ABSTRACT

Title of Document: PRICING CARBON: ALLOWANCE PRICE DETERMINATION IN THE EU ETS

Beat Hintermann, Ph.D., 2008

Directed By: Prof. A. Lange, Department of Agricultural and Resource Economics (AREC)

The allowance price in Phase I of the European Union Emissions Trading Scheme (EU ETS) followed a peculiar path, increasing from €7 in 2005 to over €30 in 2006, before crashing, recovering and ultimately finishing at zero by the end of 2007. I examine if the price can be explained by marginal abatement costs as predicted by economic theory, or if there were other price determinants. This has important policy implications, since the least-cost solution depends on the equality of permit price and marginal abatement costs and is the main argument in favor of permit markets.

I start with a model that incorporates the most commonly cited market fundamentals and find that the latter only explain a small part of the allowance price variation, raising the question of a bubble. I carry out two different bubbles tests, the results of both of which are consistent with the presence of an allowance price bubble.

I then address whether market manipulation by dominant power generators could have lead to the initial allowance price increase. I extend economic theory to include the interaction between output and permit markets. I derive a threshold of free allocation beyond which firms find it profitable to manipulate the permit price upwards, even if they are net allowance buyers. Market data indicates that this threshold was exceeded for EU power generators.

Finally, I investigate the possibility that due to the speed at which the market was set up, firms may have been unable to engage in effective abatement before the end of Phase I. I develop a model under the assumption of no abatement, where firms aim to reach compliance exclusively by purchasing allowances on the market. Thus, the allowance payoff becomes that of a binary option, for which I derive a pricing formula. The model fits daily data from the years 2006-7 well.

I conclude that the allowance price in Phase I was not driven by marginal abatement costs, but by a combination of price manipulation, self-fulfilling expectations and/or the penalty for noncompliance weighted by the probability of a binding cap.

THE PRICE OF CARBON: ALLOWANCE PRICE DEVELOPMENT IN THE EU ETS

By

Beat Hintermann

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2008

Advisory Committee:
Professor Andreas Lange, Chair
Professor Albert S. Kyle
Professor Marc L. Nerlove
Professor John K. Horowitz
Professor S. Boragan Aruoba

Preface

This dissertation is a hybrid between a three-paper dissertation and a unified dissertation. On the one hand, it is based on three separate papers, two of which I already submitted to an economic journal; they are currently under review. I hope to submit the third paper shortly.

On the other hand, the three papers all treat the same subject matter: What drove the allowance price during the first phase of the EU ETS?

Chapters 1 and 6 contain a general introduction and conclusion, respectively, that are applicable to all three articles, and I removed the description of the market from the individual papers and concentrated it in a separate section (Chapter 2). I also made minor changes such as renaming equations, tables and figures. In spite of this, Chapters 3-5 remain largely self-contained and may give rise to some redundancy. They also are independent in terms of notation, such that a symbol or letter appearing in two different chapters may represent two different variables or parameters.

Dedication

To Mary.

Acknowledgements

I would like to thank all members of my dissertation committee for their support and guidance in this project. Special thanks go to the committee chair, Andreas Lange.

Many thanks also to faculty and fellow students at UMD-AREC for valuable insights and suggestions.

I gratefully acknowledge the Swiss National Fund, which provided funds during the last six months of this dissertation.

Table of Contents

Preface ii
Dedication iii
Acknowledgements iv
Table of Contents v
List of Tables vii
List of Figures viii
Chapter 1: Introduction 1
Chapter 2: The EU ETS 7
Chapter 3: Price Drivers and CO2 Bubbles in the EU ETS 12
  Abstract 12
  3.1. Introduction 13
  3.2. Allowance market model 16
    3.2.a.) Literature 16
    3.2.b.) Base model 19
    3.2.c.) Introducing dynamic expectations of fundamental prices 27
    3.2.d.) Introducing lagged EUA price changes 29
  3.3. Results 31
  3.4. A CO_2 Bubble? 36
    3.4.a.) Some bubble background 36
    3.4.b.) Bubble tests 38
    3.4.c.) Cointegration test 40
    3.4.d.) Regime-switching test 42
  3.5. Conclusions 45
Chapter 4: Market Power and Windfall Profits in Emission Permit Markets 48
  Abstract 48
  4.1. Introduction 49
  4.2. Market power in output and permit market 54
  4.3. Application to the EU ETS 64
    4.3.a.) General applicability 64
    4.3.b.) The UK power market 66
    4.3.c.) The German power market 70
  4.4. Conclusions 72
Chapter 5: An Options Pricing Approach to CO_2 Allowances in the EU ETS 75
  Abstract 75
  5.1 Introduction 76
  5.2. Emission allowance pricing in the absence of abatement 80
    5.2.a.) Literature on permit pricing 80
    5.2.b.) Derivation of option pricing formula 81

    5.3. Deriving the mean and standard deviation of future emissions 85
        5.3.a.) CO_2 emissions as a function of exogenous stochastic processes 85
        5.3.b.) Properties of the stochastic processes c_t and h_t 90
    5.4. Estimation 95
        5.4.a.) Data 96
        5.4.b.) Parameter estimation for electricity consumption and precipitation 99
        5.4.c.) Evaluation of the options pricing formula 102
    5.5 Conclusions 107
Chapter 6: Conclusions 110
Tables 114
Figures 122
Appendices 130
    Appendix A: Proof of Equation (3.8) 130
    Appendix B: Proof of Lemma 1 and Eq. (4.9) 132
    Appendix C: Derivation of variance and covariance of future emissions 137
References 141

List of Tables

Table 2.1: Summary results for Phase I of the EU ETS 114
Table 3.1: Results from estimating Equation (3.10) 115
Table 3.2: Results from estimating equation (3.11)... 116
Table 3.3: Cointegration test results 117
Table 3.4: Results from regime-switching tests.. 117
Table 5.1: Data availability and installed hydroelectric capacity by country........... 118
Table 5.2: Parameter estimates for diffusion processes... 119
Table 5.3: Correlation coefficients[a] among different series..................................... 120
Table 5.4: Parameter estimates from options pricing formula................................. 121

List of Figures

Figure 1.1: EUA price and trading volumes, Phase I 122
Figure 2.2: Allowance allocation and emissions by sector (total values)................ 123
Figure 2.3: Allowance allocation and emissions by sector (percent of total)........... 124
Figure 3.1: EUA, coal, gas, DAX and reservoir levels.. 125
Figure 4.2: Dark spreads and green dark spreads in Germany 126
Figure 5.1: Available electricity consumption data, pre-2006................................. 127
Figure 5.2: Weighted average precipitation in the EU 128
Figure 5.3: EUA price, prediction and forward price for Phase II 129
Figure 5.4: Sensitivity of prediction to variance of future electricity demand......... 129

Chapter 1: Introduction

On January 1, 2005, the world's first non-voluntary CO_2 emissions market opened for business. The European Union Emissions Trading Scheme (EU ETS) is the European Union's prime instrument to achieve its Kyoto targets. The system covers emissions from energy-intensive industries that are responsible for about 45% of the EU's total CO_2 emissions. The EU ETS is by far the largest regulated emissions permit market to date, dwarfing other markets in terms of total emissions, included installations and market value.

The market is organized into distinct phases that each have different caps and rules. The first phase covered the years 2005-2007, followed by the second phase, which coincides with the 2008-2012 Kyoto compliance period. No banking was allowed between the first and second phases, such that the first phase was a self-contained market with a finite time horizon. First-phase emission permits (called EU allowances, or EUAs) lost their value if unused for compliance.

The EUA price during the first phase followed a rather peculiar path, shown in Figure 1.1. It started around €7 but rapidly increased to levels above €20, even surpassing €30 at some point, before crashing to half of its value in April 2006, stabilizing again in the €13-18 region and finally decreasing to zero by mid 2007, where it remained for the rest of the market.

The initially very high allowance price is surprising considering that the first phase was understood to be a pilot run for the second phase, with the cap not expected to be very stringent. Even more surprising is the stabilization after the price crash, followed by a slow march to zero. Given that the market turned out to be oversupplied with permits, the price should have dropped to zero immediately, rather than over the course of a year, if it equals marginal abatement costs (unless, of course, the fundamentals driving marginal abatement costs also slowly declined over time).

The three main chapters in this dissertation (Chapters 3-5) are self-contained and different in their methods, tools, and even notation to some extent, but they all aim to answer the same question: What drove the allowance price during the first phase of the EU ETS?

This question is interesting from an economic theory perspective, but it is equally important in terms of policy implications. The main reason to institute a cap-and-trade market, as opposed to using command-and-control methods, is that it yields the lowest overall cost to reduce emissions to a specific target.[1] But if allowance prices are too high (i.e. above marginal abatement costs), then the least-cost argument vanishes and overall welfare might be better served using a different policy. Note that firms will pass on much of the marginal cost of carbon as they do with any other

---

[1] It shares this property with an emissions tax. In a world without uncertainty and full auctioning of permits (or at least no updating of free permit allocations based on events during the market), the permit price should equal the emissions tax for the same amount of emissions reduction.

input to production,[2] so in the end it will be consumers that pay too much for a given emissions reduction if allowance prices are above their efficient level.

In Chapter 3, I focus on widely identified fundamental price drivers and test whether and to what extent they are able to explain the observed allowance price path. A deviation between price and fundamentals is commonly referred to as a price bubble. To the extent that the existence of a bubble can never be fully proven due to an identification problem, I carry out two tests that examine whether or not the data is consistent with the presence of a bubble. The first test relies on a market model that assumes that the allowance price equals marginal abatement costs. I estimate this model using a regime-switching approach that allows the allowance price to depend differently on market fundamentals during different time periods. A likelihood ratio test reveals that the two regimes are not mutually independent, but that the state in the current period has an impact on the state probability in the next period (Markov switching). This is consistent with a bubble, or a series of stochastically crashing bubbles with interchanging boom and bust phases.

The second test relies on cointegration. If the allowance price and the supposed market fundamentals exhibit cointegration, this would be evidence that the price was indeed driven by fundamentals, and that therefore there was no bubble. I

---

[2] The degree of cost pass-through depends on the price elasticity of consumer demand. With completely inelastic demand, costs are fully passed through.

find no such cointegration in the data. Thus, while not conclusive, the results from both tests are consistent with the bubbles hypothesis.

Emission permits were initially given away for free in accordance with the European Commission's mandate that countries could sell at most 5 % of their total allowances, a measure taken to obtain industry support for the Directive. Chapter 4 examines one potential effect of free allocation on the allowance price. If firms were able to pass through the marginal cost of CO_2 to consumers, they were in a position to reap large windfall profits. In a competitive and efficient market, windfall profits should not lead to permit price distortions. However, this changes in the presence of market power. I examine how the initial allowance allocation affects the permit price under the assumption of market power in both the output and the permit market. This is an extension of Hahn's (1986) results, which prescribe that a dominant firm will manipulate the permit price upwards (downwards) if it is a net seller (buyer) of permits. I show that when taking the interactions between the output and permit market into account, this prescription changes in a significant way, meaning that the largest permit holders in the EU ETS (i.e. power producers) would have found it profitable to drive up the permit price despite the fact that they were net allowance buyers, assuming that they had some market power.

Although market power per se is unrelated to the issue of bubbles, every price bubble has to get started somehow. In addition to the basic subject matter that is the thread throughout this dissertation, this provides another link between Chapters 3 and

4: Market-power related price manipulation could have driven the allowance price upwards, leading to the beginning of an eventually self-sustaining price bubble.

Chapter 5 is motivated by the possibility that firms may have been unable to engage in significant abatement in time for the first phase. The market was set up at breakneck speed relative to "normal" time frames for instituting such markets,[3] providing little time for countries to determine historic emissions, define their caps and distribute them among different installations. Firms had even less time to prepare for the market, given that their individual permit allocations, the country-level caps and thus the total cap was not known until the market had already come into effect.

Because CO_2 cannot be captured in a cost-effective manner today, the main sources of abatement are changes in production technology towards less emission-intensive processes, and the substitution of fuels with a lower emission factor per unit of output. Since a change in production technology requires significant planning and construction time combined with a minimum level of price certainty, fuel switching[4] was commonly assumed to be the abatement method of choice in the first phase of the market. However, energy-intensive industries are generally locked into long-term fuel contracts and may have been unable to switch, or unwilling to do so until the price signal was more stable.

---

[3] The directive that mandated the EU ETS (Directive 2003/87/EC) was issued in October 2003, just over a year before the market started.

[4] This is not necessarily a substitution within the same plant, but a substitution across plants. For example, more of the total electricity demand could be produced using gas-fired generation while reducing the output of coal-fired generators.

If abatement is not feasible, firms will aim to reach compliance exclusively by purchasing allowances on the market.[5] With stochastic emissions the exact number of allowances needed for compliances is unknown ex ante. Firms face a situation where an additional allowance will be worth the same as the penalty for noncompliance if overall emissions exceed the cap at the end of the market, but be worthless if the cap turns out not to be binding. Thus, the payoff of an allowance becomes that of a binary cash-or-nothing option. In Chapter 5, I set up an options pricing model under the assumption of no abatement that expresses the allowance price purely as a function of the penalty and the probability of a binding cap, and fit the resulting options pricing formula to market data.

Chapter 6 draws conclusions on the combined findings in this dissertation.

---

[5] Note that the electricity sector cannot reduce output below demand, otherwise the grid would crash. The other sectors could in theory reduce output in order to curb emissions, but this is generally assumed to be a costlier measure than buying permits and/or paying the penalty for noncompliance.

Chapter 2: The EU ETS

In the following I describe the main features of the European Union Emissions Trading Scheme (EU ETS). For a more detailed introduction to the market, see Kruger & Pizer (2004) and the White Paper by the PEW Institute (2005).

The EU ETS covers CO_2 emissions from 6 broadly defined industry groups in all countries of the EU. These sectors are power & heat, metals and coke ovens, oil refineries, glass & ceramics, cement & lime, and paper & pulp. The emissions included in the market account for almost half of the EU's total CO_2 output. In the first phase, about 11,000 individual installations received a total of 2.1 billion EU allowances (EUAs) annually, mostly at no cost. One EUA gives the bearer a one-time right to emit one ton of CO_2.

The market is organized into distinct trading phases. The first phase spanned the years 2005-2007[6] and was considered a pilot run for the second phase, which coincides with the Kyoto compliance period of 2008-2012. Pilot phase allowances could not be banked into the second phase and lost their value if unused for compliance. Future phases are planned to last five years each, with no banking restrictions from one phase to the next. On the other hand, borrowing is not allowed between any two phases. But because firms receive annual allowances in March of

---

[6] The first trade of the EU ETS was made on February 27, 2003, between Shell and NUON (a Dutch utility) under a forward market.

every year but don't have to surrender allowances until the end of April, they can effectively bank and borrow across time within a trading phase.

Firms can trade allowances freely within the EU. Trades may occur bilaterally, through brokers (over-the-counter or OTC trades) or on one of six exchanges.[7] By April 31 of each year, firms have to surrender permits corresponding to their emissions in the previous calendar year. For every ton of CO_2 emissions for which firms cannot surrender an allowance, they are fined a penalty of €40 in the first phase, and of €100 in the second phase. In addition, they have to surrender the missing allowances in the following year.

Jurisdiction in the EU ETS is divided between the EC and the member states. The latter are required to submit detailed national allocation plans (NAPs) to the EC for every phase anew (in other words, the cap changes in every phase). This is a two-step procedure: First, member states have to decide how much of their overall emissions reduction burden (as defined by their individual Kyoto commitments) they want to assign to the EU ETS sectors within their countries, with the remainder of the burden falling on other sectors such as transportation and households. In a second step, the allowances have to be distributed among the individual installations. All NAPs have to be approved by the EC in order to minimize competitive distortions among similar companies in different member states.[8]

---

[7] These are ECX, EEX, EXAA, Climex, Nordpool and Powernext.

[8] Although the Trading Directive defines both least-cost achievement of the Kyoto targets and harmonization between member states as explicit goals, Boehringer and Lange (2005a) show that both cannot be achieved simultaneously, given the constraint of free permit allocation.

The scheme is based on Directive 2003/87/EC, which became law on October 25, 2003. This left little time for firms and EU member countries to prepare for the market. In setting up the first-phase NAPs, countries were faced with the problem that they had very little information about firms' historic emissions. Unlike US power plants that were subject to emissions regulations since at least the mid 1990's, most firms in the EU had never had to disclose emissions of other than local pollutants. The member countries addressed this lack of data by using industry projections generated by the firms themselves. In addition, most market participants expected that second-phase NAPs were going to be based on verified 2005 emissions (which was vehemently opposed by the EC, but which took place nonetheless given that this was the best data available to the member countries). Using industry projections and defining second-phase allowance allocations based on first-phase emissions clearly introduces incentive problems in the sense that firms were encouraged to over-state their expected emissions (in order to receive more first-phase allowances), and to under-abate (in order to receive more second-phase allowances).[9]

Permit allocations, trades and actual emissions are recorded in national registries run by each Member State, where all installations that are subject to the EU ETS have their individual accounts. The Central Administrator of the EU runs a central registry, called the Community Independent Transaction Log (CITL), which connects the 27 national registries and checks the recorded transactions for

---

Thus, there is a tradeoff between efficiency and fairness in terms of a "level playing field" between similar firms located in different member states.

[9] For the effects of updating on firms' decisions, see Boehringer and Lange (2005b).

irregularities. It is the duty of member states to establish and/or verify firms' actual emissions by multiplying energy inputs with appropriate conversion factors.

The EU ETS is linked to other carbon markets in the sense that certificates from Kyoto's Clean Development Mechanism (CDM), called CERs, and from Joint Implementation (JI), called ERUs, can be surrendered instead of EUAs. Some countries imposed a limit as to what the percentage of a firm's emissions can be covered with such non-EU based emission currencies, but these are still being worked out. In any case, neither CERs nor ERUs were actually available throughout the first phase, so for all practical purposes, the first phase of the EU ETS was self-contained.

Figure 2.1 shows allowances and emissions by EU member country for the year 2006. The largest six countries account for over 70%, both in terms of allocation and emissions. Allocation and emissions by sector are shown in Figures 2.2 and 2.3. The power & heat sector received nearly 70% of the total allocation. At the same time, this was the only sector with a net shortage of allowances, with all other sectors acting as net allowance suppliers.[10] In terms of installation size, about 90 % of the covered firms are relatively small (<1 Mt CO_2/y) and received about 19% of the total allocation. On the other extreme of the spectrum are the very large emitters (>10 Mt/y), which make up less than one percent of all installations in number but received more than a third of all allowances. Most of these large emitters are power plants.

---

[10] Note that these are aggregate numbers; individually, there were power stations with an allowance surplus in 2005 and 2006, and many industrial firms with a shortfall.

Pre-market expectations of the allowance price were generally very low,[11] and the steep price increase took many observers by surprise. For over a year, the allowance price was above €20, and at its peak it reached over €31 in April 2006. The April price crash was triggered by the first round of emissions verifications, which revealed that 2005 emissions were 94 MT below the cap.[12] The second round of emissions verifications in May 2007 again found an allowance surplus, but this no longer had a significant impact since prices had decreased to a few cents. Liquidity was overall high, and a significant amount of the total allocation was traded even in the first year. Table 2.1 shows a market summary of the first phase.

---

[11] In a simulation-based analysis of the EU ETS, Reilly and Paltsev (2005) calculated market-clearing marginal abatement costs to be € 0.6-0.9 for their base scenario, with prices in even the most extreme scenarios below €7. Medium price estimates by brokers were somewhat higher, around of €5.00 for the first phase (PEW, 2005).

[12] Emissions verification numbers were planned to be announced in May, but in late April reports were leaked that Belgium, France, the Czech Republic, the Netherlands and Estonia all had allowance surpluses, and the allowance shortage in Spain was much smaller than anticipated. By early May, the market was found to be 63.6 Mt long, with 21 countries reporting. It is interesting to note that the announcement of the Polish surplus of another 26 Mt in September 2006 did not affect prices very much.

Chapter 3: Price Drivers and CO2 Bubbles in the EU ETS

(Paper submitted to JEEM in July 2008)

Abstract

In the first phase of the EU Emissions Trading Scheme (EU ETS), the price per ton of CO_2 rose to over €30 before decreasing to zero by mid 2007. I examine to what extent this variation can be explained by market fundamentals, and whether there was a price bubble. The presence of the latter would question the main argument in favor of permit markets, which is to achieve a given emissions cap at least cost. I derive a structural model of the allowance price under the assumption efficient markets, which I gradually relax by allowing for delayed adjustment of price to fundamentals, as well as by introducing lagged LHS variables. The pattern of the results suggests that a price bubble is at least possible. I then pursue this hypothesis further by carrying out two different bubbles tests, both of which are consistent with the presence of a bubble.

Keywords: Emissions permit markets, air pollution, climate change, bubble, speculation, CO_2, asset pricing, EU ETS.

JEL classification: D84, G12, G14, Q52-54

3.1. Introduction

The allowance price per ton of carbon dioxide (CO_2) in first phase of the European Union Emissions Trading Scheme (EU ETS) exhibited tremendous variation. It started around €5 but quickly increased to a range of €20-30 where it remained for over a year. The price crashed after the first round of emissions verifications that showed the market to be long, but recovered somewhat and remained around €15 for another few months, before starting a gradual decline. By mid 2007, an allowance was virtually worthless.

Market analysts and economists alike have been looking for reasons behind the peculiar allowance price movement. Some have pointed to market fundamentals such as fuel prices and the weather (Alberola et al., 2008, Bunn and Fezzi, 2007, Mansanet-Bataller et al., 2007, Rickels et al., 2007) but others found no such correlation and confined themselves to forecasting based on pure time-series approaches (Chesney and Taschini, 2008, Paolella and Taschini, 2006). Whereas the April 2006 crash can be explained by the lower-than-expected overall emission reports, it is not clear why the allowance price was driven that high in the first place.[13] Also, the fact that it did not collapse completely but remained at a (in hindsight) very high level through 2006 lacks a satisfactory explanation.

---

[13] In theory, market participants need not know aggregate emissions for the price to be efficient. If every firm with a permit surplus (deficit) sells (buys) permits on the market, the price should marginal abatement costs regardless of emissions verifications.

Chapter 3: Bubbles

In this paper I examine if and to what extent the allowance price in the first phase of the EU ETS was based on market fundamentals. I first set up an economic model that specifies allowance price changes as a function of a set of widely accepted price drivers (fuel prices, temperature, reservoir levels, economic indicators and announcements of verified emissions), under the assumption of efficient markets and using the best data available. I then relax this model by introducing lagged fundamentals to account for non-immediate adjustment of allowance prices to changes in fundamentals and to proxy for unobserved expectations about fundamentals. In a further step I add past price changes as predictors of current price changes and gage their importance relative to the fundamentals.

I find that only a small portion of the allowance price variation can be explained by market fundamentals, even when taking into account dynamic expectations about fundamentals. A situation where an asset price is driven by expectations about future increases in a manner that is detached from fundamentals is commonly referred to as a price bubble. All tests to identify bubbles are inherently plagued by an identification problem, since the researcher can never know whether a difference between the price and the “true” value of an asset is due to a bubble, or to a misspecification of the market structure when calculating the intrinsic value (Flood and Garber, 1980, Garber, 1989, Gurkaynak, 2005). However, a permit market seems an especially appropriate place to investigate the presence of a bubble because the asset in question has a clearly defined value: One allowance is worth the cost of reducing aggregate CO_2 emissions to one ton below the aggregate cap. This is in contrast to stock prices, where it is often unclear what a stock is really worth and should lead to a fairly trustworthy estimate of the intrinsic value, thus reducing the danger of identification error considerably.

The contribution of this section of the dissertation is threefold: First, the stepwise procedure of starting with economic theory and then relaxing the most stringent constraints allows insights into the determinants of the EU ETS allowance price that go beyond existing analyses, which typically do not start from a rigorous economic model and determine model specification on a mostly ad-hoc basis. Second, I use a dataset of daily weather measurements in dozens of monitoring stations across Europe reaching back over three decades, which I combine with detailed information about regional population density to account for population-weighed temperature deviations from their long-term expectations. No dataset of comparable quality has been used in the literature address the influence of weather shocks on the allowance price. Last, to my knowledge no permit market has ever been tested for the presence of a price bubble, although such markets appears to offer more favorable conditions than stock markets to mitigate the identification problem encountered in any bubbles test.

In the next section I review the literature and derive the market model. In Section 3.3, I introduce the data and present the estimation results for the proposed models. Section 3.4 contains two bubbles tests, one based on regime switching and the other on cointegration between allowance prices and market fundamentals, and Section 3.5 concludes.

3.2. Allowance market model

3.2.a.) Literature

There is a large volume of empirical work about the SO_2 permit trading system in the USA (Carlson, 2000, Joskow et al., 1998, Montero, 1999, Schmalensee, 1998, Stavins, 1998) and more recently (Burtraw et al., 2005, Kosobud et al., 2005), to name only a few. For the EU ETS, the empirical literature is scarcer because it is a much newer market, and because fewer data are available in general since the involved firms previously faced very little regulation.[14] There exists a number of studies that model the EUA price and its volatility mainly for risk management and forecasting purposes (Benz and Trueck, 2006, Chesney and Taschini, 2008, Fehr and Hinz, 2006, Seifert et al., 2008). While useful for companies that need to hedge against the risk embedded in carbon prices, they do not shed much light on fundamental price drivers.

I am aware of four papers that explicitly aim to determine the impact of market fundamentals: Bunn and Fezzi (2007) use a cointegrated VAR model with allowances, electricity and gas in the UK and daily temperature in London as an exogenous variable, and impose the necessary identifying restrictions using auxiliary

---

[14] In the USA, historic emissions and information about production, fuel use and abatement are readily available, which is not the case in the EU.

regressions. They find that the gas price influences the EUA price, and that both gas and EUA prices help determine the electricity price.

Mansanet-Batallet et al. (2007) focused on EU-wide fuel prices and a weather index comprised of several cities. They focus on the first year of the market only and include dummies for the six largest price changes, which end up accounting for most of the explanatory power of their model.[15] This sidesteps the question of what actually drives the allowance price. In addition, they include regressors that are not obviously related to allowance prices, such as the Brent oil price.[16] They find that oil prices, natural gas prices and temperature in Germany are the only significant allowance price drivers, whereas other determinants (such as the EU weather index and coal prices) turned out to be uncorrelated.

Alberola et al. (2008) use temperatures in capital cities of six EU countries, along with a number of EU-wide energy variables, and extent the analysis to the first two years of the market. Unfortunately, they treat highly endogenous variables such as electricity prices, clean dark and clean spark spreads[17] as exogenous determinants

---

[15] It is not clear what the explanatory power of the fundamentals themselves is since no estimation results are presented for a model without dummies.

[16] The explanation given for including oil prices is not very clear. They cite a study by Christiansen et al. (2005) which looked at very general determinants for greenhouse gas markets, but is not specific to fuel switching in the EU's power sector. Very little power is generated using oil in Europe, so a switch from oil to gas is not likely to be the marginal abatement activity.

[17] The dark spreads is the theoretical gross profit of a power plant to generate a unit of electricity using coal, having bought the fuel necessary to produce it: Dark spread = power price-fuel price*heat rate. The heat rate is the efficiency at which a power plant converges energy in fuel into electric output. The clean dark spread is the dark spread minus CO_2 costs embedded in producing a unit of electricity: Clean dark spread=dark spread-CO_2

of the allowance price.[18] This is no problem for forecasting, but endogeneity will lead to biased coefficient estimates of the price drivers.

Rickels et al. (2007) build on Mansanet-Bataller et al. (2007) but include data through 2006. They separate allowance price determinants into supply and demand side, and their choice of market fundamentals seems more appropriate than that of Alberola et al. (2008) and more complete than that of Bunn & Fezzi (2007). However, their econometric specification is questionable: Although they check for cointegration between allowance and fuel prices (they find none) and thus implicitly acknowledge the presence of unit roots in the price data, they specify their model in levels as opposed to differences (or returns) to render the data stationary. A nonstationary error may lead to untrustworthy coefficient estimates.

All four studies are valuable contributions to finding allowance price determinants, but neither is based on a rigorous economic market model. The inclusion/exclusion of market fundamentals as well as the econometric specification is mostly ad-hoc, which leads to the aforementioned problems. They also do not take into account the no-banking provision from the first into the second phase, and they include lagged market fundamentals as well as lagged EUA prices as allowance price fundamentals from the outset without discussing the economic meaning of this. If yesterday's price change determines today's, then what determines yesterday's price

---

price*emission intensity. The spark spread and clean spark spread are analogous measures for gas-generated electricity.

[18] Although the electricity price, and thus spreads, is correlated with the EUA, the causation is very likely the other way around, because electricity producers pass carbon costs (at least partly) through to consumers.

change, and what are the true determinants of allowance prices? In the following I set up a simple economic model of the allowance price that explicitly addresses these issues.

3.2.b.) Base model

In order to incorporate the uncertainty inherent in the demand and supply of allowances as well as the fixed time horizon of the first market phase I follow an approach by Maeda (2004), who analyzed the effect of uncertainty in business-as-usual (BAU) emissions (referring to emissions in the absence of a carbon cost). I extend his model to T periods, where each period represents one day and T corresponds to the number of business days during the first phase of the EU ETS. Let BAU_{it} represent firm i's random BAU emissions in period t, which depend on a vector of normally distributed risk factors Ψ shared by all N firms in the market:

$$
\begin{gathered}
BAU_{it}(\Psi_t) = E_{t-1}[BAU_{it}(\Psi_t)] + \beta_{it}\left(\Psi_t - E_{t-1}[\Psi_t]\right) + \varepsilon_{it} \\
\beta_{it} = \frac{Cov(BAU_{it},\Psi_t)}{Var(\Psi_t)} \quad ; \qquad E[\Psi_t \varepsilon_{it}] = E[\varepsilon_{it}\varepsilon_{jt}] = 0, i \neq j
\end{gathered} \tag{3.1}
$$

Firm i's BAU emissions in the current period are the sum of expected emissions and an adjustment term that is proportional to a shock in Ψ_t which contains exogenous variables that influence either demand or supply of emissions. Abatement is defined as the difference between firm i's BAU and actual emissions e:

(3.2) $$a_{it} = BAU_{it}(\Psi_t) - e_{it}$$

Abatement has a cost defined by a firm's abatement cost function or its derivative, the marginal abatement cost (MAC) function. As is well known from permit market theory, each firm chooses abatement such that its MAC is equal to the permit price in every period, which implicitly defines the optimal amount of abatement:

$$\sigma_t = MAC_{it}(a_{it}^*, X_t, BAU_{it}(\Psi_t)) \Rightarrow a_{it}^* = MAC_{it}^{-1}(\sigma_t, X_t, BAU_{it}(\Psi_t)),$$

where X_t refers to a vector of variables that determines the MAC function. To clear the market, aggregate abatement has to equal the difference between overall BAU emissions and the emissions cap S:

(3.3) $$\sum_{k=1}^{T}\sum_{i=1}^{N} a_{ik}^* = \sum_{k=1}^{T}\sum_{i=1}^{N} BAU_{ik} - S$$

Because firms involved in the production of power & heat are dominant within the EU ETS, it makes sense to focus on emissions and abatement in this sector. I will further assume that the predominant method of abatement is a (marginal) shift in the generation dispatch order away from coal towards gas, as the former is more than twice as emissions-intensive per unit of output than the latter.[19] Fuel switching is

---

[19] This shift will take place in the medium load spectrum, as peak load is already generated using gas (and hydro) and base load is generated using nuclear, lignite and coal. Most likely

generally considered to be important in the EU ETS (Alberola, et al., 2008, Christiansen, et al., 2005, Delarue and D'haeseleer, 2007, Fehr and Hinz, 2006). This means that in addition to BAU emissions, abatement costs in the EU ETS depend on gas and coal prices, which I will denominate as G_t and C_t. If aggregate marginal abatement costs are approximately linear over the range where fuel switching is feasible,[20] the market's abatement cost function can be written as[21]

$$(3.4) \qquad MAC_t(\sum_{i=1}^{N} a_{it}, G_t, C_t, \sum_{i=1}^{N} BAU_{it}) = c + b\sum_{i=1}^{N} a_{it} + d_1 G_t + d_2 C_t + g\sum_{i=1}^{N} BAU_{it}$$

The coefficients c>0 and b>0 indicate nonzero and increasing marginal abatement costs, respectively. Aggregate MAC increases with gas prices and decreases with coal prices, such that $d_1 > 0$ and $d_2 < 0$. Increased BAU emissions translate in more necessary abatement to achieve the fixed cap S, which means that $g > 0$.

In equilibrium, allowance demand must equal supply and the aggregate MAC has to equal the permit price. This allows me to solve for the optimal aggregate abatement:

---

it would entail the replacement of some very inefficient coal generators by combined cycle gas generators (CCGTs).

[20] In reality, the MAC functions of individual firms are step functions. However, aggregate MACs on a sectoral level will be almost continuous over a certain range due to the range in different generator efficiencies.

[21] I also tried a specification where prices enter as logs, as is usually done in the finance literature. It is not obvious in this case which specification is more appropriate. In any case, the final results turned out to be very similar.

(3.5) $$\sum_{i=1}^{N} a_{it}^{*} = \frac{\sigma_t}{b} - \frac{c + dF_t \ + g\sum_{i=1}^{N} BAU_{it}}{b}$$

where I set $dF_t \equiv d_1 G_t + d_2 C_t$ for notational convenience. Substituting (3.5) into (3.3) yields

(3.6) $$\frac{1}{b}\sum_{k=1}^{T}\sigma_k - \frac{cT}{b} - \frac{d}{b}\sum_{k=1}^{T}F_k - \frac{g}{b}\sum_{i=1}^{N}\sum_{k=1}^{T}BAU_{ik} = \sum_{i=1}^{N}\sum_{k=1}^{T}BAU_{ik} - S$$

I now take expectations at time t, subtract them from (3.6) and simplify:

$$\sum_{k=t+1}^{T}\left(\sigma_k - E[\sigma_k]\right) = d\sum_{k=t+1}^{T}\left(F_k - E_{k-1}[F_k]\right) + \left(g+b\right)\sum_{i=1}^{N}\sum_{k=t+1}^{T}\left(BAU_{ik} - E_{k-1}[BAU_{ik}]\right)$$

Entries for periods before t cancel out because their ex-post expectation is the same as their realization. Likewise, the terms cT/b and S do not vary over time and cancel. Substituting (3.1) and dividing by N yields

$$\frac{1}{N}\sum_{k=t+1}^{T}\left(\sigma_k - E_{k-1}[\sigma_k]\right) = \frac{d}{N}\sum_{k=t+1}^{T}\left(F_k - E_{k-1}[F_k]\right) + \frac{g+b}{N}\sum_{i=1}^{N}\sum_{k=t+1}^{T}\beta_{it}\left(\Psi_k - E_{k-1}[\Psi_k]\right) + \frac{g+b}{N}\sum_{i=1}^{N}\sum_{k=t+1}^{T}\varepsilon_{it}$$

Provided that the error is stationary, the last term's mean and variance go to zero as N goes to infinity. The intuition behind this is that uncorrelated, firm-specific shocks cancel each other out in a large market, i.e. only shocks that affect all firms simultaneously have an impact on BAU emissions (and thus on marginal abatement costs). Simplifying the notation and solving for allowance prices results in

(3.7) $$\sum_{k=t+1}^{T}\sigma_k = \sum_{k=t+1}^{T} E_{k-1}[\sigma_k] + d\sum_{k=t+1}^{T}\left(F_k - E_{k-1}[F_k]\right) + N(g+b)*\overline{\beta}\sum_{k=t+1}^{T}\left(\Psi_k - E_{k-1}[\Psi_k]\right)$$

where $\overline{\beta}$ is the average covariance between aggregate BAU emissions and Ψ_t under the assumption that this relationship is time-invariant, i.e. $\overline{\beta} = \overline{\beta}_t = \frac{1}{N}\sum_{i=1}^{N}\beta_{it}\,\forall t$.

If markets are efficient, prices incorporate changes in underlying fundamentals immediately (Malkiel, 2007), implying that $E_t[P_{t+1}] = (1+r)P_t \equiv \rho P_t$, where r is the interest rate. Equation (3.7) can be solved recursively (see Appendix A) to

(3.8) $$\sigma_t = \rho\sigma_{t-1} + d\,\frac{F_t - \rho F_{t-1}}{\sum_t^T \rho^{T-k}} + N(g+b)\overline{\beta}\,\frac{\left(\Psi_t - E_{k-1}[\Psi_t]\right)}{\sum_t^T \rho^{T-k}}$$

The allowance price is determined by the previous-day price, changes in fuel prices and shocks to Ψ_t. The summation term in the denominators of the RHS decreases through time and indicates that shocks to exogenous variables increasingly affect the permit price. This makes intuitive sense: In the beginning of the market, a shock to emissions should not influence the permit price much, as it will likely be neutralized by shock in the opposite direction later on. As time progresses this probability diminishes. This means that in theory, fluctuations in the allowance price should increase towards the end of the market. In practice, there is also an opposite effect: New markets typically show more volatility than mature ones because market participants learn. Combined with the (in hindsight) apparent allowance surplus which drove the price down to transaction costs by mid 2007, it seems likely that this effect overshadows the inherent increasing uncertainty in a time-limited permit market without banking.

In theory, the discount rate in equation (3.8) could be estimated directly using nonlinear tools. However, in practice the day-to-day discount rate is very close to zero. I therefore simplify the equation (3.8) to

$$\Delta\sigma_t = d\,\frac{\Delta F_t}{\sum_t^T \rho^{T-k}} + N(g+b)\overline{\beta}\,\frac{\left(\Psi_t - E_{t-1}[\Psi_t\,]\right)}{\sum_t^T \rho^{T-k}} \tag{3.9}$$

where Δ refers to the first-difference operator. To keep the estimation linear I use an annual discount rate of 10% to calculate the denominators on the RHS.[22]

I assume that consumer demand is inelastic in the short term. Because demand must meet supply at all times in the electricity grid, Ψ_t includes factors that determine either demand or supply of BAU emissions. Specifically, I will include temperatures across Europe, reservoir levels in the Nordic countries, the DAX and a dummy indicating the first round of emissions verifications. The assumptions behind this choice are the following: Temperatures affect consumer demand through increased changes in heating (winter) or cooling (summer); reservoir levels influences

---

[22] The choice of discount rate is more important for the RHS because small changes can cause significant differences in the numerical value for the summation term. However, using discount rates of 5% and 20% did not significantly change the results.

emissions on the supply side through the availability of renewable energy;[23] and the DAX is a proxy for overall economic performance in the EU's largest economy. This leads to the following econometric specification:

$$
\begin{aligned}
\Delta\sigma_t &= \beta_1 \frac{\Delta G_t^F}{\Sigma_t} + \beta_2 \frac{\Delta C_t}{\Sigma_t} + (\beta_3 W_t + \beta_4 S_t)\frac{T_t - E[T_t]}{\Sigma_t} + \beta_5 \frac{R_t - E[R_t]}{\Sigma_t} + \beta_6 \frac{\Delta DX_t}{\Sigma_t} + \delta D_t + \varepsilon_t \\
&\varepsilon_t \sim N(0,\sigma_t^2);\sigma_t^2 = v_0 + v_1\varepsilon_{t-1}^2 + u_t
\end{aligned}
$$

$$
\begin{array}{ll}
\Sigma_t & \sum_t^T \rho^{T-k} \\
G_t^F & \text{one} - \text{month forward price for UK natural gas} \\
C_t & \text{coal marker for Northwestern Europe} \\
T_t & \text{average daily temperature} \\
W_t & \text{winter dummy}: W_t = 1 \text{ Nov to Mar}, W_t = 0 \text{ otherwise} \\
S_t & \text{summer dummy}: S_t = 1 \text{ Jun to Sep}, S_t = 0 \text{ otherwise} \\
R_t & \text{nordic reservoir levels} \\
DX_t & \text{DAX} \\
D_t & \text{emissions ver. dummy}: D_t = 1 \text{ on } 4/25/06 - 4/28/06, D_t = 0 \text{ otherwise} \\
u_t & \text{white noise}
\end{array}
\tag{3.10}
$$

Although the error ε_t is uncorrelated over time, I allow its conditional variance to change using an ARCH(1) specification, which is standard procedure in the analysis of price series as price changes tend not to follow a normal distribution with a fixed variance.[24]

---

[23] The more hydro and wind power available, the less power has to be produced using fossil fuels, and thus the lower are BAU emissions. See also Christiansen (2005).

[24] The alternative would be to drop the assumptions of Gaussian errors altogether, which has been forcefully advocated by Mandelbrot (1997, 2004). In my regime-switching bubbles test (see below) I use a t-distribution.

In order to define shocks to reservoir levels and the weather, I need a measure of what “normal” levels are. For reservoir levels, I use weekly median levels based on the years 1991-2006. Because reservoir levels are cumulative by nature, a level of one TWh below the median level today will lead to an expectation of tomorrow’s level also to be one TWh too low, assuming that precipitation is “normal”. To represent an unanticipated shock in reservoir levels I form first differences, such that $R_t - E_{t-1}[R_t] \equiv \Delta\tilde{R}_t = \Delta(R_t - R_t^{med})$.

For temperature, I construct daily expectations using 30-y means, i.e. $E_{t-1}[T_t] = 1/30 * \sum_{y=1975}^{2004} T_{dy}$, where d refers to the calendar day corresponding to day t and y to years. Because traders are likely to take weather forecasts into account and the weather over the weekends should influence Monday trades I calculate 5-day moving averages of temperature minus its expectation centered on the current day: $T_t - E_{t-1}[T_t]^{5d} \equiv \tilde{T}_t^{5d} = \sum_{k=t-2}^{t+2} \left(T_k - E[T_k]\right)/5$. An alternative would be to use first differences for reasons analogous to those discussed for reservoir levels, but the problem with this approach is that smoothing combined with differencing leads to very low variation, possibly diminishing any real signal below noise.

Comparing (3.9) to (3.10) shows that the latter is a reduced form of the former because the parameters b, g and $\overline{\beta}$ are not individually identified, only their combined impact. While specification (3.10) is well grounded in economic theory, it is based on two rather strong assumptions. First, expectations of tomorrow’s fundamental prices are today's fundamental prices. Second, allowance price changes are not autocorrelated over time. In the following two subsections I relax these assumptions.

3.2.c.) Introducing dynamic expectations of fundamental prices

So far I have assumed that EUA prices have the Markov property in the sense that tomorrow's price is a function only of today's price, but not of the preceding price path. The Markov property is the centerpiece of asset pricing for stocks and derivatives, and essentially implies that there are no arbitrage opportunities.[25] If all traders have rational expectations and access to the same information, a belief (for whatever reason) that a price will reach a certain level in the future will push the price to that level today. The Markov property also implies that without storage costs, spot and futures prices are equal, and that spot and forward prices differ exactly by the rate of interest (Hull, 2002).

In reality, however, the relationship between spot and futures prices can be quite different, even when taking storage costs into account. Whatever the reason (asymmetric information, risk aversion, fixed contracts or bounded rationality), it is possible that traders form their expectations about prices for EUA fundamentals not only based on today's prices, but also on past prices and a combination of spot and futures prices.

---

[25] If prices were a function of the past price path, chartist traders could use this information to their advantage. However, there is little evidence that they are in fact able to do so.

The problem is that it is impossible to know a priori which variables that model traders' unobserved expectations best. In order to search for the combination of variables that best explains EUA price changes I set up the following specification:

$$\begin{aligned}\Delta\sigma_t = \delta D_t &+ \beta_1 \frac{G^i}{\Sigma_t} + \beta_2 \frac{G^j}{\Sigma_t} + \beta_3 \frac{G^k}{\Sigma_t} + \beta_4 \frac{C^l}{\Sigma_t} + \beta_5 \frac{C^m}{\Sigma_t} \\ &+ (\beta_6 W_t + \beta_7 S_t)\frac{\breve{T}^n}{\Sigma_t} + (\beta_8 W_t + \beta_9 S_t)\frac{\breve{T}^o}{\Sigma_t} + \beta_{10}\frac{\breve{R}^p}{\Sigma_t} + \beta_{11}\frac{\breve{R}^q}{\Sigma_t} + \varepsilon_t\end{aligned} \tag{3.11}$$

The indices (i, …, q) refer to a draw from a set of candidate variables. Specifically,

$$\begin{aligned}&G^{i,j,k} \in \left(\Delta G_t^F, \Delta G_{t-1}^F, \Delta G_{t-2}^F, G_t^F - G_{t-5}^F, \Delta G_t^S, \Delta G_{t-1}^S, \Delta G_{t-2}^S, G_t^S - G_{t-5}^S\right) \\ &C^{l,m} \in \left(\Delta C_t, \Delta C_{t-1}, C_t - C_{t-5}, C_t - C_{t-20}\right) \\ &\breve{T}^{n,o} \in \left(\breve{T}_t^{5d}, \breve{T}_t^M\right) \\ &\breve{R}^{p,q} \in \left(\Delta \breve{R}_t, \breve{R}_t - \breve{R}_{t-5}, \breve{R}_t - \breve{R}_{t-20}\right)\end{aligned}$$

where G_t^S refers to the spot (day-ahead, to be exact) price for UK natural gas, T_t^M is the monthly deviation of temperature from the expected value and all other variables are defined as above. I estimate (3.11) for each possible combination of the indices (i, …, q) using an ARCH(1) model and choose the specification that yields the lowest BIC.[26] The best-fitting specifications for the full, pre-crash and post crash periods are the following:

---

[26] Bayesian Information Criterion, also known as Schwartz' Information Criterion. This criterion trades off model fit and model parsimony and puts more weight on the latter than Akaike's Information Criterion. This procedure results in estimating 8*8*8*4*4*2*2*3*3= 294,912 ARCH regressions, and it took the 24 computers in AREC-UMD's experimental lab

$$Full\,period: i=\Delta G_t^F, j=k=\Delta G_{t-2}^F; l=m=C_t - C_{t-20}; n=o=T_t^M; p=R_t - R_{t-5}, q=R_t - R_{t-20}$$

$$Pre-crash: i=\Delta G_t^F, j=\Delta G_{t-1}^F, k=\Delta G_{t-2}^F; l=m=\Delta C_{t-1}; n=o=T_t^M; p=q=R_t - R_{t-20}$$

$$Post-crash: i=\Delta G_t^F, j=k=\Delta G_t^S; l=m=C_t - C_{t-20}; n=o=T_t^M; p=R_t - R_{t-5}, q=R_t - R_{t-20}$$

3.2.d.) Introducing lagged EUA price changes

Although the variance in specifications (3.10) and (3.11) is allowed to vary over time due to the ARCH(1) term, the error itself is still supposed to be uncorrelated over time. If the residuals are autocorrelated, it is common to either specify an ARMA (p, q) error or to introduce lagged LHS variables on the RHS of the equation.[27]

Inclusion of lagged LHS variables can reduce or eliminate autocorrelation of the residuals and increase the overall fit of the model. This is the reason why most analyses of time series include either lagged prices or AR terms in the error. However, this comes at a price: Because of different possible causes for autocorrelation, the interpretation of the regression coefficients can become difficult.

---

over two days to complete this task. Including either more variables in (3.11) or widening the candidate sets would be very challenging in terms of raw computing power (in May 2008, that is). Note that if either of (i, j, k), (l, m), (n, o) and (p, q) draw the same variable from their respective candidate set, one of them is dropped due to multicollinearity, which means that the number of regressors included in (3.11) ranges from a minimum of 6 (5 plus a dummy) to a maximum of 12.

[27] Without any exogenous variables, AR (p) in the error term and p lagged LHS variables are equivalent specifications, but this changes in the presence of exogenous variables (Bauwens et al., 1999, p. 144). Also note that including lagged LHS variables and MA(q) error terms at the same time will lead to biased estimation, because the regressors are no longer independent of the error term.

This is not a problem if the main goal is price forecasting, but what is the meaning of a lagged LHS variable in a structural equation that seeks to define price determinants? This question is routinely ignored, but in this context this would be inappropriate.

Autocorrelation in the residuals from estimating (3.11) could in principle be caused by three different reasons: First, there could be an omitted fundamental variable that is related to the allowance price, and which exhibits autocorrelation. In this case, lagged LHS variables would serve as instruments for the omitted exogenous variable. Second, expectations about future fundamental prices could not be captured adequately by the additional terms in (3.11), and the true expectations exhibit autocorrelation. Third, allowance prices could increase simply because they are expected to do so based on past increases, regardless of fundamentals. This would be the case of a price bubble. The coexistence of these three possibilities has made conclusive testing for the existence of a price bubbles an almost impossible task, especially in the absence of clearly defined market fundamentals. I will examine this issue further in section 3.4.

Because the residuals from (3.11) indeed exhibit autocorrelation (see below), I include five lags of allowance price changes in (3.11) but leave the equation otherwise unchanged. I discuss the economic meaning of including lagged LHS variables in a regression below.

3.3. Results

The type and provenance of my data is as follows:

EUA prices: Daily series of over-the-counter (OTC) prices, Point Carbon.[28]

Gas prices: Daily series of ICE month-ahead futures and Zeebrugge day-ahead prices for UK natural gas.

Coal prices: McCloskey coal marker for North-Western Europe, which incorporates information on all trades concerning coal that enters Europe from abroad and which reach maturity within 3 months. It is an average of actual transactions or, in their absence, an assessment of fair value by traders. This marker is published weekly.

Temperature: From the European Climate Assessment & Dataset[29], which has daily entries from a large number of monitoring locations across Europe. I weighted temperature deviations by population around each monitoring location, using a World Bank city area population dataset.

Nordic reservoir levels: Weekly reservoir levels (in TWh) and median levels based on 1991-2006 taken from Nordpool exchange. The Nordpool market (Norway, Sweden and Finland) is the main hydropower-producing region in Europe.

---

[28] Available at www.pointcarbon.com, last accessed in February 2008.

[29] Klein Tank et al., "Daily Dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment", 2007, available at http://eca.knmi.nl.

I estimate equation (3.10) separately for the January 2005 to June 2007,[30] as well as for the period before the price crash induced by the first round of emissions verifications in April 2006 ("pre-crash") and after ("post-crash"). Visual inspection of the price graph as well as previous analyses (Alberola, et al., 2008, Bunn and Fezzi, 2007) indicate that the relationship between market fundamentals and the allowance price likely changed after the price adjustment. Because the DAX lacked correlation in this as well as all following models, and its inclusion increased both Akaike's and Schwarz' information criteria, I removed it from all regressions and re-estimated them without it.

The results are presented in Table 3.1. The coefficient estimates are significantly different before and after the price crash based on an LR test, confirming the suspected structural break. Gas prices are positive and significant for all periods, and summer temperatures are significant in the two subperiods. The crash dummy and the ARCH terms (not shown) are highly significant, as expected, but none of the other variables appears to be associated with EUA price changes. The residuals from all three regressions exhibit autocorrelation.

The goodness of fit of the model (calculated as the model sum of squares divided by the total sum of squares) shows that the overwhelming part of the model's predictive power is due to the emissions verification dummy. Less than 4 % of the

---

[30] As can be seen in Fig. 2. 2, prices reached transaction costs of a few cents by mid 2007, which makes the inclusion of the second half of 2007 pointless.

variation is explained in the pre-crash model, whereas the fit in the post-crash period is even worse with 1%.

Results from estimating (3.11) are shown in the first two columns of Table 3.2. Once again, the coefficients before and after the price crash are significantly different, confirming the structural break. Autocorrelation persists in the residuals from (3.11), although to a lesser degree than for (3.10). Due to the presence of various "flavors" of the same type of variable, the coefficients and associated p-values of the individual lags lose their straightforward interpretation. For example, the two coefficients on the reservoir level variables are of opposite sign but similar magnitude for the full and the post-crash period. In contrast, gas prices are consistently positive except for the coefficient on spot prices in the post-crash period. Winter temperatures now have the expected sign in all periods (and are significant in the full and post-crash period), whereas summer temperatures are positive for the full and pre-crash period but negative and for the post-crash period. In any case, the main focus here is on model fit, which has improved in terms of BIC by construction, but not by very much, in spite of the serious data-mining exercise to find the "best" specification: [31] The model predicts about 11% of the variation in the pre-crash period, and less 3 % for the period after the crash.

---

[31] I want to emphasize that the point of data-mining equation (3.11) for the best fit is to show that even so, the model does not explain much of the variation in EUA prices, and is highly sensitive to the inclusion of lagged LHS variables. A good fit from such a procedure would not prove anything.

Introducing 5 lags of allowance price changes into specification (3.11) yields the results presented in columns 3 and 4 of Table 3.2. Lagged EUA price changes are very effective in explaining current price changes in all periods. However, the inclusion of the LHS lags takes its toll on the explanatory power of the exogenous variables. Other than gas and the crash dummy, none of the coefficients is statistically significant. Note that in spite of the lagged price changes, autocorrelation persists, as well as evidence for a structural break.

Taken together, the results shown in Tables 3.1-3.2 imply the following:

1.) Allowance prices appear to violate the Markov property. Market fundamentals are not immediately internalized, as past changes in fundamentals help explain a portion of the price movements. Furthermore, price changes exhibit autocorrelation.

2.) There was a structural break in the allowance price series after the price adjustment due to the emissions verifications in April 2006. The coefficients on market fundamentals from estimating the subperiod before and after the price crash are significantly different.

3.) UK Gas prices are consistently associated with the allowance price before the price adjustment in April 2006. This is consistent with results obtained by Bunn & Fezzi (2007) and Alberola et al. (2008).

4.) Coal prices do not appear to be significantly correlated with the EUA price, even though they should be important if fuel switching is an important form of abatement. This is probably due to the fact that they exhibit much less variation than gas prices.

5.) Temperatures and reservoir levels help determine the allowance price, but they are sensitive to the model specification and time period.

6.) When lagged EUA price changes are introduced into the model, they absorb most of the price variation while all exogenous variables lose their significance, with the exception of gas prices. The overall model fit greatly increases, but some autocorrelation persists.

As discussed in more detail above, persistent autocorrelation and the dominance of lagged LHS variables in explaining the EUA price variation could be due to omitted exogenous (autocorrelated) variables, expectations about fundamentals or a bubble-like phenomenon. However, the pattern of results gives some indications as to which possibility is more likely.

My model contains all of the variables that are widely considered to drive the allowance price. In order for an unobserved exogenous variable to drive the results, this variable would have to be very important, exhibit strong autocorrelation and a pattern similar to the very distinct price movement of the EUA. The existence of such an exogenous variable seems unlikely.

I proxied expectations about fundamentals by introducing various time lags of these variables into the model. Although this method is certainly an imperfect measure of expectations, even the best-fitting combination of fundamentals out of almost 300,000 possibilities did not provide a very good model of EUA price changes. Naturally there are more variables and lags that could be included in the model, but based on my results so far it seems unlikely that expectations about market fundamentals are behind the very distinct EUA price path.

The overall poor performance of the models without lagged EUA price changes, the instability of the exogenous variables across models and time periods, the fact that all fundamentals except for UK gas prices lose their significance as soon as lagged prices are introduced and the persistence of autocorrelation across models are all consistent with self-fulfilling expectations about the allowance price as a main price driver, as would be the case in a price bubble. In the next section I examine this issue further and carry out two bubbles tests.

3.4. A CO_2 Bubble?

3.4.a.) Some bubble background

Regardless of whether or not prices have the Markov property, they are supposed to be driven by market fundamentals (hence the name) according to the Capital Asset Pricing Model and Modern Portfolio Theory, two workhorses of modern financial economics. Generally, an asset's price P_t can be represented as $P_t = F_t + B_t + \varepsilon_t$ (Diba and Grossman, 1987, 1988, Flood and Garber, 1980), where F_t represents the market fundamental (or intrinsic asset value), B_t is a bubble term and ε_t white noise. Prices that are determined exclusively by F_t are a special case where the bubble term is set to zero.

A positive bubble term is due to traders' expectations. If traders believe that prices will increase, or believe that most other traders believe this (and so forth ad infinitum), any random price expectation can be self-fulfilling.[32] After a time of expectation-driven price increases, market participants will eventually realize that the price is too high.[33] This will set in motion a positive feedback loop of asset sales, downward adjustment of future price expectations and yet more sales. Note that in a bubble, traders know that an asset's price is above its intrinsic value, but they buy (or hold) the asset anyway because they expect further price increases.

There exists an ample literature about price bubbles, an illuminating survey of which is given by Camerer (1989) and, more recently by Abreu & Brunnermeier (2003). The cornerstone of bubble theory is something called a growing rational bubble, which refers to a constant term that appears in solutions to difference equations that describe price formation in a market. Growing rational bubbles increase exponentially at the rate of interest.[34] Under the standard assumption of rational expectations, growing rational bubbles cannot exist with a finite number of

---

[32] The assumption that prices are not driven by fundamentals but by traders' beliefs is the basis for technical or "chartist" analysis. Chartists aim to predict future price movements based on past price alone, and have come up with a range of tools and indicators such as price floors and ceilings, "head-and-shoulders", turning points and more.

[33] This can be triggered by an event such as one large seller coming to the market, a bearish news report, or a round of emissions verifications as was the case in April 2006.

[34] Blanchard and Watson (1982) developed the theory for stochastically crashing bubbles, where traders know that the bubble will burst but not when. Stochastically crashing bubbles have to grow at a rate greater than the rate of interest.

agents trading a limited number of assets in a discrete time setting. The reasons for this were formally developed by Tirole (1982), but to put it simply, it will be irrational to hold the asset just before the bubble bursts, and therefore by backward induction it will be irrational to hold the asset in any earlier period.

A widely used approach to solving the bubble existence problem has been to allow for either some sort of irrationality or for incomplete information (Black, 1986, Day and Huang, 1990, Frankel and Froot, 1990, Friedman and Aoki, 1992), and bubbles have been shown to persist in lab experiments even with experienced subjects (Hussam et al., 2008). In the following I will sidestep the question of theoretical existence and focus on investigating whether a bubble *did* exist.

3.4.b.) Bubble tests

Bubbles tests have been largely confined to stocks that pay dividends. In such a setup, the market fundamental can be shown to be the expected current value of the dividend stream. Gurkaynak (2005) reviewed a series of bubbles tests, all of which base their analysis on S&P 500 prices and dividends going back to 1871. Some appear not to be appropriate to test for the presence of a bubble either on conceptual and/or econometric grounds,[35] whereas others are more convincing (West, 1987) but

---

[35] For example, variance bounds tests as introduced by Shiller (1981) and LeRoy and Porter (1981) rely on dividends observed into the infinite future, which clearly cannot be implemented. However, ways of getting around this problem (such as using the last observed dividend as the terminal price) void the test of its meaning, as rejection of the null is no longer linked to the presence of a bubble (Flood et al., 1994).

cannot be implemented for an asset that has no stream of returns such as one-time allowances. The classes of bubbles tests that can most readily be implemented in the EUA context involve cointegration and regime switching tests.

Cointegration tests are based on the assumption that any bubble term would have to increase faster than the underlying fundamentals. If the price and fundamental series are cointegrated, this is clearly not the case. Therefore, a test for cointegration between asset price and fundamental amounts to a bubbles test. Such tests have been proposed by Diba & Grossman (1987, 1988) and by Hamilton and Whiteman (1985).

Bubbles tests based on cointegration have been attacked on two grounds (Evans, 1986): Whereas bubble theory predicts that a bubble can never be rendered stationary no matter how many times it is differenced, this may not be true with real data and small samples. In reality, prices do not follow a purely exponential increase because they are influenced by too many other observed and unobserved factors. Hence, any real price will eventually become (or at least appear) stationary when differenced a sufficient number of times.

Second, a price that contains a series of stochastically crashing bubbles may well pass a stationarity test, especially if the magnitude of price increases and decreases is roughly equal (Evans, 1986, Hall et al., 1999). To solve this problem, regime switching methods have been developed (Engel and Hamilton, 1990, Hall, et al., 1999, Kim et al., 2008, Schaller and van Norden, 1997). Such models allow the data to be in more than one state. The presence of different regimes is then interpreted as evidence for a series of bubbles.

3.4.c.) Cointegration test

Cointegration between EUA prices and market fundamentals would imply that price movements can be accounted for by changes in fundamentals, and that therefore there cannot be a bubble. Note that this is not the same as the estimations described in section 4, as the presence of cointegration would imply that eqs. (3.10-11) are misspecified, because they are written entirely in terms of differences but not levels of the integrated variables.

Unit root tests indicate that the EUA price series, fuel prices, reservoir level deviations and the DAX each are integrated of order 1, whereas temperature deviations are stationary. The five integrated variables are plotted in Figure 3.1.

To test for cointegration, I start by re-specifying (3.10) as an Autoregressive Distributed Lag (ADL) model while dropping the denominator terms on the RHS:

$$\begin{aligned} A(L)\sigma_t &= m + B_1(L)G_t + B_2(L)C_t + B_3(L)R_t + B_4(L)DX_t \\ &\quad + C_1(L)TW_t + C_2(L)TS_t + \delta D_t + \varepsilon_t \end{aligned} \tag{3.12}$$

$A(L)$ is a lag polynomial defined by $A(L)\sigma_t = 1 - \alpha_1\sigma_{t-1} - \alpha_2\sigma_{t-2} - ... - \alpha_p\sigma_{t-p}$; $B_i(L)$ and $C_j(L)$, $i \in (1,2,3,4)$ and

$j \in (1,2)$, are lag polynomials of potentially different order each. I choose 5 lags for all variables in order to incorporate weekly cycles. The cointegration vector

$$z_t = \sigma_t - \frac{m}{A(1)} - \frac{B_1(1)}{A(1)} G_t - \frac{B_2(1)}{A(1)} C_t - \frac{B_3(1)}{A(1)} R_t - \frac{B_4(1)}{A(1)} DX_t \tag{3.13}$$

is stationary if the EUA price is cointegrated with the fundamentals,[36] with $A(1)$ and $B_i(1)$ referring to the sum of all coefficients of the corresponding polynomials. The variable z_t measures how much out of equilibrium the cointegrated variables are in any given period, with $z_t = 0$ indicating the long-term equilibrium. If $z_t > 0$, σ_t is too high in relation to the other variables and will tend to decrease towards the equilibrium (provided that $A(1) > 0$), and vice versa for $z_t < 0$. The more out of equilibrium the cointegrated variables are, the stronger the forces that push them back towards it.

Testing for cointegration is equivalent to testing whether z_t has a unit root. There are two different ways of obtaining an estimate for z_t. One is to estimate (3.12) and compute an estimate $\bar{z}_t$ with the parameter estimates. Another is to simply fit a linear regression of the allowance price on a constant, fuel prices and reservoir level deviations. [37] I will label he residuals of this regression $\breve{z}_t$. This

---

[36] For a derivation, see Johnston and Di Nardo (1997)

[37] This approach relies on the concept of superconsistency introduced by Engle and Granger (1991). A problem with this could be that superconsistency is strongly based on asymptotic

approach neglects all stationary exogenous variables, but (in theory) adding a stationary variable should have no impact on a unit root test.

Standard critical values for unit root tests cannot be used in either case, because I don't know z_t but only its prediction. MacKinnon (1991) derived relevant critical values using Monte Carlo simulations. For a system of 5 potentially integrated variables and a constant term, the critical values are -4.13 (10%), -4.42 (5%) and -4.96 (1%).

The cointegration test results are presented in Table 3.3. The two approaches to compute the estimate for z_t yield different results in terms of the actual values for $\bar{z}_t$ and $\hat{z}_t$, but for both series the null of a unit root cannot be rejected by a wide margin. There appears to exist no cointegrating vector between the EUA and integrated fundamentals. While no definitive proof, lack of cointegration between price and fundamentals is certainly consistent with a price bubble.

3.4.d.) Regime-switching test

I carry out a regime switching test outlined by Hamilton (1989) and Engel and Hamilton (1990), and, among others, applied by van Norden and Schaller (1997, 1996). Kim and Nelson (1999) extended this class of tests to a state-space framework and a Bayesian analysis, but for the purpose of this paper, the traditional approach

---

properties, which may not be a practical assumption in finite samples (Johnston and DiNardo, 1997).

suffices. The basic idea of a regime switching test is that not one, but two (or more) different distributions govern price changes. In the bubbles context, a different distribution would be expected in the growth and in the bust phase. Regime switching is especially useful to detect a sequence of stochastically crashing bubbles where the transition between growth and bust is not known, but it can also be used to detect a single bubble as long as both the growth and bust phase are included in the data. Let the variable $S_t \in (1,2)$ refer to one of two states. Allowance price changes can then be written as

$$(3.14) \qquad \Delta EUA_t = X_t^1 \beta_1^{S_1} + X_t^2 \beta_2 + \sigma^{S_t} \varepsilon_t \; \varepsilon_t \sim N(0,1)$$

The variables whose influence on the allowance price is different in the two regimes are collected in the vector X_t^1, whereas those with a stable impact across states are represented by X_t^2. This means that $\beta_2^1 = \beta_2^2 = \beta_2$, but that the vector $\beta_1^{S_1}$ is different for different values of S_t. Likewise, I allow the variance to vary across states. The transition between states is governed by a first-order Markov process:

$$\Pr[s_t = 1 \mid s_{t-1} = 1] = p$$
$$\Pr[s_t = 0 \mid s_{t-1} = 1] = 1 - p$$
$$\Pr[s_t = 0 \mid s_{t-1} = 0] = q$$
$$\Pr[s_t = 1 \mid s_{t-1} = 0] = 1 - q$$

The system can be solved for the parameter vector $\theta = (\beta_1^1, \beta_1^2, \beta_2, \sigma^1, \sigma^2, p, q)$ by maximum likelihood using numerical methods as shown by (Engel and Hamilton, 1990, Hamilton, 1989, Kim and Nelson, 1999). Under the null hypothesis of no bubble, the state in period t-1 has no impact on the state in period t, which means that $q = 1 - p$. The likelihood ratio statistic to test the null is

$$LR = 2\left[\log\left(L^U\right) - \log\left(L^R\right)\right] \sim \chi^2(r)$$

where q is forced to equal $1 - p$ in the restricted (R) model but is left as a free parameter in the unrestricted (U) model, and r is the number of parameters in the restricted model, in this case $r = 2 * \text{length}(\beta_1) + \text{length}(\beta_2) + 3$.

I estimate (3.14) based on model (3.10) plus an intercept for the entire period as well as the pre-crash and post-crash subperiods. I allow all fundamentals to influence the allowance price differently in the two states with the exception of the emissions verification dummy. Results for the transition probabilities and the LR statistic are given in Table 3.4.[38] The null of no state dependence is clearly rejected for all periods.

These results imply the existence of (at least two) distinct regimes, and that the sequence of regimes is nonrandom. Like the cointegration test, this is no conclusive proof for a bubble, but it is consistent with the presence of a one or a series of stochastically crashing bubbles.

---

[38] Full results available from the author upon request.

3.5. Conclusions

In the first phase of the EU ETS, the allowance price exhibited high volatility and followed a peculiar path. While the crash in April 2006 was clearly caused by an adjustment of expectations about aggregate emissions, it is not obvious what drove the price that high in the first place, and why it took so long to finally decrease to zero. In this paper I examine if and to what extent the allowance price was consistently driven by market fundamentals.

I set up a market model that relates the change in the allowance price to changes in fuel prices, temperature and reservoir level, under the assumption of efficient markets. I estimate this model for the entire period, as well as for the subperiods before and after the allowance price crash. I then relax the model by first allowing for delayed adjustment to fundamentals, and then by including lagged price changes as predictors for current price changes.

The specification that relies exclusively on contemporaneous and exogenous price drivers performs quite poorly, in spite of the fact that I'm using the best data available. The introduction of lagged exogenous variables improves price predictions for the period before the price crash, but as soon as lagged EUA price changes are allowed in the model, all explanatory variables lose their significance with the exception of UK gas prices.

Although lagged LHS variables are routinely used in time series analysis, it is important to ask what exactly a dependence of price on its own past means if the goal is an analysis of price drivers. Autocorrelation could be caused by an omitted autocorrelated exogenous variable, expectations about fundamentals or self-fulfilling expectations about future price changes that are not related to fundamentals. The last situation is equivalent to a price bubble.

In a price bubble, firms that held surplus allowances would be reluctant to sell because they expected future prices to increase. For the same reason, buyers wanted to buy sooner rather than later, driving prices to whatever level expectations happened to be. The presence of a price bubble would in effect destroy the prime advantage of a permit market, which is the achievement of a given emissions cap at least cost, because the inflated permit price is at least partially passed on to consumers.

I examine this hypothesis further by carrying out two bubbles test, one based on cointegration between the EUA price and market fundamentals and the other on regime switching. Both tests indicate that a price bubble, or a series of bubbles, is consistent with the data. The positive test results add another layer of evidence to the bubbles hypothesis, especially since market fundamentals in a permit market are better known than in the typical context of bubbles tests, which so far have been almost exclusively been applied to stock markets.

To formulate it the other way around, in order for these results not to indicate the presence of a price bubble in EU ETS allowances, there must either exist a crucial but as of yet unrecognized fundamental price driver whose realizations tally with the peculiar price movement of the EUA, or expectations about fundamentals had to be extreme enough (and, in hindsight, far away from actual realizations) to account for this price variation. In the absence of either of these two –in my view unlikely- scenarios, one would have to conclude that the first phase of the EU ETS indeed was characterized by one or a series of speculative price bubbles.

Chapter 4: Market Power and Windfall Profits in Emission Permit Markets

Abstract

Although market power in permit markets has been examined in detail following the seminal work of Hahn (1984), the effect of free allocation on price manipulation with market power in both output and permit market has not specifically been addressed. I show that in this case, the threshold for free allocation above which dominant firms find it profitable to increase the permit price is below their emissions. In addition to being of general economic interest, this issue is relevant in the context of the EU ETS, where it appears that power producers profited from a high permit price. Because power producers were net permit buyers, Hahn's results imply that market power in this sector could not have been involved. My results change this conclusion. Using data from the UK and German power markets, I find that power generators received free allowances well in excess of the derived threshold.

Keywords: Market power, emissions permit markets, air pollution, EU ETS, CO_2, electricity generation, permit allocation, windfall profits, cost pass-through.

JEL classification: H23, L11-13, L94, L98, Q48, Q52-54, Q58

4.1. Introduction

During the first eighteen months of the European Union Emissions Trading Scheme (EU ETS), the allowance price per ton of CO_2 was far above ex-ante expectations. It fell to one-half of its value in April 2006 after the first round of emissions verifications showed the market to be long and eventually reached zero by mid 2007, but it is not clear what drove the price so high in the first place. A series of studies (Alberola, et al., 2008, Bunn and Fezzi, 2007, Mansanet-Bataller, et al., 2007, Rickels, et al., 2007) has tried to empirically explain the price path by market fundamentals such as fuel prices and weather variables, but only with limited success as fundamentals appear to only account for a small fraction of the allowance price variation. Especially the very high price levels before the April price crash lack a satisfactory explanation.

An inflated permit price in the sense that it is above marginal abatement costs of the market as a whole destroys the most powerful argument in favor of instituting pollution permit markets, which is to achieve a given emissions target at least cost. The increased costs are due to over-abatement on behalf of any firm that does set its marginal abatement cost equal to the permit price, and to consumers paying too high prices for pollution control if permit prices are passed through in the output market.

In this paper, I examine whether price manipulation within the EU’s power & heat sector could have been a cause of the apparent allowance price inflation. I extend economic theory by setting up a model that allows for market power in both the output and the permit market and explicitly accounts for a link between these markets. I derive the conditions under which a dominant firm will exercise its market power to increase the permit price in order to maximize overall profits in both markets. Finally, I apply my theory results to data from the EU ETS and show that these conditions were fulfilled, i.e. provided that such “double” market power existed, it would have led to an inflation of both permit and output price.

The interplay between permit and output market is at the root of what has become known as “windfall profits” in the empirical literature. If firms are able to pass through pollution costs to consumers but receive most (or all) permits allocated for free, they get reimbursed for costs they never had to incur. Windfall profits have been identified as an issue in permit markets in general (Bovenberg and Goulder, 2000, Vollebergh et al., 1997), and in particular in the EU ETS (Grubb and Neuhoff, 2006, Hepburn et al., 2006, Neuhoff et al., 2006, Sijm et al., 2006, Smale et al., 2006). Such profits constitute a wealth transfer from consumers to firms but they do not impact efficiency directly[39] nor affect the permit price in a competitive market. This no longer holds under the presence of market power in both the output and permit market, because a price-setting firm will take windfall profits into account when making its production and permit purchase decisions.

One of the best-known results about market power in permit markets is Hahn’s (1984) finding that the permit price is an increasing function of the dominant firm’s

---

[39] Handing out permits for free impacts efficiency through existing distortions such as income taxes. In theory, the revenue from a tax or selling permits has to be recycled through lower distortionary taxes to achieve (Bovenberg and Goulder, 1996, Parry, 1995).

permit allocation. If this firm is a net buyer of permits, it will exert its power to decrease the permit price in order to minimize compliance costs, and vice versa. Other studies have confirmed and extended these findings (Isaac and Holt, 1999, Liski and Montero, 2005, Maeda, 2003, Westskog, 1996). Hahn's results imply that a dominant firm in the power & heat sector could not possibly have used its market power to increase the allowance price, because this sector was *under*provided with permits and thus, if anything, would have used its power to *decrease* the price.

Hahn derived his results by focusing exclusively on the permit market while ignoring any distortions in the output market. However, if a firm has market power in the permit market, it is likely to also perceive market power in the output market.[40] Misiolek and Elder (1989) introduced exclusionary manipulation whereby the dominant firm intends to drive competitors out of the output market by manipulating the permit price, an approach also followed by von der Fehr (1993) and Godby (2000). A series of lab experiments empirically tested the relevance of combining market power in the output and permit markets (Cason et al., 2003, Godby, 2002, Muller and Mestelman, 1998). These studies found that a combination of market power in both markets increased the dominant firm's power to manipulate prices and that the overall effect on industry profits and consumer welfare depended on firms' relative efficiencies and permit allocation and thus was ambiguous. However, they did not address whether and how Hahn's threshold of "neutral" allocation is altered

---

[40] If a permit market covers several industrial sectors, the firm's market share in the permit market will be lower than its share in the output market, which implies market power in the latter market given market power in the former.

by the presence of market power in both permit and output market which are explicitly linked.

The issue of double market power is closely related to the literature pertaining to “raising rivals’ costs” (Hart and Tirole, 1990, Krattenmaker and Salop, 1986a, b, Ordover et al., 1990, Salop and Scheffman, 1987, 1983). The focus of this literature is the theory that predatory firms may increase their market share and overall profits by artificially increasing industry costs, given certain assumptions. This can take many forms, including the institution of mandatory standards, labeling, advertising etc, all of which are expected to be less costly on a per-output basis for the dominant firm than for the price-taking fringe. One particular version of raising rivals’ costs is to over-purchase necessary inputs of production (Salop and Scheffman, 1987), which is a profitable strategy if the output price increase from this manipulation exceeds the firm’s average cost increase. Sartzetakis (1997) applied this framework specifically to emissions permits as a necessary input to production, but he refrained from examining how free allocation determines the existence and direction of price manipulation.[41]

However, certain aspects of the interplay between market power in the output and an associated pollution permit market are not well captured by this literature. First, raising rivals’ costs focuses on increasing profits of a dominant firm at the expense of rivals while decreasing overall industry profits. Profits from jointly

---

[41] Indeed, he mentions that a policy based on such a threshold would require full information and the “willingness to base permits allocation on efficiency rather than distributional considerations”.

manipulating output and permit prices on the other hand accrue to all firms in the industry and they come at the expense of consumers and taxpayers. In fact, fringe firms can free ride on the manipulative actions of the dominant firm as they enjoy increased profits without incurring the costs of price manipulation. Second, there are no strong assumptions needed about a dominant firm's efficiency relative to that of the fringe in order for price manipulation to be profitable: As I show below, even a dominant firm that is very inefficient at abating or producing can find it optimal to increase the permit price, given that it receives a sufficiently generous free allocation.

In the next section I derive a threshold of free allocation beyond which a dominant firm will find it profitable to increase the permit price. The threshold is a function of the firm's market power in both markets as well as its emission intensity but is always below the full-allocation threshold defined by Hahn. This is my core result and means that a dominant firm may find it optimal to increase the permit price even if it is a net buyer of permits. I then apply this finding to the EU ETS and examine whether firms in the power & heat sector likely received a free allocation in excess of this threshold, and therefore whether market power in this sector could be a cause for the high allowance price. Section 4.4 concludes.

4.2. Market power in output and permit market

In the following I set up a simple model for an industry sector containing N firms that is subject to an emissions permit market.[42] I define the cost function for firm i=1, ..., N as $C^i(q_i, e_i)$, a continuous function which depends on output q_i and emissions e_i and is twice differentiable in both arguments. Costs are increasing in output, decreasing in emissions and convex in both arguments, such that $C_q^i > 0$, $C_{qq}^i > 0$, $C_e^i < 0$, $C_{ee}^i > 0$, $C_{qe}^i < 0$ and $C_{qq}^i C_{ee}^i - \left(C_{qe}^i\right)^2 > 0$. I assume that firm 1 has market power in both the output and the permit market.[43]

To study the equilibrium, I start by analyzing the behavior of firms i=2, …, N that comprise the price-taking fringe, before I move on to the dominant firm. The fringe's profit maximization problem is

$$\begin{aligned} \max_{q,e,x} \Pi_i &= pq_i - C^i(q_i, e_i) - (x_i - \overline{x}_i)\sigma \\ &s.t. e_i \le x_i \end{aligned} \tag{4.1}$$

where p is the output price, σ the permit price, x_i refers to permit purchases and $\overline{x}_i$ is firm i's free permit allocation. With a binding cap, I can substitute the constraint into the objective function and arrive at the familiar first-order conditions that

---

[42] This permit market may also include other sectors, but for simplicity I will confine the analysis to one sector.

[43] With a permit market that covers just one sector, assuming market power in one market but not the other seems arbitrary. If the permit market covers many other sectors as well, then it is conceivable that a firm has market power in the output market but not the permit market. The converse, however, would not make economic sense.

marginal production costs equal the output price, and marginal abatement costs equal the permit price. This implicitly defines the fringe's optimal output, emissions and permit purchase decisions:

$$\text{(4.2)} \qquad \begin{array}{l} p = C_q^i(\cdot) \\ \sigma = -C_e^i(\cdot) \end{array} \quad \Rightarrow \quad \begin{array}{l} q_i^* = q_i^*(p,\sigma) \\ e_i^* = x_i^* = x_i^*(p,\sigma) \end{array}$$

The dominant firm takes (4.2) into account when maximizing its own profits. It faces an inverse demand function and a permit market-clearing condition of

$$\text{(4.3)} \qquad \begin{array}{l} p = P(Q) = P\left(q_1 + \sum_{i=2}^{N} q_i^*(p,\sigma)\right) \\ S = x_1 + \sum_{i=2}^{N} x_i^*(p,\sigma) \end{array}$$

where S is the overall emissions cap and q_1 and x_1 are the dominant firm's output and permit purchase decisions, respectively. This system of equations describes a fixed point with a mapping of $F\left[p(q_1,x_1),\sigma(q_1,x_1)\right] \to \left(p(q_1,x_1),\sigma(q_1,x_1)\right)$. A unique solution exists if the vector (p,σ) belongs to a convex set (which is trivially true for prices), and $F[\cdot]$ is upper-semicontinuous and monotone, which is assured by the continuity and monotonicity of the demand function $P(Q)$ and the cost functions $C^i(q_i,e_i)$.

From equations (4.1)-(4.3) it follows that the output price and the permit price are both a function of the dominant firm's output and permit purchase decisions:

$$p = p(q_1, x_1)$$
$$\sigma = \sigma(q_1, x_1)$$

The impact of the dominant firm's output and permit purchase decisions on the output and permit price can be assessed using comparative static calculations and is summarized in the following Lemma:

Lemma 1:

The dominant firm's output and permit purchase decisions will influence output and permit price jointly such that

$$\frac{\partial \mathbf{p}}{\partial \mathbf{q_1}} < \mathbf{0}; \quad \frac{\partial \mathbf{p}}{\partial \mathbf{x_1}} > \mathbf{0}$$
$$\frac{\partial \sigma}{\partial \mathbf{q_1}} < \mathbf{0}; \quad \frac{\partial \sigma}{\partial \mathbf{x_1}} > \mathbf{0}$$

(Proof: Appendix B)

The dominant firm's profit maximization problem and the resulting first-order conditions are

(4.4) $$\max_{q_1, x_1, e_1} \Pi_1 = p(q_1, x_1)q_1 - C^1(q_1, e_1) - (x_1 - \bar{x}_1)\sigma(q_1, x_1) + \lambda(x_1 - e_1)$$

(4.4a) $$p(\cdot) + \frac{\partial p}{\partial q_1} q_1 - C_q^1(\cdot) - (x_1 - \bar{x}_1)\frac{\partial \sigma}{\partial q_1} = 0 \qquad (q_1 > 0)$$

(4.4b) $$\frac{\partial p}{\partial x_1} q_1 - \sigma(\cdot) - (x_1 - \bar{x}_1)\frac{\partial \sigma}{\partial x_1} + \lambda = 0 \qquad (x_1 > 0)$$

(4.4c) $$-C_e^1(\cdot) = \lambda$$

(4.4d) $$x_1 \geq e_1; \lambda \geq 0; \lambda(x_1 - e_1) = 0$$

The last first-order condition implies that the constraint may or may not be binding. To analyze the incentive of the firm to manipulate the permit price in either direction I combine (4.4b) and (4.4c) to get

(4.5) $$-C_e^1(\cdot) = \sigma(\cdot) + (x_1^* - \bar{x}_1)\frac{\partial \sigma}{\partial x_1} - \frac{\partial p}{\partial x_1} q_1^*$$

where the asterisks indicate that the permit purchases and output are chosen optimally by the firm according to (4.4). If with a permit price increase the additional revenue from cost pass-through (the last term on the RHS) outweighs the higher permit purchase costs (the second term), then the firm's marginal abatement costs are below the permit price. This means that it will under-abate -or, equivalently, over-purchase permits-relative to the situation where it perceives no price-setting power through its permit purchase decision in either market[44] ($\partial \sigma / \partial x_1 = \partial p / \partial x_1 = 0$) and thus push up the permit price. Moreover, if the revenue effect outweighs the compliance cost effect to the point where $-C_e^1 = 0$, then it will not abate at all and $e_1^* = e_1^{BAU} \leq x_1^*$,

---

[44] Note that it still may perceive market power through its output decision. Equation (4.5) strictly applies to output and permit price manipulation through the permit purchase pathway.

where e_1^{BAU} refers to business-as-usual (BAU) emissions in the absence of a permit market. Conversely, if compliance costs outweigh increased revenue the firm will find it optimal to under-purchase permits in order to depress the permit price and over-abate accordingly and over-abate accordingly. This can be summarized as

$$\frac{\partial p}{\partial x_1} q_1^* \begin{matrix} > \\ = \\ < \end{matrix} (x_1^* - \bar{x}_1)\frac{\partial \sigma}{\partial x_1} \Rightarrow \begin{matrix} -C_e^1 < \sigma \\ -C_e^1 = \sigma \\ -C_e^1 > \sigma \end{matrix} \tag{4.6}$$

Condition (4.6) implies that there is a specific amount of free allocation that will cause the dominant firm to set its marginal abatement costs equal to the permit price. Solving (4.6) for this threshold allocation $\bar{x}_1^0$ yields

$$\bar{x}_1^0 = x_1^* - \frac{\partial p / \partial x_1}{\partial \sigma / \partial x_1} q_1^* \tag{4.7}$$

This quantity is unambiguously smaller than the firm's optimal permit purchases, provided that $C_{qe}^1 < 0$.[45] Note that the firm's optimal permit purchases and output are a function of its allocation, such that the threshold in (4.7) is difficult to compute ex-ante, except for very simple functional forms of the cost function and permit and electricity demand. However, the threshold can be evaluated relatively

---

[45] If $C_{qe}^1 = 0$, then $\partial p / \partial x_1 = \partial \sigma / \partial q_1 = 0$ (see Appendix A), and $\bar{x}_1^0 = x_1^*$

easily ex-post when making some simplifying assumptions about consumer demand response (see below).[46] Equations (4.6)-(4.7) lead to the following result:

Result 1:

After the market has been instituted and firms' allocation, emissions and output decisions have been observed, we can infer that:

a. **If the dominant firm received a free permit allocation equal to $\bar{\mathbf{x}}_1^0$, it acted as a price taker in the permit market in the sense that it set its marginal abatement costs equal to the permit price.**

b. **If the dominant firm's allocation was greater (smaller) than $\bar{\mathbf{x}}_1^0$ its marginal abatement costs were below (above) the permit price and it manipulated the permit price upwards (downwards) by over- (under-) purchasing permits.**

c. **The threshold allocation $\bar{\mathbf{x}}_1^0$ is smaller than the firm's emissions and necessarily makes the firm a net buyer of permits**.

---

[46] This caveat applies to some extent also to Hahn's results. Only if the firm's cost function is known can the regulator compute its efficient emissions and thus determine $\bar{x}_1^H$. The difference is that in my setup, the regulator also needs to know the firm's degree of market power and find a closed-form or numerical solution for $x_1^*(\bar{x}_1)$. I will leave the proof for the existence and uniqueness of such a solution for future work.

Result 1 is the core finding of this paper and states that even if the dominant firm is a net buyer of permits it can find it in its interest to manipulate the permit price upwards, provided that its allocation is sufficiently high.

Note that this is a generalization of Hahn's result, which I will denominate as $\bar{x}_1^H = x_1$: A dominant firm will only abstain from manipulating the price if it receives exactly the number of allowances necessary to cover its emissions and therefore does not trade. To see this, simply set $\partial p / \partial x_1 = 0$ in (4.6) or (4.7), thus eliminating the link between output and permit markets. Also note that if the second term on the RHS on (4.7) is sufficiently large (i.e. if the impact of the firm's permit purchases on output and permit price is sufficiently strong) then $\bar{x}_1^0 < 0$. In this case, even full auctioning would lead the firm to choose a permit price that is greater than its abatement costs.

On the other hand, if a firm has been observed to emit more (less) than its initial permit allocation, Hahn's model would imply that the firms marginal abatement costs are below (above) the market price. My model therefore shows that this conclusion is premature if output markets are taken into account.

So far I have focused on the effect of permit allocation on the permit price. However, as is clear from (4.3) and (4.4), the dominant firm's allocation also has an impact on the output price. I start by re-writing (4a) as

$$(4.8) \qquad p(\cdot) = C_q^1(\cdot) - \frac{\partial p}{\partial q_1} q_1^* + (x_1^* - \bar{x}_1)\frac{\partial \sigma}{\partial q_1}$$

With neither market power nor a permit market there would be the standard outcome that price equals marginal production cost, i.e. $p = C_q^1$. Market power in the output market increases the output price by the second term on the RHS, which is also a familiar result. The last term describes the effect of linking a permit market to the output market. Because $\partial\sigma / \partial q_1 < 0$, this term decreases (increases) the output price if the firm is a net buyer (seller) of permits. Substituting Hahn's result of $\bar{x}_1^H = x_1^*$ would cancel this third term, but it would not remove the output price distortion introduced by the second term. To see how my generalized threshold $\bar{x}_1^0$ performs in this case, I solve (4.5) for $x_1^* - \bar{x}_1$ and substitute into (4.8) to get

$$p(\cdot) = C_q^1(\cdot) - \frac{\partial p}{\partial q_1} q_1^* + \frac{\partial p / \partial x_1}{\partial\sigma / \partial x_1} \frac{\partial\sigma}{\partial q_1} q_1^* + \frac{\partial\sigma / \partial q_1}{\partial\sigma / \partial x_1} (-C_e^1 - \sigma) \tag{4.9}$$

By construction, allocating $\bar{x}_1^0$ to the dominant firm eliminates the last term, as in this case the marginal abatement costs are equal to the permit price. The third term on the RHS is negative and thus decreases output price distortion. However, the price distortion is not fully removed because it can be shown that

$$\frac{\partial p / \partial x_1}{\partial\sigma / \partial x_1} \frac{\partial\sigma}{\partial q_1} > \frac{\partial p}{\partial q_1} \tag{4.10}$$

(Proof: Appendix B)

It follows immediately that the output price can be brought to its efficient level only by allocating less than $\bar{x}_1^0$ to the dominant firm, because in this case the last term will be negative. The threshold allocation to the dominant firm that yields $p = C_q^1$ can be computed using (4.8) and is

$$\bar{x}_1^{00} = x_1^* - \frac{\partial p / \partial q_1}{\partial \sigma / \partial q_1} q_1^* \tag{4.11}$$

The fact that $\bar{x}_1^{00} < \bar{x}_1^0$ can easily be verified by using the inequality in (4.10). As before, due to the dependence of x_1^* on $\bar{x}_1$, this threshold can be evaluated ex-ante only under very simple functional forms. This leads to the following result:

Result 2:

After the market has been instituted and firms' allocation, emissions and output decisions have been observed, we can infer that:

a. **If the dominant firm received an allocation of $\bar{x}_1^{00}$, its marginal production costs were equal to the output price.**
b. **If the firm received more (less) than $\bar{x}_1^{00}$, marginal production costs were greater (smaller) than the output price.**
c. **The threshold allocation $\bar{x}_1^{00}$ is smaller than $\bar{x}_1^0$.**

The fact that marginal costs are equal to price in the two markets at two different levels means that efficiency cannot be restored completely. Either the permit price is distorted, or the output price, or both:

Result 3:

a. **The first-best solution in the sense that both the output and the permit price are at their competitive levels cannot be achieved by means of permit allocation alone, because $\bar{x}_1^{00} < \bar{x}_1^{0}$.**

b. **If the firm received more than $\bar{x}_1^{0}$ (less than $\bar{x}_1^{00}$), both output and permit price were distorted upwards (downwards) relative to marginal costs. If the firm's allocation was $\bar{x}_1^{00} < \bar{x}_1 < \bar{x}_1^{0}$, the output price was above and the permit price below marginal costs.**

Results 1-3 imply that under the assumption of market power in both markets, the amount of free allocation is crucial for price distortion, and that Hahn's "neutralizing" allocation prescription will result in an inflation of both output and permit price. In the following section I will empirically address the relevance of these findings in the context of the EU ETS.

4.3. Application to the EU ETS

4.3.a.) General applicability

Although the EU ETS covers six broad industry sectors, the main players both in terms of allocation and emissions are firms within the power & heat sector. There is evidence that this sector was subject to significant windfall profits (Grubb and Neuhoff, 2006, Hepburn, et al., 2006, Neuhoff, et al., 2006, Sijm, et al., 2006), which sets the stage for price manipulation as analyzed in the previous section. According to market observers (e.g. Point Carbon), it was the sustained allowance purchases from power & heat, combined with a relatively short allowance supply from the other sectors, that drove the price to the –in hindsight-very high level. There are a number of very large power producers for which the assumption of some market power seems at least possible.

On aggregate, firms in the power & heat sector were net demanders of allowances, whereas the other sectors covered by the EU ETS were over-allocated as a whole (Figs. 2.2-3). Hahn's results imply that in this case, price manipulation by dominant firms within this sector could not have been behind the allowance price increase, but as I show in section 4.2, this does not hold if firms are able to influence both the output and the allowance price. According to Result 1, a dominant firm would have found it optimal to use its market power to increase the allowance price even if it was a net buyer of allowances, as long as its free allocation exceeded $\bar{x}_1^0$.

I will now address the question whether there is any evidence relating firms' actual allocation to $\bar{x}_1^0$. To do this, it will be convenient to introduce a substitution in notation. At $\bar{x}_1 = \bar{x}_1^0$ the emissions constraint will be binding such that $x_1 = e_1$. Defining $\bar{y}_1 = \bar{x}_1 / e_1$ to be the proportion of actual emissions that the dominant firm receives allocated for free, I can re-state (4.7) in terms of the corresponding $\bar{y}_1^0$:

$$\text{(4.7')} \qquad \bar{y}_1^0 = 1 - \frac{\dfrac{\partial p / \partial x_1}{\partial \sigma / \partial x_1}}{\bar{\rho}_1} < 1 \qquad \bar{\rho}_1 \equiv \frac{e_1}{q_1}$$

The threshold in (4.7') is exactly equivalent to $\bar{x}_1^0$ as defined by (4.7), but instead of depending on the dominant firm's output q_1 it now contains its emission intensity (average emissions per unit of output), denoted $\bar{\rho}_1$.

The main difficulty to empirical assessment of (4.7) is to determine the effect of a dominant firm's permit purchase decisions on the output and the permit price. To get around this problem, I will use the fact that the numerator on the RHS of (4.7') is equivalent to the impact of the permit price on the output price if there is no demand response:[47]

---

[47] Totally differentiating output and permit price and dividing yields
$$\frac{dp}{d\sigma} = \frac{\partial p / \partial q_1 * dq_1 + \partial p / \partial x_1 * dx_1}{\partial \sigma / \partial q_1 * dq_1 + \partial \sigma / \partial x_1 * dx_1}$$

(4.12)
$$\frac{\partial p / \partial x_1}{\partial \sigma / \partial x_1} = \left.\frac{dp}{d\sigma}\right|_{dq_1 = 0}$$

I will argue that the short-term demand response for electricity by households is very small, as the most efficient means to reduce demand is to make changes in the portfolio of household appliances towards more energy-efficient items, which takes time. Assuming no consumer demand response during the first 18 months of the EU ETS, I can substitute (4.12) into (4.7'). The effect of the allowance price on the electricity price ($dp/d\sigma$) can be estimated by looking at the electricity spreads before and after the institution of the permit market relative to the allowance price. I will do this separately using market data from the UK and Germany, two of the largest players in the EU ETS.

4.3.b.) The UK power market

Gas-fired power plants are at the margin during medium and peak hours in the UK and are therefore price setting during these loads (Grubb and Newbery, 2007).[48] Figure 4.1 shows year-ahead spark spreads and clean spark spreads in the UK. The spark spread is the theoretical gross profit of a gas-fired power plant from selling a unit of electricity, having bought the fuel necessary to generate it:

---

[48] During base loads, the marginal generator is coal and nuclear for most hours, as they are generally ranked lower in the merit order than gas plants.

(4.13) $$\underset{(Euro/MWhe)}{Sparkspread} = \underset{(Euro/MWhe)}{p} - \underset{(Euro/MWhg)}{p^{gas}} * \underset{(MWhg/MWhe)}{\eta}$$

Here, p refers to the power price as before, p^{gas} to the price for natural gas and η to the heat rate (or efficiency). The clean spark spread, also called green spark spread, further adjusts the revenue stream by the CO_2 costs embedded in power generation:

(4.14) $$Cleansparkspread = sparkspread - \sigma * \rho^{gas}$$

where ρ^{gas} denotes the emission intensity of a typical gas plant. Solving (4.14) for the electricity price and its derivative with respect to the permit price yields

(4.15) $$p = cleansparkspread + p^{gas}\eta - \sigma * \rho^{gas} \Rightarrow \frac{dp}{d\sigma} = \rho^{gas}$$

At first sight, this seems to imply that the extent to which the electricity price is increased due to CO_2 costs is simply the emissions intensity used to compute the clean dark spread. However, these spreads are created as benchmarks and don't imply that the emission intensity used in their calculation is necessarily the average emission intensity of the marginal generator in the market. In theory, one could calculate the clean spark spread for any type of generator.

To see how ρ^{gas} relates to $dp / d\sigma$ it is useful to compare pre-market spark spreads with post-market clean spark spreads. With full cost pass-through,[49] constant demand and stable technology, the clean spark spread will be equal to the pre-market spread if the "correct" emission factor is used in (4.14), i.e. if $\rho^{gas} = dp / d\sigma$. In other words, theoretical gross profits[50] of a power producer will not change if the power price is increased by an amount exactly equivalent to the embedded carbon cost.

Figure 4.1 shows almost precisely such a market. Before the carbon market, UK spark spreads fluctuated around a level of £6-8. In January 2004, the year-ahead spreads immediately incorporated the carbon cost of producing electricity based on the year-ahead forward price for CO_2, with the spark spread increasing and the clean spark spread taking the place of the spark spread. The equalization of pre-market spark spreads and post-market clean spark spreads implies that the CO_2 costs embedded in the production of peak electricity are those that correspond to the allowance price multiplied by ρ^g used to calculate the clean dark spread, which is 0.41 tCO_2/MWh, the emission intensity of a typical Combined Cycle Gas Turbine (CCGT) (PointCarbon, 2007). This means that in the UK, $dp / d\sigma \approx \rho^g = 0.41 tCO_2 / MWhe$. Naturally, this is an approximation as the clean spark spread has its own variation over time, and factors other than the allowance

---

[49] Assuming a completely inelastic demand, profit-maximizing firms will pass their costs fully through to consumers.

[50] As discussed above, there may well be windfall profits due to the institution of the market because of free allocation.

price could potentially have affected the spreads. However, the figure and other evidence (Grubb and Newbery, 2007, Vorspools, 2006) implies that electricity prices increased roughly by the amount that corresponds to carbon costs incurred by an average CCGT.

I will now do the following back-of-the envelope calculation: Firms in the UK power sector on average received 77.1% of their emissions allocated for free.[51] Substituting a value of 0.77 for the UK, setting $dp/d\sigma = 0.41$ and solving (4.7') for the emission intensity, this means that it would have been profitable for dominant UK power firms to use their market power to increase the allowance price (and with it the electricity price) by over-purchasing allowances if

$$(4.16) \qquad \bar{\rho} < 0.41/(1-0.77) = 1.78 tCO_2 / MWhe$$

In comparison, the emission intensity of an anthracite coal power plant (the most emission-intensive method of power generation used today in Europe) with a heat rate of 33.3%,[52] is 1.06 tCO_2 per MWh of output. In other words, even the least efficient of all power production companies received an allocation in excess of $\bar{y}_1^0$ (or $\bar{x}_1^0$) and would have found it profitable to manipulate the permit price upwards, provided that it had some market power.

---

[51] Power & heat generators with an allocation of at least 100,000 allowances, based on 2005 numbers. This list is a subset of installations with activity code 1 (combustion) in the Community Independent Transaction Log (CITL). Many code-1 installations produce process power & heat only and are much smaller than power plants. For all code 1 installations combined, the fraction of free allocation is even larger.

[52] Power plants with such a low heat rate are most likely not allowed to operate in the UK.

Note that this result is quite robust to what cost pass-through rate I substitute into the numerator of (4.7’). The fact that companies received a free allocation covering around 77 % of their emissions means that the inequality in (4.16) holds as long as a firm’s emission intensity is smaller than (1/0.23=) 4.3 times the cost pass-through rate. Also note that power companies in the UK received the least generous allowance allocation in the EU ETS.

4.3.c.) The German power market

Large power producers in Germany received an average of 99.5% of their actual emissions allocated for free, much more than their UK counterparts. Differences in allocation for firms in the same sector but different countries have raised discussions about the ability to achieve economic efficiency in a system where each member country is able to independently define its own National Allocation Plan (Boehringer and Lange, 2005a).

In Germany, the marginal generator is a coal-fired power plant during most hours of the year, including the entire base load (Grubb and Newbery, 2007, Sijm, et al., 2006). German dark spreads and clean dark spreads are presented in Figure 4.2, along with their average (middle line). The dark spread is equivalent to the spark spread described above, but instead of gas it is applied to coal generation. Likewise, the clean dark spread is the dark spread adjusted for the CO_2 emission costs inherent in coal generation. The heat rate and emission intensity used to calculate dark spreads and clean dark spreads are 35% and 0.96 tCO_2/MWh of output, respectively (PointCarbon, 2007).

Cost pass-through was not immediate as in the UK, but 50% of carbon costs were passed through after one year, as indicated by the center line reaching the pre-market level of €10/MWh. By January 2006, the clean dark spread reached the pre-market dark spread level, implying that by then the carbon costs embedded in coal generation had been fully passed through to consumers. Again, the movement of clean dark spreads towards pre-market dark spread levels could include reasons other than CO_2 cost, but the figure implies that some cost pass-through was very likely.

Suppose now that cost pass-through on average was $0.5*\rho^c$, where ρ^c is the carbon intensity of coal generation used for the calculation of the green dark spread. Substituting this value along with an allocation of 99.5 % into (4.7') reveals that German power firms with market power would have found it profitable to inflate the allowance price if their emission intensity was below

$$\bar{\rho} < 0.5 * 0.96 \big/ (1 - 0.995) = 96 tCO_2 / MWhe$$

which is trivially the case for any power company. The choice of pass-through rate (and the assumption of zero demand response) is even less important here than for the UK, because almost any positive cost pass-through rate multiplied by (1/0.005=) 200 will lead to a number that exceeds real-world emission intensities.

Naturally, these calculations do not show in any way that electricity producers in the UK or in Germany actually had market power in both the output and permit market, and used this power to inflate the allowance price. But they do show that *assuming* that some firms had market power, 1.) they would have found it profitable to over-purchase allowances and under-abate emissions in order to inflate the permit price, because the ensuing increase in the electricity price would have more than compensated them for increased allowance purchase costs, and 2.) this would have lead to an electricity price increase relative to a situation with less free allocation.

4.4. Conclusions

There is a large literature about market power in permit markets, but, to my knowledge, no paper has directly addressed the effect of free allocation on price manipulation in the presence of market power in both permit market as well as the linked output market. Besides being of general economic interest, this particular question is motivated by a very high (in hindsight too high) allowance price during the first phase of the EU ETS, which reportedly led to large windfall profits especially for firms in the power & heat sector. These firms received most of their allowances for free but were able to pass through a large part of the opportunity costs to consumers. The reason for the apparent price inflation is not clear to date, but the presence of windfall profits (which are increasing in the permit price) and the history of imperfect competition in the power & heat sector raises the question whether dominant power producers could have used their market weight in order to increase the permit price.

According to Hahn's (1984) well-known results, the answer to this question is clearly negative, because power & heat is the only sector that was under-allocated with permits and thus was a net allowance buyer. In Hahn's framework, any dominant permit buyer would depress rather than inflate the permit price, and would act competitively only when given the exact amount of free allocation that covers its emissions.

In this paper, I show that Hahn's results no longer hold with market power in both markets. I derive the threshold of free allocation above which the dominant firm finds it profitable to under-abate and over-purchase allowances in order to push up the permit price. This threshold is a function of cost pass-through and firms' average emission intensity and is always less than a firm's emissions were it to set its marginal abatement costs equal to the permit price.

These findings are not subject to stringent assumptions about relative efficiency in production and/or abatement among firms, as is typically the case in the raising rivals' costs literature that discusses market manipulation in input and output markets. Firms do not profit at the expense of their industry rivals but that of consumers via the increased output price. In fact, the industry fringe profits from market manipulation on behalf of the dominant firm, as its revenue increases as well.

I apply my theoretical results to the UK and German power market. Using market evidence, I show that power generators in these countries received an allocation in excess of $\overline{x}_1^0$ and would therefore have been interested in increasing the allowance price, provided they had the ability to do so. In the UK, this result is due to an almost complete and immediate cost pass-through, whereas in Germany costs were passed through more slowly and/or less completely. However, because of the very generous allocation to German power generators, almost any positive pass-through rate would have made it profitable for them to manipulate the permit price upwards.

Chapter 5: An Options Pricing Approach to CO_2 Allowances in the EU ETS

Abstract

The EU ETS was set up very quickly, which could have made it impossible for firms to adjust their production technology before the end of Phase I. I derive an allowance pricing formula under the assumption that abatement was infeasible, which renders the allowance price a function of the penalty for noncompliance and the probability that the cap turns out to be binding. This is the pricing formula of a binary option, with the underlying process being CO_2 emissions. The options pricing formula depends on the mean and variance of future emissions.

I define the processes driving (stochastic) emissions and estimate their parameters using market data. I then incorporate these parameter estimates into the options pricing formula and estimate the remaining free parameters. The results make economic sense, and the model fits the data reasonably well. This implies that allowance prices may indeed not have been determined by marginal abatement costs during the first market phase.

Keywords: Emissions permit markets, air pollution, CO_2, climate change, options pricing, asset pricing, EU ETS.

JEL classification: G12, G14, G18, Q52, Q53, Q54

5.1 Introduction

The centerpiece of emissions permit market theory is that firms equate their marginal abatement costs to the permit price. Intuitively, if a firm finds it cheaper to abate an additional unit of emissions than what a permit is worth, it will make a profit from abating and either buy one fewer or sell one more permit on the market. Likewise, if the firm finds that purchasing a permit on the market is cheaper than to abate another unit of emissions, it will not abate but use the market to reach compliance. The efficient solution of this arbitrage game is that all firms abate exactly to the point where their marginal abatement costs are equal to the permit price.

However, this leaves out two important possibilities: For one, firms don't know exactly what their emissions are going to be, even if they are engaging in abatement, if abatement consists of reducing emissions per unit of (stochastic) output. And second, abatement may not be feasible, or at least not practical, for the involved firms in the short run. Most permit markets to date, including the EU ETS, impose a penalty for noncompliance: For every unit (usually a ton) of emissions for which the firm cannot surrender a permit, it is fined a penalty; in addition, the missing permits have to be surrendered in the following year.

In this paper I will address precisely this question: Was the allowance price in the EU ETS determined predominantly by firms looking with one eye to the penalty and with the other on the realized emissions to date and the expected emissions to come?

I develop an allowance pricing formula using options pricing techniques that does not incorporate abatement, but instead relies on the penalty and expected overall emissions levels as price drivers. While eliminating abatement from the problem is mainly intended to simplify the calculations, one can also argue that this assumption is quite realistic for the following reasons:

First, the timely construction of cleaner production technology (e.g. more efficient power plants) was largely infeasible before the end of the first phase. The market was set up at a very rapid speed, with only a little over year between its legal conception and the start of the first phase. Some EU member countries did not finalize their national allocation plans (NAPs) until mid 2005, which created considerable uncertainty about the total cap and the resulting allowance price. Uncertainty over the return of irreversible investment delays such investment.[53] Besides, even under complete certainty, many new plants simply take longer than 4 years (the time between the inception of the market and the end of the first phase) to plan and construct.

In the absence of cost-effective technology that filters CO_2 from exhaust gases, this leaves essentially only fuel switching as a method of abatement (Alberola, et al., 2008, Bunn and Fezzi, 2007, Mansanet-Bataller, et al., 2007, Rickels, et al.,

---

[53] For a thorough treatment of investment under uncertainty and the ensuing option value of waiting, see Dixit and Pindyck (1994).

2007, Sijm, et al., 2006). However, energy-intensive industries are typically locked into long-term contracts. It is questionable whether firms were able to adjust these contracts in time (Chesney and Taschini, 2008), and/or whether they were willing to do so, considering the large uncertainty about future caps.

Second, firms probably anticipated that their first-phase emissions were going to be used to guide the distribution of second-phase allowances. The EC vehemently argued against this and repeatedly promised that this was not going to be the case, but it happened nevertheless: Most EU member countries based their second-phase NAPs on verified 2005 emissions. One possible reason for this –from an economic point of view highly inefficient- choice is the scarcity of information about historic emissions in the EU, which made it almost impossible for the EU member countries to fight the temptation to use the information gained from the first round of emissions verification. Basing future allocation on current emissions creates a disincentive to abate, because every unit of abatement comes causes not only costs in the current period (e.g. due to fuel switching) but also a reduction in future free allocation (Boehringer and Lange, 2005b).

Third, aggregate emissions were below the total cap for each individual year of the market.[54] An allowance surplus by itself does not automatically mean that there was no abatement, especially during the first 16 months of the market when the allowance price was very high and actual emissions had yet to be verified (Ellerman

---

[54] During the first phase as a whole, the cap and total emissions were 6.250 and 6.081 billion tons, respectively. The allowance surplus of 168 million tons corresponds to about 2.7 % of the cap.

and Buchner, 2006). On the other hand, it is precisely the beginning of the market that was especially constrained in terms of building new infrastructure and adjusting long-term fuel contracts. And last but not least, I found no consistent correlation between allowance prices and commonly identified abatement price drivers (see Chapter 3 of this Dissertation). For all these reasons, the assumption of no abatement during the first phase may not be far from the truth.

The purchase of an allowance gives the bearer the option to use it for compliance at the end of the period, or, equivalently, to sell it. However, if the cap turns out to be not binding, the bearer can retire the allowance. In other words, the holder has the right, but not the obligation to use the allowance. This makes an allowance a financial option. Specifically, the payoff function is that of a type of binary option called a cash-or-nothing call option. There exist well-established pricing formulae for binary options if the underlying asset follows a lognormal distribution. I develop a pricing formula based on two normally distributed underlying processes, namely electricity consumption and precipitation.

The fact that allowances can be viewed as financial options is neither remarkable in itself nor new. A handful of studies have used financial methods to either predict allowance prices themselves, or to price options on allowances. However, to my knowledge, no one has used observed allowance prices and then used options pricing formulas to back out the underlying parameters.

In Section 5.2 I give some more background and derive an options pricing formula for EU ETS allowances as a function of past and future emissions in the power & heat sector, the cap, the penalty for noncompliance and a set of free parameters. This pricing formula contains the mean and variance of expected future emissions between the current day and the end of the market, which I derive in Section 5.3 as a function of exogenous stochastic processes. Section 5.4 contains empirical estimates for these underlying processes as well as estimates for the free parameters in the options pricing formula. Section 5.5 concludes.

5.2. Emission allowance pricing in the absence of abatement

5.2.a.) Literature on permit pricing

Historically, permit pricing formulas were derived by solving an optimal control problem, originating with Montgomery (1972). This was later extended to the dynamic case (Leiby and Rubin, 2001), to incorporate banking and borrowing (Cronshaw and Brown-Kruse, 1996, Rubin, 1996) and to address uncertainty (Schennach, 2000, Zhao, 2003) and to some extent volatility (Newell et al., 2005). But it was not until recently that financial methods have been employed to derive emissions permit prices.

Kosobud et al. (2005) introduced financial tools to the analysis of SO_2 permits in the US Acid Rain program. Other contributions that approach permit markets and the efficient price of an allowance from a financial perspective include Benz and Trueck (2006) and Fehr and Hinz (2006). Seifert et al (2008) explicitly mention the option value of a permit when compared with the alternative of irreversible investment in emissions abatement. Chesney and Taschini (2008) go one step further and define EU ETS allowances to be financial (as opposed to "real" options) and derive a pricing formula that comes close to options pricing. However, all of these approaches start with the definition of underlying pollution processes, and then derive a market-clearing permit price by method of simulation. This allows for valuable insights in terms of price volatility and hedging strategies, but it does not address the question of what actually drives permit prices. My paper intends to fill this gap by taking the allowance price series in the EU ETS as given and test whether it is consistent with a model that is based on options pricing techniques, and, in particular, whether it was driven by the penalty of noncompliance and the probability that the cap would turn out to be binding.

5.2.b.) Derivation of option pricing formula

Let P_t be the closing price for an allowance on day t, with the day index $t = (1,2,...,T)$ starting on January 1, 2005, and ending at t =T on December 31, 2007.

Let g_t represent CO_2 emissions on day t, $G_1^t \equiv \sum_{k=1}^{t} g_k$ cumulative emissions since the beginning of the market, and $G_t^T \equiv \sum_{k=t+1}^{T} g_k$ cumulative future emissions until the end of the market. It follows from these definitions that at time t, G_1^t is observed and G_t^T is stochastic. Furthermore, let $\overline{P}$ be the penalty for noncompliance and S_0 be the total emissions cap over the entire market period imposed by the regulator. Finally, it will also be useful to define $S_t = S_0 - G_1^t$ to be the "remaining cap" until the end of the market.

At time T, the price of an allowance is zero if emissions are below the cap, or equal to the penalty if the cap turned out to be binding. Naturally, if the cap is already exceeded at time t<T, the probability that the allowance price is equal to the penalty is one:

$$P_T = \begin{cases} 0 & if \quad S_T > 0 \\ \overline{P}_T & if \quad S_T \leq 0 \end{cases} \tag{5.1}$$

The penalty is the sum of the per-unit penalty and the cost of buying an additional permit for the second phase, for which I use the forward price of second-phase allowances $P_t^{Phase\ II}$:

$$\overline{P}_T = €40 + P_T^{Phase\ II}$$

At t<T, it is not known with certainty whether the cap will be exceeded, provided that it has not been exceeded already. The expected price is

$$\begin{aligned} &E_t[P_T \mid S_t > 0] = E_t[\overline{P}_T] * \int_{S_t}^{\infty} \zeta_t(G_t^T) dG_t^T \\ &E_t[P_T \mid S_t \leq 0] = E_t[\overline{P}_T] \end{aligned} \tag{5.2}$$

where $\zeta_t(G_t^T)$ denotes the probability density function over cumulative future CO_2 emissions and $E_t[\cdot]$ stands for the expectation taken using all information available at time t. Note that equation (5.2) is very similar to an equation derived by Chesney and Taschini (2008).

I will assume that daily emissions g_t are normally distributed.[55] As I will argue below, emissions are a linear function of underlying normally distributed AR(1) processes, meaning that the assumption of normally distributed emissions is really an assumption about normally distributed underlying processes. Because G_t^T represents the summation of random events g_k for $k > t$, it follows that G_t^T is normally distributed as well. I will denote the mean and standard deviation as μ_t and s_t, respectively. It follows that

$$Q_t \equiv \frac{G_t^T - \mu_t}{s_t} \sim N(0,1)$$

has a standard normal distribution. Let $\varphi(\cdot)$ and $\Phi(\cdot)$ be the probability density function (pdf) and cumulative probability density function (cdf) of the standard

---

[55] In theory, the choice of a normal distribution makes a truncation at zero necessary since negative emissions are not defined. But because CO_2 emissions in the EU are many standard deviations away from zero, the correction implied by the truncation is very small, such that for the remainder of this paper I will neglect the truncation issue and assume that emissions are normally distributed. Note that this assumption is similar to that of demographers who assume that people's height is normally distributed.

normal distribution, respectively. I now convert the integral in (5.3) into an integral over Q_t :

(5.4) $$E_t[P_T \mid S_t > 0] = E_t[\overline{P}_T]*\int_{(S_t-\mu_t)/s_t}^{\infty}\varphi(Q_t)dQ_t$$

which is equivalent to

(5.5) $$E_t[P_T \mid S_t > 0] = E_t[\overline{P}_T]*\Phi\left(\frac{\mu_t - S_t}{s_t}\right)$$

Arbitrage considerations dictate that the price at time t be equal to the expected price at T, discounted by the risk-free rate of interest r.[56] The same reasoning applies to the forward price for Phase II allowances, such that $E_t[P_T^{Phase\,II}] = P_t^{Phase\,II} * e^{r(T-t)}$. This means that the allowance price is a martingale defined by

(5.6) $$\begin{aligned} P_t \mid S_t > 0 &= [40e^{-r(T-t)} + P_t^{Phase\,II}]*\Phi\left(\frac{\mu_t - S_t}{s_t}\right) \\ P_t \mid S_t \le 0 &= [40e^{-r(T-t)} + P_t^{Phase\,II}] \end{aligned}$$

---

[56] Real-world markets are typically not risk-neutral, but option prices based on risk neutrality nevertheless yield the correct (meaning no-arbitrage) solution for traded assets (Hull, 2002). Risk aversion may be more important for the pricing of non-traded assets such as the weather or electricity demand, but the price of market risk can never be measured with a sufficient degree of confidence in order to make its inclusion in a pricing formula worthwhile, due to measurement and identification issues (e.g. a greater market fundamental and a higher price of risk have the same effect on the price). In absence of a convincing prior for market risk, I will omit the latter in my analysis.

This is the option pricing formula for a cash-or-nothing call option based on a normally distributed underlying asset or process.

Given knowledge of past emissions G_0^t, the overall cap S_0, the forward price penalty $P_t^{Phase\,II}$ and the interest rate r, and estimates for the mean μ_t and standard deviation s_t of future emissions at every point in time, an estimate for the allowance price $\hat{P}_t$ can be computed for reach day, and the resulting time series compared with the observed series P_t for $t = 1,2,...,T$. A situation where the two series correspond to one another would be interpreted as evidence that the allowance price was driven by emissions and the penalty, but not abatement.

What remains to be determined in order to evaluate (5.6) are past emissions and the mean and standard deviation of cumulative future emissions. These are not directly observed, but have to be derived from underlying processes and ultimately estimated using market data. This is the subject of the following section.

5.3. Deriving the mean and standard deviation of future emissions

5.3.a.) CO_2 emissions as a function of exogenous stochastic processes

Emissions are verified only once a year, and there exists no direct data about daily emissions. However, for the power and heat sector (which is by far the most important in the EU ETS) here is something that comes close: Daily electricity consumption.

Electricity is special in the sense that demand has to be met with a matching supply at all times in order for the grid not to crash. I will make the simplifying assumption of zero short-term demand elasticity of electricity. This makes electricity demand an exogenous process driven by stochastic elements such as the weather.[57]

More precisely, it is not generation of electricity in general that drives CO_2 emissions, but generation of electricity using conventional thermal generators by burning fossil fuels like coal and natural gas. Thus, daily emissions are a function of consumer demand, as well as the availability of "clean" (i.e. non-CO_2-emitting) sources of energy, mainly hydroelectric and nuclear power.[58] Hydroelectric generation depends on rainfall and varies within and between years, but nuclear generation is largely constant due to prohibitively high start-up costs.

Let c_t represent overall electricity consumption; c_t^c consumption of conventional fossil-fueled generation; n nuclear power generation (all in Giga-Watt-hours (GWh) per day); and h_t rainfall in the EU in millimeters (mm) per day, weighted by installed hydroelectric capacity. Assuming that all available

---

[57] In the long run, consumers will react to higher electricity prices by changing their consumption habits and appliance portfolio, such that electricity demand is also a function of the electricity price. But regardless of the time horizon, exogenous weather shocks will always drive short-term consumption.

[58] Although wind generation has increased rapidly during the past few years, it still accounts for a relatively small fraction of total power production.

hydroelectric and nuclear power is used (i.e. that they are lowest in the merit order[59]), demand for conventional generation can be expressed as

$$c_t^c = c_t - \eta h_t - n \tag{5.7}$$

where η is a fixed coefficient translating precipitation into hydroelectric power.

Since precipitation can be stored to some extent, either in reservoirs or as snow in the mountains, there is no immediate relationship between precipitation and hydro generation on any given day, which makes a regression of hydro output on daily precipitation impractical. On the long run, however, all net hydro generation is ultimately due to precipitation, and even though rainfall today may not translate into more generation today, it nevertheless reduces expected conventional generation needed to satisfy consumer electricity demand until the end of the market. I compute the precipitation-to-rainfall conversion factor η by dividing the EU's total hydro generation[60] in 1990-2005 of 4,852,339 GWh by cumulative weighted precipitation over the same period of 9,775.28 mm, using installed hydroelectric capacity per country as weights. This results in a conversion factor of η=496.389 GWh/mm.

In the EU, 12 member countries have nuclear power plants (BE, CZ, DE, ES, FI, FR, HU, NL, SK, SL, SW, UK). Their average total output in the years 2003-2005 was 2,679 GWh per day, which I will use as a measure for n.

---

[59] The merit order is the sequence by which individual generators are brought online and is usually based on marginal cost.

[60] From World Development Indicators database, World Bank.

The emission intensity (in CO_2/GWh) of the marginal generator varies with demand. The correct way to express emissions in Europe's power & heat sector is

(5.8) $$g_t = \int_0^{c_t^c} \Psi(y)dy$$

where $\Psi(c_t^c)$ is an emission intensity function transforming conventional thermal power generation into CO_2 emissions. To compute the integral in (5.8) I would need to know the exact dispatch order and the marginal emission intensity of all generators involved, which is information that is not readily available. Instead, I assume that the emission intensity of the marginal generators (i.e. all generators that are not running all the time) follow a quadratic function. This allows me to express (5.8) as

(5.9) $$\begin{aligned} g_t &\approx \mathrm{K} + \gamma * c_t^c \\ \mathrm{K} &\equiv g^{\min} - \gamma * \min(c_t^c) \end{aligned}$$

The parameter γ translates fossil-fueled electricity generation into CO_2 emissions. K is a constant defined as the difference between CO_2 emissions associated with minimum thermal generation $g^{\min}$ and the (theoretical) emissions if the emission intensity γ were applicable to the inframarginal generation.[61]

---

[61] In theory, the average emission intensity of inframarginal generation could be greater or smaller than the emission intensity of marginal generation. For example, if inframarginal generation consists to a large part of lignite or anthracite coal power plants, then K>0, but if it exists largely of efficient generators such as combined cycle gas turbines (CCGTs) that are low in the dispatch order due to their small marginal costs, then K<0. In the EU, the former

Combining (5.7) and (5.9), daily CO_2 emissions can be expressed as

$$g_t = \mathrm{K} + \gamma * (c_t - \eta h_t - n) \tag{5.10}$$

In this specification, emissions are a function of a set of parameters and the two stochastic and exogenous processes c_t and h_t. The properties of g_t, and thus of μ_t and s_t, are therefore a function of the properties of c_t and h_t. At time s, the mean of future CO_2 emissions at $t \geq s$ is defined by

$$\begin{aligned} \mu_t = E_s[G_t^T] &= E_s\left[\sum_{k=t+1}^{T} g_k\right] \\ &= E_s\left[\sum_{k=t+1}^{T} K + \gamma * (c_t - \eta h_t - n)\right] \\ &= (T-t)K + \gamma * \sum_{k=t+1}^{T}\left(E_s[c_t] - \eta E_s[h_t] - n\right) \end{aligned} \tag{5.11}$$

The calculation of the variance of future emissions is a little more complicated. In Appendix C (Result 1), I show that at time $s \leq t \leq u$, the variance is

(5.12)

$$\begin{aligned} s_t^2 = Var_s[G_t^T] = \sum_{k=t+1}^{T} Var_s[g_k] + 2\sum_{k=t+1}^{T}\sum_{u=k+1}^{T} Cov_s[g_k, g_u] \\ = \gamma^2 \sum_{k=t+1}^{T}\left(Var_s[c_k] - 2\eta Cov_s[c_k, h_k] + \eta^2 Var_s[h_k]\right) \\ + 2\gamma^2 \sum_{k=t+1}^{T}\sum_{u=k+1}^{T}\left(Cov_s[c_k, c_u] + \eta^2 Cov_s[h_k, h_u] - \eta Cov_s[c_k, h_u] - \eta Cov_s[h_k, c_u]\right) \end{aligned}$$

---

is much more likely given the large number of lignite plants in Germany and the new EU member countries from Eastern Europe.

Both expressions are functions of the constants η and n, the parameters K and γ, the mean and variance of electricity consumption and precipitation, and the covariance of electricity consumption and precipitation between different days.

I defined the constants η and n above and will treat them as known; K and γ will enter the estimation as free parameters. The derivation of the mean, variance and covariance of electricity consumption and rainfall is the subject of the next subsection.

5.3.b.) Properties of the stochastic processes c_t and h_t

For the definition of the stochastic processes of electricity demand and precipitation, I will draw extensively from a paper by Peter Alaton, Boualem Djehiche and David Stillberger (2002). Although their analysis focuses on pricing a weather option over heating-degree days with the underlying process being temperature, it is very similar in principle to both electricity demand and precipitation, as both are exogenously driven stochastic processes that contain deterministic annual fluctuation and long-term trends. The contribution of my paper is not the derivation of the property of such processes, but the application of these methods to model CO_2 emissions and, ultimately, to CO_2 allowance pricing.

I will model both electricity consumption and precipitation diffusion processes[62] consisting of a deterministic mean and a stochastic part, and which exhibit mean-reversion.[63] For mathematical tractability, I include the stochastic element in the form of a generalized Wiener process. Combining the processes in the index x, they can be described as

$$dx_t = \left[\frac{dx_t^m}{dt} + a_x *(x_t^m - x_t) \right] dt + \sigma_x [i(t)] dW_t^x; \qquad x = c, h \tag{5.13}$$

This is known as an Ornstein-Uhlenbeck process with a non-zero mean and time-varying volatility.[64] The term in brackets represents the drift of the processes, followed by the diffusion term defined by the standard Wiener process dW_t^x times the corresponding volatility. The first element of the drift term in (5.13) is due to the fact that mean consumption and precipitation change throughout the year. The mean reversion parameters a_x measure the speed at which the processes revert back to their long-term mean.

I constrain the volatility to be constant within each calendar month, but allow it to differ across months. The index i labels the month to which the time index t

---

[62] A diffusion process is the solution to a stochastic differential equation. In particular, it is a continuous-time Markov-process with a continuous sample path. This is a realistic description for electricity consumption and precipitation and makes the derivation and exposition easier, but the market and weather data discrete are naturally only available for discrete points in time.

[63] Mean reversion is a commonly observed characteristic in many naturally occurring processes, as they generally do not grow without bounds and eventually return to their long-term mean.

[64] See, for example, Bibby and Sorensen (1995).

refers. For reasons of data availability (see below) I will start this index at 1 in January 1976 and finish at 384 in December 2007. Thus,

$$\begin{aligned} i(t) &= 1\, if\, t \in \text{Jan1976} \\ &= 2\, if\, t \in \text{Feb1976} \\ &\vdots \\ &= 384\, if\, t \in \text{Dec2007} \end{aligned}$$

Because I assume that the volatility is the same for each calendar month, it must be that $\sigma[i] = \sigma[i + k * 12]$ for any integer k.

I define the long-term mean of electricity consumption and precipitation as

$$\begin{aligned} c_t^m &= \beta_0^c + \beta_1^c * t + \beta_2^c * \sin[2\pi t / 365 + \omega^c] + D^c * WD_t \\ h_t^m &= \beta_0^h + \beta_1^h * t + \beta_2^h * \sin[2\pi t / 365 + \omega^h] \end{aligned} \tag{5.14}$$

The parameters β_0^x and β_1^x ($x = c, h$) describe the level and trend of the two process, respectively, whereas β_2^x describe the amplitudes of the respective sine waves. The phase angles ω^x shift the oscillation of the two processes to their correct position. Lastly, the vector of coefficients D^c (not applicable to rainfall) accounts differences in electricity consumption across different weekdays, and WD_t is a vector of weekday dummies.

Equation (5.13) describes two stochastic differential equations. At time $s \leq t$, their solution is[65]

---

[65] See, for example, Øksendahl (2007) Chapter 2.

$$x_t = (x_s - x_s^m)e^{-a_x(t-s)} + x_t^m + \int_s^t e^{-a_x(t-\tau)}\sigma_x[i(\tau)]dW_\tau^x; \qquad x = c, h \tag{5.15}$$

The first term on the RHS is the deviation of actual consumption/precipitation at the present time s from its mean. As time goes on, the impact of this deviation will diminish due to the mean-reversion property of both processes, measured by the exponent. If one of the processes is at its average at time s, or if $t >> s$, then the first term will drop out, and the expectation at time t simply becomes the mean expectation x_t^m defined by (5.14).

The mean and variance of electricity demand and precipitation can be computed as

$$E_s[x_t] = [x_s - x_s^m]e^{-a_x(t-s)} + x_t^m; \qquad x = c, h \tag{5.16}$$

$$\begin{aligned} Var_s[x_t] &= E_s\left[\left(x_t - E_s[x_t]\right)^2\right] \\ &= E_s\left[\int_s^t \sigma_x^2[i(\tau)]e^{-2a_x*(t-\tau)}\left(dW_\tau^2\right)^2\right] \\ &= \int_s^t \sigma_x^2[i(y)]e^{-2a_x*(t-y)}dy; \qquad x = c, h \end{aligned} \tag{5.17}$$

The second equality follows from the fact that $E\left[(dW_t^x)^2\right] = dt$. If the volatility does not change between s and time t, (5.17) can be solved to

$$Var_s[x_t] = \frac{\sigma_x^2[i(t)]}{2a_x}\left(1 - e^{2a_x(t-s)}\right); \qquad x = c, h; \quad i(s) = i(t) \tag{5.18}$$

If s and t are not within the same month, the expression becomes more complicated. I will denote the first day of each month as $t^{\min}[i(t)] = \min\{t : i(t) = i\}$. In Appendix C (Result 2) I show that for $x = c, h$ and $i(s) \le i(t)$, the general expression for the variance is

$$(5.19)\ Var_s[x_t] = \frac{1}{2a_x}\left\{\sum_{k=i(s)}^{i(t)-1}\left(\sigma_x^2[k] - \sigma_x^2[k+1]\right)e^{-2a_x(t-t^{\min}[k+1])} + \sigma_x^2[i(t)] - e^{-2a_x(t-s)}\sigma_x^2[i(s)]\right\}$$

It is easy to verify that if the volatility is the same for each month, (5.19) collapses to (5.18).

To calculate the covariance between electricity consumption and rainfall on the same day, note that $E[dW_t^c dW_t^h] = \rho^{ch} dt$, where $\rho^{ch} \equiv Cov[c_t, h_t] / \sqrt{Var\,[c_t] * Var\,[h_t]}$ is the correlation coefficient between the two processes. Thus,

$$\begin{aligned} Cov_s[c_t, h_t] &= E_s\left[\left(c_t - E_s[c_t]\right)\left(h_t - E_s[h_t]\right)\right] \\ &= E_s\left[\int_s^t \sigma_c[i(\tau)]\sigma_h[i(\tau)]e^{-(a_c+a_h)*(t-\tau)}dW_\tau^c dW_\tau^h\right] \\ &= \int_s^t \rho^{ch}\sigma_c[i(y)]\sigma_h[i(y)]e^{-(a_c+a_h)*(t-y)}dy \end{aligned}$$

Analogous to the procedure used for the variance, this can be solved to

$$(5.20)\qquad Cov_s[c_t,h_t]=\frac{\rho^{ch}}{a_c+a_h}\left\{\begin{array}{l}\sum_{k=i(s)}^{i(t)-1}\left(\sigma_c[k]\sigma_h[k]-\sigma_c[k+1]\sigma_h[k+1]\right)e^{-(a_c+a_h)(t-t^{\min}[k+1])}\\ +\sigma_c[i(t)]\sigma_h[i(t)]-e^{-(a_c+a_h)(t-s)}\sigma_c[i(s)]\sigma_h[i(s)]\end{array}\right\}$$

Lastly, the covariance between electricity consumption/precipitation on day t and u for $s \le t \le u$ is defined by (see Appendix C, Result 3):

$$(5.21)\qquad \begin{array}{ll} Cov_s[x_t,x_u]=e^{-a_x*(u-t)}*Var_s[x_t]; & x=c,h\\ Cov_s[c_t,h_u]=e^{-a_h*(u-t)}*Cov_s[c_t,h_t] & \\ Cov_s[h_t,c_u]=e^{-a_c*(u-t)}*Cov_s[c_t,h_t] & \end{array}$$

Expressions (5.16) and (5.19)-(5.21) can now be substituted into (5.11) and (5.12). In the following section I obtain empirical parameter estimates for $\beta_0^x,\beta_1^x,\beta_2^x,\omega^x,D^c,a_x,\rho^{ch}$ and $\sigma_x(i)$.

5.4. Estimation

There are two different steps in the estimation. The final goal is to express equation (5.6) as a function of data, known constants, and a set of free parameters, and calculate these free parameters using market data. Since most countries lack daily electricity consumption data prior to 2006, I will evaluate (5.6) for the period between January 1, 2006 and December 31, 2007.

Because in January 2006, realizations of electricity consumption and precipitation for later days were not yet known, I estimate μ_t and s_t using data through 2005 only, with some exceptions where necessary. In theory I could update the estimates for every day, but for simplicity I will use pre-2006 data.

5.4.a.) Data

Daily data about electricity consumption is available from the Union for the Coordination of Transmission of Electricity (UCTE)[66] for continental European countries, including all EU member states except for the Nordic countries,[67] the UK, Ireland, the Baltic States, Malta and Cyprus. Electricity consumption has been measured on every third Wednesday of each month[68] since 1994 for 9 EU countries, since 1996 for Germany and since 1999 for another 5 EU countries. Weekend consumption is available for every Weekend following the third Wednesday of each month in the year 2000. Starting in January 2006, electricity consumption is available on a daily basis for all UCTE countries. To supplement the UCTE data I obtained all available historic electricity consumption data directly from the transmission system operators (TSOs) in the UK, Ireland and the Nordic countries.[69]

---

[66] Available at www.ucte.org, last accessed in September 2008.

[67] Sweden, Denmark and Finland. Note that Norway is not part of the EU, and although it is now linked to the EU ETS, this was not the case during the first phase of the market.

[68] Wednesdays are supposed to be the most typical weekdays (as opposed to Mondays and Fridays, which may be slightly different), and the third week is supposed to be the typical week of a month.

[69] UK: Daily data since 2001 from the National grid, available at http://www.nationalgrid.com/uk/Electricity/Data/; Ireland: Daily data since 2002 from Eirgrid, available at http://www.eirgrid.com; Denmark: Daily data since 2000 from Energinet, available at http://www.energinet.dk; Finland: Daily data since 2004 from Fingrid,

I exclude Malta, Cyprus and the Baltic States from the analysis, because the former are not integrated into Europe's electricity grid and no daily electricity consumption data for the latter is available. In terms of annual electricity production, the 20 countries included account for 99% of total production in the EU-25.[70]

The EU produces nearly all of the electricity it consumes, with net imports/exports accounting for less than 0.1 percent overall consumption. I therefore exclude imports/exports in my calculations and set consumption equal to production.

In order to accommodate the variation in type and provenance of the data I will carry out the analyses separately for each group of countries for which the available data is of the same type (e.g. daily vs. monthly) and covers the same time period. The six groups are listed in Table 5.1. Figures 5.1a-f show the available pre-2006 electricity consumption data by group. All countries have daily data for the years 2006 and 2007.

For precipitation, I use the European Climate Assessment and Dataset.[71] This dataset contains daily data for 1,048 monitoring stations located in 42 countries. The length of the series varies from a few years to >150 years, with most series spanning

---

available at http://www.fingrid.fi; Sweden: Daily data since 2000 from Svenska Kraftnät, available at http://www.svk.se/web/Page.aspx?id=5794.

[70] In 2007, Romania and Bulgaria joined the Union to make it the EU-27. However, because they were not part of the market during the first two years, and their registries were not ready until the end of 2007, they can be excluded from Phase I.

[71] Klein Tank et al. (2007): "Daily Dataset of 20th-Century Surface Air Temperature and Precipitation Series for the European Climate Assessment", available at eca.knmi.nl, last accessed in September 2008.

several decades. To model the stochastic process underlying precipitation, I use data covering the years 1976-2005.

The conversion of precipitation into hydroelectric power is location-specific. For example, rainfall in the Netherlands or in Denmark is largely irrelevant for power generation because these countries have very little installed hydroelectric generation capacity, whereas hydro generation constitutes a large share of total power production in Alpine and Scandinavian countries. I average station entries by country,[72] and then create a weighted European average using installed hydroelectric capacity in 2006 as weights.[73] Installed hydro generation is given in the last column of Table 5.1.

Weighted precipitation in millimeters (mm) is shown in Figure 5.2 for a subset of the sample period. Whereas it is difficult to visually discern a pattern in the raw data (Fig. 5.2a), using moving 7-day-average (Fig. 5.2b) reveals a clear seasonality.

---

[72] For low-lying countries such as Belgium and Luxembourg, I simply take an average of all monitoring stations. However, since hydro generation in the Alps and in Scandinavia is highly location-specific, I take an average of the subset of monitoring stations that are located in or near mountains. A full list of the selected stations is available from the author upon request.

[73] This data comes from UCTE (www.ucte.org) for continental Europe; from Nordpool (www.nordel.org) for Scandinavia; from the Austrian Energy Agency (www.energyagency.at/enercee/) for the Baltic States; from Harrison (2005) for the UK; and from the Electricity Supply Board (ESB, available at http://www.esb.ie/main/about_esb/power_stations_intro.jsp) for Ireland; all accessed in September 2008.

5.4.b.) Parameter estimation for electricity consumption and precipitation

I estimate the parameters $\beta_0^x, \beta_1^x, \beta_2^x, \omega^x, D^x$ and $\sigma_x[i]$ with a model that features an autoregressive error to account for mean-reversion and multiplicative heteroskedasticity to allow the variance to differ across months:

$$\begin{aligned}
&x_t = \beta_0^x + \beta_1^x * t + \alpha_1^x * \sin(2\pi t/365) + \alpha_2^x * \cos(2\pi t/365) + D^x * WD_t + \varepsilon_t^x \\
&\varepsilon_t^x = \phi_x * \varepsilon_{t-1}^x + u_t^x \\
&u_t^x \sim N(0, \xi_x^2[i(t)] \\
&\xi_x^2[i(t)] = \exp\{\lambda_0^x + \lambda_1^x * Jan_t + ... + \lambda_{11}^x * Nov_t\}; \qquad x = c^1, c^2, ..., c^6, h
\end{aligned} \tag{5.22}$$

Note that the index x now covers six different electricity consumption series, plus the (weighted) precipitation series, all of which are estimated separately by maximum likelihood.

The parameters β_0^x, β_1^x and D^x are the same as in (5.14) and are estimated directly. The transformation of the sine wave plus the phase angle into a sine and cosine wave is based on a Fourier transform and serves to linearize the equation. The parameters β_2^x and ω^x can be computed using the estimates of α_1^x and α_2^x:[74]

$$\begin{aligned}
&\beta_2^x = \sqrt{(\alpha_1^x)^2 + (\alpha_2^x)^2} \\
&\omega^x = \arctan[\alpha_2^x / \alpha_1^x]
\end{aligned}; \qquad x = c^1, c^2, ..., c^6, h \tag{5.23}$$

The t-statistics and confidence intervals have to be calculated using the delta method.

---

[74] See, for example, Beckwith et al. (1995), p. 131.

I estimate the daily variance $\sigma_x^2[i]$ from the autocorrelation parameters ϕ^x and the variance of the white noise $\xi_x^2[i]$.[75] For a stationary AR(1) process, the variance is given as

$$\sigma_x^2[i] = E\left[(x_t - E[x_t])^2\right] = E[\varepsilon_t^2] = \frac{\xi_x^2[i]}{1-\phi_x} \tag{5.24}$$

The mean-reversion parameters a_x measure the speed at which a shock to x_t is felt at later times. From (5.16), the expectation of future electricity consumption or precipitation is

$$\begin{aligned} E_s[x_t] &= [x_s - x_s^m]e^{-a_x(t-s)} + x_t^m \\ &= \varepsilon_s^x * e^{-a_x(t-s)} + x_t^m \qquad\qquad x = c, h \end{aligned}$$

This makes it clear that the term $e^{-a_x(t-s)}$ is equivalent to the impulse-response function of the AR(1) process defined by[76]

$$\chi(t,s) = \phi^{|t-s|}$$

---

[75] Because I cannot estimate an AR(1) parameter with data that only contains entries for every 3rd Wednesday per month, I use the 2006-7 data to estimate this parameter for Series 1-3. Likewise, the estimate of the variance is sensitive to the frequency of measurement (Hayashi and Yoshida, 2005) and generally improves with greater frequency. I therefore also use the 2006-7 data to estimate the variance and the correlation coefficients (see below). Note that for all other parameters, I use pre-2006 data only. Note that the daily variance and mean reversion parameter for Series 4-6 are not significantly different between pre- and post-2006 data.

[76] See Hamilton (1994) p. 53-54.

which measures the impact of an exogenous shock occurring in period s on the variable in period t. Equating the two and solving yields

$$a_x = -\ln(\phi_x) \tag{5.25}$$

All parameter estimates are given in Table 5.2.

I compute the correlation coefficients among the different series ρ^{kl} $(k, l = c^1, c^1, ..., h)$ by using the data from 2006-2007, for which all series have daily entries.[77] The results in Table 5.3 show that electricity consumption across the six different regions is highly correlated, but that precipitation weighted by available hydroelectric power and electricity consumption is not. Because the correlation coefficient between precipitation and all six electricity consumption series is zero, I will set $Cov_s[c_t^j, h_t] = Cov_s[c_t, h_t] = 0 \forall j$.

I derived the expressions for the variance and covariance in (5.16), (5.19) and (5.21) for total electricity consumption. Due to the six different data groups the parts

---

[77] Hayashi and Yoshida (2005) developed an unbiased estimator to compute the correlation coefficient between time series of different measuring intervals, but that estimator is not bounded by unity in magnitude, relying on truncation instead. Also, this would only address the problem of differing frequencies within the same time period, but not that of different time periods.

Using the much higher-frequency data for 2006-2007 is equivalent to assuming that the covariance between electricity consumption in the six different regions and EU-wide weighted precipitation is the same before and after January 1, 2006. For the two groups for which ample data is available (groups 4-6), this assumption appears to hold. Note that the market participants very likely have much better information about these covariances than what would be gleaned based on a few monthly data points from pre-2006 data available to the researcher.

involving electricity consumption that are based on overall consumption have to be adjusted to

$$(5.16') \quad E_s[c_t] = \sum_{j=1}^{6} E_s[c_t^j]$$

$$(5.19') \quad \begin{aligned} Var_s[c_t] &= \sum_{j=1}^{6} Var_s[c_t^j] + 2\sum_{j=1}^{6}\sum_{l=j+1}^{6} Cov_s[c_t^j, c_t^l] \\ Cov_s[c_t^j, c_t^l] &= \frac{\rho^{jl}}{a_{c^j} + a_{c^l}} \left\{ \begin{array}{l} \sum_{k=i(s)}^{i(t)-1} \left(\sigma_{c^j}[k]\sigma_{c^l}[k] - \sigma_{c^j}[k+1]\sigma_{c^l}[k+1] \right) e^{-(a_{c^j}+a_{c^l})(t-t^{\min}[k+1])} \\ + \sigma_{c^j}[i(t)]\sigma_{c^l}[i(t)] - e^{-(a_{c^j}+a_{c^l})(t-s)} \sigma_{c^j}[i(s)]\sigma_{c^l}[i(s)] \end{array} \right\} \end{aligned}$$

$$(5.21') \quad Cov_s[c_t, c_u] = \sum_{j=1}^{6} e^{-a_{c^j}*(u-t)} * Var_s[c_t^j] + \sum_{j=1}^{6}\sum_{l=j+1}^{6} \left(e^{-a_{c^j}*(u-t)} + e^{-a_{c^l}*(u-t)} \right) Cov_s[c_t^j, c_t^l]$$

5.4.c.) Evaluation of the options pricing formula

With these parameter estimates, I can now proceed to evaluating the options pricing formula. Because emissions were below the total cap at the end of the market, as well as for each year individually, I will disregard the second line of equation (5.6). I use first- and second-phase over-the-counter (OTC) allowance prices from Point Carbon.

The mean and standard deviation of future emissions are a function of free parameters and estimates of the mean, variance and covariance of the processes for electricity consumption and precipitation. Substituting (5.11) and (5.12) into (5.6) and simplifying gives

$$P_t = [40e^{-r(T-t)} + P_t^{Phase\,II}] * \Phi\left(\frac{(TK + \gamma A_t - S_0}{\gamma B_t} \right)$$

(5.26) *with*

$$A_t \equiv \sum_{k=t+1}^{T} \left(E_s[c_k] - \eta E_s[h_k] - n \right) + \sum_{k=1}^{t} \left(c_k - \eta h_k - n \right)$$

$$B_t \equiv \left(\sum_{k=t+1}^{T} Var_s[c_k] + \eta^2 Var_s[h_k] + 2 \sum_{k=t+1}^{T} \sum_{u=k+1}^{T} Cov_s[c_k, c_u] + \eta^2 Cov_s[h_k, h_u] \right)^{1/2}$$

where A_t and B_t are known functions of the parameters of the diffusion processes for electricity consumption and precipitation.

To account for the price crash after the first round of emissions verifications, I add dummy variable to allow for the updating of firms' expectation about emissions from other sectors (and emissions of other firms in the power & heat sector for that matter, but these parameters cannot be individually identified). Simplifying leads to

$$Y_t = \frac{\overline{K} - D_t^{EV} S^{EV}}{\gamma}$$

(5.27)

$$with \quad Y_t \equiv B_t * \Phi^{-1}\left(\frac{P_t}{40e^{-r(T-t)} + P_t^{Phase\,II}} \right) - A_t$$

$$\overline{K} \equiv TK - S_0 + V$$

where Φ^{-1} refers to the c.d.f of the standard normal distribution and D_t^{EV} is a dummy that takes on the value of zero before the first round of emissions verifications, and of one thereafter. Given the price crash in April 2006, S^{EV} has to be positive, implying that firms updated their expectation of the total number of remaining available permits upwards. I use an annual interest rate of 10% for the calculation of the discounted penalty.[78]

Total emissions from other sectors or emissions during 2005 are contained in $\overline{K} \equiv TK - S_0 + V$, where V stands for any time-invariant parameter that shifts the amount of permits available to the power & heat sector for the years 2006-2007. Note that $\overline{K}$ has to be negative, since S_0 is the total cap and the number of permits available to power generators (net of the correction associated with minimum generation TK) has to be positive.

Estimates for the free parameters $\overline{K}$, γ and S^{EV} can be computed by taking averages of Y_t for the period before and after the allowance price crash. Note that the parameters are not individually identified, such that one of them has to be held fixed in order to calculate the others. For example, when holding S^{EV} fixed, $\hat{\overline{K}}$ and $\hat{\gamma}$ are defined as

---

[78] Use of 0% and 20% did not alter the results significantly.

$$(5.28) \qquad \begin{array}{l} \lambda_1 \equiv \overline{Y}_t \mid (D_t^{EV} = 0) = \dfrac{\overline{K}}{\gamma} \\ \lambda_2 \equiv \overline{Y}_t \mid (D_t^{EV} = 1) = \dfrac{\overline{K} - S^{EV}}{\gamma} \end{array} \qquad \Rightarrow \hat{\overline{K}} = \frac{S^{EV}}{1 - \lambda_2 / \lambda_1}; \ \hat{\gamma} = \frac{S^{EV}}{\lambda_1 - \lambda_2}$$

where $\overline{Y}_t \mid (\cdot)$ refers to the conditional sample average. Results for fixed values of S^{EV} are shown in the left panel of Table 5.4. The shaded areas are the parameter combinations that make economic sense. The emission intensity γ has to be somewhere between 600 and 900 tCO_2/GWh,[79] which is the case for $100MT < S^{EV} < 150MT$, and for $-2{,}660MT < \overline{K} < -1{,}770MT$. Both ranges are plausible: The range for S^{EV} implies that firms expected 2005 emissions to exceed the annual cap by 6-56 MT, but instead they turned out to be 94 MT below.[80] The range for $\overline{K}$ means that of the about 4,200 MT of permits issued for the years 2006 and 2007, between 42-63 % were used to cover emissions of power generators.[81] The goodness of fit (defined by the model sum of squares divided by total sum of squares) is 0.81, much larger than the corresponding values for the model presented in Chapter 3 (see Tables 3.1-2).

---

[79] The average emissions intensity of the marginal generators in the EU will not exceed that of a coal-fired power plant, which emits about 920 tCO2/GWh. The emission intensity of Combined Cycle Gas Turbines (CCGTs) is about half of this, but coal is at the margin for the majority of the load in the EU.

[80] The first round of emissions verifications found emissions to be 94 MT below the total 2005 allocation.

[81] Note that the sector defined as “Power & Heat” accounts for about 70% of total emissions, but this includes production of heat as well as industrial process combustion, not just electricity producers.

Using the estimates $\hat{\bar{K}}, \hat{\gamma} \mid S^{EV}$ I compute the estimated price series $\hat{P}_t$:

$$\text{(5.29)} \qquad \hat{P}_t = [40e^{-r(T-t)} + P_t^{PhaseII}] * \Phi\left(\frac{(\hat{\bar{K}} - D_t^{EV} S^{EV}}{\hat{\gamma} B_t} + \frac{A_t}{B_t} \right)$$

Figure 5.3 shows the predicted price series, along with the actual allowance price and the forward price for second-phase allowances. The estimated series follows the data quite well until the April 2006 price crash, after which it falls below the actual price, before crossing it and finishing the period slightly too high. Importantly, the prediction shows the post-crash stabilization followed by a gradual decline to zero observed in the real price series, which has puzzled market observers. This is the result of the probability of a binding cap slowly approaching zero, as time progresses and actual emissions are observed.

A striking difference between prediction and actual price is the volatility. The allowance price series appears to fluctuate much more than the prediction, which of course could be due to shocks in unobserved variables that drive emissions that end up in the model residual. However, there is an alternative explanation: If power generators had a better idea about the variance of future demand than the researcher (because they have access to better data, especially for the area which they have exclusively serviced for decades before market liberalization), then I would have overestimated the standard deviation of future generation denominated by B_t in

(5.27). A too large standard deviation would attenuate demand shocks, leading to a prediction that is too smooth and too inert to electricity demand shocks.

To evaluate this possibility, I test the results for their sensitivity to B_t. I divide B_t by $\sqrt{10}$ and 10, corresponding to a factor of 10 resp. 100 by which my estimate for the variance exceeds the estimate used by the market participants.[82] The predictions are shown in Figure 5.4. It is clear that the results are greatly influenced by the uncertainty embedded in future emissions. Whereas the larger correction appears to overshoot and lead to excessive price volatility, the more modest correction by one order of magnitude fits the data much better, with a goodness of fit of 0.92. The corresponding estimates for $\overline{K}$, γ and S^{EV} are shown in the right panel of Table 5.4. Again, for sensible emission intensities (shaded region), the associated values for S^{EV} and $\overline{K}$ are plausible.

5.5 Conclusions

In this paper I derive an allowance pricing formula based on the assumption that firms were not able to engage in significant abatement during the first three years of the EU ETS, and therefore had no control over their emissions. In this case, the value of an allowance can be characterized by an options pricing formula for a cash-

---

[82] Note that when computing the standard deviation of future consumption using the 2006-7 data and adding all the series up, I get a result that is about 1.4 times lower than the standard deviation calculated using separate series.

or-nothing call option. This formula contains the mean and standard deviation of CO_2 emissions for the remainder of the market.

I calculate daily emissions based on daily demand for electricity generated by conventional thermal combustion. This is a function of total electricity consumption and the availability of non-emitting sources for electricity such as hydro and nuclear. I assume that these processes are characterized by diffusions and estimate the diffusion parameters using market data. This allows me to express the allowance price as a function of data, estimates for future emissions and three free parameters.

The parameter estimates are highly significant and make economic sense. The predicted allowance price series fits the actually observed prices quite well, especially when adjusting the estimate for future electricity demand volatility downwards, based on the hypothesis that power generators had a better idea about it. Importantly, the model is able to explain the price stabilization after the price crash, followed by a long and steady decline towards zero, which can be explained by a declining probability that the cap was going to be binding. A model based on abatement parameters would only be able to explain such a movement if the price of fundamentals related to abatement also expressed such a steady decline, which was not the case (see Chapter 3).

I conclude that the allowance price during the first phase of the EU ETS was to a large extent driven by the penalty for noncompliance and the probability of a binding cap, at least for the years 2006 and 2007. This could be due to the speed of market-setup, which did not allow the involved firms to adjust their emissions in time, and/or the realization after the April 2006 price crash that the market was likely to be oversupplied with permits and that therefore abatement measures would not be profitable.

Chapter 6: Conclusions

In my dissertation I examine the relationship between first-phase allowances in the EU ETS and various price drivers. In Chapter 3 I start with the most commonly cited market fundamentals that are assumed to drive marginal abatement costs, but find them to have little explanatory power for the allowance price path, despite using the best available data. I then go on to test the allowance market for the presence of a price bubble. The results are consistent with the presence of a bubble (or a series of bubbles), although a conclusive proof of the existence of a bubble is impossible on theoretical grounds.

In my analysis I skip the issue of how the bubble(s), if any, got started, and focus exclusively on their presence. But something must drive the price up initially before self-fulfilling expectations can form and take over. In Chapter 4 I focus on the group that profited most from the high allowance price: Power producers, due to free allocation and cost pass-through to electricity prices. Although no reason for price inflation in competitive markets, the presence of market power can change this. The problem with this hypothesis is that power producers were net buyers of allowances, and existing economic theory predicts that they would decrease, rather than increase, the allowance price, provided that they had market power. I show that when taking the interaction between output and permit market into account, this prescription no longer holds true. Actual allocation amounts and cost pass-through rates in the EU ETS indicate that dominant power producers would indeed have found it profitable to inflate the allowance price.

Chapter 5 is to some extent complementary to Chapter 3: If allowance prices were not driven by marginal abatement costs, is there an alternative explanation to a bubble? There is some evidence supporting the hypothesis that firms simply did not have enough time to adjust their process emissions in time for the first phase. In this case, the allowance price would be driven by the penalty for noncompliance and the probability that the overall cap turns out to be binding. I set up an options pricing model that has these characteristics and find that it fits the data well, better indeed than the market model in Chapter 3. One caveat for the findings of the options pricing paper is that they only apply to the years 2006-7.

Taken together, my findings imply the following:

First, the allowance price during the first phase of the EU ETS was not equal to marginal abatement costs. This could be due to the formation of a price bubble, market power in the power sector or firms' inability to engage in timely and significant abatement. It is quite possible that all three of these reasons were involved simultaneously or sequentially: A bubble needs to get started somehow, which would reconcile the first two reasons. Also, the bubbles results are much stronger for the period before the crash, whereas the options pricing story may apply to the latter part of the market only. In this case, it would not have been so much inability, but rather unwillingness to abate on the part of power producers, once they were fairly certain that the market was going to be long after the price crash. Thus, my findings are consistent with market power starting a bubble, which then sustained itself for a while until it was popped by the first round of emissions verifications. From then on, firms were no longer concentrating on abatement but rather on optimizing their allowance portfolio, taking the stochastic nature of emissions into account.

Second, regardless of the exact combination of reasons, the fact that first-phase allowance prices were not equal to marginal abatement costs means that the first phase of the EU ETS failed from the perspective of reaching a given emissions goal at least cost. It is possible that the prime goal of the EU was not the design of an efficient policy instrument for 2005-2007, but instead to prepare the EU for the Kyoto compliance period of 2008-2012. But this could arguably have been achieved at a lower cost to consumers and the economy as a whole, considering the large increase in output prices without the benefit of an emissions reduction.

Future cap-and-trade markets should be set up such that they avoid the problems encountered during the first phase of the EU ETS. Specifically, regulators of future markets should consider auctioning most if not all allowances, which would avoid the problem of market manipulation while giving the regulator the opportunity to reimburse consumers for higher output prices from carbon cost pass-through. Further, more frequent rounds of emissions verifications would prick any price bubble sooner by breaking the cycle of self-fulfilling expectations and bring the price back to its fundamental value. Lastly, companies should be given sufficient time and regulatory certainty to engage in large-scale abatement decisions. If the time is too short, or the price signal to uncertain, the allowance market may deteriorate into a betting game where firms aim to reach compliance exclusively by buying allowances on the market, rather than abating emissions.

Future research is needed in this area. The second phase of the EU ETS, as well as upcoming carbon markets in the eastern USA, Japan, Australia and Canada should be examined as to whether the permit price is truly driven by marginal abatement costs. Another promising area of research would be the design of sophisticated auctioning schemes that would allow the regulator to gather more information about firms' marginal abatement costs. This knowledge would aid in setting the cap as well as in determining whether there is a discrepancy between permit price and marginal costs, once the market is under way.

Tables

Table 2.1: Summary results for Phase I of the EU ETS

	2005	2006	2007	Total Phase I
Price (time average)	€ 18.40	€ 18.05	€ 0.72	€ 12.39
Trading volume[a]	262 Mt	817 Mt	1,364 Mt	2,443 Mt
Trading value[a]	€ 5.4 billion	€ 14.6 billion	€ 28.0 billion	€ 48.0 billion
Allocation	2,099 Mt	2,072 Mt	2,079 Mt	6,250 Mt
Emissions	2,010 Mt	2,031 Mt	2,041 Mt	6,081 Mt
Surplus (volume)	89 Mt	41 Mt	39 Mt	168 Mt
Surplus (%)	4.22 %	1.98 %	1.85 %	2.69 %

a: OTC and exchange trading for phase I and II, but excluding bilateral trades

Table 3.1: Results from estimating Equation (3.10)

	Full period	Pre-crash	Post-crash
$D.Gas^F$	26.0812***	37.5707***	20.0823***
p	<0.0001	<0.0001	<0.0001
D.Coal	-26.1478	333.9588	-22.2437
p	0.8549	0.2534	0.7444
$Temp^{5d}$ W	-3.7832	-7.2270	-1.7798
p	0.5922	0.6950	0.6378
$Temp^{5d}$ S	11.2833	65.2161*	13.3100**
p	0.3355	0.0606	<0.0001
D.Res	0.4370	-29.7230	0.2881
p	0.9744	0.4210	0.9652
Crash	-4.1946***		
p	<0.0001		
N	609	333	272
Chi^2	2143.59	29.95	54.23
p	<0.0001	<0.0001	<0.0001
LL	-415.91	-244.37	-143.59
AIC	847.81	502.74	301.17
BIC	883.11	529.39	326.41
Goodness of fit#	0.2481	0.0376	0.0105

*: p<0.1; **: p<0.05; ***:p<0.01; all variables defined in text

#: Model sum of squares/total sum of squares

Table 3.2: Results from estimating equation (3.11)

	(1) Pre-crash	(2) Post-crash	(3) Pre-crash	(4) Post-crash
D.GasF	53.1555***	28.7834***	42.2153***	32.4172***
p	<0.0001	<0.0001	0.0001	<0.0001
L.D.GasF	30.1149***		20.3575***	
p	<0.0001		0.0100	
L2.D.GasF	9.0277		-10.7088	
p	0.4483		0.4630	
D.GasS		-17.1810***		-7.4000**
p		<0.0001		0.0182
L.D.Coal	268.0765		93.2723	
p	0.2671		0.7679	
D20.Coal		-16.3700		4.3739
p		0.1694		0.8020
Temp1M W	-0.0008	-0.0010**	-0.0007	0.0002
p	0.2149	0.0171	0.3869	0.7611
Temp1M S	0.0074***	-0.0015***	-0.0025*	-0.0003
p	<0.0001	0.0010	0.0696	0.5886
D5.Res		-18.2342***		2.2228
p		<0.0001		0.6021
D20.Res	-0.1130	18.6926***	-0.0460	-2.2647
p	0.2287	<0.0001	0.7251	0.6056
L.D.EUA			0.1724***	0.4123***
p			0.0085	<0.0001
L2.D.EUA			-0.0827*	-0.1305***
p			0.0756	0.0043
L3.D.EUA			0.1140***	0.0973***
p			0.0008	0.0001
L4.D.EUA			0.1699***	0.0379**
p			<0.0001	0.0358
L5.D.EUA			-0.0224	0.1149***
p			0.6284	<0.0001
N	329	272	318	253
Chi2	152.08	293.00	260.52	188.26
p	<0.0001	<0.0001	<0.0002	<0.0003
AIC	469.88	234.24	439.52	162.35
BIC	504.04	266.69	492.18	211.82
Goodness of fit	0.1092	0.0278	0.1325	0.2374

*: p<0.1; **: p<0.05; ***:p<0.01; all variables defined in text

Table 3.3: Cointegration test results

	Full period	Pre-crash	Post-crash
A(1)	-0.09517	-0.49985	0.38262
p	0.247	<0.001	0.006
B1(1) (Gas)	-0.00016	0.00146	0.00225
p	0.971	0.822	0.868
B2(1) (Coal)	-0.03021	-0.31725	0.10131
p	0.764	0.018	0.749
B3(1) (Reservoirs)	0.00210	-0.03683	0.00839
p	0.497	0.005	0.350
B4(1) (DAX)	-0.00002	0.00032	-0.00043
p	0.671	0.024	0.107
_const	0.3711	1.1521	2.3260
p	0.589	0.152	0.412
Unit Root test on $\bar{z}_t$	-0.391	-0.974	-0.543
Unit Root test on $\hat{z}_t$	-2.241	-1.915	-2.751

Table 3.4: Results from regime-switching tests

	Full period	pre-crash	post-crash
p	0.979	0.984	0.995
q	0.994	0.931	1.000
LR statistic	118.320	38.940	60.360
p	<0.0001	0.0007	<0.0001

Table 5.1: Data availability and installed hydroelectric capacity by country

Country per data series	Start of data series[a] Type	Year	Source[b]	Hydro capacity in 2006 (MW)
Series 1				
Austria	3rd Wed.	1994	UCTE	11,811
Belgium	3rd Wed.	1994	UCTE	1,411
France	3rd Wed.	1994	UCTE	25,457
Greece	3rd Wed.	1994	UCTE	3,133
Italy	3rd Wed.	1994	UCTE	21,070
Luxembourg	3rd Wed.	1994	UCTE	1,128
Netherlands	3rd Wed.	1994	UCTE	37
Portugal	3rd Wed.	1994	UCTE	4,948
Spain	3rd Wed.	1994	UCTE	20,714
Series 2				
Germany	3rd Wed.	1996	UCTE	9,100
Series 3				
Czech Republic	3rd Wed.	1999	UCTE	2,175
Hungary	3rd Wed.	1999	UCTE	46
Poland	3rd Wed.	1999	UCTE	2,324
Slovak Republic	3rd Wed.	1999	UCTE	2,429
Slovenia	3rd Wed.	1999	UCTE	873
Series 4				
UK	daily	2002	Country TSO	4,256
Ireland	Daily	2002	Country TSO	512
Series 5				
Sweden	daily	2001	Country TSO	16,180
Denmark	daily	2000	Country TSO	10
Series 6				
Finland	daily	2004	Country TSO	3,044

a: All countries have daily data starting in 2006

b: UCTE: Union for the Coordination of transmission of electricity;
TSO: Transmission system operator

Table 5.2: Parameter estimates for diffusion processes

	c1	c2	c3	c4	c5	c6	h
N	168	144	108	1,460	2,190	730	10,950
Const.	1486.06	1248.56	654.25	763.47	569.68	207.54	23.45
z	22.73	36.44	17.47	16.92	25.12	1.95	44.10
Trend	86.98	5.33	4.84	9.06	-2.07	1.20	-0.01
z	32.44	3.92	3.42	5.57	-2.44	0.33	-0.28
Mo	n/a	n/a	n/a	-20.84	-3.51	0.66	n/a
z	n/a	n/a	n/a	-22.31	-5.98	1.60	n/a
Fr	n/a	n/a	n/a	-20.31	-13.98	1.01	n/a
z	n/a	n/a	n/a	-20.31	-22.31	2.31	n/a
Sa	-416.47	-207.72	-72.13	-128.22	-67.15	-15.71	n/a
z	32.44	3.92	3.42	-101.66	-97.18	-28.56	n/a
Su	-750.21	-328.49	-128.43	-157.64	-72.43	-21.45	n/a
z	-13.80	-26.70	-12.23	-133.32	-103.87	-43.08	n/a
XNY	n/a	n/a	n/a	-86.72	-37.25	-11.54	n/a
z	n/a	n/a	n/a	-20.08	-12.89	-4.85	n/a
β_2^x (sine)	375.85	145.36	116.96	134.10	104.99	36.98	3.00
z	18.99	25.19	32.22	35.09	41.12	10.91	7.06
ω^x (phase)	1.33	1.39	1.41	1.23	1.34	1.35	-0.40
z	42.06	49.94	46.71	38.54	47.09	14.26	-2.96
AR(1)*	0.58	0.39	0.59	0.84	0.86	0.91	0.52
z	18.95	11.32	21.52	95.98	87.02	74.92	103.92
a*	0.54	0.94	0.53	0.18	0.15	0.09	0.65
z	10.24	10.68	11.38	17.15	13.20	6.94	68.02
$\sigma[i]$*							
Jan	499.71	133.17	88.72	65.21	46.42	23.69	17.21
Feb	316.67	94.92	53.10	45.35	42.27	23.84	16.15
Mar	366.30	119.39	64.96	67.47	41.32	21.19	19.15
Apr	453.41	142.96	79.08	79.32	51.52	31.36	14.49
May	400.48	135.97	55.56	92.75	48.67	33.66	16.28
Jun	387.02	132.80	59.94	45.64	46.51	34.84	16.54
Jul	427.82	116.79	55.50	20.17	30.71	12.12	18.07
Aug	305.51	97.78	50.71	69.65	12.10	7.77	20.91
Sep	389.43	122.02	61.45	23.50	18.56	7.65	20.21
Oct	387.15	120.30	64.95	31.66	27.65	11.17	22.63
Nov	432.38	108.56	73.35	39.00	35.50	19.57	21.50
Dec	414.69	163.85	85.40	96.82	55.91	42.84	17.68

*For series 1-3, based on 2006-7 data; all other estimates based on pre-2006 data

Table 5.3: Correlation coefficients[a] among different series

	c1	c2	c3	c4	c5	c6	h
c1	1.000						
c2	0.8814*	1.000					
c3	0.9016*	0.8730*	1.000				
c4	0.4554*	0.2976*	0.4927*	1.000			
c5	0.5170*	0.3897*	0.6032*	0.9231*	1.000		
c6	0.4588*	0.3672*	0.5573*	0.8496*	0.9418*	1.000	
h	-0.067	0.014	-0.036	-0.038	-0.033	-0.020	1.000

*p<0.05; all coefficients based on 2006-7 data

a: The correlation coefficient between series x_t^i and x_t^j and the corresponding p-value are computed as

$$\hat{\rho} = \frac{\sum_{t=1}^{T^{i,j}} (x_t^i - \bar{x}^i)(x_t^j - \bar{x}^j)}{\sqrt{\sum_{t=1}^{T^{i,j}} (x_t^i - \bar{x}^i)^2} \sqrt{\sum_{t=1}^{T^{i,j}} (x_t^j - \bar{x}^j)^2}} \quad ; \qquad p = 2 * \text{ttail}\left(T^{i,j} - 2, |\hat{\rho}| \sqrt{T^{i,j} - 2} \,/ \sqrt{1 - \hat{\rho}^2}\right)$$

where $T^{i,j}$ refers to the number of days for which both series have valid entries.

Table 5.4: Parameter estimates from options pricing formula

Original Model using B_t			Model using $B_t/\sqrt{10}$		
λ_1	-2,967,479		λ_1	-2,955,860	
λ_2	-3,134,951		λ_2	-2,991,328	
Good. of fit:[a]	0.8055		Good. of fit:[a]	0.9232	
S^{EV} (MT)	$\hat{\bar{K}}$ (MT)	$\hat{\gamma}$	S^{EV} (MT)	$\hat{\bar{K}}$ (MT)	$\hat{\gamma}$
10	-177	60	10	-833	282
20	-354	119	20	-1,667	564
30	-532	179	30	-2,500	846
40	-709	239	40	-3,334	1,128
50	-886	299	50	-4,167	1,410
60	-1,063	358	60	-5,000	1,692
70	-1,240	418	70	-5,834	1,974
80	-1,418	478	80	-6,667	2,256
90	-1,595	537	90	-7,500	2,537
100	-1,772	597	100	-8,334	2,819
110	-1,949	657	110	-9,167	3,101
120	-2,126	717	120	-10,001	3,383
130	-2,304	776	130	-10,834	3,665
140	-2,481	836	140	-11,667	3,947
150	-2,658	896	150	-12,501	4,229
160	-2,835	955	160	-13,334	4,511
170	-3,012	1,015	170	-14,168	4,793
180	-3,189	1,075	180	-15,001	5,075
190	-3,367	1,135	190	-15,834	5,357
200	-3,544	1,194	200	-16,668	5,639

Shaded areas: Economically plausible parameter ranges for γ

a: Goodness of fit= $\sum_{t=1}^{T}(\hat{P}_t - E[\hat{P}_t])^2/(P_t - E[P_t])^2$

Figures

Figure 1.1: EUA price and trading volumes, Phase I

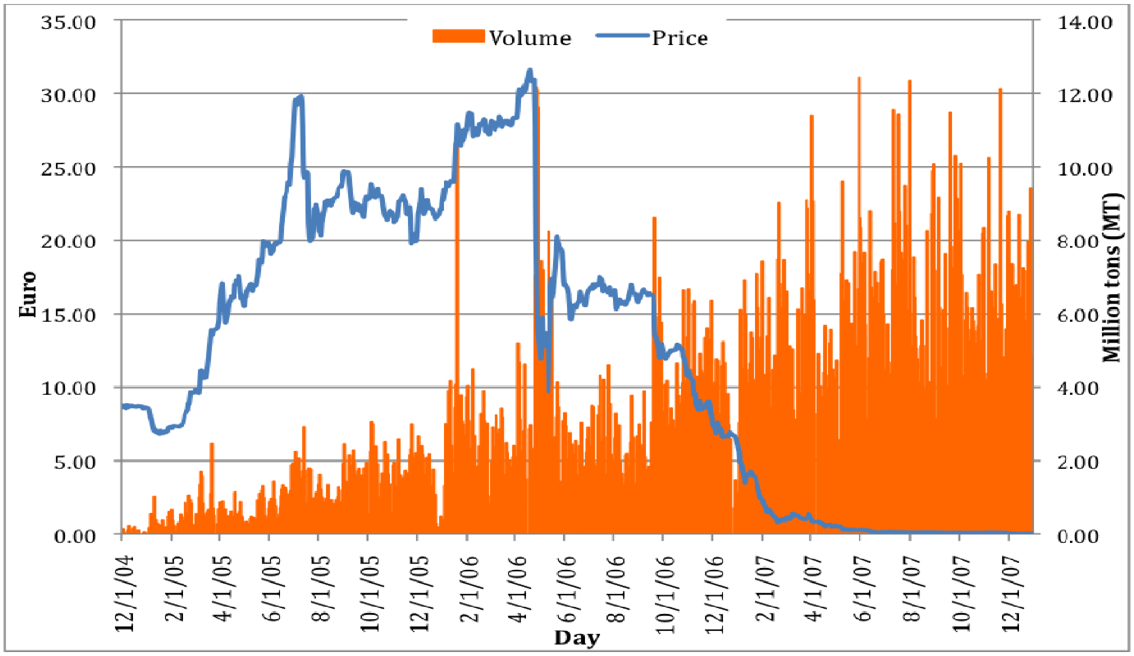


Figure 2.1: Allowance allocation and emissions by EU member country

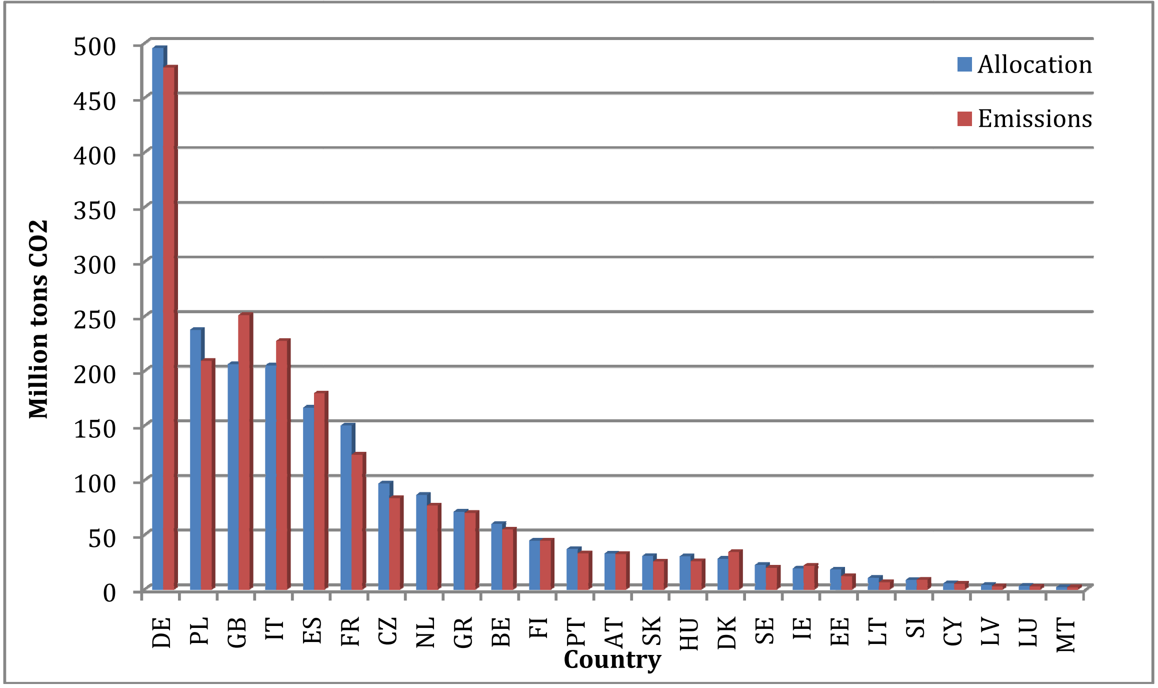


Figure 2.2: Allowance allocation and emissions by sector (total values)

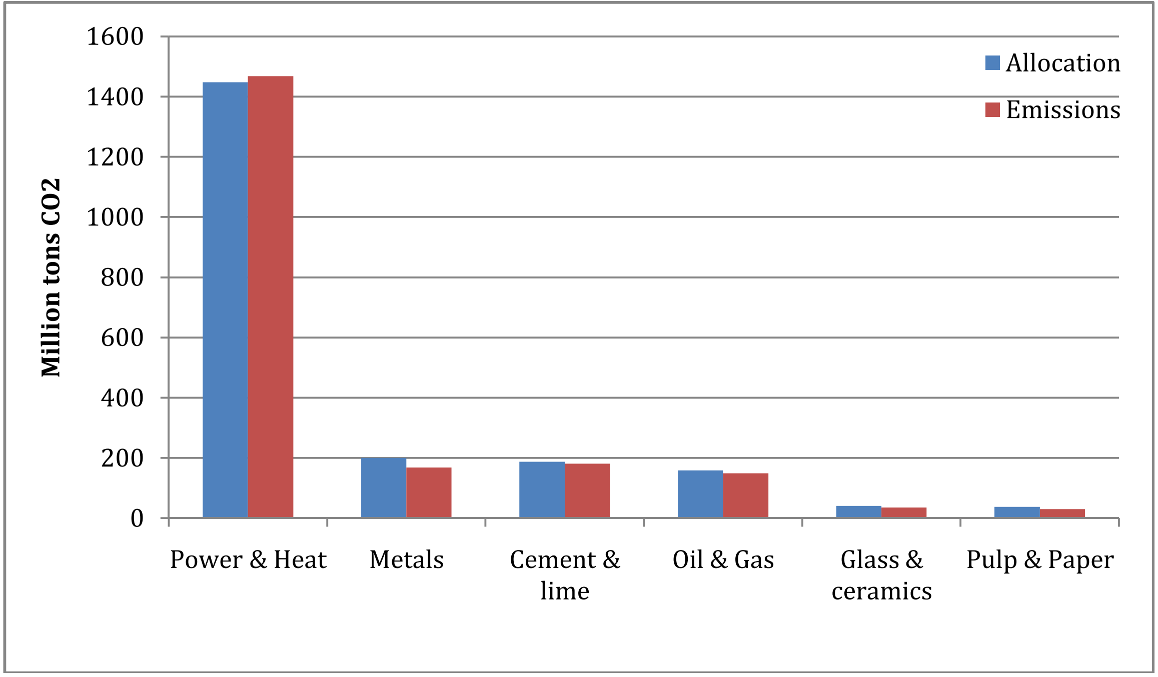


Figure 2.3: Allowance allocation and emissions by sector (percent of total)

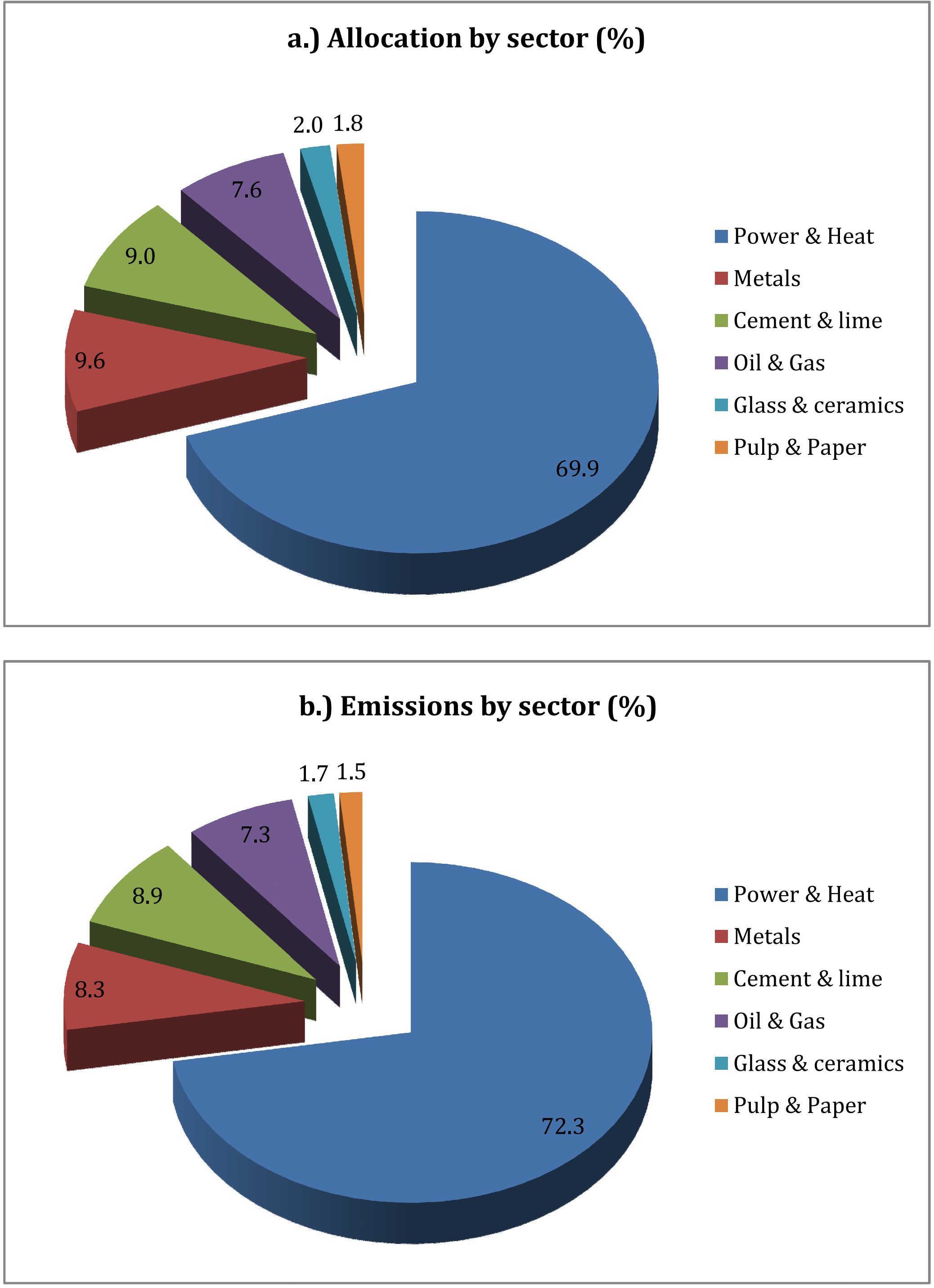


Figure 3.1: EUA, coal, gas, DAX and reservoir levels

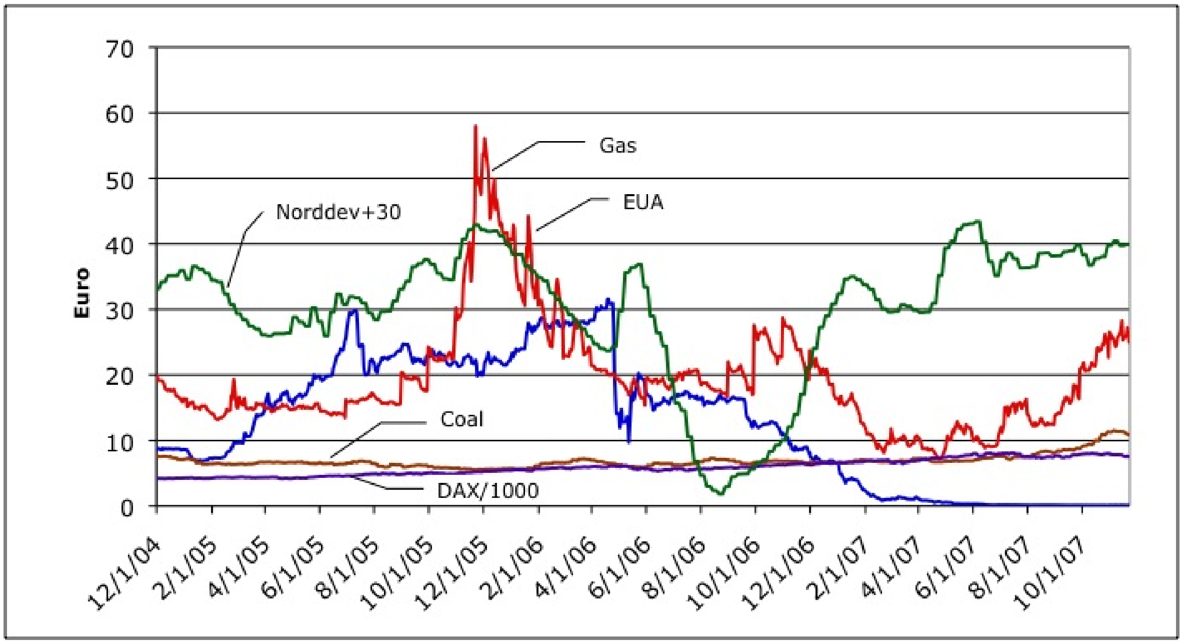


Figure 4.1: Spark spread and green (clean) spark spread in the UK

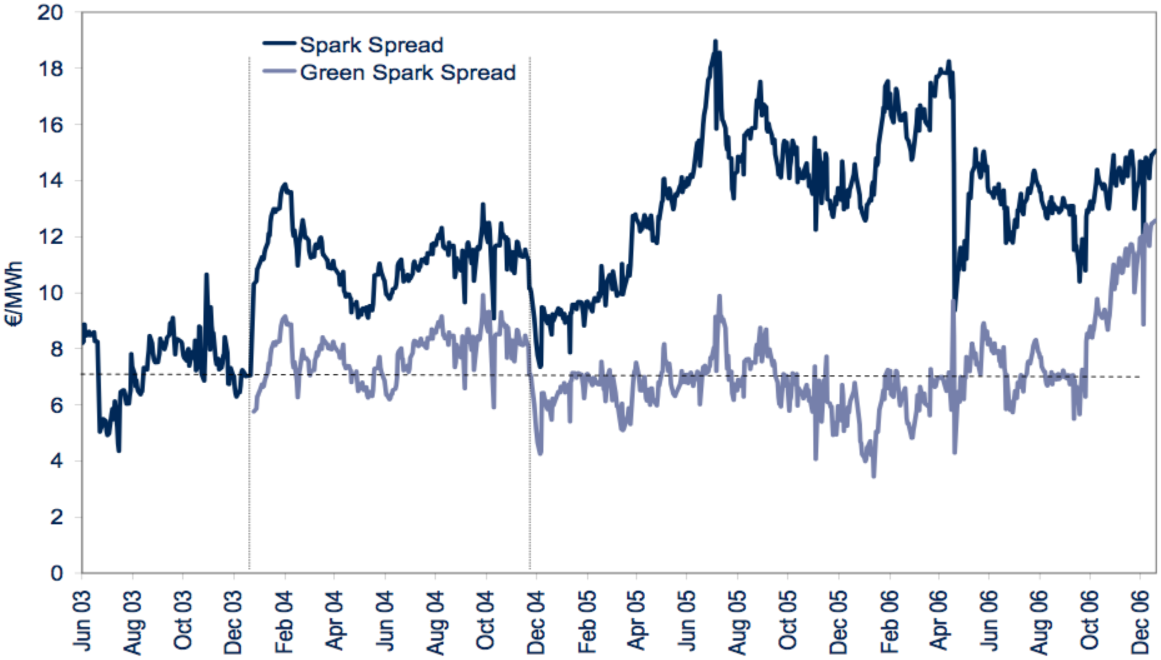


Figure 4.2: Dark spreads and green dark spreads in Germany

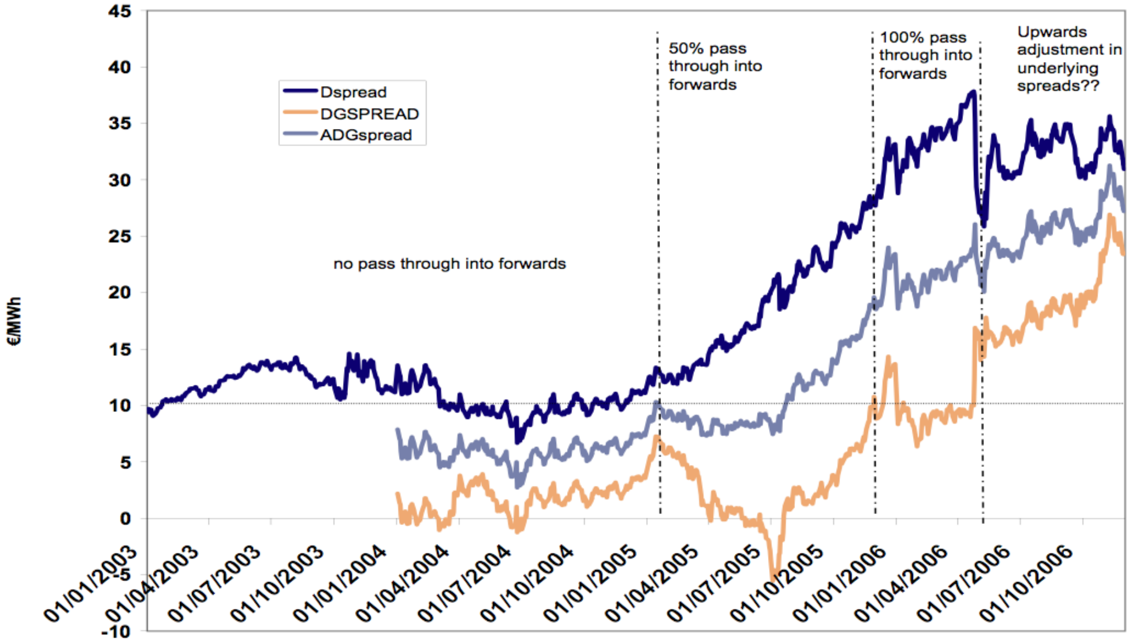


Figure 5.1: Available electricity consumption data, pre-2006

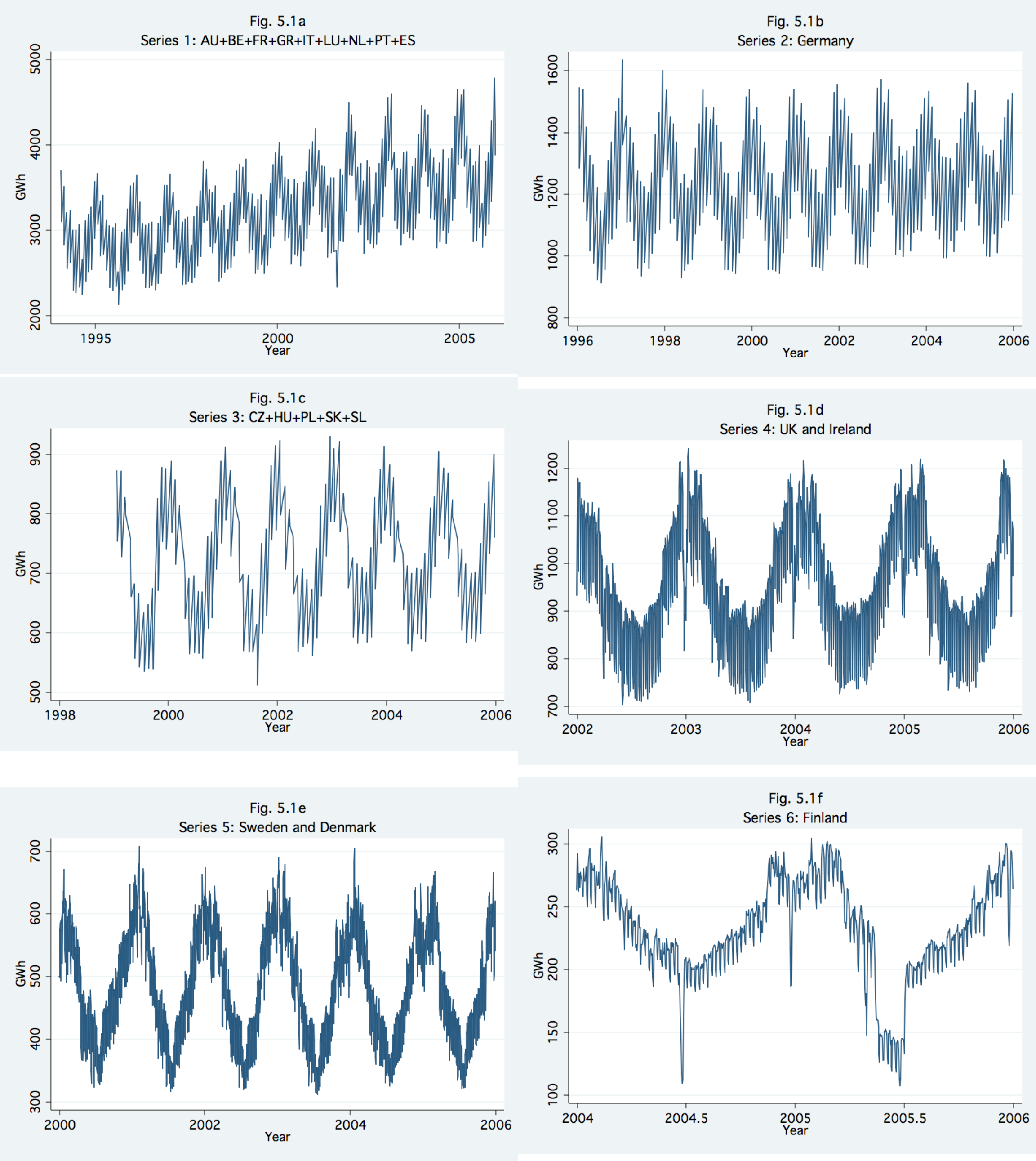


Figure 5.2: Weighted average precipitation in the EU

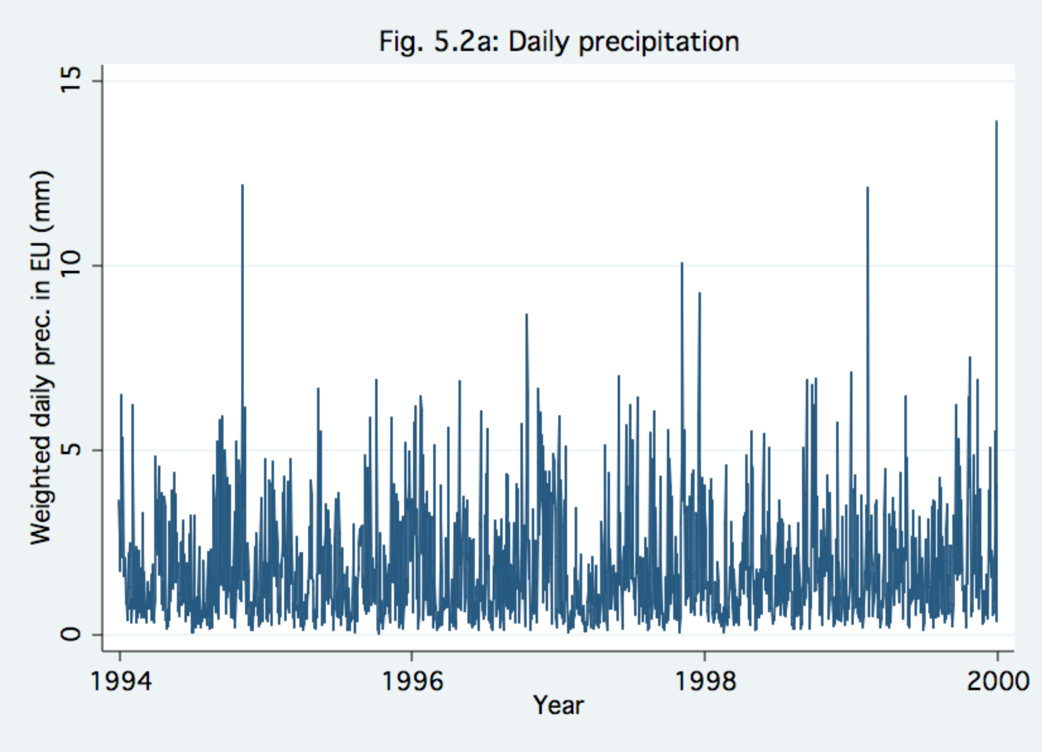


Fig. 5.2a: Daily precipitation

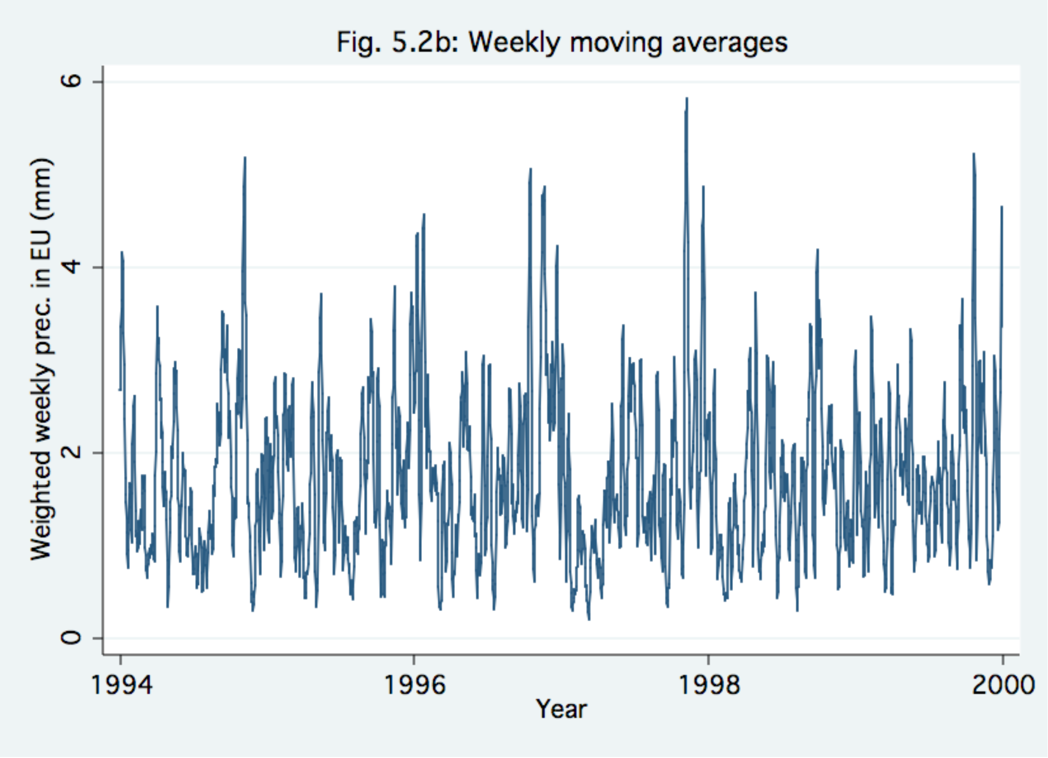


Fig. 5.2b: Weekly moving averages

Figure 5.3: EUA price, prediction and forward price for Phase II

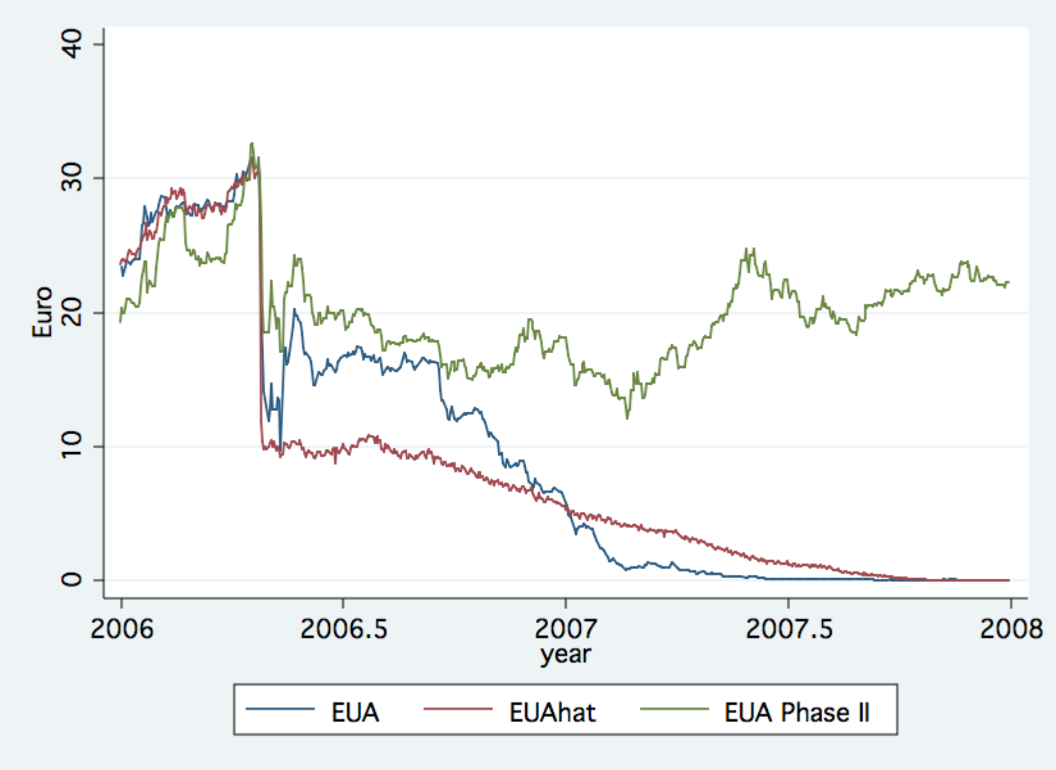
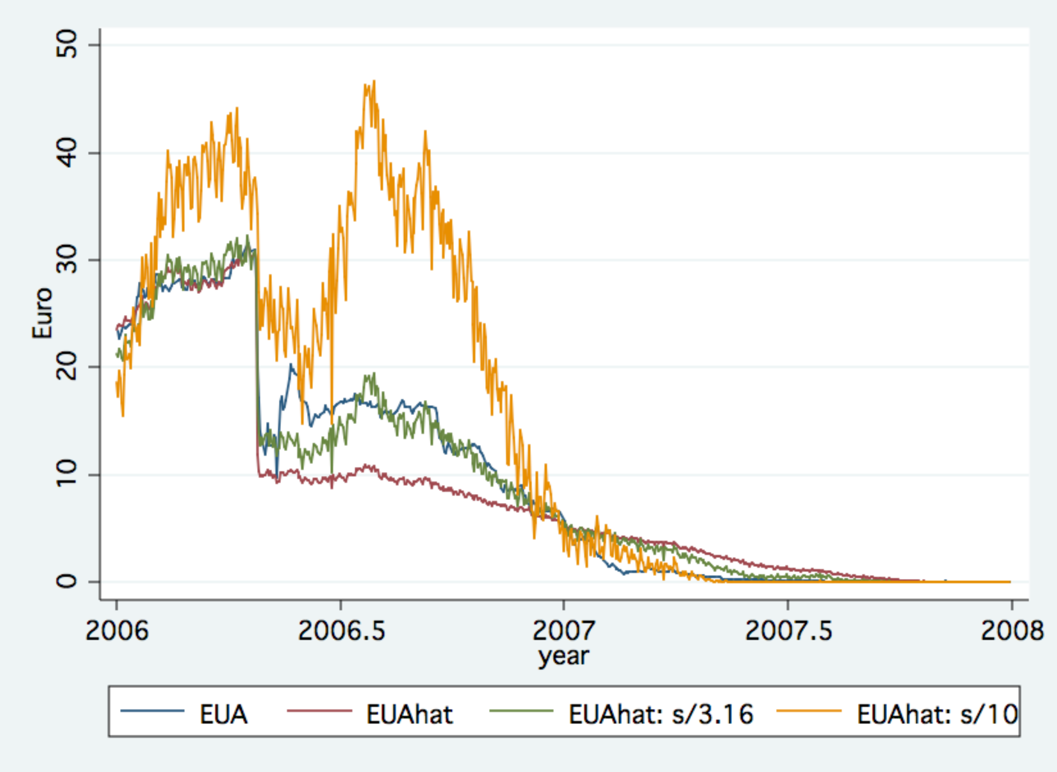


Figure 5.4: Sensitivity of prediction to variance of future electricity demand



Appendices

Appendix A: Proof of Equation (3.8)

Derivation of Equation (3.8)

I start by restating equation (3.7):

$$(3.7) \qquad \sum_{k=t+1}^{T} \sigma_k = \sum_{k=t+1}^{T} E_{k-1}[\sigma_k] + d \sum_{k=t+1}^{T} \left(F_k - E_{k-1}[F_k]\right) + N\left(g+b\right) * \overline{\beta} \sum_{k=t+1}^{T} \left(\Psi_k - E_{k-1}[\Psi_k]\right)$$

If allowance and fuel prices have the Markov property such that $E_t[P_{t+1}] = \rho P_t$ where P_t represents any price, $\rho = 1 + r$ the discount factor and r the interest rate, at k=T-1 it must be that

$$(\text{A1}) \qquad \sigma_T = \rho\sigma_{T-1} + d\left(F_T - \rho F_{T-1}\right) + h\left(\Psi_T - E_{T-1}[\Psi_T]\right)$$

where $h \equiv N(g+b)\overline{\beta}$. Now I move one period back to k=T-2:

$$\sigma_{T-1} + \sigma_T = (\rho^2 + \rho)\sigma_{t-2} + d\left(F_{T-1} - \rho F_{T-2} + F_T - \rho F_{T-1}\right) + h\left(\Psi_{T-1} - E_{T-2}[\Psi_{T-1}] + \Psi_T - E_{T-1}[\Psi_T]\right)$$

Substituting (A1) for σ_T and rearranging yields

$$(\text{A2}) \qquad (\rho+1)\sigma_{T-1} = (\rho^2 + \rho)\sigma_{T-2} + d\left(F_{T-1} - \rho F_{T-2}\right) + h\left(\Psi_{T-1} - E_{T-2}[\Psi_{T-1}]\right)$$

Moving another period back to k=T-3:

$$\begin{aligned}\sigma_{T-2}+\sigma_{T-1}+\sigma_{T} &= (\rho^{3}+\rho^{2}+\rho)\sigma_{T-3}+d\left(F_{T-2}-\rho F_{T-3}+F_{T-1}-\rho F_{T-2}+F_{T}-\rho F_{T-1}\right)\\ &\quad +h\left(\Psi_{T-2}-E_{T-3}[\Psi_{T-2}]+\Psi_{T-1}-E_{T-2}[\Psi_{T-1}]+\Psi_{T}-E_{T-1}[\Psi_{T}]\right)\end{aligned}$$

As before, I substitute (A1) for σ_T and simplify:

$$\begin{aligned}\sigma_{T-2}+(1+\rho)\sigma_{T-1} &= (\rho^{3}+\rho^{2}+\rho)\sigma_{T-3}+d\left(F_{T-2}-\rho F_{T-3}+F_{T-1}-\rho F_{T-2}\right)\\ &\quad +h\left(\Psi_{T-2}-E_{T-3}[\Psi_{T-2}]+\Psi_{T-1}-E_{T-2}[\Psi_{T-1}]\right)\end{aligned}$$

Now I further substitute (A2) for $(1+\rho)\sigma_{T-1}$ to get

(A3) $(\rho^{2}+\rho+1)\sigma_{T-2}=(\rho^{3}+\rho^{2}+\rho)\sigma_{T-3}+d\left(F_{T-2}-\rho F_{T-3}\right)+h\left(\Psi_{T-2}-E_{T-3}[\Psi_{T-2}]\right)$

The next step would be to move to period k=T-4 and successively substituting (A1), (A2) and (A3). However, the general solution is apparent:

$$\text{(A4)}\qquad \sigma_{t}\sum_{k=t}^{T}\rho^{T-k}=\sigma_{t-1}\sum_{k=t}^{T}\rho^{T-k+1}+d\,(F_{t}^{GC}-F_{t-1}^{GC})+h\left(\Psi_{t}-E_{t-1}[\Psi_{t}]\right)$$

The first term on the RHS can be re-written as $\sigma_{t-1}*\rho*\sum_{k=t}^{T}\rho^{T-k}$. Dividing (A4) by the summation term on the LHS yields the result:

$$\text{(3.8)}\qquad \sigma_{t}=\rho\sigma_{t-1}+d\,\frac{F_{t}-\rho F_{t-1}}{\sum_{t}^{T}\rho^{T-k}}+N\left(g+b\right)\overline{\beta}\,\frac{\left(\Psi_{t}-E_{t-1}[\Psi_{t}]\right)}{\sum_{t}^{T}\rho^{T-k}}$$

Appendix B: Proof of Lemma 1 and Eq. (4.9)

Proof of Lemma 1

Differentiating (4.2) w.r.t. p and rearranging gives

$$\begin{bmatrix} C_{qq}^i & C_{qe}^i \\ C_{qe}^i & C_{ee}^i \end{bmatrix} \begin{bmatrix} \partial q_i / \partial p \\ \partial e_i / \partial p \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Solving for the effect of a price change on output and emissions yields

(B1)
$$\frac{\partial q_i}{\partial p} = \frac{C_{ee}^i}{\Delta^i} > 0$$
$$\frac{\partial e_i}{\partial p} = \frac{-C_{qe}^i}{\Delta^i} > 0 \qquad \Delta^i \equiv C_{qq}^i C_{ee}^i - \left(C_{qe}^i\right)^2 > 0$$

Similarly, differentiating (4.2) w.r.t. the permit price and solving yields

(B2)
$$\frac{\partial q_i}{\partial \sigma} = \frac{C_{qe}^i}{\Delta^i} < 0$$
$$\frac{\partial e_i}{\partial \sigma} = \frac{-C_{qq}^i}{\Delta^i} < 0$$

To analyze the effect of the dominant firm’s output on output price p and permit price σ, differentiate (4.3) w.r.t. q_1 and rearrange:

(B3) $$\begin{bmatrix} P'\sum_{i=2}^{N}\frac{\partial q_i}{\partial \sigma} & \left(P'\sum_{i=2}^{N}\frac{\partial q_i}{\partial p}-1\right) \\ \sum_{i=2}^{N}\frac{\partial x_i}{\partial \sigma} & \sum_{i=2}^{N}\frac{\partial x_i}{\partial p} \end{bmatrix}\begin{bmatrix} \frac{\partial \sigma}{\partial q_1} \\ \frac{\partial p}{\partial q_1} \end{bmatrix}=\begin{bmatrix} -P' \\ 0 \end{bmatrix}$$

Solving for the effect of q_1 on the permit price:

(B4) $$\frac{\partial \sigma}{\partial q_1}=\frac{-P'\sum_{i=2}^{N}\frac{\partial x_i}{\partial p}}{\sum_{i=2}^{N}\frac{\partial x_i}{\partial \sigma}+P'\left[\sum_{i=2}^{N}\frac{\partial q_i}{\partial \sigma}\sum_{i=2}^{N}\frac{\partial x_i}{\partial p}-\sum_{i=2}^{N}\frac{\partial q_i}{\partial p}\sum_{i=2}^{N}\frac{\partial x_i}{\partial \sigma}\right]}$$

Because P'<0 and $e_i=x_i$ for i=(2,…,N), it follows immediately from (B1) that the numerator is positive. As for the denominator, the fist term is negative from (B2). In order to show that (B4) is negative I have to show that the term in the brackets is positive, i.e. that

(B5) $$\Phi \equiv \sum_{i=2}^{N}\frac{\partial q_i}{\partial \sigma}\sum_{i=2}^{N}\frac{\partial x_i}{\partial p}-\sum_{i=2}^{N}\frac{\partial q_i}{\partial p}\sum_{i=2}^{N}\frac{\partial x_i}{\partial \sigma}\overset{?}{>}0$$

Substituting (B1) and (B2), this is equivalent to showing that

(B6) $$\sum_{i=2}^{N}\frac{C_{qe}^{i}}{\Delta^{i}}\sum_{i=2}^{N}\frac{-C_{qe}^{i}}{\Delta^{i}}-\sum_{i=2}^{N}\frac{C_{ee}^{i}}{\Delta^{i}}\sum_{i=2}^{N}\frac{-C_{qq}^{i}}{\Delta^{i}}\overset{?}{>}0$$

to prove the inequality in (B5). Separating out the a single firm, it is clear that

$$\frac{C^i_{qq}C^i_{ee}}{\left(\Delta^i\right)^2} - \frac{\left(C^i_{qe}\right)^2}{\left(\Delta^i\right)^2} = \frac{1}{\Delta^i} > 0$$

which enables me to express (B6) as

$$\frac{1}{\Delta^i} + \sum_{\substack{i=2\\ i\neq j}}^{N} \frac{C^i_{qq}C^j_{ee} - C^i_{qe}C^j_{qe}}{\Delta^i} \overset{?}{>} 0$$

Noting the symmetry between i/j and j/i multiplications and dropping the first (positive) term, I can express this as

(B7) $$\sum_{2\le i<j}^{N} \frac{C^i_{qq}C^j_{ee} + C^j_{qq}C^i_{ee} - 2C^i_{qe}C^j_{qe}}{\Delta^i} \overset{?}{>} 0$$

Squaring both sides of the numerator in (B7) yields

$$\left(C^i_{qq}C^j_{ee}\right)^2 + 2C^i_{qq}C^j_{ee}C^j_{qq}C^i_{ee} + \left(C^j_{qq}C^i_{ee}\right)^2 \overset{?}{>} 4C^i_{qq}C^i_{ee}C^j_{qq}C^j_{ee} > 4\left(C^i_{qe}C^j_{qe}\right)^2$$

where the second inequality comes from the fact that

$$C^i_{qq}C^i_{ee} > \left(C^i_{qe}\right)^2 \forall i \Rightarrow C^i_{qq}C^i_{ee}C^j_{qq}C^j_{ee} > \left(C^i_{qe}C^j_{qe}\right)^2$$

Subtracting the RHS of the first inequality completes the proof:

(B8) $$\left(C^i_{qq}C^j_{ee}\right)^2 - 2C^i_{qq}C^j_{ee}C^j_{qq}C^i_{ee} + \left(C^j_{qq}C^i_{ee}\right)^2 = \left(C^i_{qq}C^j_{ee} - C^j_{qq}C^i_{ee}\right)^2 \overset{!}{>} 0 \Rightarrow \Phi \overset{!}{>} 0 \qquad \blacksquare$$

Now I derive the sign of the other three expressions in Lemma 1 by solving (B3) for the effect of firm 1's output on the output price and using (B2) and (B5):

(B9)
$$\frac{\partial p}{\partial q_1} = \frac{P' \sum_{i=2}^{N} \partial x_i / \partial \sigma}{\sum_{i=2}^{N} \frac{\partial x_i}{\partial \sigma} + P'\Phi} < 0$$

because the numerator is positive. Finally, differentiating (4.3) w.r.t. x_1 gives

$$\begin{bmatrix} P' \sum_{i=2}^{N} \frac{\partial q_i}{\partial \sigma} & P' \sum_{i=2}^{N} \frac{\partial q_i}{\partial p} \\ \sum_{i=2}^{M} \frac{\partial x_i}{\partial \sigma} & \sum_{i=2}^{M} \frac{\partial x_i}{\partial p} \end{bmatrix} \begin{bmatrix} \frac{\partial \sigma}{\partial x_1} \\ \frac{\partial p}{\partial x_1} \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \end{bmatrix}$$

Solving this yields

(B10)
$$\frac{\partial \sigma}{\partial x_1} = \frac{\sum_{i=2}^{N} \partial q_i / \partial p}{\Phi} > 0$$

(B11)
$$\frac{\partial p}{\partial x_1} = \frac{-\sum_{i=2}^{N} \partial q_i / \partial \sigma}{\Phi} > 0$$

Proof of equation (4.9)

Keeping in mind that $\partial \sigma / \partial q_1 < 0$, I re-write (4.9) as

$$\frac{\partial p / \partial x_1}{\partial \sigma / \partial x_1} \overset{?}{<} \frac{\partial p / \partial q_1}{\partial \sigma / \partial q_1}$$

Substituting (B4) and (B9)-(B10) into this expression and simplifying yields

(B12) $$\frac{-\sum_{i=2}^{N} \partial q_i / \partial \sigma}{\sum_{i=2}^{N} \partial q_i / \partial p} \overset{?}{<} \frac{\sum_{i=2}^{N} \partial x_i / \partial \sigma}{-\sum_{i=2}^{N} \partial x_i / \partial p}$$

Multiplying both sides by the two denominators (again reversing the inequality) and bringing both terms to the left hand side gives

(B13) $$\sum_{i=2}^{N} \frac{\partial q_i}{\partial \sigma} \sum_{i=2}^{N} \frac{\partial x_i}{\partial p} - \sum_{i=2}^{N} \frac{\partial q_i}{\partial p} \sum_{i=2}^{N} \frac{\partial x_i}{\partial \sigma} = \Phi \overset{!}{>} 0$$

which I prove above.

Appendix C: Derivation of variance and covariance of future emissions

Result 1: Variance of future CO$_2$ emissions

The variance of G_t^T is defined by

$$s_t^2 = Var_s[G_t^T] = \sum_{k=t+1}^{T} Var_s[g_k] + 2\sum_{k=t+1}^{T}\sum_{u=k+1}^{T} Cov_s[g_k, g_u] \tag{C1}$$

The variance of g_t and the covariance between g_t and g_u are

$$\begin{aligned} Var_s[g_t] &= Var_s\left[K + \gamma_1 c_t^c\right] \\ &= \gamma_1^2 Var_s\left[c_t^c\right] \\ &= \gamma_1^2\left(Var_s[c_t] - 2\eta Cov_s[c_t, h_t] + \eta^2 Var_s[h_t]\right) \end{aligned} \tag{C2}$$

$$\begin{aligned} Cov_s[g_t, g_u] &= E_s\left[(g_t - E_s[g_t])(g_u - E_s[g_u])\right] \\ &= \gamma^2 E_s\left[(c_t^c - E_s[c_t^c])(c_u^c - E_s[c_u^c])\right] \\ &= \gamma^2 E_s\left[\{c_t - E_s[c_t] - \eta(h_t - E_s[h_t])\}\{c_u - E_s[c_u] - \eta(h_u - E_s[h_u])\}\right] \\ &= \gamma^2 E_s\left[(c_t - E_s[c_t])(c_u - E_s[c_u])\right] + \eta^2\gamma^2 E_s\left[(h_t - E_s[h_t])(h_u - E_s[h_u])\right] \\ &\quad - \eta\gamma^2 E_s\left[(c_t - E_s[c_t])(h_u - E_s[h_u])\right] - \eta\gamma^2 E_s\left[(h_t - E_s[h_t])(c_u - E_s[c_u])\right] \\ &= \gamma^2\left(Cov_s[c_t, c_u] + \eta^2 Cov_s[h_t, h_u] - \eta Cov_s[c_t, h_u] - \eta Cov_s[h_t, c_u]\right) \end{aligned} \tag{C3}$$

Combining (C2) and (C3) establishes the result shown in equation (5.12)

(5.12)
$$\begin{aligned} s_t^2 &= \gamma^2 \sum_{k=t+1}^{T} \left(Var_s[c_t] + \eta^2 Var_s[h_t]\right) \\ &+ 2\gamma^2 \sum_{k=t+1}^{T} \sum_{u=k+1}^{T} \left(Cov_s[c_t, c_u] + \eta^2 Cov_s[h_t, h_u] - \eta Cov_s[c_t, h_u] - \eta Cov_s[h_t, c_u]\right) \end{aligned}$$

Result 2: Generalization of the variance for different volatilities

I start by restating the equation (5.17): The variance of c_t and h_t for $0 \le s \le t$ is

(5.17)
$$Var_s[x_t] = \int_s^t e^{-2a_x(t-\tau)} \sigma_x^2[i(y)]dy \qquad x = c, h$$

Suppose that at time s, we're in month 5 and want to calculate the variance of consumption/precipitation in month 8. Using the notation defined in the text that $t^{\min}[i(t)] = \min\{t : i(t) = i\}$, we have that $s < t^{\min}[6] < t^{\min}[7] < t^{\min}[8] < t < t^{\min}[9]$. I now split up the integral in (17) into four integrals with constant volatility:

$$\begin{aligned} Var_s[x_t] = &\int_s^{t^{\min}[6]} e^{-2a_x(t-y)} \sigma_x^2[5]dy + \int_{t^{\min}[6]}^{t^{\min}[7]} e^{-2a_x(t-y)} \sigma_x^2[6]dy \\ &+ \int_{t^{\min}[7]}^{t^{\min}[8]} e^{-2a_x(t-y)} \sigma_x^2[7]dy + \int_{t^{\min}[8]}^{t} e^{-2a_x(t-y)} \sigma_x^2[8]dy \end{aligned}$$

Next, I split the exponents such that they match with the new upper limits of the integrals and move the remainder (a constant) in front:

$$Var_s[x_t] = e^{-2a_x(t-t^{\min}[6])}\int_{s}^{t^{\min}[6]} e^{-2a_x(t^{\min}[6]-y)}\sigma_x^2[5]dy + e^{-2a_x(t-t^{\min}[7])}\int_{t^{\min}[6]}^{t^{\min}[7]} e^{-2a_x(t^{\min}[7]-y)}\sigma_x^2[6]dy$$
$$+e^{-2a_x(t-t^{\min}[8])}\int_{t^{\min}[7]}^{t^{\min}[8]} e^{-2a_x(t^{\min}[8]-y)}\sigma_x^2[7]dy + \int_{t^{\min}[8]}^{t} e^{-2a_x(t-y)}\sigma_x^2[8]dy$$

Because the volatilities are constant within each integral, each of them can be easily solved:

$$Var_s[x_t] = e^{-2a_x(t-t^{\min}[6])} * \frac{\sigma_x^2[5]}{2\rho^x} * \left(1-e^{-2a_x(t^{\min}[6]-s)}\right) + e^{-2a_x(t-t^{\min}[7])} * \frac{\sigma_x^2[6]}{2\rho^x} * \left(1-e^{-2a_x(t^{\min}[7]-t^{\min}[6])}\right)$$
$$+e^{-2a_x(t-t^{\min}[8])} * \frac{\sigma_x^2[7]}{2\rho^x} * \left(1-e^{-2a_x(t^{\min}[8]-t^{\min}[7])}\right) + \frac{\sigma_x^2[8]}{2\rho^x} * \left(1-e^{-2a_x(t-t^{\min}[7])}\right)$$

Multiplying out and some rearranging gives

$$Var_s[x_t] = \frac{1}{2a_x}\left\{\begin{array}{l}\left(\sigma_x^2[5]-\sigma_x^2[6]\right)e^{-2a_x(t-t^{\min}[6])} + \left(\sigma_x^2[6]-\sigma_x^2[7]\right)e^{-2a_x(t-t^{\min}[7])} \\ +\left(\sigma_x^2[7]-\sigma_x^2[8]\right)e^{-2a_x(t-t^{\min}[8])} + \sigma_x^2[8]-\sigma_x^2[5]e^{-2a_x(t-s)}\end{array}\right\}$$

which can be generalized to

$$(5.19)\qquad Var_s[x_t] = \frac{1}{2a_x}\left\{\sum_{k=i(s)}^{i(t)-1}\left(\sigma_x^2[k]-\sigma_x^2[k+1]\right)e^{-2a_x(t-t^{\min}[k+1])} + \sigma_x^2[i(t)] - e^{-2a_x(t-s)}\sigma_x^2[i(s)]\right\}$$

Result 3: Covariance of x on two different days

The covariance between x_t and x_u, for $x = c, h$ and $s \le t \le u$ is given by

$$\begin{aligned} Cov_s[x_t, x_u] &= E_s\left[\left(x_t - E_s[x_t]\right)\left(x_u - E_s[x_u]\right)\right] \\ &= E_s\left[\int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau * \int_s^u e^{-\rho^x(u-\tau)}\sigma_x[i(\tau)]dW_\tau\right] \end{aligned}$$

I split up the second integral into two parts and pull out the constant term:

$$Cov_s[x_t, x_u] = E_s\left[\int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau * \left(e^{-\rho^x(u-t)}\int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau + \int_t^u e^{-\rho^x(u-\tau)}\sigma_x[i(\tau)]dW_\tau\right)\right]$$

Multiplying out gives

$$\begin{aligned} Cov_s[x_t, x_u] = e^{-\rho^x(u-t)}E_s&\left[\int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau * \int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau\right] \\ +E_s&\left[\int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau * \int_t^u e^{-\rho^x(u-\tau)}\sigma_x[i(\tau)]dW_\tau\right] \end{aligned}$$

The second term is the expectation of the product of two stochastic processes occurring during non-overlapping time periods. Because a Wiener process is iid, this term drops out. Using the fact that $(dW)^2 = dt$ establishes the result:

$$\begin{aligned} Cov_s[x_t, x_u] &= e^{-\rho^x(u-t)}E_s\left[\int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau * \int_s^t e^{-\rho^x(t-\tau)}\sigma_x[i(\tau)]dW_\tau\right] \\ &= e^{-\rho^x(u-t)}E_s\left[\int_s^t e^{-2\rho^x(t-\tau)}\sigma_x^2[i(\tau)](dW_\tau)^2\right] \\ &= e^{-\rho^x(u-t)} * Var_s[x_t] \end{aligned} \tag{5.20}$$

References

Abreu, Dilip and Brunnermeier, Markus "Bubbles and Crashes." *Econometrica*, 2003, *71*(1), pp. 173-204.

Alaton, Peter; Djehiche, Boualem and Stillberger, David. "On Modelling and Pricing Weather Derivatives." *Applied Mathematical Finance*, 2002, *9*, pp. 1-20.

Alberola, Emilie; Chevallier, Julien and Cheze, Benoit. "Price Drivers and Structural Breaks in European Carbon Prices 2005-2007." *Energy Policy*, 2008, *36*, pp. 787-97.

Bauwens, Luc; Lubrano, Michel and Richard, Jean-Francois. *Bayesian Inference in Dynamic Ecnonometric Models,*. New York: Oxford University Press, 1999.

Beckwith, Thomas G.; Marangoni, Roy D. and Lienhard, John H. V. *Mechanical Measurements*. Reading, Massachusetts: Addison-Wesley, 1995.

Benz, Eva and Trueck, Stefan. "Modeling the Price Dynamics of CO2 Emission Allowances," Working Paper, University of Bonn, Germany, 2006.

Bibby, Martin and Sorensen, Michael. "Martingale Estimation Functions for Discretely Observed Diffusion Processes." *Bernoulli*, 1995, *1*(1-2), pp. 17-39.

Black, Fischer. "Noise." *Journal of Finance*, 1986, *41*(3), pp. 529-43.

Blanchard, Olivier J. and Watson, Mark W. "Bubbles, Rational Expectations and Financial Markets," NBER Working Paper Nr. 945, 1982.

Boehringer, Christoph and Lange, Andreas. "Mission Impossible!? On the Harmonization of National Allocation Plans under the EU Emissions Trading Directive." *Journal of Regulatory Economics*, 2005a, *27*(1), pp. 81-94.

____. "On the Design of Optimal Grandfathering Schemes for Emission Allowances." *European Economic Review*, 2005b, *49*(8), pp. 2041-55.

Bovenberg, A. Lans and Goulder, Lawrence H. "Neutralizing the Adverse Industry Impacts of CO2 Abatement Policies: What Does It Cost?," *RFF Discussion Papers*. Washington, DC: Resources for the Future, 2000.

____. "Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses." *American Economic Review*, 1996, *86*(4), pp. 985-1000.

Bunn, Derek W. and Fezzi, Carlo. "Interaction of European Carbon Trading and Energy Prices," Fondazione Eni Enrico Mattei, Milano: FEEM Working Paper Nr. 63, 2007.

Burtraw, Dallas; Palmer, Karen; Cropper, Maureen L. and Carlson, Curtis. "Sulfur-Dioxide Control by Electric Utilities: What Are the Gains from Trade? ," Resources for the Future, Washington, DC, 2005.

Camerer, Colin. "Bubbles and Fads in Asset Prices." *Journal of Economic Surveys*, 1989, *3*(1), pp. 3-41.

Carlson, Curtis. "Sulfur Dioxide Control by Electric Utilities: What Are the Gains from Trade?" *Journal of Political Economy*, 2000, *108*(6), pp. 1292-326.

Cason, Timothy N.; Gangadharan, Lata and Duke, Charlotte. "Market Power in Tradable Emission Markets: A Laboratory Testbed for Emission Trading in Port Phillip Bay, Victoria." *Ecological Economics*, 2003, *46*(3), pp. 469-91.

Chesney, Marc and Taschini, Luca. "The Endogenous Price Dynamics of the Emission Allowances: An Application to CO2 Option Pricing," Swiss Finance Institute Research Paper Nr. 08-02, Zurich, 2008.

Christiansen, A. C.; Arvanitakis, A. and Hasselknippe, H. "Price Determinants in the EU Emissions Trading Scheme." *Climate Policy*, 2005, *5*(1), pp. 15-30.

Cronshaw, Mark B. and Brown-Kruse, Jamie. "Regulated Firms in Pollution Permit Markets with Banking." *Journal of Regulatory Economics*, 1996, *9*(2), pp. 179-89.

Day, Richard H. and Huang, Weihong. "Bulls, Bears and Market Sheep." *Journal of Economic Behavior and Organization*, 1990, *14*(3), pp. 299-329.

Delarue, Erik D. and D'haeseleer, William D. "Price Determination of ETS Allowances through the Switching Level of Coal and Gas in the Power Sector." *International Journal of Energy Research*, 2007, *31*(11), pp. 1001-15.

Diba, Behzad T. and Grossman, Herschel I. "On the Inception of Rational Bubbles." *Quarterly Journal of Economics*, 1987, *102*(3), pp. 697-700.

____. "The Theory of Rational Bubbles in Stock Prices." *Economic Journal*, 1988, *98*(392), pp. 746-54.

Dixit, Avinash K. and Pindyck, Robert S. *Investment under Uncertainty*. Princeton University Press, 1994.

Ellerman, A. Denny and Buchner, Barbara. "Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the Emissions 2005 Data," Cambridge, MA: MIT Center for Energy and Environmental Policy Research (CEEPR), 2006.

Engel, Charles and Hamilton, James D. "Long Swings in the Dollar: Are They in the Data and Do Markets Know It?" *American Economic Review*, 1990, *80*(4), pp. 689-713.

Engle, Robert F. and Granger, Clive W. J. "Cointegration and Error Correction: Representation, Estimation, and Testing." *Long-run economic relationships: Readings in cointegration*, 1991, pp. 81-111.

Evans, George W. "A Test for Speculative Bubbles in the Sterling-Dollar Exchange Rate: 1981-84." *American Economic Review*, 1986, *76*(4), pp. 621-36.

Fehr, Max and Hinz, Juri. "A Quantitative Approach to Carbon Price Risk Modeling," ETH Zurich Working Paper, 2006.

Flood, Robert P. and Garber, Peter M. "Market Fundamentals Versus Price-Level Bubbles: The First Tests." *Journal of Political Economy*, 1980, *88*(4), pp. 745-70.

Flood, Robert P.; Hodrick, Robert J. and Kaplan, Paul. "An Evaluation of Recent Evidence on Stock Market Bubbles." *Speculative bubbles, speculative attacks, and policy switching*, 1994, pp. 105-33.

Frankel, Jeffrey A. and Froot, Kenneth A. "Chartists, Fundamentalists, and Trading in the Foreign Exchange Market." *American Economic Review*, 1990, *80*(2), pp. 181-85.

Friedman, Daniel and Aoki, Masanao. "Inefficient Information Aggregation as a Source of Asset Price Bubbles." *Bulletin of Economic Research*, 1992, *44*(4), pp. 251-79.

Garber, Peter M. "Tulipmania." *Journal of Political Economy*, 1989, *97*(3), pp. 535-60.

Godby, Robert. "Market Power and Emissions Trading: Theory and Laboratory Results." *Pacific Economic Review*, 2000, *5*(3), pp. 349-63.

____. "Market Power in Laboratory Emission Permit Markets." *Environmental and Resource Economics*, 2002, *23*(3), pp. 279-318.

Grubb, Michael and Neuhoff, Karsten. "Allocation and Competitiveness in the EU Emissions Trading Scheme: Policy Overview." *Climate Policy*, 2006, *6*(1), pp. 7-30.

Grubb, Michael and Newbery, David. "Pricing Carbon for Electricity Generation: National and International Dimensions," University of Cambridge Working Paper, Nr. CWPE 0751, 2007.

Gurkaynak, Refet S. "Econometric Tests of Asset Price Bubbles: Taking Stock," Washington, DC: Federal Reserve Board, Division of Research & Statistics and Monetary Affairs, 2005.

Hahn, Robert W. "Market Power and Transferable Property Rights." *Quarterly Journal of Economics*, 1984, *99*(4), pp. 753-65.

Hall, Stephen G.; Psaradakis, Zacharias and Sola, Martin. "Detecting Periodically Collapsing Bubbles: A Markov-Switching Unit Root Test." *Journal of Applied Econometrics*, 1999, *14*(2), pp. 143-54.

Hamilton, James D. "A New Approach to the Economic Analysis of Nonstationary Time Series and the Business Cycle." *Econometrica*, 1989, *57*(2), pp. 357-84.

____. "Time Series Analysis." 1994, *799*, pp. 799.

Hamilton, James D. and Whiteman, Charles H. "The Observable Implications of Self-Fulfilling Expectations." *Journal of Monetary Economics*, 1985, *16*(3), pp. 353-73.

Harrison, G.P. "Prospects for Hydro in the UK: Between a Roc and a Hard Place?," Working Paper, University of Edinburgh, 2005.

Hart, Oliver and Tirole, Jean. "Vertical Integration and Market Foreclosure." *Brookings Papers on Economic Activity*, 1990, (Special issue), pp. 205-76.

Hayashi, Takaki and Yoshida, Nakahiro. "On Covariance Estimation of Non-Synchronously Observed Diffusion Processes." *Bernoulli*, 2005, *11*(2), pp. 359-79.

Hepburn, Cameron; Grubb, Michael; Neuhoff, Karsten; Matthes, Felix and Tse, Maximilien. "Auctioning of EU ETS Phase II Allowances: How and Why?" *Climate Policy*, 2006, *6*(1), pp. 137-60.

Hull, John C. *Options, Futures, and Other Derivatives, Ch. 11,*. Upper Saddle River, NJ: Prentice Hall,, 2002.

Hussam, Reshmaan N.; Porter, David and Smith, Vernon. "Thar She Blows: Can Bubbles Be Rekindled with Experienced Subjects?" *American Economic Review*, 2008, *98*(3), pp. 924-37.

Isaac, R. Mark and Holt, Charles. *Emissions Permit Experiments*. Stamford, Conn.: JAI Press, 1999.

Johnston, Jack and DiNardo, John. *Econometric Methods,*. New York: McGraw-Hill, 1997.

Joskow, Paul L.; Schmalensee, Richard and Bailey, Elizabeth M. "The Market for Sulfur Dioxide Emissions." *American Economic Review*, 1998, *88*(4), pp. 669-85.

Kim, Chang-Jin and Nelson, Charles B. *State-Space Models with Regime Switching: Classical and Gibbs-Sampling Approaches with Applications,*. Cambridge and London: MIT Press, 1999.

Kim, Chang-Jin; Piger, Jeremy and Startz, Richard. "Estimation of Markov Regime-Switching Regression Models with Endogenous Switching." *Journal of Econometrics*, 2008, *143*, pp. 263-73.

Kosobud, Richard F.; Stokes, Houston H.; Tallarico, Carol D. and Scott, Brian L. "Valuing Tradable Private Rights to Pollute the Public's Air." *Review of Accounting and Finance*, 2005, *4*(1), pp. 50-71.

Krattenmaker, Thomas G. and Salop, Steven C. "Anticompetitive Exclusion: Raising Rivals' Costs to Achieve Power over Price." *Yale Law Journal*, 1986a, *96*(2), pp. 209-93.

____. "Competition and Cooperation in the Market for Exclusionary Rights." *American Economic Review*, 1986b, *76*(2), pp. 109-13.

Kruger, Joseph and Pizer, William. "The EU Emissions Trading Directive: Opportunities and Potential Pitfalls," Washington, D.C.: Resources for the Future discussion papers, 2004.

Leiby, Paul and Rubin, Jonathan. "Intertemporal Permit Trading for the Control of Greenhouse Gas Emissions." *Environmental and Resource Economics*, 2001, *19*(3), pp. 229-56.

LeRoy, Stephen F. and Porter, Richard D. "The Present-Value Relation: Tests Based on Implied Variance Bounds." *Econometrica*, 1981, *49*(3), pp. 555-74.

Liski, Matti and Montero, Juan-Pablo. "A Note on Market Power in an Emission Permits Market with Banking." *Environmental and Resource Economics*, 2005, *31*(2), pp. 159-73.

MacKinnon, James G. "Critical Values for Cointegration Tests." *Long-run economic relationships: Readings in cointegration*, 1991, pp. 267-76.

Maeda, Akira. "Impact of Banking and Forward Contracts on Tradable Permit Markets." *Environmental Economics and Policy Studies*, 2004, *6*(2), pp. 81-102.

____. "The Emergence of Market Power in Emission Rights Markets: The Role of Initial Permit Distribution." *Journal of Regulatory Economics*, 2003, *24*(3), pp. 293-314.

Malkiel, Burton G. *A Random Walk Down Wall Street: The Time-Tested Strategy for Successful Investing,*. New York: W. W. Norton & Company,, 2007.

Mandelbrot, Benoit B. and Cootner, P. H. *Fractals and Scaling in Finance: Discontinuity, Concentration, Risk*. Springer, 1997.

Mandelbrot, Benoit B. and Hudson, Richard L. *The (Mis)Behavior of Markets,*. New York: Basic Books,, 2004.

Mansanet-Bataller, Maria; Pardo, Angel and Valor, Enric. "CO2 Prices, Energy and Weather." *The Energy Journal*, 2007, *28*(3), pp. 73-92.

Misiolek, Walter S. and Elder, Harold W. "Exclusionary Manipulation of Markets for Pollution Rights." *Journal of Environmental Economics and Management*, 1989, *16*(2), pp. 156-66.

Montero, Juan-Pablo. "Voluntary Compliance with Market-Based Environmental Policy: Evidence from the U S Acid Rain Program." *Journal of Political Economy*, 1999, *107*(5), pp. 998-1033.

Montgomery, W. David. "Markets in Licenses and Efficient Pollution Control Programs." *Journal of Economic Theory*, 1972, *5*(3), pp. 395-418.

Muller, R. Andrew and Mestelman, Stuart. "What Have We Learned from Emissions Trading Experiments?" *Managerial and Decision Economics*, 1998, *19*(4-5), pp. 225-38.

Neuhoff, Karsten; Keats, Kim and Sato, Misato. "Allocation, Incentives and Distortions: The Impact of EU ETS Emissions Allowance Allocations to the Electricity Sector." *Climate Policy*, 2006, *6*(1), pp. 73-91.

Newell, Richard; Pizer, William and Zhang, Jiangfeng. "Managing Permit Markets to Stabilize Prices." *Environmental and Resource Economics*, 2005, *31*(2), pp. 133-57.

Oksendal, Bernt K. *Stochastic Differential Equations: An Introduction with Applications*. New York: Springer, 2007.

Ordover, Janusz A.; Saloner, Garth and Salop, Steven C. "Equilibrium Vertical Foreclosure." *American Economic Review*, 1990, *80*(1), pp. 127-42.

Paolella, Marc S. and Taschini, Luca. "An Econometric Analysis of Emission Trading Allowances," *Research Paper Series.* Zurich: Swiss Finance Institute, 2006.

Parry, Ian W. H. "Pollution Taxes and Revenue Recycling." *Journal of Environmental Economics and Management*, 1995, *29*(3), pp. S64-77.

PEW. "The European Emissions Trading Scheme (EU-ETS); Insights and Opportunities," PEW Center on Global Climate Change, 2005.

PointCarbon. "Carbon 2007: A New Climate for Carbon Trading," K. Roine and H. Hasselknippe, 62 p, 2007.

Reilly, John M. and Paltsev, Sergey. "An Analysis of the European Emission Trading Scheme," *Joint Program on the Science & Policy of Global Change.* Cambridge, MA: Massachussetts Institute of Technology, 2005.

Rickels, Wilfried; Dusch, Vicki; Keller, Andreas and Peterson, Sonjia. "The Determinants of Allowance Prices in the European Emissions Trading Scheme - Can We Expect an Efficient Allowance Market 2008? ," Kiel Institute for the World Economy Working Paper No. 1387, 2007.

Rubin, Jonathan D. "A Model of Intertemporal Emission Trading, Banking, and Borrowing." *Journal of Environmental Economics and Management*, 1996, *31*(3), pp. 269-86.

Salop, Steven C. and Scheffman, David T. "Cost-Raising Strategies." *Journal of Industrial Economics*, 1987, *36*(1), pp. 19-34.

____. "Raising Rivals' Costs." *American Economic Review*, 1983, *73*(2), pp. 267-71.

Sartzetakis, Eftichios S. "Raising Rivals' Cost Strategies Via Emission Permits Markets." *Review of Industrial Organization*, 1997, *12*(5-6), pp. 751-65.

Schaller, Huntley and van Norden, Simon. "Regime Switching in Stock Market Returns." *Applied Financial Economics*, 1997, *7*(2), pp. 177-91.

Schennach, Susanne M. "The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments." *Journal of Environmental Economics and Management*, 2000, *40*, pp. 189-210.

Schmalensee, Richard. "An Interim Evaluation of Sulfur Dioxide Emissions Trading." *Journal of Economic Perspectives*, 1998, *12*(3), pp. 53-68.

Seifert, Jan; Uhrig-Homburg, Marliese and Wagner, Michael. "Dynamic Behavior of CO2 Spot Prices." *Journal of Environmental Economics and Management*, 2008, *56*(2), pp. 180-94.

Shiller, Robert J. "Do Stock Prices Move Too Much to Be Justified by Subsequent Changes in Dividends?" *American Economic Review*, 1981, *71*(3), pp. 421-36.

Sijm, Jos; Neuhoff, Karsten and Chen, Yihsu. "CO2 Cost Pass through and Windfall Profits in the Power Sector." *Climate Policy*, 2006, *6*(1), pp. 49-72.

Smale, Robin; Hartley, Murray; Hepburn, Cameron; Ward, John and Grubb, Michael. "The Impact of CO2 Emissions Trading on Firm Profits and Market Prices." *Climate Policy*, 2006, *6*(1), pp. 29-46.

Stavins, Robert N. "What Can We Learn from the Grand Policy Experiment? Lessons from SO2 Allowance Trading." *Journal of Economic Perspectives*, 1998, *12*(3), pp. 69-88.

Tirole, Jean. "On the Possibility of Speculation under Rational Expectations." *Econometrica*, 1982, *50*(5), pp. 1163-81.

van Norden, Simon. "Regime Switching as a Test for Exchange Rate Bubbles." *Journal of Applied Econometrics*, 1996, *11*(3), pp. 219-51.

Vollebergh, Herman R. J.; De Vries, Jan L. and Koutstaal, Paul R. "Hybrid Carbon Incentive Mechanisms and Political Acceptability." *Environmental and Resource Economics*, 1997, *9*(1), pp. 43-63.

von der Fehr, Nils-Henrik Morch. "Tradable Emission Rights and Strategic Interaction." *Environmental and Resource Economics*, 1993, *3*(2), pp. 129-51.

Vorspools, Kris. "The Carbon Component of the U.K. Power Price." *Environmental Science & Technology*, 2006, *40*(15), pp. 4543-46.

West, Kenneth D. "A Specification Test for Speculative Bubbles." *Quarterly Journal of Economics*, 1987, *102*(3), pp. 553-80.

Westskog, Hege. "Market Power in a System of Tradeable CO2 Quotas." *Energy Journal*, 1996, *17*(3), pp. 85-103.

Zhao, Jinhua. "Irreversible Abatement Investment under Cost Uncertainties: Tradable Emission Permits and Emissions Charges." *Journal of Public Economics*, 2003, *87*(12), pp. 2765-89.