of fuel-switching in electricity production as a price fundamental. Keppler and Mansanet-Bataller (2010) and Bredin and Muckley (2011) included electricity prices in the set of possible price determinants. Fezzi and Bunn (2009) and Creti et al. (2012) used cointegrating analysis for the interdependencies between the price of an EUA and the energy market prices.

A range of studies has investigated many other aspects of the market as well. Examples include Hintermann (2010), who explains the price development in terms of the marginal abatement costs. Chevallier (2009) studied the relation between macroeconomic factors and the price of carbon. Mansanet-Bataller et al. (2011) focused on the price spread between certified emission reductions, CERs, and EUAs, and Paolella and Taschini (2008) use econometric models to study the very special period of EUA returns when the price was falling to zero due to a surplus at the end of the first trading period (2005–2007).

The price signal creates incentives for emission reductions. How much emissions are reduced and what actions are taken to that end is defined by the marginal abatement costs. But the reductions also depend on the time span. *In the short run*, the choice of fuel in electricity production is the key means to reduce emissions. Switching from a more - polluting to a less-polluting fuel is one of the few short-run abatement options that the actors have under the EU ETS. Fuel-switching can only be used where the technical requirements (e.g. multi-fuel combustion) and the economic incentives exist. The largest potential for fuel-switching has been in the UK and Italy. (Delarue et al. (2008) and Pettersson et al. (2011)). In practice and on the largest scale, fuel-switching means replacing coal with natural gas, which produces only half the emissions compared to coal. The popularity of gas is increasing in Europe and globally even though coal is keeping its position as the most important fossil fuel in electricity production. *In the long run*, the cost of carbon might also affect larger energy investment decisions. To date, the price of carbon has neither been a driving force for investments in large-scale energy projects nor caused substantial carbon leakage within the process industries from Europe to areas with fewer carbon constraints (Wråke et al., 2012; Calel and Dechezleprêtre, 2012).

2.2 Market efficiency and market interactions

For a market to serve as an efficient policy instrument it needs to be well functioning. A well-functioning market mechanism allocates scarce resources efficiently from the surplus sector to the deficit sector, equalizing supply and demand. The demand for EUAs is defined by the marginal abatement cost of companies. The authorities according to the policy target set the supply of allowances. The tradability of permits allows the market mechanism to work towards maximizing social welfare. A well-functioning market needs to be allocative, operational and informational efficient. The market price might be biased if the market is not informational efficient. Informational efficiency is of particular interest in new and emerging markets. A market is informational efficient if the price reflects all the available information and adjusts quickly to new information; that is, the price and return are not predictable and it is impossible to make a constant economic profit in the market. (Fama, 1970, Timmermann and Granger, 2004). The market return should be a random-walk process. Emerging and new markets often suffer from informational inefficiency and may offer opportunities for arbitrage if a company can beat the market by using the information at hand. Usually these characteristics fade quickly as the market evolves. The first studies of informational efficiency in the EU ETS were those by Daskalakis and Markellos (2008), Milunovich and Joyeux (2010) and Chevallier (2009). These papers tested for the weak form of informational efficiency and found no clear evidence of efficiency in any form in the first phase. Montagnoli and de Vries (2010) studied EUA prices in both phases I and II using variance ratio tests and their results show signs of market efficiency during phase II. Miclaus et al. (2008) used the event study methodology to examine the effect of the announcements of the national allocation plans and the publication of emissions verifications on the carbon prices. They found that the market was efficient during the first phase. Conrad et al. (2012) also studied the adjustment of the EUA price to news announcements. Using high-frequency intraday data and modeling the volatility, they concluded that the price of an EUA adjusts well to news of economic development. In addition, in a corresponding market – the US SO_2 market – Albrecht et al. (2006) found evidence of the weak form of informational efficiency by applying the standard statistical tests.

Operational efficiency in the permit market requires that the institutional structure be well defined and the trading rules are harmonized. The market needs to be liquid and have enough traders; compliant and speculative, as well as bearable transaction costs (see e.g. Jaraite et al. 2010). This guarantees that permits will move from the surplus to deficit sector and that the marginal abatement costs will be equalized; in other word, the market will also be allocatively efficient. Ellerman et al. (2010) and Zhang and Wei (2010) provide insights into the operating mechanism and economic efficiency of the EU ETS. Ellerman and Joskow (2008), Egenhofer et al. (2011), Wråke et al. (2012) review the institutions and give a perceptive assessment of the first years of the ETS.

The electricity sector is the single largest sector in the EU ETS and thus interactions with it have been widely studied and debated. The increase of production costs in polluting production aims at creating an incentive to move towards less-polluting, cleaner technology. However, despite the importance of incentives for policy, much of the discussion of the impacts of permit trading on the electricity market has centered on the pass-through rates (e.g. Sijm et al. 2006, Zachmann and Hirschhausen (2008), Walker (2006), Oberndorfer et al. (2010)) and windfall profits (e.g. Lise et al. 2010 and Woerdman et al. 2009). Electricity producers pass the carbon cost on to the end product prices, and given the relatively inelastic demand, the extra cost is often passed on almost entirely. The impact of the price of carbon on the price of electricity depends on, among other factors, the carbon content of the marginal fuel. These windfall profits caused by carbon-driven, higher electricity prices have been the focus of the policy debate.

3. The European Union Emissions Trading Scheme

3.1 Institutional framework

The development of the EU Emission Trading Scheme (EU ETS) has been interesting. The system was drafted in the aftermath of the signing of the Kyoto Protocol in 1997. An international emissions trading scheme was listed in the Protocol as one of the mechanisms to achieve the agreed emission reduction targets. It was in this setting that the EU decided to build up its own emissions trading system. After a couple of years of negotiations within the EU institutions, the ETS was established in 2003 (EC, 2003/87/EC). This relatively rapid process in EU decision making shows the commitment and role that the system gained in European climate policy; it became the flagship of that policy. One of the challenges has been the overall trade-off between the flexibility and uncertainty of the mechanism. On the one hand, the system seeks to provide predictability, allowing market actors to boost their investments; on the other, the possibility to adjust the mechanism according to changes in international climate policy is essential as well.

From 2005 onwards, ETS compliant installations have been required to have permits for their CO_2 emissions. One European Union emissions allowance, or EUA, equals one ton of CO_2. The first trading period, 2005–2007, was dedicated to learning the trading mechanism and no internationally legally binding commitments were imposed; however, the second trading period, 2008–2012, is concurrent with the Kyoto compliance period. The third period will be slightly longer than the earlier ones, running from 2013 to 2020. Despite the current impasse in the international climate negotiations of the post-Kyoto period, the EU has committed itself to continuing the market mechanism as part of its climate policy (see Hermeling et al. 2013 for the assessment of EU 2020 targets and role of EU ETS).

The ETS is a cap-and-trade market. The cap, the total number of allowances allocated to the market players, is determined by political decisions in the European Commission in line with the climate policy target set for the ETS sector. After receiving their allowances, in accounts, actors are free to trade in them. In Phases I and II the allowances were allocated to the participants mostly free of charge. By contrast, from the beginning of phase III, auctioning will gradually become the main initial allocation method for most of the participants. (see Benz et al. (2010) for the assessment of auctions in Phase 3).

The scheme covers the CO_2 emissions of approximately 12,000 installations and over 500 companies in the energy production and energy-intensive process industries. These account on average for 50% of the EU's CO_2 emissions. Electricity production is the largest single sector in the system and it covers over

45% of the allocated allowances. Of the member states, Germany, France, Italy and Poland have been allocated the largest share of the allowances. The Commission and the member states cooperate closely in supervising the system. All the trades and permit transfers must be registered in the actors' accounts in the national and EU-wide registers, and the emission balance sheets are audited annually in March. All actors must show that their emissions do not exceed the quantities permitted by the allowances in their account. If an actor fails to do this, it must pay a penalty of 100 €/CO_2 ton and buy allowances corresponding to the exceeding. After the installation-level reporting, the Commission publishes the emission data online yearly. These data are publicly available from the transaction log and provide a large database for anyone interested. (European Commission Transaction Log, CITL, 2012)

The actual trading takes place in several exchanges and via brokers. In one sign of a liquid and maturing market, trading is executed using various spot and financial instruments, such as forwards and options and spreads of EUAs. The forward trade via brokers is the most liquid form of trade, but the role of trade via exchanges is growing rapidly. In addition to the compliance traders, there is a large number of speculative traders operating in the market, among them banks and investment funds. The market is open to any actor that has an account in one of the national registers. (State and Trends of Carbon Market, 2011).

After the initial allocation of EUAs the market supply is increased by the credits coming from the clean development mechanism (CDM) and joint implementation (JI) projects. These credits are called certified emission reductions (CER), and emission reduction units (ERU), respectively. The CDM and JI are baseline and credit-based emission trading within the framework of Kyoto Protocol. These projects are conducted together with developing countries and the addition of emissions reduction programs is the key to getting credits from these projects. The use of these credits in the EU ETS market is regulated by the linking directive (EC, 2004/101/EC). In the 2008-2012 trading period, the EU laws allow operators to use JI/CDM credits up to a percentage determined in the National Allocation Plans (NAP). Unused entitlements are transferred to the next trading period, 2013–2020. In 2008–2012, participants in the ETS have been able to buy a total of as much as 1.4 billion tons in credits. As of 2013, the EU ETS legislation will change such that between 2008 and 2020 participants may use credits in an amount up to 50% of the overall reductions below 2005 levels made under the ETS. The exact amount per operator is to be determined in line with the methodology outlined in Directive 2009/29/EC. The system by which CDM/JI credits are brought to the EU ETS market has been struggling, but the role of these credits, especially CERs, in adding to the supply in the market has been substantial. (State and Trends of Carbon Market, 2011).

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3.2 Phases I and II of the EU ETS market

The first years of the EU ETS have shown that the market mechanism works, and carbon now has a price. However, the development of the scheme has been plagued by concerns of overallocation of allowances, price manipulation and register fraud. In addition, the uncertainties of the institutional framework and climate policy have made the market price volatile and impeded investments in clean technology. At the same time, however, the ETS has witnessed a rapid increase in trading volumes and in the number of participants in the market. This is clearly reflected in the price development and the emissions data for the first years.

A total of over two billion allowances were allocated annually to the actors in the market during the first trading period, 2005–2007. Emissions were slightly less than two billion tons and thus the price of an allowance fell to zero before the end of the phase. During the second period (2008–2012) the cap has been tightened and it is to be tightened even more in the coming years. Based on the verified emissions for the year 2011, the market is now cumulatively long by approximately 280 Mt; that is, there has been 280 Mt less emissions than the allocated allowances would permit. Recently, the price of an EUA has fluctuated between 5€ and 8€ per ton. (ThomsonReuters, 2012). For a detailed review of the first years of the EU ETS, the reader is referred to, among other sources, Ellerman and Joskow (2008), Egenhofer et al. (2011) and Wråke et al. (2012).

Table 1 shows the emission balance for the first years of the EU ETS. The first period ended approximately 160 Mt long. The second period is expected to have an even larger surplus, due to the economic downturn and decreased demand for allowances. However, the possibility of banking and borrowing allowances in coming years will keep the price at positive levels. Combustion installations (including the energy sector) have long been the only sector short in allowances, that is, the only one where emissions have been higher than the number of allowances granted to the sector would permit. In contrast, the process industry has been the main source of the surplus on the market.[3]

[3] The prediction of third period scarcity of allowances is threatened and there is a on-going debate of the EU Commission intervention to the market by setting aside some of the allowances from the market to guarantee the scarcity of allowances in the deeper than expected production reductions due to market downturn. (ThomsonReuters, 2012)

Table 1. Allocation of permits vs. emissions by sector (Mt). Source: CITL, 2012.

Activity	2005	2006	2007	Phase I	2008	2009	2010	2011	Cumulative Phase II
Combustion installations (>20 MW)	10.1	-21.3	-26.1	-37.2	-253.44	-114.01	-126.67	21.41	-472.71
Mineral oil refineries	8.1	8.9	8.6	25.6	-1.58	7.47	14.80	33.14	53.84
Metal industry	39.0	31.3	34.0	104.2	57.36	107.05	83.04	105.74	353.19
Mineral industry	18.6	13.7	8.9	41.1	28.83	77.73	76.87	100.92	284.35
Production of pulp, paper and board	6.9	7.1	8.5	22.5	7.05	11.59	10.31	13.38	42.33
Total	82.9	39.9	36.1	159.0	-161.53	94.20	59.46	292.11	284.25

How are these figures reflected in the market prices? Figure 1 shows the price development of the allowances in all three periods. The first-period price approached zero far before the end of the period in 2007. This was due to the joint effect of overallocation of allowances and actual abatement, which caused a surplus in the market (Ellerman and Buchner, 2008, Anderson and Di Maria, 2011). The second period permit price has been less volatile, but the economic turmoil in late 2008 and early 2009 is reflected in the EUA price as well. The recession caused production and emissions levels to decrease and thus the demand for and price of permits decreased as well. The third period prices follow the second period prices closely, as so many aspects of the third period are still uncertain and banking of allowances from the second period to the third are allowed. Emissions forecasts for the third period are based on the expected economic growth rates in the EU area. The surplus is most likely to be consumed by the middle of the third phase, and the price estimates and predictions for the third period are between 15 and 20 € per ton. (ThomsonReuters, 2012). At this writing, it seems that the possibility of banking and borrowing will keep third period price levels close to the current second period forward prices. The value of the EU ETS market was approximately 120 billion USD in 2010, having increased from a value of 8 billion dollars in 2005. (State and Trends of the Carbon Market, 2011).

Figure 1. Price series of three different permits during the study period. Source: ThomsonReuters, 2012.

Despite seven years of active trading, the market is still developing and many aspects of it need to be reconsidered and modified if it is to give a more accurate price signal. To improve the reliability of the price signal, the Commission has decided to implement several changes and improvements for the third period. The most influential changes will be the longer trading period and the change of the main allocation method from grandfathering to auctioning. Allocation will be carried out at the EU-level and not by the member states, and national registers will be replaced by a single EU-level register to avoid the problems of VAT fraud and IT hacking that the system encountered during the first period. Moreover, new greenhouse gases and sectors are included in the system. In addition, the process of linking the ETS with other emissions trading schemes towards a global carbon price is ongoing. (State and Trends of the Carbon Market, 2011).

4. Data and econometric models

4.1 Time series data

Time series data represent a compound of observations of a statistical variable made successively in time. Time determines the order of the observations. The statistical analysis of a time series is based on the fact that a time series is interpreted as a realization of a stochastic process. A stochastic process $\{x_t\}_{t=-\infty}^{\infty}$ is a sequence of random variables indexed in time *t*. We are interested in the conditions under which we can treat the stochastic process as a random sample as the sample size goes to infinity. Stationarity is a characteristic of the sequence of moments of a distribution. A time series process $\{x_t\}_{t=-\infty}^{\infty}$ is covariace stationary if it is true for its moments that

$$E[x_t] = \mu \tag{1}$$

$$Var(x_t) = \sigma^2 \tag{2}$$

$$Cov(x_t, x_s) = \gamma_{t-s}, t \neq s \tag{3}$$

Equations (1) – (3) indicate that the process has a constant mean and variance and that the covariance is not dependent on the time, but only on the distance between *t* and *s*. A stationary process thus does not exhibit characteristics of deterministic or stochastic trends, systematic variation in variance, deterministic seasonality or changes in internal structure.

The time series data used in this thesis consist of price series data on daily, weekly and monthly bases from varying time spans from 2003 to 2011. The main data sets are the price series for an EUA, fuel prices (coal, gas and oil prices) and European electricity prices. Figure 2 describes the key variables as daily observations. The data sets are presented in detail in each of the essays. The series seem to follow relatively similar time paths and thus anticipate high correlation levels, the correlation being particularly high between regional electricity prices. They follow each other closely but only at different levels. The price of electricity in the Nordic countries has traditionally been below the central European price due to the high proportion of hydropower in the north. Recently, however, price levels have converged within Europe as transmission capacities have increased (Weigt, 2009).

Fuel prices also appear to be closely related. As a global commodity with a world market price, coal has had a stable price for a long time. However, the increasing demand in China and logistical problems caused a price spike in 2008. The economic recession later brought the price back to its long-term levels. The price of gas has been more volatile and as a local product it is more sensitive to changes in the market. Its correlation with the price of an EUA is the highest of that for any of the fuels. This might be due to the central role of fuel-switching for the ETS participants in emission reductions. We use the difference in prices between gas and coal as a proxy for fuel-switching. The gas price is also often indexed to the oil price, which reflects the economic situation quite closely. Economic growth seems to be the main driving force of market fundamentals such as electricity and fuel prices and thus the price of an EUA as well. Electricity and energy prices are also affected by weather fundamentals. (ThomsonReuters, 2012).[4]

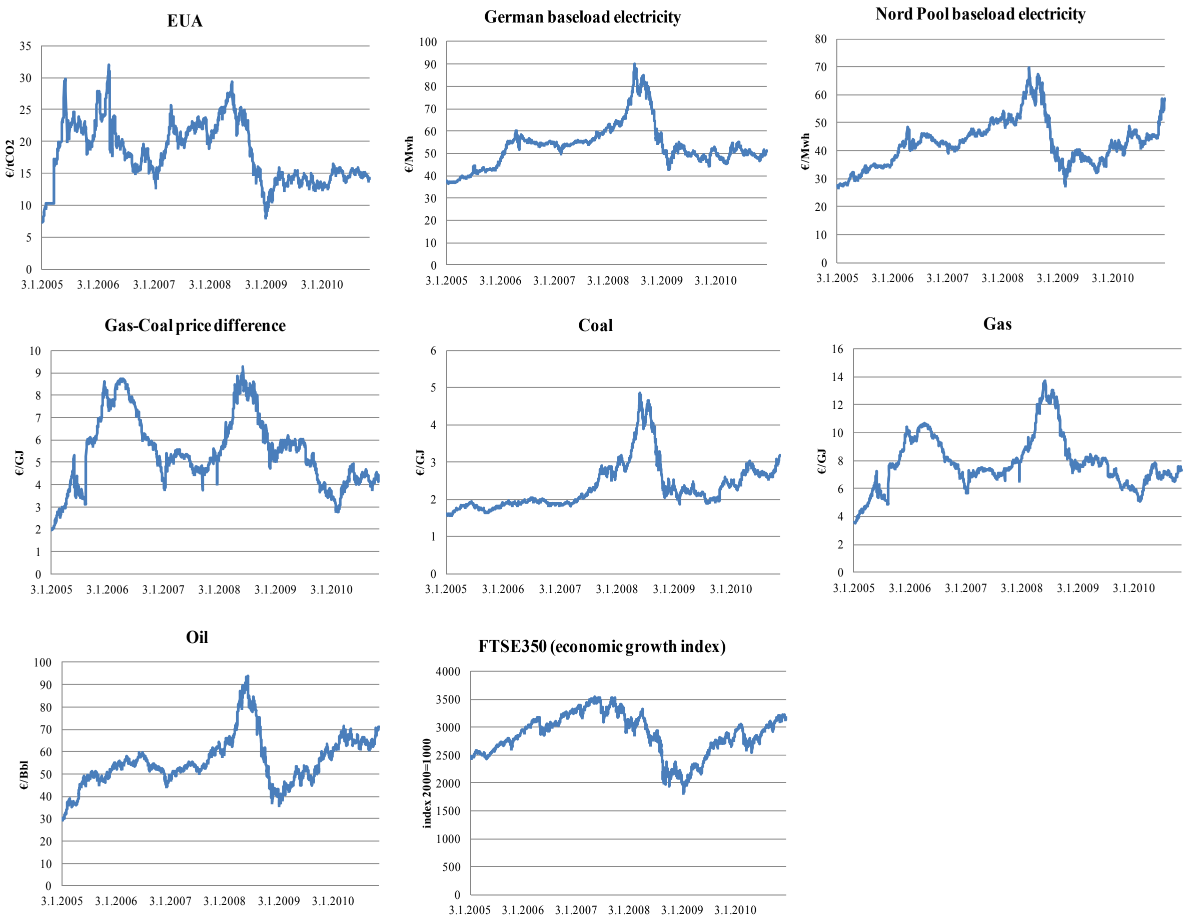

Figure 2. The main data variables of the thesis.
Source: ThomsonReuters, 2012.

[4] All prices are converted to euros using the relevant exchange rates. Fuels are converted to €/GJ. The EUA price is the compound of the yearly forwards. Electricity prices represent the baseload yearly forwards from EEX and NordPool. Gas is the UK winter gas price forward and coal (CIF ARA2) is the world market price for a yearly forward. Oil is the Brent oil yearly forward.

There are several ways to examine the character of the time series. Eyeball econometrics suggests that the series in Figure 1 is non-stationary, but only proper tests can confirm this. Studying the correlograms and running unit root tests for the series reveals the stationarity of the series. Based on autocorrelation and partial autocorrelation functions, the correlograms bring to light the autoregressive and moving average characteristics of the series. Correlograms show the correlations between two points in time. If there is no correlation in time, the process has no memory and is thus stationary. If, however, the process has a memory that is evolving in time, it is said to have a unit root. A linear stochastic process has a unit root if one is a root of the process's characteristic equation. The most common tests for determining whether a process has a unit root or exhibits stationarity are the Dickey-Fuller and augmented Dickey-Fuller (Dickey and Fuller, 1981), Phillips-Perron (Phillips and Perron, 1988) and KPSS (Kwiatkowski et al., 1992) tests. These are the ones used in our applications

Figure 3 shows the EUA price in stationary form, which is obtained by taking the logarithm of the first difference. The EUA price series in level (see Figure 1 and 2) is non-stationary*,* integrated of order of one, *I(1)*. It has to be differenced once to obtain a stationary series. In general, a non-stationary series is integrated of order *d, I(d)* if it becomes stationary after being differenced *d* times. A stationary stochastic process has many favorable properties in estimation work and it is a prerequisite for obtaining consistent estimates with least-square estimations. The stationary assumptions may seem restrictive, but many processes can be transformed into stationary form. These transformations include taking logarithms, differencing, eliminating outlying observations, and decomposing series. Of these, the most commonly used in our applications are differencing and taking logarithms. But we also use seasonal decomposition, affected by employing seasonal dummies and eliminating outlying observations according to the influential observation statistics.

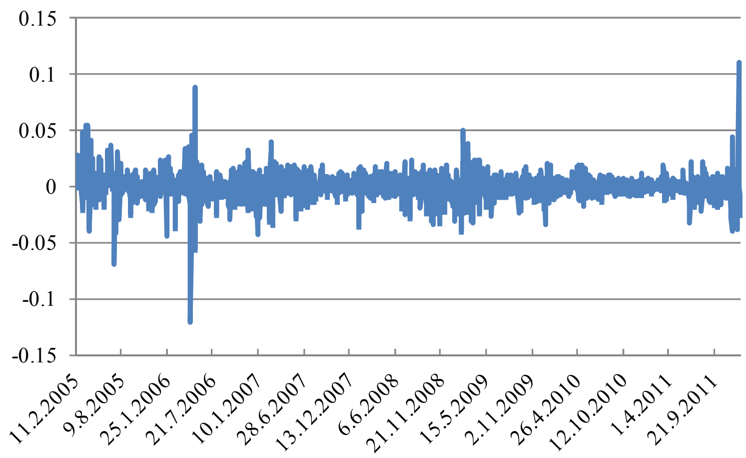

Figure 3. The log-differenced price of EUA.

4.2 Applications in this thesis

This section presents the basic features of the applied econometric models. The models, data and the statistical tests used in each sub study are presented in more detail in each paper.

Classical linear regression model

The multiple linear regression model as shown in equation (4) is the point of departure for the empirical part in this thesis. We are basically interested in the relationship that the independent variables $x_1, x_2, ..., x_k$ have with the dependent variable y_t. This relationship is summarized by the β parameters that are to be estimated.

$$\begin{aligned} y_t &= f(x_1, x_2, ..., x_k) + \varepsilon_t \\ &= x_1\beta_1 + x_2\beta_2 + ... + x_K\beta_K + \varepsilon_t \end{aligned} \tag{4}$$

ε_t is the random disturbance term that captures the effect of all omitted variables on the dependent variable. The observed value of y_t has thus two parts, a deterministic part and the random part. The objective is to estimate the unknown parameters of the model and use data to study the validity of theoretical propositions. How the parameters should be estimated depends critically on what is assumed about the stochastic process that has led to the observations of the data in use. (Greene, 2003)

The focus of this thesis is on the analysis of multiple time series, with the estimations run using the classical ordinal least squares (OLS) method and its extensions. As a simple estimation technique, OLS is widely used in the econometric literature. OLS is applicable under a set of assumptions regarding the underlying data-generating process. These assumptions of linearity, full rank, exogeneity of the independent variables, homoscedasticity, as well as the non-autocorrelation and normal distribution of disturbances, make the interpretation of the OLS estimators straightforward. (Greene, 2003). If the assumptions hold, OLS produces efficient (minimum variance) and consistent (unbiased mean) estimators. If, in addition, the residuals are normally distributed, OLS coincides with maximum likelihood (ML) estimation.

In the first paper, we estimate the log-differenced price of a EUA using market fundamentals. We use the log-linear functional form and test the hypotheses derived from the analytical model. All the data series are transformed into the log-differenced stationary form, in which the coefficients can be interpreted as cross-commodity elasticities. We include lagged variables in the model, applying a common feature of time series data. Lagged variables bring dynamics into the models and, where causality is dynamic, may allow us to interpret the causal relationships underlying price adjustments. The right lag order for the variables is tested for using information criteria tests.[5]

Instrument variables models

In the first paper, the price of electricity is one of the explanatory variables in estimating the returns of the EUA price. Economic reasoning suggests this might cause a problem of endogeneity. The way of causality runs between the price of EUA and electricity is not straightforward. So the assumption of exogeneity of the independent variables with the dependent variable does not hold any more and this might cause OLS to produce biased estimators. We address this problem by using instrument variables. Using stock variables related to electricity production, such as water reservoirs, gas storages and the economic growth as instruments for the electricity price, we can avoid the endogeneity problem. Instrument variable models are run in two stages with a two-stage least squares (TSLS) procedure. In the first stage the endogenous variable is regressed on the instrument variable. This estimate is then on the second stage used as the independent variable to get the unbiased instrument variable estimate.

In order to maintain the assumptions of efficient and unbiased estimations, the chosen instruments, z_t, must fulfill two properties: valid instruments must be relevant and exogenous; that is, the correlation between the instrument and the endogenous variable must be non-zero (5a) and the instrument must not correlate with the models' error term (5b).

$$corr(z_t, x_t) \neq 0 \tag{5a}$$

$$corr(z_t, \varepsilon_t) = 0 \tag{5b}$$

The correlation between the variables can be tested using the weak instrument tests. To ascertain whether the instruments exhibit exogeneity, we ran the weak exogeneity test for all instrument variable models. The Cragg-Donald statistic is proposed by Stock and Yugo (2005) as a measure of the relevance of the instruments in an instrument variable regression. Exogeneity of the instrument variables is not fully testable. In case we have more instruments than necessary, we can perform a so-called J-test for over-identifying restrictions. This tests whether all instruments are exogeneous assuming that a least one of the instruments is exogenous. The J-Test will therefore not necessarily detect a situation in which all instruments are endogenous. (Hansen, 1982).

[5] Akaike and Schwarz (Bayesian) information criteria. (See e.g. Greene, 2003).

Vector autoregressive models

In order to get robust estimations and to avoid setting a priori assumptions on the stationary time series regarding endogeneity or exogeneity of the variables, we also estimate the system of price relationships with a vector autoregressive model (VAR), which estimates the linear dependences between multiple time series as a generalization of the autoregressive models. In a VAR model several equations are run simultaneously to find out how they react to shocks of other variables. In general, a VAR model is of the form

$$X_t = \eta + \sum_{i=1}^{p} \Phi_i' X_{t-1} + U_t \tag{6}$$

where $X_t = m \text{ x } 1$ is a vector of endogenous variables, η, a vector of deterministic and exogenous variables, and Φ_i is a $m \text{ x } m$ coefficient matrix. U_t is the error process. VAR models were originally introduced by Sims (1980) as a criticism towards the large structural models with identification restrictions. VAR models do not need any expert knowledge but can be estimated without a prior assumption of the structure of the problem.

VAR models are widely used in the macroeconomic applications. In this thesis they are applied in their two other primary functions namely for testing Granger causality and impulse responses. With the Granger causality test, we can study the relationship and the predictability between the time series (Granger and Newbold 1986). Granger causality does not reveal structural causality between the variables; it only tells whether adding one variable improves the predictability compared to autoregressive (AR) models. We can extract three different outcomes for Granger causality: unidirectional causality, bidirectional causality and independence, meaning exogeneity of prices. Sims (1980) points out that a necessary condition for X to be exogenous of Y is that X fails to Granger-cause Y.

In VAR analyses it is standard practice to report impulse responses and forecast error variance decompositions. These are more informative in understanding the relationships than the VAR regression coefficients or R^2 statistics. The variance decomposition (forecast error decomposition) is the percentage of the variance of the error made in forecasting a variable due to a specific shock at a specific time horizon. Impulse responses reflect the response of current and future values of each of the variables to a one-unit change in the current value of one of the VAR errors.

In VAR estimation the determination of the lag length is essential to avoid residual serial correlation, which is tested with the standard LM-test. The right lag order can be tested for by information criteria, an LR test or log likelihood tests. Also crucial, in addition to the lag length, is the order of variables, for it might affect the results impulse response results. Accordingly, it is important to use the generalized impulse response functions proposed by Pesaran and Shin (1998), which are invariant to the ordering of the variables in the system.

Vector error correction and cointegration models

By transforming the non-stationary series into stationary form, one loses the possibility to interpret the long-run effects. To capture those effects – the long-term equilibrium –estimation with non-stationary data is needed. In the third essay, we study the electricity and EUA price series in their non-stationary form to investigate the integration of the electricity markets and the impact of the price of carbon on converging electricity prices. Even with non-stationary time series, one might find stationary cointegrated relationships between the variables. Cointegration analysis makes it possible to estimate non-stationary data without running into problems of spurious regression. Cointegration analysis examines possible common trends between the variables. If the series move together, they share a common trend and are cointegrated.

If all the variables in a VAR model are *I(d)* with *d>0* (non-stationary) we can apply the cointgeration method for estimations. With the Johansen (1988) cointegration method, we can write the basic VAR model as in the equation (7) to separate the long-run, Π, and short-run, Γ, effects.

$$\Delta X_t = \Pi X_{t-1} + \Gamma_1 \Delta X_{t-1} + \ldots + \Gamma_{k-1} \Delta X_{t-(k-1)} + \varepsilon_t \tag{7}$$

where $\Pi = -(I - A_1 - \ldots - A_k)$ and $\Gamma_i = -(I - A_1 - A_2 \ldots - A_i)$, $i = 1, \ldots k-1$

Π is a $(K \text{ x } K)$ matrix. The rank of $\Pi = \alpha\beta'$ defines the number of cointegrating relations, r, in the data. The rank is chosen based on the trace and eigenvalue tests.[6] If Π has a full ′rank, $r = K$ all the variables are stationary in levels, if $r = 0$ there are no stationary linear combinations. For $0 < r < K$ there are r cointegration vectors of stationary linear combinations of y_t. After finding the cointegrating relations we can impose them to the reduced vector error correction (VECM) model and write it in the following way:

[6] Trace test testes the hypothesis of *r* cointegrating vectors with a following test statistics

$$\lambda_{\text{trace}} r = -T \sum_{r+1}^{n} \ln(1 - \hat{\lambda}_i) \tag{*}$$

The maximum eigenvalue test has a null hypothesis of *r* and the alternative hypothesis of *r+1* cointegrating vectors

$$\lambda_{\max} r, r+1 = -T \sum_{r+1}^{n} \ln(1 - \hat{\lambda}_{r+1}) \tag{**}$$

In (*) and (**) *T* is the number of observations and $\hat{\lambda}$ is the eigenvalue of the matrix Π. Johansen and Juselius (1990) provide critical values for both tests.

$$\Delta X_t = \alpha\beta' X_{t-1} + \Gamma_1 X_{t-1} + .. + \Gamma_{k-1}\Delta X_{t-(k-1)} + Cd_t + u_t \tag{8}$$

Equation (8) shows the long term equilibrium relation and short term adjustment coefficients with the cointegrated vector error correction model where the deterministic factors (d_t), dummy variables and constant affect the short run dynamics of the price series that revert towards the equilibrium vectors $\beta' X_{t-1}$ according to the adjustment coefficient α.

The decomposition of the matrix $\Pi = \alpha\beta'$ as a product of two *(K x r)* matrices is not unique and thus it crucial to impose restrictions to get identified and stable cointegration relations. In our case the restrictions are imposed based on the theoretical hypotheses. If the restrictions are binding, we get identified relations. One has to also normalize the vector on one of the variables to get easily interpretable results. We can set restrictions on both α and β. By setting restrictions on β we can test e.g. the degree of market integration or the law of one price. With the restrictions on α we can test the long term weak exogeneity of a variable. If a variable is weakly exogenous the other variables are not affecting it but it is driving the other prices. With the weak exogeneity test it is possible to identify the driving forces behind the common trends. (Lütkepohl, 2007).

GARCH models

Our papers on price determination (Essay I) and informational efficiency (Essay II) use daily and weekly data. With high frequency financial data volatility clustering is common**.** Volatility clustering refers to an observation where large changes follow large changes and small changes follow small ones – in both signs. (Mandelbrot, 1963). Volatility clustering can be seen in Figure 3 in the log returns of the EUA. The other data series have similar characters. To address this feature we apply the generalized autoregressive heteroscedasticity models known as GARCH models, which incorporate a separate equation for the variance of the residual term, to be estimated simultaneously with the mean equation. The original contributions are by Bollerslev (1986) and Engle (1982). GARCH(*p,q*) is a model where *q* is the order of the autoregressive term and *p* stands for the moving average term. Models used in the analysis are in general of the following form:

$$X_t = \phi' Z_t + \varepsilon_t, \quad \varepsilon_t = \sqrt{\sigma_t^{\,2}}\, v_t \tag{9a}$$

and

$$\sigma_t^2 = \omega + \sum_{i=1}^{p} \alpha_i \varepsilon_{t-1}^2 + \sum_{j=1}^{q} \beta_j \sigma_{t-j}^2 \tag{9b}$$

where X_t is the dependent variable, Z_t, is a matrix of explanatory variables in the mean equation (9a), and (9b) shows the conditional variance, σ_t^2, of the error term that is regressed on its lagged values and the lagged values of the squared error term of the mean equation. v_t is an i.i.d. sequence with zero mean and unit variance. [7]

Model diagnostics

In the empirical work it is standard procedure to run post-estimation tests to check the model fit, coefficient significance, and stability. In time series analysis, the most important step is to run residual diagnostics. This applies to all of the models discussed above. Serial autocorrelation can be tested in several ways. Two common tests that are applicable in our papers are the Q-statistic and the Breusch-Godfrey LM-test. They overcome limitations that the basic Durbin-Watson test faces, and are preferred in most applications. Correlograms and the Ljung-Box Q-statistics are often used as a test of whether a series is white noise (Ljung and Box (1978)).The Breusch-Godfrey LM-test belongs to the class of asymptotic tests known as Lagrange Multiplier (LM) tests. Unlike the Durbin-Watson statistic for AR(1) errors, an LM-test may be used to test for higher-order ARMA (autoregressive and moving average) errors and is applicable whether or not the model includes lagged dependent variables. Heteroscedasticity of the residuals affects not only the serial correlation, but also the estimations. Ordinary least squares estimates are consistent in the presence of heteroscedasticity, but conventionally computed standard errors are no longer valid. We run all the models with heteroscedasticity and autocorrelation consistent covariance (HAC) with a Newey-West estimator. (Newey and West, 1987).

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[7] GARCH-M (Engle, Lilien and Robins, 1987) and EGARCH-M (Nelson, 1991) are models to capture the volatility clustering in the price series. These models allow one to study the relationship between the market risk and expected returns. In the GARCH-M models, the conditional variance of the return is added as an independent variable in the mean equation to explain the conditional return. δ in (*) captures the effect that the higher variability in ε_t has on the return. We use the GARCH-M model, which is described with the following mean equation:

$$X_t = \phi' Z_t + \delta\sigma_t^2 + \varepsilon_t \qquad (*)$$

The exponential general autoregressive conditional heteroskedastic (EGARCH) model by Nelson (1991) is another extension of the GARCH model. EGARCH models allow the volatility to react in an asymmetric way to changes in the volatility. It has been shown empirically that volatility tends to rise in response to a decrease in returns and fall in response to an increase in returns (see e.g. Pagan and Schwert (1990), Engle and Ng (1993)). Now the conditional variance for an EGARCH in ARMA (*p,q*) form is

$$\log(\sigma_t^2) = \omega + \sum_{k=1}^{p}[\alpha_j \varepsilon_{t-i} + \gamma(|\varepsilon_{t-i}| - E[|\varepsilon_{t-i}|])] + \sum_{j=1}^{q}\beta_j \log(\sigma_{t-j}^2) \qquad (**)$$

with lag of order *p* and *q* respectively.

The post-estimation tests and diagnostics vary if the model is used for forecasting purposes rather than for finding causal relationships. This is the case in the second paper, in which we build up models forecasting EUA returns to detect signals in the trading simulation. We build up several forecasting models with the fundamental variables. The selection of a forecasting model is based on the accuracy of the resulting forecast rather than on the model fit or statistical significance of the coefficients. In our case, the model selection criteria include the rolling and recursive root mean square forecasting error (RMSFE), the Bayesian information criterion (BIC), and adjusted R^2. The choice of criteria in selecting a model is not, however, straightforward. Inoue and Kilian (2006) have proven that using information criteria (IC) would be consistent, under suitable conditions, with choosing the best forecasting model, whereas calculating the RMSFE (rolling or recursive) might end up suggesting over-parameterized models.

5. Summaries of the essays

5.1 Price determination in the EU ETS market: theory and econometric analysis with market fundamentals

In the first paper, we investigate the price determination and development in the EU ETS market during its first five years (2005–2010) in action. The EU ETS covers the energy sector and energy-intensive industries, which encompass over 12 000 installations within the EU. The first five years of trading have shown that the system works well and has reduced emissions below the cap. Market development has not been without difficulties, however. For instance, during the first phase (2005–2007), the over-allocation of permits affected market development and price formation, showing up as high volatility and eventually a zero price. Yet, even though the first phase suffered from these problems, it served its purpose as a learning-by-doing period quite well (see e.g. Ellerman and Buchner, 2008; Egenhofer et al. 2011).

More specifically, we ask to what extent the permit price reflects market fundamentals, that is, abatement possibilities, end product prices and production costs. To develop hypotheses for the econometric analysis, we build an analytical model of permit market equilibrium given stochastic permit prices and risk-averse firms. Drawing on Holthausen (1979), we assume that firms hedge against the uncertain permit price. The firms engage in forward trading to manage their portfolio so that their production and abatement decisions can be made using the expected value of the allowance forward price. We test the model empirically using econometric time series models.

Our analysis differs from that in previous studies in several respects that yield more adequate and robust estimations. First, unlike previous studies on emissions permit prices, our research combines insights from a theoretical model with empirical estimations to get a robust view of the market and price estimates. Second, to get robust results and to avoid the problems caused by possible endogeneity of electricity prices we employ three different econometric models to estimate the permit price: OLS, IV and VAR models. Third, we use a whole daily data set with no breaks from the very beginning of the trading period to the end of 2010, during which time the development of the market was rapid and price volatility quite high. Finally, and in contrast to many empirical papers relying on spot data (e.g. Alberola et al. (2008) and Rickels et al. (2007)), we use forward price data throughout the data set to underline the nature of the market, where risk-averse firms hedge by forward trading. This has an additional advantage: forward trading is far more liquid than spot trading and we can therefore expect that forward trading better reflects the fundamentals. Forward trading has accounted for 80–90% of the trading in the market, and spot trading for only 10%. (State and Trends of Carbon Market, 2011).

5.2 Informational efficiency of the EU ETS market – a study of price predictability and profitable trading

In this second essay, we investigate the informational efficiency of what was a new and emerging EU ETS market. If the market is information-efficient, the best predictor of the next period's price is the current price; the rest of the price evolvement is just white noise. Thus, predicting the price of an EU Emission Allowance (EUA) provides no systematic economic profits, meaning that the returns can at most cover the risk premium and transaction costs. These definitions of informational efficiency stem from theories introduced in the late 1960s and early 1970s. Seminal contributions include the studies by Roberts (1967), Fama (1970) and Jensen (1978), the last of whom describes a market as efficient if the market price reflects all information and adjusts immediately to any new information.

In this paper we examine the informational efficiency of the EU ETS market by focusing on the first category, that is, the return predictability, in Fama's classification of informational efficiency. In contrast to weak form efficiency or event studies, no standard test procedures exist for examining predictability. We base our analysis on the innovative definition of efficient markets provided by Timmermann and Granger (2004). Following this definition we use, for the first time in the emissions trading literature, trading simulations as a means of examining informational efficiency. In our simulation, the information set, X_t, includes the price series that most probably are connected to the EUA price, such as electricity prices or fuel prices. Search technology, S_t, refers to the model selection criteria and the choice of buying and selling signals. Thus, our model set, M_t, and trading strategies consist of a large number of strategies that traders could have adopted in the EU ETS markets. We use three set of models: 1) technical analysis models, 2) fundamental-based regression models and 3) GARCH models.

This is the first study to examine the efficiency and, in particular, the predictability of the price of an EUA using a trading simulation. We find that if traders had used a large set of models in their trading analysis toolbox and, in particular, had combined the models, profitable trading during the first years of the EU ETS would have been possible, a situation indicating that the market was not information-efficient at that time. These results give insights into the progress of the new climate policy market mechanism.

5.3 Impact of the carbon price on the integrating European electricity market

In this paper, we investigate market integration within the four different electricity markets representing six price areas in the EU in the presence of two policies: EU ETS and integrating electricity markets. We study these questions using the price data from February 2003 until August 2011 for different regional electricity markets: the Nordic countries, the UK, Central Europe and the Iberian Peninsula. We investigate the focal issues in sub-periods to see how the interdependences have evolved over time. Our research questions and hypotheses are the following: How has the EU ETS market affected the integration of the European electricity markets and convergence of electricity prices? How is the price of an EUA reflected in the long-run relations between electricity prices? Do the prices share a common trend?

As a common, EU-wide market the EU ETS creates a new cost factor for fossil-fuel-based electricity production. This cost factor may impact regional electricity prices differently due to differences in the energy mixes. Yet, at the same time, the integrating electricity market and increasing transmission capacities create incentives for electricity prices to converge. We estimate the long-run price relationships between the different prices before the implementation of the EU ETS (2003–2004) and during the two phases of the system (2005–2007) and (2008–2012). We expect the integration of electricity prices to be stronger during the latter parts of the periods studied due to the increasing transmission capacities and institutional building in the single EU-wide electricity markets.

To study these questions, we derive a theoretical framework for the residual demand and supply for a competitive profit-maximizing firm operating in the energy market and engaging in emissions trading. From this analysis we derive the hypotheses to be tested in the empirical work. There we incorporate the hypotheses into the examination of market integration and the law of a single price, addressing these questions using methods for time series analysis. We start with a simple correlation analysis and pairwise Granger causality analysis to elicit the relationships between the variables. Then we run a cointegrated VAR model with multivariate time series based on cointegration analysis as described in Johansen (1988). We study the common trends within these markets and examine the variance decompositions to find the price relationships and driving forces.

To our knowledge, this is first study to look at the impact of the carbon market on the integrating electricity markets. By studying these questions, we shed light on the integration and price convergence process in these strongly related markets. The results that show integration among the prices has improved over time and that, in line with our hypotheses, the impact of the price of an EUA on the electricity prices has been a positive but uneven one. In the short run, the price of an EUA might even disperse the prices, whereas in the long run increasing transmission capacities and the incentive of the carbon price will accelerate the price convergence.

5.4 Climate change and electricity consumption – witnessing increasing or decreasing costs?

Climate change affects the need for heating and cooling. This paper examines the impact of a gradually warming climate on the need for heating and cooling using an econometric multivariate regression model for five countries in Europe along the south–north line. The predicted changes in electricity demand are then used to analyze how climate change will impact the cost of electricity use, including carbon costs.

The two research questions of the paper are the following. First, will the electricity demand increase or decrease in the five countries? Second, how large will the costs associated with the expected change be, measured in terms of the estimated electricity and carbon prices? To answer these questions we estimate the response of electricity consumption to heating and cooling degree days in each country using historical data with a country-based multivariate regression model. Drawing on these estimates, we use regional climate projections (PRUDENCE, 2004), which are scaled by global projections taken from the Intergovernmental Panel on Climate Change (IPCC) (Meehl et al., 2007). Uncertainties in climate projections are taken into account using three IPCC SRES emission scenarios (A2, A1B, and B1) for the period 2008–2050, 2007 being the baseline. Estimated temperature increases are used to assess the expected change in electricity demand. Finally, we estimate the costs of the anticipated gradual temperature increase as a sum of electricity and carbon prices.

We follow previous analyses in estimating the impact of temperature on electricity consumption, but extend those studies by estimating the future impacts of climate change as well. Furthermore, unlike Amato et al. (2005) and Ruth and Lin (2006), we assess both the costs of electricity use and the associated carbon costs using country-specific information on the marginal fuel in electricity production. Our main findings are that in central and northern Europe a decrease in heating due to climate warming will dominate and thus costs will decrease both for users of electricity and in carbon markets. In southern Europe, however, climate warming and the resulting increase in cooling and the demand for electricity will exceed the decreased need for heating and will thus increase costs overall. The main contributors are the role of electricity in heating and cooling and the climatic zone.

6. Conclusions

This thesis contributes to the empirical literature on the EU ETS market. By analyzing the market based on analytical and empirical models the essays shed light on the first years of the new market. For the EU ETS to serve as a policy instrument that reduces emissions, the markets should be well functioning and produce a credible price signal. The essays comprising this thesis study efficiency and price determination in the market. The results provide insight of the functioning of this policy instrument.

The results of the first study, based on analyses of time series data, reveal that the EUA reflects the market fundamentals in line with the hypotheses from the relevant theoretical framework. In the second essay, we build up a trading simulation model to study the market's informational efficiency. The simulation brings to light possibilities for profitable trading and thus reveals a lack of informational efficiency in the market during the second trading period (2008–2012). The third and fourth essays demonstrate the close relationship between the carbon and the electricity markets. The carbon price is shown to have a positive impact on the electricity price: as the price of carbon increases, the price of electricity increases as well. How strong this impact is depends on, among other things, the marginal fuel in electricity production. Carbon has a greater impact on the production of coal-based electricity than, for example, gas-based.

The main goal of the EU ETS is to price carbon and internalize the pollution externality into that price. The system is one of the first-large scale attempts worldwide to do so. The price of an EUA gives a signal and incentive for compliant participants in the ETS to seek carbon-free solutions for production and reduce their emissions. In the short run, this means switching fuel in electricity production; in the long run the price of carbon might affect investments. For policy planners, the price of carbon provides unique insights into the private costs of the energy sector as well as possibilities to adjust policy to meet overall emission reduction targets.

The EU ETS has created a price for carbon, but its ultimate goal is to have a global price for carbon in order to avoid what has been an uneven cost burden across multinational industries. Linking the EU ETS with other carbon markets around the world is the next step towards a global carbon market and a single global price for carbon. There is a long way to go before this goal is achieved, however, even though the ETS and market-based instruments have recently become more popular in environmental policy. The harmonization of trading rules and institutions within the EU alone has been a challenge; including more actors would make the task even more demanding.

There are several options for extending empirical research on the carbon market. The tight relationship between the electricity markets could be studied more closely by modeling the two markets simultaneously; for example, relaxing the assumption of competitive markets in the EU ETS and end-product markets would offer exciting empirical research questions. A study of data on how the overlapping of the ETS with other policy instruments, for example, the promotion of renewable energy with feed-in tariffs, impacts the price of carbon would probably yield some interesting results as well. In addition, applying other econometric models and larger data sets would be useful as robustness checks of the results obtained to date.

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