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Essays on Energy and Climate Policy - Green Certificates, Emissions Trading and Electricity Prices

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To Jonas, Axel and Molly

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Anna Widerberg

Göteborg, May 2011

Summary of the thesis

The thesis consists of five self-contained papers.

Paper I: *An Electricity Trading System with Tradable Green Certificates and CO_2 Emission Allowances*

Combinations of various policy instruments to deal with the threat of climate change are used throughout the world. The aim of this article is to investigate an electricity market with two different policy instruments, Tradable Green Certificates (TGCs) and CO_2 emission allowances (an Emission Trading System, ETS). We analyze both the short- and long-run effects of a domestic market and a market with trade. We find that increasing the TGC quota obligation will decrease the electricity produced using non-renewable sources as well as the long-run total production of electricity. For the electricity produced using renewable energy sources, an increase in the quota obligation leads to increased production in almost all cases, with assumptions based on historical data. The impacts of the ETS price on the electricity production are negative for all electricity production, which is surprising. This means that the combination of ETS and TGCs gives unexpected and unwanted results for the electricity production using renewable sources, since an increase in the ETS price leads to a decrease in this production.

Paper II: *The Impact of the EU Emissions Trading System on CO_2 Intensity in Electricity Generation*

The primary objective of EU Emissions Trading System (EU ETS) is to reduce CO_2 emissions. We study the effect of the EU ETS on CO_2 intensity of Swedish electricity generation, using an econometric time series analysis on weekly data for the period 2004–2008. We control for effects of other input prices and hydropower reservoir levels. Our results do not indicate any link between the price of EU ETS and the CO_2 intensity. The most likely reasons to explain this is that emission reductions are generally cheaper in other sectors and that other determinants of fossil fuel use diminish the effects of the EU ETS.

Paper III: *Attitudes to Personal Carbon Allowances*

A personal carbon allowance (PCA) scheme targets emissions from individual consumption and allocates allowances directly to individuals by dividing the carbon budget on a per capita basis. In this study we analyse the results of a survey sent out to a representative sample of the Swedish population regarding attitudes to a potential PCA scheme. The distinctive design of a PCA scheme is likely to give rise to specific factors affecting individuals' attitudes, such as the perceived fairness of the allocation of allowances and corresponding redistribution of wealth, as well as the perceived complexity of the scheme. We perform an ordered probit analysis with attitude to PCAs as the dependent variable, controlling for a number of variables potentially affecting such attitudes. Interestingly, our findings indicate that the most important variable explaining attitudes to the scheme is the perception of respondents that this type of policy instrument seems very complex.

Paper IV: *The stability of electricity prices: Estimation and inference of the Lyapunov exponents*

The aim of this paper is to illustrate how the stability of a stochastic dynamic system is measured using the Lyapunov exponents. Specifically, we use a feedforward neural network to estimate these exponents as well as asymptotic results for this estimator to test for unstable (chaotic) dynamics. The data set used is spot electricity prices from the Nordic power exchange market, Nord Pool, and the dynamic system that generates these prices appears to be chaotic in one case since the null hypothesis of a non-positive largest Lyapunov exponent is rejected at the 1 per cent level.

Published in Physica A

Paper V: *Market structure and the stability and volatility of electricity price*

By using a novel approach in this paper, (λ,σ^2)-analysis, we have found that electricity prices most of the time have increased in stability and decreased in volatility when the Nordic power market has expanded and the degree of competition has increased. That electricity prices at Nord Pool have been generated by a stochastic dynamic system that most often has become more stable during the step-wise integration of the Nordic power market means that this market is less sensitive to shocks after the integration process than it was before this process. This is good news.

Published in Energy Economics

Paper I

An Electricity Trading System with Tradable Green Certificates and CO_2 Emission Allowances.

Anna Widerberg*

Abstract

Combinations of various policy instruments to deal with the threat of climate change are used throughout the world. The aim of this article is to investigate an electricity market with two different policy instruments, Tradable Green Certificates (TGCs) and CO_2 emission allowances (an Emission Trading System, ETS). We analyze both the short- and long-run effects of a domestic market and a market with trade. We find that increasing the TGC quota obligation will decrease the electricity produced using non-renewable sources as well as the long-run total production of electricity. For the electricity produced using renewable energy sources, an increase in the quota obligation leads to increased production in almost all cases, with assumptions based on historical data. The impacts of the ETS price on the electricity production are negative for all electricity production, which is surprising. This means that the combination of ETS and TGCs gives unexpected and unwanted results for the electricity production using renewable sources, since an increase in the ETS price leads to a decrease in this production.

Keywords: Climate change; Tradable green certificates; Emission allowances; Electricity.

JEL Classification: Q40; Q42; Q48.

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1 Introduction

Growing concerns about climate change have led to a variety of mechanisms for promoting electricity from renewable energy sources. A number of different policy instruments are used throughout the world, and as the global climate negotiations slowly move forward, this situation will continue. Policy instruments to support electricity from renewable energy sources (RES-E) can be designed to directly increase RES-E production or to indirectly promote RES-E as a substitute for fossil fuel-based production (i.e. to reduce carbon emissions). Examples of the latter are the European Union Emissions Trading System (EU ETS), the Regional Greenhouse Gas Initiative (RGGI), active across ten U.S. states, and a CO_2 tax. Examples of policies directly promoting RES-E are feed-in tariffs (FiTs) and tradable green certificates (TGCs). Numerous countries have combinations of policy instruments that affect the electricity production, directly and indirectly. On top of this, some policy instruments are domestic and others are traded internationally. In Sweden, the electricity market is deregulated since 1996 and the trade in electricity takes place at Nord Pool, the marketplace for trades in electricity for Sweden, Norway, Finland and Denmark.[1] The EU ETS started in 2005,[2] as an extension to the Kyoto agreement, with the objective to reduce CO_2 emissions at the lowest possible cost. At present, the EU ETS consists of 30 European countries, including Sweden and Norway. In May 2003 the market for TGCs started in Sweden and it will be extended to include Norway in 2012. The objective of the TGC market is to increase the percentage of the total electricity production that relies on renewable energy sources, so-called green electricity. Electricity consumers are obliged to possess a number of TGCs in relation to their total electricity consumption, determined by the quota obligation set by the Swedish Government. The producers that use renewable energy sources are allocated TGCs, representing the supply of TGCs. In Sweden, the type of energy plants that entitles TGCs are wind power, solar, wave and geothermal energy as well as bio-fuels, peat[3] and hydropower[4]. These two policy instruments coexist in the Swedish and Norwegian electricity markets, where the TGC system is designed to increase the part of the total generated electricity that comes from renewable energy sources, whereas the ETS is designed to decrease CO_2 emissions.

Some recent research has focused on these different policy instruments, but with less attention to how well the supporting policies work together or whether they may work at cross purposes. Fischer and Preonas (2010) review the recent environmental economics literature on the effectiveness of RES-E policies and on interactions between them. Special attention is given to Fischer (2009), that demonstrates how the relative slopes of supply and demand curves determine the price incidence of portfolio standards, showing that assumptions about renewable energy sources are more important than those about non-renewable supplies. Early contributions to the area include Morthorst (2001) and Jensen and Skytte (2002). Morthorst analyzes the pricing mechanism of a TGC system

[1] Not all countries have been part of the market since 1996. Norway was the first member (since 1993), and then Finland joined in late 1997, western Denmark in July 1999 and eastern Denmark joined in October 2000.

[2] The first three years, 2005-2007, it was a trial period called Phase I.

[3] When burnt in combined heat and power production (CHP) plants.

[4] With restrictions in capacity.

and an ETS in relation to the value of the emissions reductions, while Jensen and Skytte find that a combination of a TGC system and an ETS results in a lower consumer price. Böhringer and Rosendahl (2010) show that introducing a policy instrument that promotes electricity from renewable energy sources, in a market under autarky, leads to production increases in the dirtiest technology using non-renewable energy sources. Unger and Ahlgren (2005) show that most TGC markets will favor cheap renewable technologies before expensive ones. This will not promote the inventions and development of new renewable technologies. In line with Unger and Ahlgren, Bergek and Jacobsson (2010) and Jacobsson et al. (2009) criticize the TGC system due to the ineffectiveness in driving technical change. Bye (2003) models a TGC market and Bye and Bruvoll (2008) extend his model to include other subsidies and taxes, yet neither of these studies takes the ETS market into account. Rathmann (2007) shows that German electricity prices are reduced due to an RES-E system implemented in the German electricity market with EU ETS, for the period 2005-2007. Amundsen and Nese (2009) investigate the analytics of a TGC system and find that the TGC system may be an imprecise instrument to regulate the generation of green electricity, and that combining TGC with ETS may yield outcomes contrary to the intended purpose. Even though our model is inspired by the model in Amundsen and Nese, the settings in the models differ, especially as regards how the ETS is treated. Our study gives more structure to the model and analyses short- and long-run effects. The earlier study by Amundsen and Mortensen (2001) preceding Amundsen and Nese investigates the relationship between the TGC and ETS markets by focusing on the Danish market. Thus, they assume a given capacity in the green electricity production, since in Denmark all green electricity production is wind power. Amundsen et al. (2006) use an intertemporal simulation model that allows for banking, and conclude that banking reduces the price of green certificates. Pethig and Wittlich (2009) find that if a country targets both emissions and renewable targets, mixed policies are preferred, provided that both policy instruments are binding, while Abrell and Wiegt (2008) find that with ETS and TGC or feed-in tariffs (FiTs), the price of carbon drops to zero due to the existing high share of CO_2-neutral renewable generation.

The above discussion on previous literature shows the great variety in the previous research. Moreover, the qualitative model results are to a large extent undetermined. We believe that the complexity of the policies is one reason for this. Thus to remove some of the question marks and obtain more clear results, it seems necessary to introduce stronger, but reasonable, assumptions imposing more structure on the TGC market models. Our study will analyze a country with an existing well-functioning electricity market with an emission trading system (ETS) and a TGC market. We will cover both a domestic TGC system and an extended TGC system with trade, both with a short-run and a long-run perspective. The distinction between short run and long run is of great importance since this makes it possible to introduce stronger assumptions about the shape of the marginal cost functions. The focus will be on the TGC market and its impact on the production using renewable versus the production using non-renewable energy sources. We will set up a model and perform an analytical discussion on the electricity production and the impacts of a TGC quota and the ETS price, distinguishing between short- and long-run effects. The simplifying but reasonable assumptions we make is that in the short run marginal cost in renewable electricity production is constant and zero (due to hydro and wind power), while in the long run the marginal cost in black electricity production is constant because of long-run constant returns to scale. We will also look into the empirical data, where needed. We believe that the short-run/long-run distinction is the key to obtain distinct results. Although we observe no differences for the time horizons in the actual results, it should be remembered that the underlying assumptions are different between the short- and the long-run. The paper is organized as follows. We will start with a model description and the general results in Section 2. Section 3 discusses the short-run assumptions used and presents the results for the short run analysis, and Section 4 does the same for the long run analysis. In Section 5 we take a closer look at the Nordic electricity market, and Section 6 discusses an extended TGC market. Section 7 concludes the paper, with the results and a discussion.

2 The general model

We will formulate a static model of an electricity market. We have two types of producers; black electricity producers, using non-renewable energy sources, and green electricity producers, using renewable energy sources. The following labels and functions will be used in the model:

Labels and functional relationships

y_b	black electricity, produced using non-renewable sources
y_g	green electricity, produced using renewable sources
y	total production of electricity, $y = y_b + y_g$
$p(y)$	price of electricity, with $\frac{\partial p}{\partial y} < 0$
p_{tgc}	price of green certificates
p_{ets}	price of emission allowances
α	quota obligation for green certificates, as a percentage of total electrici
γ	CO_2 emission density
$c_i(y_i)$	cost function for black/green electricity production with $\frac{\partial c_i}{\partial y_i} > 0$ and $\frac{\partial^2 c_i}{\partial y_i^2} \geq 0$, for $i = b, g$

The number of TGCs is measured in the same unit as the amount of green electricity. The demand for TGCs is given by αy, since all producers are obliged to hold a number of TGCs equal to α times their production[5]. The supply is given by y_g, since this is the number of TGCs available in the market. This gives $y_g = \alpha y$. There will be producers that do not qualify as green electricity producers but have no CO_2 emissions; this is not a problem since they will be classified as black electricity producers with γ set to zero.[6] The model originates in the profit maximization problem for the producers. The maximization problem for the producer of black electricity is

$$\max p y_b - c_b(y_b) - \alpha p_{tgc} y_b - \gamma p_{ets} y_b,$$

[5] In this model we assign the obligation to hold TGCs to the producers of electricity, while in reality the obligation is assigned to the suppliers/consumers of electricity. However, theoretically this does not make a difference and does not restrict the model.

[6] Unfortunally it is, in this setting, not possible to treat these producers separately.

giving the first-order conditions for an optimum

$$p = \frac{\partial c_b}{\partial y_b} + \alpha p_{tgc} + \gamma p_{ets}. \tag{1}$$

The maximization problem for the producer of green electricity is

$$\max p y_g - c_g(y_g) + (1-\alpha)\, p_{tgc} y_g$$

and the first-order conditions for an optimum is

$$p = \frac{\partial c_g}{\partial y_g} - (1-\alpha)\, p_{tgc}. \tag{2}$$

Solving equation (2) for p_{tgc} and inserting the expression for p_{tgc} in equation (1) gives

$$p = (1-\alpha)\frac{\partial c_b}{\partial y_b} + \alpha \frac{\partial c_g}{\partial y_g} + (1-\alpha)\,\gamma p_{ets}. \tag{3}$$

Impacts of the quota obligation

Implicitly differentiating equation (3) with respect to α, and using that $y = y_b + y_g$ and $y_g = \alpha y$, we get the impacts of the quota obligations on y_b, y_g and y:[7]

$$\frac{\partial y_b}{\partial \alpha} = \frac{\frac{1}{1-\alpha} y_b \left(\alpha \frac{\partial^2 c_g}{\partial y_g^2} - \frac{\partial p}{\partial y}\right) + \left(\frac{\partial c_g}{\partial y_g} - p\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{4}$$

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{a} y_g \frac{\partial p}{\partial y} - \frac{(1-\alpha)}{a} y_g \frac{\partial^2 c_b}{\partial y_b^2} + \frac{a}{1-\alpha}\left(\frac{\partial c_g}{\partial y_g} - p\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}, \tag{5}$$

$$\frac{\partial y}{\partial \alpha} = \frac{a y \frac{\partial^2 c_g}{\partial y_g^2} - y(1-\alpha)\frac{\partial^2 c_b}{\partial y_b^2} + \frac{1}{(1-\alpha)}\left(\frac{\partial c_g}{\partial y_g} - p\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}. \tag{6}$$

When looking at the impacts of the quota obligation, we see that the denominator is the same and negative for the impacts on both types of electricity production and the total production. The impact of the quota obligation on the black electricity is negative, since all included terms in the numerator are positive. This means that if the quota obligation, α, increases, then the production of black electricity decreases. The numerators are undetermined for green electricity and total consumption, so we need to take a closer look at the included terms, and in the following sections we study the two different time preferences, i.e. the short- and long-run aspects. But first we use the general model to reveal the impacts of the ETS price.

[7] The calculations are available on request

Impacts of the ETS price

Moving on to study the impact of the ETS price on electricity production, we take the implicit derivative with respect to p_{ets} in equation (3) and get the impacts of the price of ETS on y_b, y_g and y:

$$\frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}}, \tag{7}$$

$$\frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}}, \tag{8}$$

$$\frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}}. \tag{9}$$

We see that the signs of the impacts on the black, green and total production will always be the same and depend on the magnitude of γ (the CO_2 emission density) in relation to the sign and magnitude of $p_{ets}\frac{\partial \gamma}{\partial p_{ets}}$. We need to study the included terms in more detail, in the short- and long-run analyses, but let us first summarize the results for the general model in Table 1.

Table 1: Summary of the results for the general model.

	General model
$\frac{\partial y_b}{\partial \alpha}$	-
$\frac{\partial y_g}{\partial \alpha}$	?
$\frac{\partial y}{\partial \alpha}$	?
$\frac{\partial y_b}{\partial p_{ets}}$	?
$\frac{\partial y_g}{\partial p_{ets}}$	?
$\frac{\partial y}{\partial p_{ets}}$	?

The number of question marks in Table 1 illustrates the need for stronger assumptions to obtain clear results. The next section will discuss the assumptions for the short run and present the impacts of the quota obligation and the price of the ETS on electricity production. However, interesting conclusions can still be drawn at this stage. First, the only clear impact of the quota obligation is on the production of black electricity. This is a bit surprising since the purpose of the TGC system is to *promote green electricity* and not to decrease black electricity production, even if this is an expected outcome. Further we see that the impact of the ETS price will have the same sign for both types of electricity production and for the total electricity production, which is also a bit surprising. One might expect that the sign of the impacts on the production of green electricity and on the production of black electricity to differ. We will try to straighten out all question marks in Table 1, starting with the analysis of the short run. In the following we will make assumptions based on the Nordic market situation, however we believe that the assumptions are reasonable in other markets as well.

3 The model in the short run

In the short run we will assume that the marginal cost of green electricity production is constant, since the short run changes are made in existing hydro and wind power plants. Hence $\frac{\partial^2 c_g}{\partial y_g^2} = 0$. The cost function for black electricity, c_b, can be expressed as $c_b = y^b$, where $b \approx 1.2$.[8] Further, we assume that the demand for electricity can be written $y = Dp^\eta$, and hence $y\frac{\partial p}{\partial y} = \frac{1}{\eta}p$, where η is the price elasticity of demand for electricity. A price elasticity of -0.1 is used in both Bye (2003) for the Norwegian electricity market and De Jonhe et al. (2009) for the Benelux, France and Germany markets. Johnsen et al. (2000) presents a table of price elasticities for *residential* electricity demand, ranging from -0.19 to -0.76, based on empirical studies across the world. They find that, in Norway, the price elasticity can be estimated to -0.1 to -0.2. Based on this previous research, for the short run, we assume that $0.1 < |\eta| < 0.3$.

Impacts of the quota obligation

Using some of the assumptions described above, equation (5) can be rewritten as

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2} + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2}}. \tag{10}$$

The denominator is still negative and for the numerator we have $\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2} < 0$ and $\alpha p_{tgc} > 0$. Thus if $\left|\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2}\right| > \alpha p_{tgc}$, we have that $\frac{\partial y_g}{\partial \alpha} > 0$. To simplify the analysis we use $\left|\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2}\right| > \left|\frac{1}{\eta}p\right|$, and it is therefore enough to show that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ to state that $\frac{\partial y_g}{\partial \alpha} > 0$. The restriction for η,

[8] This assumption relates to the principal merit order curve in Swedish electricity production. See for instance www.svenskenergi.se

i.e. $0.1 < |\eta| < 0.3$, is equal to $10 > \left|\frac{1}{\eta}\right| > 3\frac{1}{3}$. Since by definition $0 < \alpha < 1$, we have that $\left|\frac{1}{\eta}\right| > \alpha$.[9] Therefore, to be able to show that the impact of the quota obligation is positive, it is enough to show that $p > p_{tgc}$. We believe that $p > p_{tgc}$ most of the time, yet we are unable to state this for certain. Hence, we are not able to determine the sign of the impact of the quota obligation on the green electricity production, since we need either $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ or $p > p_{tgc}$. However, to gain more insight into this matter, we study this case in Section 5, Visiting the Nordic Electricity market.

Rewriting the derivative for the total electricity, i.e. equation (6), using the short-run assumptions gives

$$\frac{\partial y}{\partial \alpha} = \frac{-y\left(1-\alpha\right)\frac{\partial^2 c_b}{\partial y_b^2} + p_{tgc}}{\frac{\partial p}{\partial y} - \left(1-\alpha\right)^2 \frac{\partial^2 c_b}{\partial y_b^2}} = \frac{-\left(1-\alpha\right)^{b-1} b(b-1)D^{b-1}p^{(b-1)\eta} + p_{tgc}}{\frac{\partial p}{\partial y} - \left(1-\alpha\right)^2 \frac{\partial^2 c_b}{\partial y_b^2}}. \quad (11)$$

Here we have the negative term $-\left(1-\alpha\right)^{b-1} b(b-1)D^{b-1}p^{(b-1)\eta}$ and the positive term αp_{tgc}. We see that the sign of $\frac{\partial y}{\partial \alpha}$ will depend both on the assumptions for the short run, i.e. b, D and η, and on the prices of electricity and TGCs. We know that $0.1 < |\eta| < 0.3$, $b \approx 1.2$ and $y = Dp^{\eta}$ (and therefore $D = \frac{y}{p^{\eta}}$). Unfortunately, we are unable to determine the sign of the impacts on the total electricity production since we need to know the relationship between p_{tgc}, p and y. This relationship will be analyzed Section 5.

Impacts of the ETS price

In the short run we assume that $\frac{\partial \gamma}{\partial p_{ets}} = 0$ since the producers have no possibility to react to a change in the ETS price by changing their CO_2 emission density. The equations (7), (8) and (9) can now be rewritten as

$$\frac{\partial y_b}{\partial p_{ets}} = \frac{\left(1-\alpha\right)^2 \gamma}{\frac{\partial p}{\partial y} - \left(1-\alpha\right)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \quad (12)$$

$$\frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha\left(1-\alpha\right) \gamma}{\frac{\partial p}{\partial y} - \left(1-\alpha\right)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \quad (13)$$

$$\frac{\partial y}{\partial p_{ets}} = \frac{\left(1-\alpha\right) \gamma}{\frac{\partial p}{\partial y} - \left(1-\alpha\right)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0. \quad (14)$$

The impact on all types of electricity production is negative, meaning that an increase in the price of the emission allowances gives rise to a decrease in the

[9] Actually, it is possible to put a harder restriction on α since the quota obligation for the green certificates ranges (for Sweden) from 0.1 to 0.2 from 2011 to 2028. After 2028, the quotas will decrease and go down to 0,008 in 2035, which is, at this point, the last year for the TGC system in Sweden. However, at this stage of the analysis we do not need a harder restriction than $0 < \alpha < 1$.

electricity production. As stated before, the signs are the same for all types of production and noteworthy, there is a negative impact of the price of the emission allowances on the green electricity production. This is not an expected result and shows that the combination of the ETS and TGC markets appears to work contradictorily with respect to the production of electricity using renewable sources. Increasing the price of the emission allowances works restrictively on the black electricity production (in line with the aim of the ETS), but also on the green electricity production. Further we see that the impact is larger on the black electricity production than on the green electricity production.[10] In the next section we will study the long run impacts.

4 The model in the long run

In this section we move the focus to a long-run static equilibrium. We do not take investments or other capacity changes into account. Further, the cost functions in the long run are not the same as the cost functions in the short run, yet for simplicity, we have the same notations as in the short run. In the long run, we assume that the marginal cost of the black electricity is constant, so $\frac{\partial^2 c_b}{\partial y_b^2} = 0$, due to long-run constant returns to scale. Further, we still assume that the demand for electricity can be written $y = Dp^\eta$, but with η less than -0.3.

Impacts of the quota obligation

Using these assumptions, equation (5) can be rewritten as

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2 \frac{\partial^2 c_g}{\partial y_g^2}}. \tag{15}$$

Again we need a more careful study of the included terms. We study the numerator of $\frac{\partial y_g}{\partial \alpha}$, where $\frac{1}{\eta}p < 0$ and $\alpha p_{tgc} > 0$. Either we stop here and say that if $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ we have a positive impact of the quota obligation on the green electricity production or we try to split up the terms. We know that $|\eta| > 0.3$ and to get $\left|\frac{1}{\eta}\right| > \alpha$ we need to put a restriction on α. If we assume that $\alpha < 0.5$ then $|\eta| < 2$.[11] Following the discussion for the short run we therefore either need $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ or $p > p_{tgc}$ to state that the impact on the green electricity production is positive. Again we cannot determine the sign of the impact of the quota obligation on the green electricity production without further assumptions on p and p_{tgc} (see Section 5). For total electricity we have

[10] As long as α is smaller than 0.5.

[11] $|\eta| = 2 \Leftrightarrow \left|\frac{1}{\eta}\right| = 0.5$. As mentioned ealier, an $\alpha < 0.5$ is a reasonable assumption. In Sweden α ranges from 0.1 and 0.2 from 2011 to 2028. An upper limit of $|\eta| = 2$ is reasonable and we do not believe that the long-term price elasticity of electricity will be nearly as high as 2. See for instance Dahl (1993) for a literature review on price elasticities.

$$\frac{\partial y}{\partial \alpha} = \frac{\alpha y \frac{\partial^2 c_g}{\partial y_g^2} + p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{16}$$

since the numerator is positive, meaning that an increased quota obligation gives rise to a decrease in the total electricity production. This is an expected result and together with the negative impact on the black electricity production we can state that the impact on the green electricity production has to be larger than the impact on the black electricity production ($\frac{\partial y_g}{\partial \alpha} > \frac{\partial y_b}{\partial \alpha}$). This can be fulfilled with $\frac{\partial y_g}{\partial \alpha} > 0$ or $\frac{\partial y_g}{\partial \alpha} < 0$, but in the latter case we also need $\left|\frac{\partial y_g}{\partial \alpha}\right| < \left|\frac{\partial y_b}{\partial \alpha}\right|$. The expected result would of course be $\frac{\partial y_g}{\partial \alpha} > 0$, but if $\frac{\partial y_g}{\partial \alpha} < 0$, the decrease in the green electricity production would be less than the decrease in the black electricity production.

Impacts of the ETS price

In the long run, firms can shift their production towards technologies with lower emission density which means that $\frac{\partial \gamma}{\partial p_{ets}} < 0$ rather than $\frac{\partial \gamma}{\partial p_{ets}} = 0$. Further we believe that the price elasticity for CO_2 emissions is inelastic, since the ETS price has a relatively small effect on the quantity of CO_2 emissions. An inelastic price elasticity means that $\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} > -1$. Hence the impacts of the ETS price in the long run will be written,

$$\frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2 \left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{17}$$

$$\frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha (1-\alpha) \left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{18}$$

$$\frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha) \left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0. \tag{19}$$

The sign of the equations (17), (18) and (19) will depend on the mutual relationship between γ and $p_{ets}\frac{\partial \gamma}{\partial p_{ets}}$. The breakeven point, where the impacts of the ETS price change sign, is where $\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} = -1$, meaning that the breakeven point is where the price elasticity for CO_2 emissions equals -1. Therefore, since we assume that the demand for CO_2 emissions is inelastic,[12] we will have a negative impact of the ETS price on both types of electricity production and on the total electricity production.[13] Further we see that the impact is larger on the

[12] $\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} > -1$

[13] However, if the price elasticity for CO_2 emissions is elastic $\left(\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} < -1\right)$, we will have a positive impact of the ETS price on both types of electricity production and on total electricity production. We believe this to be highly unlikely.

black electricity production compared to the green production.[14] However, we still have the obscure result for the impact on the green electricity production (see the discussion in the short run and in the concluding section).

5 Visiting the Nordic Electricity Market

In order to shed some more light on the undetermined signs of the impacts of the quota obligation on electricity production, we take a closer look at the available data. We use historical time series for Sweden for the price of electricity and TGCs and for the amount of electricity produced. The undetermined impacts and the relationships we want to understand, are:

- the impacts of the quota obligation on the green electricity production (both short and long run): $\frac{1}{\eta}p$ in relation to αp_{tgc}
- the impacts of the quota obligation on the total electricity production in the short run: $-(1-\alpha)^{b-1} b(b-1)D^{b-1}p^{0,2\eta}$ in relations to αp_{tgc}.

Impacts of the quota obligation on the green electricity production

We start with the impacts on the green electricity production, and as stated above we need to know the relation between $\frac{1}{\eta}p$ and αp_{tgc}. We know that $\frac{\partial y_g}{\partial \alpha} > 0$ if $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$, both for the short and long run. The price of electricity, p, is the price before the TGCs, emission allowances and taxes, and can be interpreted as the system price of electricity at Nord Pool, while p_{tgc} is the price of the green certificates. We study the historical time series for the prices 2004-2010 (Nord Pool Spot 2011; Svenska Kraftnät[15] 2011) and see that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ for every day during this period, with $0.1 < |\eta| < 0.3$.[16] For the long run we have $|\eta| > 0.3$, and with $|\eta| < 2$ we have that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ also in the long run[17]. Therefore, based on the empirics from 2004–2010, we state that the impacts of the quota obligation on the green electricity production are positive, both in the short and long run.

Impacts of the quota obligation on the total electricity production, short run

We use time series for 2008-2010 from Nord Pool Spot(2011) for the electricity price and from Svenska Kraftnät (2011) for electricity production to determine the size of D and the prices. We see that for $0.1 < |\eta| < 0.3$ together with $1.1 < b < 1.3$, $\frac{\partial y}{\partial \alpha} < 0$, but if b exceeds 1.3 there is a shift in the sign and

[14] As long as α is smaller than 0.5.

[15] The Swedish national grid.

[16] With $\alpha = 0,081$ (2004), $\alpha = 0,104$ (2005), $\alpha = 0,126$ (2006), $\alpha = 0,151$ (2007), $\alpha = 0,163$ (2008), $\alpha = 0,17$ (2009) and $\alpha = 0,179$ (2010). Actually $p > p_{tgc}$ for almost all dates, except for a small number of days, (less than 25 days a year) where $p < p_{tgc}$. However since $\left|\frac{1}{\eta}\right| > \alpha$ for these days still $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ holds. Results are available on request.

[17] With the same α as above. Actually, the limit $|\eta| < 2$ comes from the theoretical discussion. With the data from 2004-2010, $|\eta|$ can be larger and the inequality still holds. The results are available on request.

$\frac{\partial y}{\partial \alpha} > 0$. This means that the impact of the quota obligation on total electricity production is more sensitive to changes in b than to changes in η and in variables set by the market, i.e. p, p_{tgc} and D. We believe that $1.1 < b < 1.3$ is a reasonable estimate and therefore state that the impact of the quota obligation on the total electricity production is negative. This means that increasing the quota obligation decreases the total electricity production, and also that the decrease in black electricity is larger than the increase in the green electricity production.

6 Extending a market for TGCs

Now that we have studied a domestic TGC market, what happens if we extend the market to two countries with a common market for electricity, emission allowances and tradable green certificates? Since this market extension can be seen as the upcoming Swedish-Norwegian market, the analysis is carried out in this setting. In this market we assume the price of electricity and emission allowances to be exogenous, since the two countries will be part of a larger electricity and emission allowance market[18]. We study the impacts on the country with an existing TGC system (Sweden) when another country (Norway) enters the market. The analysis is divided into two scenarios and with the general model as starting point. The two scenarios differ in what expected effect the international market has on the TGC price, which is highly uncertain.[19] Scenario I assumes that an international market pushes down the TGC price, while scenario II assumes that an international market pushes up the TGC price. We will discuss the short- and long-term effects for each scenario, and the results are summarized in Table 2 in Section 7.

The model in the short run

First, we recap the derivatives with the short-run assumptions,[20]

$$\frac{\partial y_b}{\partial \alpha} = \frac{-y\frac{\partial p}{\partial y}+(1-\alpha)p_{tgc}}{\frac{\partial p}{\partial y}-(1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0, \qquad \frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\gamma}{\frac{\partial p}{\partial y}-(1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0,$$

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p-(1-\alpha)y\frac{\partial^2 c_b}{\partial y_b^2}+\alpha p_{tgc}}{\frac{\partial p}{\partial y}-(1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}}, \qquad \frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha(1-\alpha)\gamma}{\frac{\partial p}{\partial y}-(1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0,$$

$$\frac{\partial y}{\partial \alpha} = \frac{-(1-\alpha)^{b-1}b(b-1)D^{b-1}p^{(b-1)\eta}+\alpha p_{tgc}}{\frac{\partial p}{\partial y}-(1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}}, \qquad \frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\gamma}{\frac{\partial p}{\partial y}-(1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0.$$

We see that regarding the impacts of the ETS price, nothing changes with the TGC price. The impact of the ETS price on black, green and total electricity

[18] This will be the case in the Swedish-Norwegian market. The electricity price is set on the Nordic market, which comprises Norway, Sweden, Finland and Denmark. Further, the northern European market is linked to this market. The emission allowances are part of the EU ETS, with allowances valid in 30 European countries.

[19] This will be exemplified below when presenting the scenarios.

[20] The short run assumptions are $\frac{\partial^2 c_g}{\partial y_g^2} = 0$, $\frac{\partial \gamma}{\partial p_{ets}} = 0$, $c_b = y^b$ with $b \approx 1.2$ and $y = Dp^\eta$ with $0.1 < |\eta| < 0.3$.

production is negative, so an increase in the ETS price decreases the production. This is in line with the result above for the closed TGC market. The result regarding the impacts of the quota obligation on the black electricity production is the same as for the domestic TGC market and independent of the development of TGC prices. For the other impacts of the quota obligation we need to divide the analysis into two scenarios.

Scenario I, an extended market pushes down the TGC price This scenario assumes that the opening of the TGC market pushes down the TGC price compared to the price in Sweden prior to the common market. This is a reasonable scenario, since Norway may have a surplus of TGCs as a result of its hydropower. Thus, p_{tgc} decreases compared to the closed market in the previous section. The denominator is still the same and negative, and hence we will study the numerator. For the production of green electricity, the only positive part of the numerator, αp_{tgc}, is smaller than before. However, the sign of the impact on the green electricity production in the domestic market is undetermined, without using the assumption $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$. When studying the historical time series, we saw that the impact on the green electricity production is positive since we observed that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$. Based on this, a smaller p_{tgc} also leads to a positive impact on the green electricity production, conditional on that p is the same. An indirect effect of changes in p_{tgc} is of course also possible, leading to a decrease in the price of electricity. Yet, this potential is much smaller than the direct effect on the TGC price.[21]

For the impact on the total production, the discussion is similar to the one above. The only positive part of the numerator, αp_{tgc}, is smaller than before and if there are no changes to the negative term, then the impact will still be positive. However, as before, there might be indirect effects on the price of electricity, p, and on D[22] that will change the size of the negative part of the impacts on the total electricity production. We study the included terms in the numerator and test the sensitivity of the impacts of the included parameters[23] on the total electricity production. We conclude that the impact on the total electricity production is negative also in this case. Let us now move on to scenario II.

Scenario II, an extended market pushes up the TGC price This effect may be due to a shortage of TGCs in Norway, maybe a resulting from a too sparse allocation of TGCs. Therefore, p_{tgc} increases compared to the closed market and again we will discuss the numerator of the terms. For the impact on the green and total electricity production, the only positive term, αp_{tgc}, has increased and there may also be changes in the negative terms due to indirect effects on p. Thus, we are not able to determine the sign of the impacts on the green or the total electricity production.

[21] This depends on how sensitive the price of electricity is to changes in the TGC price. In the Swedish-Norwegian case this effect will be small since the prices of both electricity and ETS are set on a bigger market.

[22] Since $D = \frac{y}{p^{\eta}}$, indirect effects in production will change the size of D.

[23] D, b, α and η.

The model in the long run

We start with the derivatives with the long-run assumptions,[24]

$$\frac{\partial y_b}{\partial \alpha} = \frac{y\alpha \frac{\partial^2 c_g}{\partial y_g^2} - \frac{1}{\eta}p + (1-\alpha)p_{tgc}}{\frac{\partial p}{\partial y} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \qquad \frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0,$$

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2 \frac{\partial^2 c_g}{\partial y_g^2}}, \qquad \frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0,$$

$$\frac{\partial y}{\partial \alpha} = \frac{\alpha y \frac{\partial^2 c_g}{\partial y_g^2} + p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2 \frac{\partial^2 c_g}{\partial y_g^2}}, \qquad \frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0.$$

And as for the short-run analysis, we see that all results for the impacts of the ETS price as well as the impact of the quota obligation on the black electricity are consistent with those for the domestic TGC market.[25] For the impacts of the quota obligation on the green and total electricity production, we need the two scenario analyses.

Scenario I, an extended market pushes down the TGC price We will now revisit scenario I, where p_{tgc} decreases compared to the closed market in the previous section. With a decrease in p_{tgc}, we see that, regarding the impacts on the green electricity production, the positive term, αp_{tgc}, decreases. The negative part, $\frac{1}{\eta}p$, may also be indirectly affected by changes in p_{tgc}, giving a decrease in the price of electricity. However, this effect is much smaller than the direct effect on the TGC price. Based on the findings in Section 5, we have a positive impact on the green electricity production, meaning that the production of green electricity increases when the quota obligation increases.

When it comes to the impact on the total electricity production, we see that the terms in the numerator are still positive, yet the magnitude of p_{tgc} has increased. This means that the impact on the total electricity production is still negative, and hence that the total production of electricity will decrease when the quota obligation increases. Summarizing the results, we see that if the international market pushes down the TGC prices, the impacts on electricity production are the same as in the domestic TGC market case. An increase of the quota obligation increases the production of green electricity and decreases the black electricity production and the total electricity production. Let us now move on to scenario II.

Scenario II, an extended market pushes up the TGC price We will now revisit scenario II, where extending the market for TGC pushes up the price of TGCs, as discussed above. For the total production, we see that the

[24] The long run assumptions are $\frac{\partial^2 c_b}{\partial y_g^2} = 0$, $\frac{\partial \gamma}{\partial p_{ets}} < 0$ and $y = Dp^\eta$ with $0.3 < |\eta| < 2$.

[25] For the impacts of the ETS price this is conditional on the assumption of inelastic demand for CO_2 emissions, and we see no reason for this to change when extending the market for TGCs.

impact is still negative. When it comes to the impact on the green electricity, we see that we may have a shift here. Before, we had that the impact was positive since $\frac{1}{\eta}p > \alpha p_{tgc}$, but now as αp_{tgc} is increasing we see that depending on the magnitude of p_{tgc}, maybe the impact will shift sign and become negative. The price of the electricity production may also be affected as an indirect effect of the price changes of the TGCs. According to this, the sign of the impact on the green electricity production will be ambiguous, and will depend on the interrelation between αp_{tgc} and $\frac{1}{\eta}p$.

7 Results and discussion

Table 2 summarizes the results from the above sections. We can see that contrary to many other studies, we are able to determine the signs of most of the derivatives. The signs are persistent for the different time horizons and for the different market settings, which is promising. The underlying assumptions should however be kept in mind when reading the table. The parentheses indicate that the result is based on assumptions using empirical data.

Table 2: Summary of the results.

	General model	Domestic TGC market		Trade in TGC scenario I		Trade in TGC scenario II	
		short	long	short	long	short	long
$\frac{\partial y_b}{\partial \alpha}$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$\frac{\partial y_g}{\partial \alpha}$	?	(+)	(+)	(+)	(+)	?	?
$\frac{\partial y}{\partial \alpha}$	?	$(-)$	$-$	$(-)$	$-$	?	$-$
$\frac{\partial y_b}{\partial p_{ets}}$	?	$-$	$-$	$-$	$-$	$-$	$-$
$\frac{\partial y_g}{\partial p_{ets}}$	?	$-$	$-$	$-$	$-$	$-$	$-$
$\frac{\partial y}{\partial p_{ets}}$	?	$-$	$-$	$-$	$-$	$-$	$-$

For the domestic market, we have very clear results that are consistent over time. For the impacts of changes in the quota obligation, we see that the total production decreases even though the production using renewable resources increases. This means that the decrease in black electricity production is larger than the increase in green electricity production. For the impacts of changes in the ETS price on electricity production, we see that both types of electricity production and the total electricity production will decrease. Also, the largest decrease occurs in the production of black electricity. As discussed before, the decrease in the production of green electricity is unexpected and shows the danger of combining policy instruments. When it comes to the market with trade, we observe some question marks in Table 2. Even though these question marks are still worrying (and dissatisfying), they show up for less important results, since we believe that long-run effects are more important than short-run effects.

Comparing our results with the results from previous research we see that they are consistent, with the common feature of fewer clear results. The reason that we are able to determine the signs of more impacts, we believe is due to the assumptions made and the division of the analysis into a short and a long run. Hence, we include more assumptions than some other studies, without losing accuracy in the analysis. For instance, Amundsen and Nese (2009) are not able to determine a distinctive impact of the quota obligation on green electricity production or total production. When it comes to the market with trade, it is hard to compare our results with Amundsen and Nese (2009) since the ways the problem is tackled differs. Also Fisher (2009) studies the impacts of the quota obligation and gets similar results for black electricity, but has problems with the impacts for green electricity. Comparing our result with Amundsen and Mortensen (2001), that also have a division into short and long run, show some consistency but the comparison is not straightforward since the underlying assumptions differ. Worth noting is that for the impacts of changes in the ETS price, the price elasticity for CO_2 emissions is driving the results. For the impacts of the quota obligation, the driving force depends on the production of interest. For the total production in the short run it is b (the exponent in the cost function) while for the green electricity the result depends on the relationship between the prices of electricity and TGC. We believe that there are still questions that need more research within this area, both theoretical and empirical. For instance, studies of the outcome of the Swedish-Norwegian market and further extensions of the TGC market are interesting areas.

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Paper II

The Impact of the EU Emissions Trading System on CO_2 Intensity in Electricity Generation

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Abstract

The primary objective of EU Emissions Trading System (EU ETS) is to reduce CO_2 emissions. We study the effect of the EU ETS on CO_2 intensity of Swedish electricity generation, using an econometric time series analysis on weekly data for the period 2004–2008. We control for effects of other input prices and hydropower reservoir levels. Our results do not indicate any link between the price of EU ETS and the CO_2 intensity. The most likely reasons to explain this is that emission reductions are generally cheaper in other sectors and that other determinants of fossil fuel use diminish the effects of the EU ETS.

Key words: Emissions trading, carbon dioxide, climate change, electricity, carbon intensity

JEL Classification: C22, D21, D24, Q54

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Introduction

January 1, 2005, saw the launch of the European Union's Emissions Trading System (EU ETS)—the EU's flagship climate policy instrument and a centrepiece in its commitment to reach established greenhouse gas reduction targets. Its primary objective is to reduce emissions reductions at least cost, over and above what would have occurred without the trading system. In this paper, we analyze to what extent the EU ETS has affected the CO_2 intensity[1] in the Swedish electricity sector with an econometric time series analysis of the period 2004–2008.

The initial allocation of emissions allowances to participants is critical when designing an emissions trading system. In the EU ETS, this allocation—constituting significant monetary value—has largely been handed out to firms at no cost. In the first and second trading periods of the EU ETS (2005–2007 and 2008–2012, respectively), each EU member state had significant discretion in how they allocated their allowances to firms, which resulted in a plethora of different allocation methodologies. One recurring feature, however, was that many member states allocated fewer allowances to the electricity sector in relation to their past emissions, compared to other industry sectors. Two arguments seem to be the principal motivations for this decision. First, because price elasticity of electricity is low and the electricity sector is not exposed to direct competition from non-European countries, electricity companies could more easily pass on additional costs to consumers without loss of output or market share. Second, several member states—including Sweden—identified the electricity sector as having better opportunities to implement low-cost abatement measures. This was stated both explicitly by government officials and implicitly through the design of the so-called National Allocation Plans (NAPs). (Swedish Government Official Reports (SOU) 2003:60, 2004:62; Kolshus and Torvanger 2005; Jansson, 2009)

In the aggregate, demand for emissions allowances in a cap and trade system will be constant, given the cap on total emissions. If demand for allowances in certain sectors of the economy increases, this will push the price of the allowances up.[2] Because marginal abatement costs vary across firms and sectors, their emissions elasticities, in regard to change in allowance price, will be different. If the Swedish electricity sector does have lower marginal abatement costs than other sectors, it is more likely to adjust its demand for EU emissions allowances (EUA) in response to price variations in the market than sectors with higher marginal costs for emissions reductions. Hence, the EU ETS would have a visible impact on the CO_2 intensity of electricity generation, even though total emissions in the economy are constant.

Our paper contributes to the scarce empirical literature on the influence of the carbon price on emissions reductions and on how emissions reductions are distributed in the economy. We hope to shed light on whether the EU ETS has encouraged any short-term abatement of emissions in the electricity sector. If no evidence of this is present, either ex ante assumptions of low-cost measures in electricity generation were incorrect or one must find other explanations for firm behaviour. To our knowledge, this is the first study of its kind. Buchner and Ellerman (2006) make an effort to untangle the relationships between fluctuating carbon prices, over-allocation of emissions allowances, and potential abatement measures at the European level. They conclude that there likely has been abatement of emissions due to the EU ETS, but find it difficult to quantify.

Lack of emissions reductions in the electricity sector may not necessarily be a problem per se - it may be more cost effective to reduce emissions in other parts of the economy in the short

[1] CO_2 intensity is defined as the emissions of CO_2 per generated unit of electricity.

[2] In the EU ETS, as discussed below, price variations also came from other factors than changes in demand, notably political decisions, new information, and external developments that influence market expectations from the demand.

run. However, many observers hope that the EU ETS will drive a transformation of the energy sector in particular, for instance arguing that negative lock in effects may over time be higher than short term cost savings. Further, information about relative costs of emissions reductions is scarce, often built on modelling rather than real evidence and is difficult to assess. Hence we believe that empirical analysis of the kind we present in this paper could provide guidance to policy makers and add value to the scientific literature. The remainder of the paper is structured as follows. Section 1 provides background on the Swedish electricity market. Section 2 presents the data used for the analysis. In Section 3, we develop our econometric specification, detail the variables, and discuss what results can be anticipated. In Section 4, we estimate the model and show the results, while Section 5 concludes.

1. Swedish Electricity Generation: Dynamics and Drivers of CO_2 Intensity

The Swedish electricity system is characterised by a high degree of liberalisation and a smaller capacity for fossil fuel-based generation, compared to other European electricity markets. The Swedish system is integrated with Norway, Finland, and Denmark. Together, they form a Nordic electricity market, which has been transformed from a regulated market into its current, more liberalised form through a gradual process that started in the early 1990s. The liberalisation of the market aimed to make its capacity more efficient, increase the choices for consumers, and develop a more cost-effective energy supply. The dominant position of some utilities, especially in local markets, was an issue (and still is according to some observers), and a common Nordic electricity market would significantly reduce their dominance and guarantee stronger competition. Generation and trade of electricity are now open to competition, although the transmission networks are still regulated monopolies with national government control.

Table 1 shows the profile of electricity generation in the Nordic countries in 2007. In Sweden, coal is used in a small number of combined heat and power plants (CHP) and in some industrial boilers. Natural gas is also used in CHP and some peak-load units[3]. Oil is mainly used in industrial boilers and in units which come on line during extreme cold spells or are reserve capacity when other plants are taken off line for maintenance.

[3] Due to restrictions in the net, natural gas is only available in a small part of Sweden.

Table 1 Electricity Production in the Nordic Electricity Market in 2007

	Denmark	Finland	Norway	Sweden
Total generation*	**37.2**	**77.8**	**137.4**	**145.1**
Total thermal power	**27.7**	**53.6**	**0.7**	**68.2**
Nuclear power	–	22.5	–	64.3
Other thermal power**	27.7	31.1	0.7	3.9
- Coal	20.3	13.6	–	0.9
- Oil	0.3	0.4	–	0.8
- Peat	0.0	7.0	–	0.1
- Natural gas	6.8	10.1	0.7	1.2
- Others***	0.3	–	–	0.9
Total renewable power	**9.6**	**24.2**	**136.7**	**76.9**
Hydro power	0.0	14.0	135	65.5
Other renewable power	9.5	10.2	1.7	11.4
- Wind power	7.2	0.2	0.9	1.4
- Biofuel	0.3	9.4	0.0	8.7
- Waste	1.6	0.6	0.8	1.3
- Geothermal power	–	–	–	0.0
Net imports	**-1.0**	**12.9**	**-10.0**	**1.3**

* In Norway, gross electricity production; ** fossil fuels; *** West Denmark includes refinery gas. *Source*: Nordel (2007).

The dynamics of fossil fuel-based electricity in Sweden are closely tied to district heating because a large proportion of non-nuclear thermal power is generated by CHP units. The low fossil fuel volume also affects the dynamics of dispatch and the flexibility of the fuel mix. The demand for heat is a major determinant of CHP generation, so the impact on electricity generation of input price fluctuations may be somewhat lower, compared to electricity-only generation. The same can be true for electricity generation by industrial boilers, which primarily support production of other goods (such as steel or paper pulp). Thus, the price of fuels may be less important for these units than for a regular power plant. Finally, some of the most CO_2-intensive plants exist as back-up capacity for unexpected events, which may decrease the elasticity regarding input prices.

We expect our model to capture opportunities to reduce emissions that are available to firms in the short run. These include fuel switching, technical means of improving efficiency, and dispatch planning, such as modifying the merit order. Large utilities, such as Vattenfall, EON, and Fortum, have portfolios of capacity units and can thus change the internal merit order in response to market fluctuations. Smaller firms have less flexibility and altered output is sometimes the only option for dispatch planning. Furthermore, the large district heating networks in Stockholm, Göteborg, and Malmö can respond more quickly to market price changes because they have more options for altering the merit order of units than do smaller networks. New investments offer the best possibilities for switching fuels in the long term. In the short term, some plants which co-fire fossil fuels with biofuels have some flexibility.[4] In sum, fossil fuel-based generation often constitutes the marginal capacity and thereby determines the electricity price in the Nordic market. It is clear that opportunities exist for abating CO_2 emissions in the electricity sector, but the structure of the Swedish electricity sector and the existing mix of fuels and plant types restrict how quickly firms can respond to changes in input prices.

A related question is how electricity prices are affected by the price of EUA. Research on this issue has been done for the Nordic market, as well as other European electricity markets (e.g., Sijm et al. 2006, 2008; Fell 2008; Bunn and Fezzi 2007; Alberola et al. 2008; Åhman et al. 2008, and Wråke et al. 2008). Fell (2008) uses a co-integrated vector autoregressive (CVAR) analysis and reports a near full pass through of carbon costs in Nordic electricity prices. Bunn and Fezzi (2007) use similar methodology and find comparable results for the U.K. market. This supports the view that electricity firms internalise the cost of carbon into their product prices. Alberola et al. (2008) apply a single equation specification, primarily to identify structural breaks in the allowance market itself.

2. Data

Getting access to accurate and detailed data has been one of the greatest challenges for quantitative assessments of the EU ETS. We are interested in the link between EUA prices and CO_2 intensity in the Swedish electricity sector. For this purpose, we combine two unique data series to calculate weekly CO_2 emissions: weekly output of different kinds of generation capacity and monthly data on fuel consumption for each type of plant. By dividing total emissions by total output, we can calculate the CO_2 intensity for each week. Although this approach is not ideal, it still permits a relatively detailed analysis of short-term responses in firm behaviour to variations in the price of allowances.

An implicit assumption in the construction of the data set is that the proportion of fossil fuels used in each plant type is constant within a month. This puts certain restrictions on what types of measures our analysis can capture and in what resolution. We cannot detect how much fuel switching occurs weekly by specific plant type, only their monthly levels. However, weekly variations in emissions for each plant type reflect variations in output, which means that we can capture variations in how the portfolio of plants is used on a weekly basis.

Our data covers the period January 2, 2004–August 29, 2008, i.e., from one year before the launch of the first trading period through three-quarters of the first year of the second trading period. Inputs relevant to Swedish electricity generation include prices of EUA, natural gas, coal, oil, electricity, and biofuels. (The time series for these variables are presented in figure 1.) As relative prices are most important for fuel choice, we normalise all prices against the price of electricity. We also include a proxy for the value of water in the hydropower reservoirs. Because nuclear power plants have limited flexibility to respond to short-term changes, we feel it unnecessary to include the price of uranium in the analysis.

CO_2 intensity has a clear seasonal pattern. Total demand for electricity increases during the colder months, and more fossil fuels are used. Also noteworthy is the spike in electricity prices during the second half of 2006. This was primarily driven by the dry conditions that year, which reduced the volume of water available as hydropower, as seen in figure 1 in the panel showing reservoir level.

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[4] (For a detailed bottom-up inventory of CO_2 abatement opportunities in the Swedish energy sector, see Särnholm 2005).

EUA price (€/ton emitted) is the weekly average of European prices.[5] The natural gas price[6] (€/Btu) is the weekly average of day-ahead prices from the Zeebrugge hub.[7] The coal price[8] (€/ton) used is the weekly average of spot prices for coal delivered to the Amsterdam/Rotterdam/Antwerp region. The oil price (€/barrel)[9] used is the weekly average of the daily prices of Brent North Sea oil. The biofuel prices[10] (€/MWh) are based on quarterly data for Sweden, interpolated to weekly resolution. As a proxy for the value of the water available for hydropower generation, we use the deviation from average levels in the Nordic hydropower reservoirs for each week to measure the relative scarcity of water:[11]

$$(level)_t = (percent\_of\_capacity)_t - \overline{(percent\_of\_capacity)_t}$$

where $(percent\_of\_capacity)_t$ is the percent of the Nordic region's reservoir capacity that is filled for week *t* and $\overline{(percent\_of\_capacity)_t}$ is the historical median of percent of capacity for week *t*. Electricity prices (€/MWh) used are the average day-ahead Elspot hourly system prices for weekdays.[12] Figure 1 displays plots of all variables, and table 2 gives descriptive statistics of the variables.

Table 2 Descriptive Statistics of the Variables

	Obs.	Mean	Std. dev.	Min.	Max.
CO_2 intensity	244	10.53	4.13	4.03	22.17
Gas price	244	37.67	17.31	16.21	109.24
Coal price	244	61.73	19.64	43.59	135.54
Oil price	244	49.30	14.88	23.32	102.68
Biofuel price	244	15.96	1.18	13.96	18.47
EUA price	244	11.38	10.58	0.00	30.14
Reservoir level	244	-2.24	8.10	-23.00	11.48

[5] We use the weighted spot/over the counter (OTC) price as reported by Point Carbon.

[6] Primary source, Reuters

[7] Prices for natural gas, oil, and biofuels were converted from British pounds, American dollars, and Swedish kronor to euros, using daily exchange rates.

[8] Primary source, Reuters

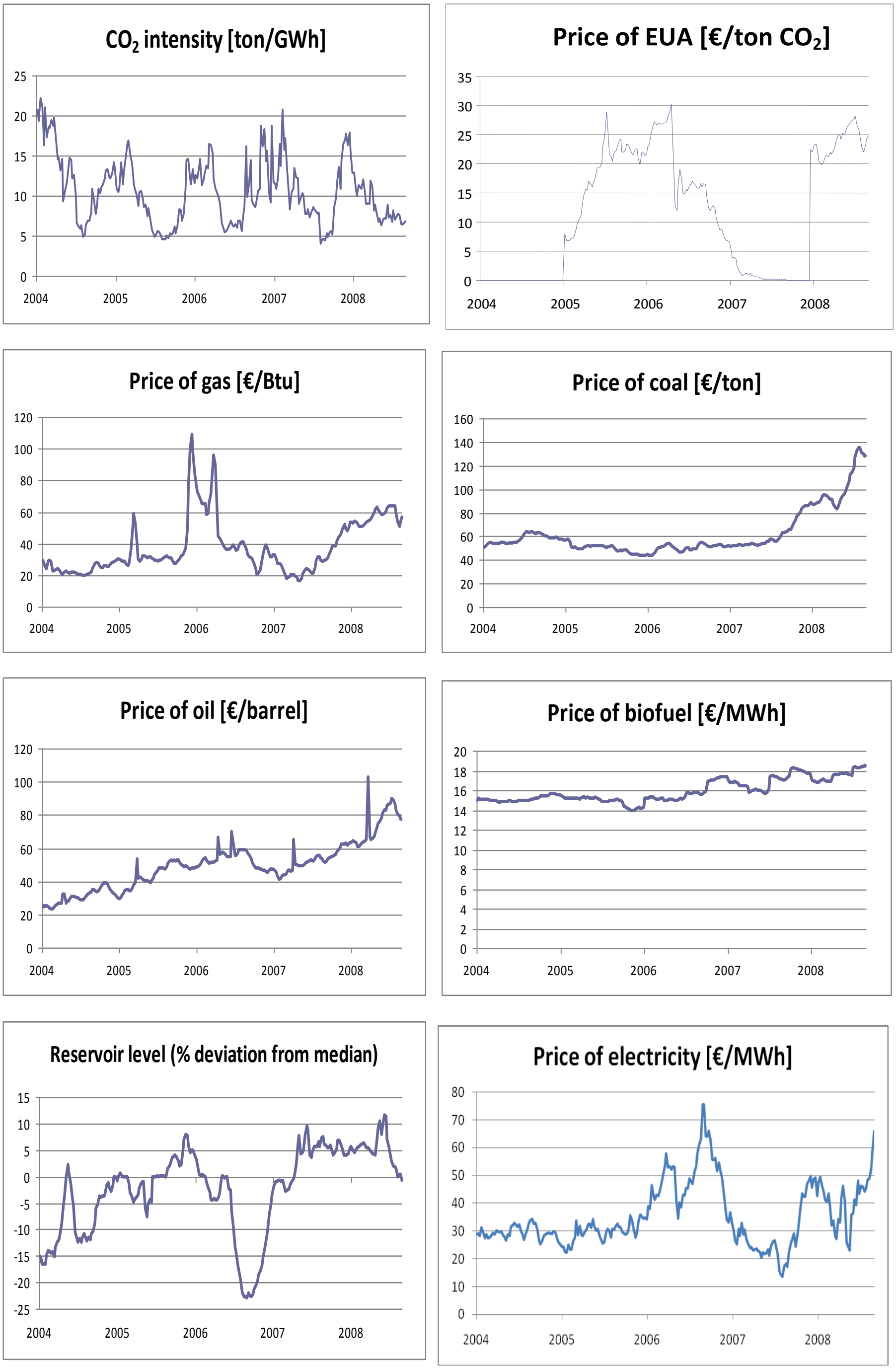
[9] Ibid.

[10] Primary source, the Swedish Energy Agency

[11] Primary source, Nord Pool.

[12] We use only weekdays since demand patterns shift during weekends when households are more important. Our focus here is on the industry actors in the market.

Figure 1 Plots of the Data



3. Econometric Specification and Anticipated Results

We apply an autoregressive distributed lag (ADL) model with the general specification:

$$Y_t = \alpha + \sum_{i=1}^{k-1}\left[\beta_i Y_{t-i}\right] + \sum_{i=0}^{k-1}\sum_{j=1}^{m}\left[\gamma_{j,i} Z_{j,(t-i)}\right] + \varepsilon_t \ ,$$

where α is the intercept; Y_t is the CO_2-intensity in week t; Z_t are the m exogenous variables in week t; k is the number of time lags chosen for each variable; β_i, $\gamma_{i,j}$ are estimated coefficients; and ε_t is the error term.

The robustness of the model and the quality of subsequent results were verified through preliminary and diagnostic tests as described below and in appendix A. In order to obtain estimates that are easy to interpret, we use the natural logarithm of the relative input prices. This also has the advantage that the variables are stationary, which simplifies the analysis. A common alternative, when variables are non-stationary in levels, is to use the first differences. We applied such a specification, but opted against it because the estimated coefficients are harder to interpret and did not make sense economically. [13]

We chose CO_2 intensity as the dependent variable in the model. Another possible approach would be to analyse CO_2 emissions and control for electricity generation. This yields very similar results[14] to those presented below, but we detected some heteroskedasticity in this model specification.

The dramatic variations in the allowance prices have featured prominently in discussions about the EU ETS. In particular, the April 2006 price crash, the October 2006 price slide, and the sharp increase in prices in 2008 (the start of the second trading period) attracted significant attention both in the public debate and the academic literature.[15] Our dependent variable does not display any structural breaks, so we have no concerns about our approach in this regard. However, in order to ensure that the breaks in the EUA price do not influence the behaviour of Swedish electricity firms, we conducted analyses where we considered this possibility without finding any evidence. (See appendix B for a discussion and results.)

The seasonality of CO_2 intensity reflects the variable Swedish climate, not surprisingly, and needs to be included in the analysis. One option is to include seasonal dummies in the model specification, but (as discussed below) the results of our regression strongly indicate that seasonality is captured with the model specification we apply without dummies. Based on previous knowledge of the characteristics of the electricity system, we anticipate certain results:

- **Past CO_2 intensity.** Since we expect the system to display some degree of inertia, it is reasonable to believe that past CO_2 intensity will have a positive but decreasing influence on present intensity. That is, we anticipate a positive sign of the estimated parameter.
- **Price of natural gas.** The effect of a change in gas price depends on the substitute for natural gas in the system. Oil or coal-fired plants are likely substitutes in the short run and, hence, we anticipate that an increase in the price of natural gas will cause an increase in CO_2 intensity (positive sign).

[13] Results are available on request.

[14] Results available on request

[15] See, for instance, Alberola et al. (2008) for a thorough discussion of structural breaks in the EUA price.

- **Price of coal.** Coal is the most CO_2-intensive fuel used in the electricity system (barring some process gases produced by the steel industry), so we expect that an increase in coal prices will prompt a fall in CO_2 intensity (negative sign).
- **Price of oil.** The effect of oil price change is more ambiguous than for natural gas and coal since it is less clear what the substituted fuel would be. If it is coal, an increase in oil price would spur an increase in emissions, but if the substitute is gas or biofuels, emissions would fall. Consequently, it is difficult to anticipate the sign.
- **Price of EUA.** EUA prices add a cost that is directly linked to emissions of CO_2, so we anticipate any effect on CO_2 intensity will be negative.
- **Price of biofuel.** As biofuels are regarded as having zero emissions, any shift away from biofuels would have a neutral or positive effect on emissions. Thus, we expect a positive estimated coefficient for the price of biofuel.
- **Reservoir level.** This variable was constructed to measure the value of water in the hydropower reservoirs. If the reservoir levels exceed the median for a particular week, we take that as a proxy for a decrease in the value of the water. Thus, we expect a negative sign on the estimated parameter for the level variable, indicating that as reservoir levels increase, more hydropower is used in the system, which prompts a fall in CO_2 intensity.

4. Results and Discussion

The significant results of the regression are shown in Table 3. In the regression, we include three lags of each variable. The number of lags was chosen through a step-by-step reduction from six lags until all lags were significant for at least one variable.

Oil price, EUA price, and reservoir level, all with three lags, are included in the regression, but the estimates are not significant. (The full table of results can be found in Table A1 in Appendix A.) We find CO_2 intensity to be significant in the first lag with a positive sign. The following lags are not significant, but show drastically decreasing coefficients, as anticipated.

To our knowledge, there is no data on biofuel prices with better resolution than ours. Still, because prices are stable (see figure 1), we have doubts about how much information the data series contains; thus, in the final model the variable is excluded from the regression.[16] The price of gas is significant, in both the unlagged price and all lags. For gas and coal, the estimated lags change between positive and negative signs. This is not surprising, as it shows that a spike in input prices at time *t* should affect the CO_2 intensity in that period, and then fade away. The CO_2 intensity returns to its average level, hence the opposite sign of t-1 estimates. In order to understand the total effect, long-term estimates[17] of the variables were calculated in Table 4. Here, all significant estimates have the anticipated signs.

[16] When the price of biofuel is included, the estimated coefficient is insignificant.

[17] The long-term solution is calculated as the sum of the coefficients for the unlagged and lagged independent variable divided by (1 minus the coefficients of the lagged dependent variable).

Table 3 Reduced Results from the Regression Analysis and Diagnostic Tests

CO_2 intensity	Coeff.		Std. err.
CO_2 intensity lag 1	0.796	***	0.068
Gas price (relative)	0.677	***	0.184
Gas price (relative) lag1	-1.244	***	0.380
Gas price (relative) lag2	0.928	**	0.381
Gas price (relative) lag3	-0.338	*	0.183
Coal price (relative)	-1.382	***	0.257
Coal price (relative) lag1	2.185	***	0.453
Coal price (relative) lag2	-1.446	***	0.481
Coal price (relative) lag3	0.634	**	0.273
Constant	0.308	**	0.096
Diagnostic Tests			
R-square		0.86	
Adjusted R-square		0.84	
F-stat, p-value		0.00	
Durbin Watson, h-value		0.33	
Breusch-Godfrey, p-value		0.31	
Breusch-Pagan, p-value		0.88	

*** significant at 1% level, ** significant at 5% level, and * significant at 10% level. Other included variables are oil price, EUA price, and reservoir level.

Table 4 Long-Term Estimates of the Variables

	Long-term estimate
Gas price (relative)	0.20
Coal price (relative)	-0.081
EUA price (relative)	0.14

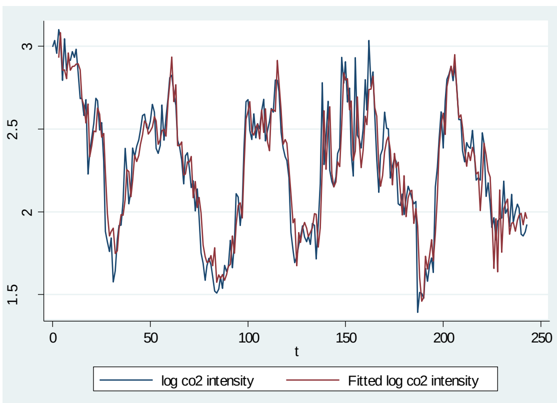
Even though the estimates of the EUA price were not significant, we chose to present the long-term estimate since this is the most important variable in the analysis. We found no other significant estimates.

The robustness of our model we verified through diagnostic statistics (see table 3). We calculated the Durbin-Watson h-value and the Breusch-Godfrey test statistic to detect autocorrelation, and the Breusch-Pagan tests for Heteroskedasticity, and test statistics showed no indication of either.[18] To ensure that the insignificant variables do not jointly influence the CO_2 intensity, we performed F-tests on the sum of the coefficients for these variables, without finding significance.

Because we began the analysis one year before the launch of the EU ETS, the first year of the study had no prices for allowances. In order to keep this year in the analysis, we set the logarithm of the relative EUA price to zero for this period. We also ran regressions with two different low prices for allowances, 0.01 €/ton and 0.0001 €/ton, for this period. To ensure robustness, we also ran regressions with 2004 omitted from the analysis altogether. In all cases, results were similar to those presented here.[19] As mentioned previously, we further tested model specifications with the variables in first differences and with CO_2 emissions as our dependent variable in lieu of CO_2 intensity.

Figure 2 shows observed values of CO_2 intensity along with model predictions for CO_2 intensity. The fit of the model indicates that the specification is able to capture most variations, including the seasonality in CO_2 intensity.

Figure 2 Observed Values of the Dependent Variable (blue line) and Predicted Values from Our Model Specification (red line)



Our results do not indicate any link between the price of EUA and the CO_2 intensity of Swedish electricity production in the period 2004–2008. We see a number of potential explanations for our findings:

- **Other drivers for CO_2 emissions, stronger than the price of carbon, are hiding or diminishing the effect of the EU ETS.** The generation in the fossil-fuel intense units,

[18] Additional plots of the data, such as the residuals versus the fitted value of the CO2-intensity, pp-plot, and qq-plot were studied. All showed the same, with no evidence of autocorrelation or heteroskedasticity.

[19] Results available on request.

such as CHP and industrial boilers, can also be driven by special circumstances (accidents in other plants, unplanned maintenance), but it can also include heat demand.

- **The price of carbon, so far, with the EU ETS has been too low to induce any significant emission reductions.** This argument carries some weight, particularly because the price of EUA approached zero toward the end of the first trading period. However, at any point in time, a positive price of EUA creates incentive to abate emissions.
- **Sectors other than electricity have implemented emission reduction measures.** This is certainly possible. This would indicate that low-cost opportunities for emissions reductions are more prevalent in other parts of the economy than the Swedish electricity sector and that the Swedish government was wrong in its assumption before the launch of the EU ETS that the opposite was true.
- **Emission reductions were made in other member states.** This is also possible, but if it were the only explanation, it would mean that firms in Sweden were only buyers in the EU ETS.[20]
- **The response time of abatement measures is longer than what our model can capture.** New, innovative abatement measures may require lead times of several years to become accepted, active, or built. However, a number of existing abatement measures could be introduced more quickly, such as fuel switching, efficiency improvements, and dispatch planning, until new measures replace old plants with new and more efficient generation capacity.
- **Firms are still learning to incorporate the cost of carbon emission into their decisions and thus did not respond fully.** This could help explain why it is difficult to link a relatively high price of EUA to abatement measures in a single sector. However, as the electricity sector is perhaps the best informed of all sectors participating in the EU ETS this argument seems weak.
- **Firms were expecting the price of EUA to reach zero at an early stage and thus had no incentive to implement abatement measures.** This reasoning does not convey why the price was positive for most of the trading period. Without speculating about an inefficient market for EUA—in which some agents may have supported the price using market power to gain economic benefits—this is difficult to explain. Ironically, those who put forward this argument often point to the electricity sector, claiming that many firms reaped substantial windfall profits from the higher electricity prices resulting from the EU ETS. We would also expect our model to capture this effect through the variables allowing for institutional changes to affect the results.
- **The response of CO_2 emissions to prices in EUA is asymmetric.** This argument is relevant for abatement measures where a reversal does not decrease operating costs. An example would be efficiency improvements; it would not make sense for a firm to reduce efficiency even if the price of EUA dropped below the level which triggered the improvement in the first place. However, for other measures, such as fuel switching, this explanation seems less likely to hold.

5. Conclusions

Given that one objective of the EU ETS is to lower CO_2 intensity in the economy in general and that the electricity sector was generally thought to hold many abatement opportunities, the

[20] Although each member state, as well as the EU Commission, collects data on market transactions, this data is not public and a deeper analysis of this issue has not been possible.

findings may be disturbing. However, even though our results do not indicate a significant impact of the EU ETS on emission intensity of Swedish electricity generation in the short run, it is difficult to see how a positive price of EUA, in general and over time, would *not* lead to any abatement of carbon emissions over and above those in a scenario without a price on carbon. If, as previous research indicates, firms incorporate the opportunity cost of carbon emissions into their operating and investment decisions, we would expect to see emission reductions measures—which would not have been implemented if there was no cost of emitting carbon. Hence, we believe that the absence of a significant impact of EUA prices on CO_2 intensity primarily hinges on the structure and characteristics of Swedish electricity generation.

We draw two main conclusions. First, it seems unlikely that the EU ETS has generated any significant reductions of CO_2 emissions in Swedish electricity generation. Second, it seems unlikely that there are significant volumes of low-cost CO_2 abatement measures with short response times in the Swedish electricity sector. In order to better understand the long-term impacts of the EU ETS on CO_2 intensity, one needs to complement the analysis with studies that have stronger emphasis on investment planning.

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Appendix A Full Regression and Preliminary Tests

Results of the Regression Analysis

Table A1 Full Results from the Regression Analysis and Diagnostic Tests

CO_2 intensity	Coefficient		Std. error
CO_2 intensity lag 1	0.796	***	0.068
CO_2 intensity lag 2	0.036		0.084
CO_2 intensity lag 3	0.051		0.067
Gas price (relative)	0.677	***	0.184
Gas price (relative) lag1	-1.244	***	0.380
Gas price (relative) lag2	0.928	**	0.381
Gas price (relative) lag3	-0.338	*	0.183
Coal price (relative)	-1.382	***	0.257
Coal price (relative) lag1	2.185	***	0.453
Coal price (relative) lag2	-1.446	***	0.481
Coal price (relative) lag3	0.634	**	0.273
Oil price (relative)	0.030		0.160
Oil price (relative) lag1	-0.119		0.191
Oil price (relative) lag2	0.071		0.191
Oil price (relative) lag3	-0.160		0.157
EUA price (relative)	-0.027		0.024
EUA price (relative) lag1	0.002		0.033
EUA price (relative) lag2	-0.003		0.033
EUA price (relative) lag3	0.012		0.023
Reservoir level	0.003		0.009
Reservoir level lag1	0.001		0.014
Reservoir level lag2	-0.001		0.014
Reservoir level lag3	-0.001		0.009
Constant	0.308	**	0.096
Diagnostic tests			
R-square		0.86	
Adjusted R-square		0.84	
F-stat, p-value		0.00	
Durbin Watson, h-value		0.33	
Breusch-Godfrey, p-value		0.31	
Breusch-Pagan, p-value		0.88	

*** significant at 1% level, ** significant at 5% level, and * significant at 10% level.

Stationarity

A visual inspection of the data in figure 1 in the text indicates potential non-stationarity in some the variables. To formally test this, we performed the Augmented Dickey-Fuller (ADF) test on all variables (table A2). We cannot reject the null of a unit root (and thus non-stationarity) for any variables except CO_2 intensity and reservoir level. In order to obtain stationary variables, we transformed the price variables into relative prices with the price of electricity as base, and then took the natural logarithm of the relative prices. Relative prices to some extent also capture the magnitude and importance of each input price in relation to the price of the output (electricity). The series are presented in figure A1 and the test statistics from the ADF test for the transformed variables are presented in table A2.

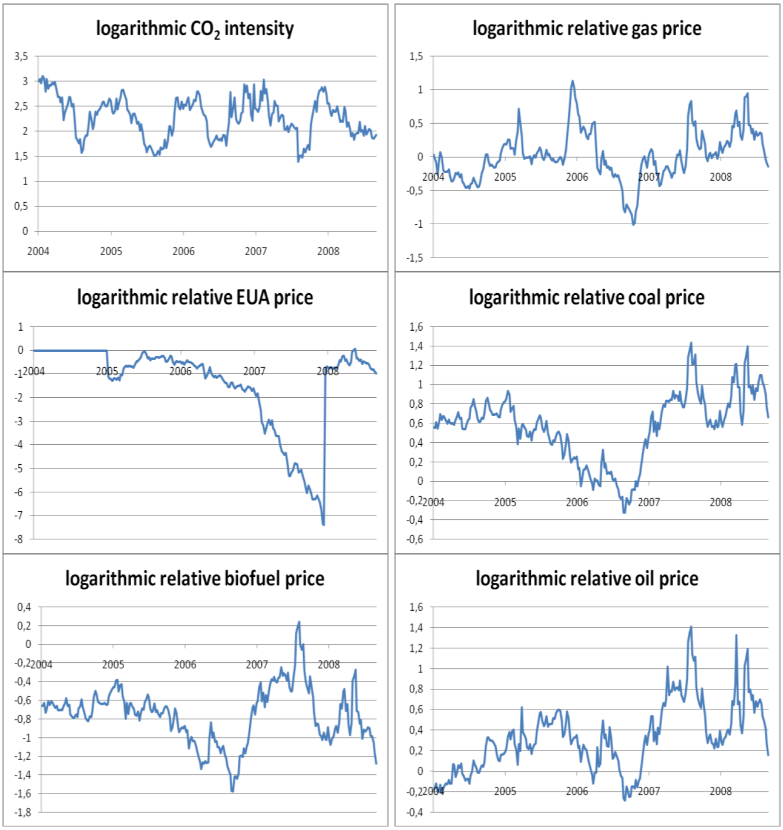
Table A2 Test Statistics for Augmented Dickey-Fuller Test with Drift, 3 Lags

CO_2 intensity	Gas price	Coal price	Oil price	Biofuel price	EUA price	Reservoir level
3.99***	-2.23	1.11	-1.03	-0.78	-1.49	-2.62*

Log CO_2 intensity	Log gas price (rel)	Log coal price (rel)	Log oil price (rel)	Log biofuel price (rel)	Log EUA price (rel)	Reservoir level
-3.58***	-2.96***	-1.91*	-2.79***	-2.27***	-1.87*	-2.65***

*** significant at 1% level, ** significant at 5% level, and * significant at 10% level. Critical values applied are -1.29 for 10%, -2.65 for 5% and -2.34 for 1%.

Figure A1 Plots of the Transformed Variables



Multicollinearity

Multicollinearity is a common cause of concern in regression modelling. A simple first step to assess the risk of multicollinearity is to check the cross correlations between the variables. These are shown in table A3.

Table A3 Correlation Coefficients

	Log CO_2 intensity	Log gas price (rel)	Log coal price (rel)	Log oil price (rel)	Log biofuel price (rel)	Log EUA price (rel)	Reservoir level
Log CO_2 intensity	1.00						
Log gas price (rel)	-0.08	1.00					
Log coal price (rel)	-0.19*	0.40*	1.00				
Log oil price (rel)	-0.49*	**0.56***	**0.67***	1.00			
Log biofuel price (rel)	-0.15*	0.31*	**0.81***	**0.64***	1.00		
Log EUA price (rel)	0.03	-0.01	-0.21*	-0.41*	-0.29*	1.00	
Reservoir level	-0.25*	**0.69***	**0.56***	**0.77***	0.44*	-0.31*	1.00

Moderate to high correlations exist between some variables (in bold in table A3). The high correlation between the biofuel price and coal and oil prices is unexpected, but could come from the construction of the variable. Quarterly prices of biofuels are fairly stable, and a large proportion of the fluctuation observed in our variable is in fact related to the SEK-Euro exchange rate. The fluctuation in the series may, therefore, be related to the general state of the economy, which in turn may be correlated with the price of coal and oil. The reservoir level shows high correlation with the prices of gas, coal and oil. We see no apparent theoretical underpinning for this correlation.

Table A4 Results of Variance Inflation Test

	Log gas price (rel)	Log coal price (rel)	Log oil price (rel)	Log biofuel price (rel)	Log EUA price (rel)	Reservoir level	Degree day	Log Nuclear gener.
VIF	2.78	3.68	5.76	3.93	1.64	4.06	2.67	2.43

To further explore whether the presence of multicollinearity could be problematic, we performed a Variance Inflation Factor (VIF) test. The results are presented in table A4. As a rule of thumb, if VIF exceeds 10, a variable can be suspected of high collinearity with some other variable.[21]

The conclusion from these procedures is that multicollinearity does not appear to be a problem for the analysis.

[21] For a discussion, see Greene (2003).

Appendix B. Structural and Institutional Changes

Assessments of the NAPs by Zetterberg et al. (2004) and Gilbert, Bode, and Phylipsen (2004), before the EU ETS was started, indicated that installations covered by the EU ETS were given more allowances than what their emissions had been historically. They also received more allowances than warranted, if each sector of the economy were to carry an equal burden in relation to the EU Kyoto target. This led many to criticise the system for not being stringent enough even before it was launched.

Nevertheless, the first year of trading saw prices of EUAs, which were higher than many observers had expected, peaking at over 30 €/ton early in 2006 (figure 1). However, the price variations were significant and during 2007 prices fell to near zero levels. Most observers now agree that there was, in fact, an over-allocation of emissions allowances which contributed to a decline in prices. This led to speculations whether the EU ETS has reached its primary goal of reducing carbon emissions. When the second trading period was launched in January 2008, prices increased again, indicating expectations of a shorter market for allowances.

When studying the plot in figure 1 in the text, four sudden changes in the EUA price series are apparent: January 2005, April 2006, mid-autumn 2006, and December 2007. The first price increase marks the launch of the EU ETS, before which there was no price on CO_2 emissions. The sudden drop in prices in April 2006 can be directly related to the release of data of verified emissions for 2005, which indicated an over-allocation of emissions allowances. The October 2006 price slide can be linked to statements by the EU Commission, which pointed to a more stringent allocation in the second trading period starting in 2008. This may have been interpreted as another indication that there was a surplus of allowances in the first trading period, prompting a further decline in prices. The final dramatic price change, in December 2007, indicates the start of the second trading period.[22]

Some observers were surprised that the price of EUA did not immediately drop to zero after the verified 2005 emissions became available in April 2006. Instead, the prices were relatively stable for a period, before they gradually fell towards zero in 2007. This seems to indicate that the market as a whole did not realise that there was a surplus of allowances until mid-2007. However, it has been suggested that electricity firms—given their long experience from trading in markets similar to the EU ETS, the importance of the EUA price to their operations, and their active role in the debate on the EU ETS—may have been in a better position to analyze the EUA market than other industry sectors. Furthermore, they did have an incentive to keep allowance prices positive, as this earned them profits on the large volumes of non-emitting power generation, such as nuclear and hydro.

This could suggest controlling for a change in behaviour of Swedish electricity firms at the times of the breaks in EUA prices, even though our dependent variable, CO_2 intensity, does not show corresponding structural breaks. For example, it is possible that seasonal variations in electricity generation are masking effects of institutional changes. Therefore, we also ran regressions with dummies aimed at controlling for these changes in the model specification.

In order to formally identify the break points in the EUA price series, we ran the test developed by Bai and Perron (1998), allowing for four potential breakpoints. The test indicates a first break in the first week of March 2005, a second break in the third week of April 2006, a third break in the second week of January 2007 and a fourth break in the last week of 2007.

If we instead allow for three structural breaks in the Bai and Perron test, the break in October 2006 appears instead of the January 2007 break. Due to the uncertainty in the October

[22] As our price series are for contracts with December delivery, the increase in prices occurred in December 2007, rather than January 2008.

2006 break, we limited our model to include the April 2006 price drop and the December 2007 price increase.

A comparison with previous research shows that Fell (2008), Bunn and Fezzi (2007), and Alberola et al. (2008) included the April 2006 break. Fell also included dummies for the start of the second trading period, while Alberola et al. included the break in October 2006 in their analysis. Alberola et al. used a slightly different approach and first identified a "compliance break period" between April 26 and June 23, 2006, and excluded this period from the data. They then identified a second break in October 2006 and explained it in a similar way as we do.

However, regression results do not show any significance in either the April 06 dummy or the December 2007 dummy.[23] Thus, we find no support for the suggestion that electricity firms altered their way of incorporating the carbon price after these events and we exclude these variables in the final model.

[23] Results available on request.

Paper III

Attitudes to Personal Carbon Allowances*

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Abstract

A personal carbon allowance (PCA) scheme targets emissions from individual consumption and allocates allowances directly to individuals by dividing the carbon budget on a per capita basis. In this study we analyse the results of a survey sent out to a representative sample of the Swedish population regarding attitudes to a potential PCA scheme. The distinctive design of a PCA scheme is likely to give rise to specific factors affecting individuals' attitudes, such as the perceived fairness of the allocation of allowances and corresponding redistribution of wealth, as well as the perceived complexity of the scheme. We perform an ordered probit analysis with attitude to PCAs as the dependent variable, controlling for a number of variables potentially affecting such attitudes. Interestingly, our findings indicate that the most important variable explaining attitudes to the scheme is the perception of respondents that this type of policy instrument seems very complex.

Keywords: Attitudes, Climate change, Environment, Fairness, Personal carbon allowances, Public opinion, Tradable energy quotas
JEL Classification: D12, D60, H23, Q48, Q58

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Introduction

Since the climate negotiations at the COP15 in Copenhagen in December 2009 stranded, the probability of a global carbon market in a near future has been low. A more likely scenario is one comprising a variety of policy instruments based on national and sub-national motives, policies, institutions and norms. An increasing number of politicians, environmental NGOs and scholars seem to agree that market-based policy instruments, such as emissions trading, are preferable as a means to reduce CO_2 emissions, based on their assumed cost-efficiency (see e.g. Fischer and Newell, 2008, for a recent contribution on this topic). Personal carbon allowances (PCAs) can be seen as a logical extension of emissions trading schemes from industry to individuals. A PCA scheme would target emissions from individual consumption and allocate allowances directly to individuals. The carbon allowances that originate from the carbon budget of the area (usually thought of as a nation) are allocated to individuals on a per capita basis. The individuals can then buy or sell any available surplus allowances in the carbon market. The market for carbon allowances may functionally operate like any commodity market: supply and demand determine the price, and excessive use raises the price accordingly. Of course, a series of technical issues must be settled before any such system can be implemented, e.g. rules for allowance allocation and trading and boundaries of the system (i.e. types of emissions that should be included and excluded, who should participate, and the geographical scope).

David Fleming explored the original idea in the UK context (Fleming, 1997) and Mayer Hillman, a well-known campaigner, popularized the idea further and also argued that the only serious and fair way to deal with climate change is to ration carbon emissions. Fleming and Hillman’s early ideas have been developed and refined in the UK, as “tradable energy quotas”, “domestic tradable quotas” or “personal carbon allowances” (Dresner and Ekins, 2004; Fawcett, 2005; Fleming, 2005; Starkey and Anderson, 2005). Recently the issue were raised again in the UK when the All Party Parliamentary Group on Peak Oil commissioned a report (Fleming and Chamberlin, 2011) investigating both how tradable energy quotas can contribute to ensure fair access of energy at time of shortages of oil and gas and how a PCA scheme would work alongside international carbon reduction policies. Although no nation or state has yet seriously developed proposals for a PCA scheme, the debate has been present within academia, NGOs and policy-making circles.

In 2010, *Climate Policy* published a special issue on personal carbon trading. The issue includes 10 articles on personal carbon trading, with a variety of perspectives and scales of investigation. Parag and Eyre (2010) study the politics of the PCA scheme and Fawcett (2010) studies the PCA scheme and the salience of various national energy- and carbon-related characteristics outside the UK. Lockwood (2010) compares a PCA scheme and a policy of upstream cap-and-trade, and Eyre (2010) tackles the previously neglected topic of enforcement of a PCA scheme. Brohé (2010) considers the interaction of PCAs with the EU ETS, while Sorrell (2010) assumes that PCAs cannot fit well with the EU ETS and instead proposes an upstream trading scheme (where the fossil fuel producers surrender allowances for the carbon contained in their fuel sales) operating together with the EU ETS. Matthews (2010) studies the influences of the psychological framing of carbon emission reduction policies on the public and political debate. More relevant for our study are the studies by Capstick and Lewis (2010), Wallace et al. (2010) and Jagers et al. (2010). Capstick and Lewis (2010) perform a computer-based simulation experiment and find evidence of energy-conserving tendencies under restricted and diminishing PCAs. Wallace et al.

(2010) investigate the public support for a PCA scheme using questionnaires and semi-structured interviews in the English Midlands. They find a notable level of support for a PCA scheme, both in the questionnaires and the interviews. Jagers et al. (2010) discuss the Swedish perspective and investigate the public acceptance of PCAs, with particular focus on the relations between attitudes to a PCA scheme and trust in politicians, perceived fairness and ideology. In the present study we extend the analysis of Jagers et al. (2010) using the same data, with an aim to contribute to the discussion on the public perception of an implementation of a PCA scheme. Our study differs from Jagers et al. (2010) mainly by analyzing the determinants of attitudes to a potential PCA scheme in an econometric model, controlling for a number of variables potentially affecting attitudes. Interestingly, our findings indicate that the most important variable explaining attitudes to the scheme is the perception of respondents that this type of policy instrument seems very complex.

In the following section, the variables explaining attitudes to a PCA scheme are discussed, followed by a description of the data and the survey. The results and conclusion are presented in the last sections of the paper.

Variables explaining attitudes to Personal Carbon Allowances

A PCA scheme and a carbon tax have major resemblances. They both use market mechanisms, internalizing externalities by putting a price on carbon. For a PCA scheme, *total emissions* are determined and then demand and supply determine the market price of carbon permits. In contrast, for a carbon tax, the *price* is determined, which affects the demand for carbon (and hence affect production and consumption that utilizes carbon). While both are in theory cost-efficient, the PCA scheme has the advantage that the level of emissions can be precisely determined in advance (provided full observance of and participation in the tradable quota system), whereas for a carbon tax the government has to rely on elasticity calculations when setting the proper level. While the public's attitudes to these two policy instruments may differ, all their similarities imply that we can expect that more or less the same factors will explain why they are popular or unpopular among the citizens. Thus, although only few studies have specifically investigated the public's opinion about a PCA scheme, we argue that we can draw from similar studies focusing on attitudes to carbon taxes. Below we discuss the variables that have proved significant for explaining attitudes to the Swedish carbon dioxide tax as well as to environmental attitudes in general.

Torgler and Garcia-Valinas (2007) provide a review of variables that have been shown to determine environmental attitudes in previous studies. These are mainly socio-demographic variables such as age and gender and variables such as education, income, environmental interest and residence. They also propose a number of ”new” variables that have been frequently used in political science studies to explain attitudes to policies in general, e.g. political interest, political awareness, trust and ideology.

The effect of age on environmental attitudes has been shown to be negative, i.e. the higher the age the lower the environmental concern. However, having children or grandchildren might affect how concerned you are about the future, having a positive effect on environmental attitudes. Women have been shown to be more environmentally aware than men (Loureiro and Lotade, 2005; Zelezny, 2000) and education seem to be positively correlated to environmental concern (Carlsson et al., 2010; Tjernström and Tietenberg, 2008; Demoskop, 2007). Earlier research has shown that income and having a less pressing financial situation each have a positive effect on pro-environmental attitudes (Torgler and Garcia-Valinas, 2007, Carlsson et al., 2010). However, the evidence is mixed as both Tjernström and Tietenberg (2008) and Demoskop (2007) report that income is negatively related to concern about climate change. Also, Torgler and Garcia-Valinas (2007) show ambiguous results indicating a Kuznets-type relationship between income and environmental attitudes. As for political affiliation, several studies have shown a positive relationship between left-wing voters and environmental concern (Torgler and Garcia-Valinas, 2007; Tjernström and Tietenberg, 2008). Also, individuals with an environmental interest tend to be more concerned with the environment.

It has been shown that trust affects people's attitudes to more and higher environmental taxes (Torgler and Garcia-Valinas, 2007), and this in two different ways. Typically, people tend to be more supportive of an environmental tax if they trust their co-citizens and/or if they trust their politicians (Hammar and Jagers, 2006).

The distinctive design of a PCA scheme is also likely to give rise to specific factors affecting individuals' attitudes. We believe that the most important characteristics distinguishing PCAs from taxes are the perceived fairness of allocation and redistribution issues, as well as the complexity of the scheme. Another specific feature of a PCA scheme is that the redistribution is determined through trade. As discussed above, the basis for a PCA scheme is that individuals have an equal right to pollute and to be protected from pollution. Hence, the most likely allocation mechanism for a PCA scheme is equal distribution of carbon allowances.[1] The likely distributional effect can be shown by using data from the Swedish Energy Agency (2007). This data shows that the use of energy is higher for people living in the countryside compared to people living in cities, for men compared to women, and for house owners compared to persons living in apartments, and it is therefore likely that wealth will be distributed from these groups. Even if this allocation mechanism at first glance seems fair in general, the explicitness of the allocation and redistribution generated by the scheme is likely to result in criticism among affected groups and engage moral intuitions on the fairness of the scheme.

[1] However, exceptions and additions to this general rule are often discussed for children (e.g. giving parents additional permits corresponding to the additional emissions caused by having children) and countryside residents (where public transportation cannot be justified from a cost/benefit perspective).

The survey

The Climate Barometer 2007 questionnaire was sent out to a random sample of 2,000 persons, age 18 to 75, drawn from the Swedish population in the national register. The net response rate was 46.8 percent.[2] Respondents were asked to answer a total of 45 questions with two thirds of them being general questions concerning background characteristics, environmental values and attitudes to present climate policies. The remaining 14 questions were directly devoted to the PCA scheme. Some of the questions are presented in Appendix II.[3]

Comparing respondent characteristics in terms of gender, education, income, and political affiliation with census data from Statistics Sweden shows that our sample is representative of the Swedish population in terms of gender and income, but not political affiliation and especially not education. A significantly larger share of our respondents is well educated compared with the population as a whole: 37% of the total Swedish population have post-secondary education versus 50% in our sample. As for the political affiliation, all the smaller parties are over-represented (except for the Left Party and the Christian Democrats) compared with the population as a whole, since the two largest parties (the Moderates and the Social Democrats) are under-represented among our respondents.

The scenario related to the PCA scheme was presented as straightforward as possible (see Appendix II), but two important aspects of the scheme were clearly stipulated in order to simplify the description of the scheme. First, in order to make the measurement of attitudes to the scheme as fair as possible, respondents were given the information that the CO_2 tax would be alleviated once the scheme was introduced but that other taxes would be increased in order to compensate for this loss. Although this need not necessarily be the case, conducting a comparison between a free allocation scheme and a tax scheme runs the risk of tilting respondents' preferences to PCAs. Second, the presentation of the scheme in the questionnaire assumes that all adults are to be allocated an equal amount of allowances, although this need not necessarily be decided in an actual policy formulation. Table 1 presents the variables used to explain the attitude to a PCA scheme, based on what we have learnt from earlier attitude studies.

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[2] The survey was followed up with two reminders.

[3] Since the survey was explicitly presented in an environmental context, there is a risk of framing bias, meaning that respondents could express stronger support for climate policies because they assume that this is expected of them. This bias may have been further affected by the exceptional media coverage of the climate change issue that took place during the autumn and winter of 2007. One additional issue relates to the fact that we asked about a hypothetical scheme. While it is generally shown that people overstate their willingness to pay in hypothetical studies (List and Gallet, 2001), it is not clear whether the difference is large (see e.g. Bertrand and Mullainathan, 2001) or small (see e.g. Hanemann, 1994). This tendency to overstate implies that people are generally more positive to a PCA scheme than to a policy instrument, such as the carbon tax, that has already been implemented, meaning that there is a bias favouring PCAs. On the other hand, we also know that people prefer the state they are currently in (Shogren et al., 1994; Kahneman and Knetsch, 1992; Slovic, Fischhoff and Lichtenstein, 1982), (the current policy in Sweden is a carbon tax), and hence we potentially have two opposing effects, and it is hard to judge which one is stronger.

Table 1: Descriptive statistics.

Variables	Variable explanation	Mean (std. dev)	Min	Max
PCA attitude	1=very negative, 2=negative, 3=positive, 4=very positive	2.094 (0.867)	1	4
Male	1=male, 0=female	0.487 (0.500)	0	1
Age	age of the respondent	48.878 (15.745)	18	75
Children	number of children	0.720 (0.449)	0	1
University	1=university studies, 0=others	0.384 (0.487)	0	1
Income	Stated income from a list of 12 categories [a]	-	1	12
Left-wing voter	1=prefer a left-wing government, 0=prefer a right-wing government [b]	0.466 (0.499)	0	1
Above average emitter	1=above average emitter, 0=at or below average emitter [c]	0.095 (0.294)	0	1
Trust in politicians	1=trust in politicians, 0=low trust in politicians [d]	0.085 (0.279)	0	1
Environmental concern	1=not worried at all, 2=not very worried, 3=neither worried nor not worried, 4=worried, 5=very worried	3.997 (1.077)	1	5
Redistribution rural	1=very unfair, 2=basically unfair, 3=basically fair, 4=very fair	1.832207(.8128054)	1	4
Redistribution income	1=very unfair, 2=basically unfair, 3=basically fair, 4=very fair	2.5963511(0.007454)	1	4
Complexity	1= not at all complex, 2= not very complex, 3= complex, 4=very complex	3.264 (0.819)	1	4
Number of respondents		785		

[a] The exact income cannot be determined since respondents indicated their income using a list of 12 categories.
[b] Left wing = the Swedish Social Democratic Party, the Swedish Green Party and the Left party. Right wing = The Alliance = the Moderate Party, the Centre Party, the Liberal Party and the Christian Democrats.
[c] In the questionnaire the response alternatives ranged from 1 to 5, where 1 = far below the average emitter and 5 = far above the average emitter. The variables were re-coded so that alternatives (4, 5) = 1 and (1, 2, 3) = 0.
[d] In the questionnaire the response alternatives ranged from 1 to 5, where alternative 3 is understood to be neutral. The variables were re-coded so that alternatives (4, 5) = 1 and (1, 2, 3) = 0.

Regarding the overall opinions about PCAs, 64 percent of the respondents oppose the PCA scheme (very negative or negative). However, this means that 36 percent are supportive of the PCA scheme (see Jagers et al., 2010, for a discussion on the relationship between attitudes towards the PCA scheme and the Swedish carbon tax). This result is similar to the findings in Wallace et al. (2010) that 40 percent are supportive. Furthermore, 81 percent of the respondents think that the PCA scheme is complex or very complex, and only 2 percent (!) think that the scheme does not seem complex at all. The future global environment seems to be of great concern to the respondents: 75 percent states that they are worried to some extent about the future global environmental and only 10 percent are not very worried or not worried. When it comes to their own emissions levels, only 10 percent of the respondents place themselves above the average CO_2 emissions per person in Sweden, while 40 percent see themselves as average emitters. A report from Statistics Sweden (Wadeskog and Larsson, 2003) analyzes the distribution of household CO_2 emissions, and states that individuals in rural areas emit more than individuals in urban areas and that high disposable incomes go hand in hand with high CO_2 emissions. We include two redistributional variables to capture the perceived fairness of the PCA scheme. The redistributional variables show that 80 percent of the respondents feel that redistribution from people in rural areas to people in urban areas is unfair (very or basically unfair), while 41 percent feel that redistribution from high-income earners to low-income earners is unfair (very or basically unfair). Thus, redistribution based on geographic location is considered as more unfair than redistribution based on income.

Results

We perform an ordered probit estimation with attitude to PCAs as the dependent variable. The results are presented in Table 2. The full set of marginal effects is presented in Table A1 in Appendix I.

Table 2: Ordered probit regression. Dependent variable: Attitude to a PCA scheme (1-4, where 4 is very positive)

	Coefficient	Standard error
Male	-0.081	0.088
Age	0.002	0.003
Children	0.048	0.111
University	-0.064	0.093
Income	-0.055***	0.018
Left-wing voter	-0.167*	0.086
Above average emitter	0.033	0.146
Trust in politicians	0.183	0.148
Environmental concern, not worried	0.103	0.282
Environmental concern, neither worried nor not worried	0.257	0.238
Environmental concern, worried	0.482**	0.226
Environmental concern, very worried	0.532**	0.227
Redistribution rural, basically unfair	0.374***	0.102
Redistribution rural, basically fair	0.719***	0.134
Redistribution rural, very fair	0.442*	0.248
Redistribution income, basically unfair	0.594***	0.147
Redistribution income, basically fair	0.894***	0.138
Redistribution income, very fair	1.299***	0.156
PCA, not very complex	-0.755***	0.288
PCA, complex	-1.040***	0.285
PCA, very complex	-2.044***	0.288
(Pseudo) R^2	0.2387	
Prob>chi^2	0.0000	
Number of observations	790	

* p<0.10; ** p<0.05; *** p<0.01

As shown in Table 2, few of the socioeconomic variables are significant. One exception is income, which is negative and significant: having a higher income decreases the probability of being positive to the PCA scheme. As noted earlier, a significantly larger share of our respondents are well-educated compared to in the population as a whole, yet there is no statistical difference in attitude to a PCA scheme between those with and without a university degree. Regarding political trust and political affiliation, we do not find any effect of political trust on attitude to the PCA scheme, yet an individual who votes for the left-wing block (the Swedish Social Democratic Party, the Swedish Green Party or the Left party) is less likely to have a positive attitude to the PCA scheme compared to those who vote for a right-wing party.

Notably, respondents who claimed to be "above average emitters" did not think worse of the PCA scheme even though this group would by definition lose from the scheme. This contradicts the standard assumption in economic theory that individuals' attitudes are mainly explained by self-interest. The lack of correlation could be due to the small size of this group (only 10 percent of the sample), but the fact that the coefficient points at a positive relationship is still puzzling. A bold interpretation of the lack of negative significance might hence be that respondents, who actually realize their relatively large greenhouse gas emissions, also feel more responsible for reducing them and hence become more prone to appreciate a relatively strict climate policy like the PCA scheme. We can of course only speculate on the above relationship, and suggest future research to analyze how detailed estimations of own-emissions affect individual behaviour.

Further, the more worried you are about the future global environment, the stronger your support of the PCA scheme. For example, an individual who is very worried about the future global environment as opposed to not being worried at all has an 18 percentage point higher probability of having a positive attitude (see marginal effects in Table A1 in Appendix I).

As discussed earlier we included two variables to control for the perceived fairness of the PCA scheme: redistribution from individuals living in rural areas to individuals living in urban areas (Redistribution rural) and redistribution from high-income earners to low-income earners (Redistribution income). These variables are significant and positive. Hence, the more fair an individual believes these redistributions to be, the more likely it is that he or she is positive to the PCA scheme. Our results indicate that the perceived fairness of the redistribution outcomes of the PCA scheme is an important determinant of somebody's attitude to it. For example, if an individual perceives the "Redistribution rural" as basically fair as opposed to very unfair, he or she has a 25 percentage point higher probability of having a positive attitude to the PCA scheme (see marginal effects in Table A1 in Appendix I). The corresponding figure for "Redistribution income" is 30 percentage points, i.e. an individual who perceives the "Redistribution income" as basically fair as opposed to very unfair has a 30 percentage point higher probability of having a positive attitude to the PCA scheme.

However, the largest impact on attitude to the PCA scheme is the perceived complexity of the scheme. The effect of this variable is negative and significant, and for example, an individual who perceives the PCA scheme as very complex as opposed to not at all complex has a 58 percentage point higher probability of having a very negative attitude to the PCA scheme. This is interesting from a policy perspective since the perception of complexity to a large extent can be mitigated by information and by the design of the scheme.

Discussion and conclusions

This study analyzes one of the first large surveys on attitudes to a PCA scheme, and serves as a starting point to identify critical aspects that policy makers, in any country, will most likely encounter when considering the implementation of a PCA scheme.

We find that the most important factor explaining people's attitudes to a PCA scheme is its perceived complexity. This is an aspect of the scheme that policy makers can affect, and probably even to a large degree, by providing information about the scheme before implementation. A British interview study concluded that the attitudes to PCAs became more positive when participants were given the opportunity to ask questions about the scheme (Bottrill, 2006). However, more research on how the scheme could make use of information and communication technology (ICT) solutions to minimize private management costs is necessary in order to work out how the scheme would actually operate. A number of other issues also need to be thoroughly thought through when designing a PCA scheme, such as whether children should be eligible to receive allowances, whether banking should be allowed etc. These questions may very well affect individuals' attitudes to the scheme and should hence be carefully analyzed.

The fairness aspects of the scheme are also shown to be important. We found this by exploring how fair individuals perceived two different types of redistributions to be, i.e. redistribution from individuals living in rural areas to individuals living in urban areas and redistribution from high-income earners to low-income earners. Our results indicate that the more fair an individual believe these redistributions to be, the more likely it is that he or she is positive towards PCAs. Since about 60 percent of the respondents approve of the implied redistribution from high to low income earners in a PCA scheme – the most comprehensive distributional consequence of the scheme – it seems likely that the fairness aspects of the scheme would affect people's attitudes to the scheme in a positive direction. We conclude that the perceived complexity of the PCA scheme obstructs this policy from being a feasible alternative for implementation at present, but that the relatively strong support for the scheme[4] and the potentially strong behavioural effects of the scheme make further analysis interesting.

[4] 36 percent of the respondents are positive to the PCA scheme which can be compared to the result presented in Jagers et. al., 2010 where 50% of the respondents (using the same sample) were positive to an increase in the current carbon tax.

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Appendix I

Table A1: Marginal effects for the ordered probit model

	PCA attitude : "very negative"		PCA attitude : "negative"		PCA attitude : "positive"		PCA attitude : "very positive"	
	Marginal effect	Standard error	Marginal effect	Standard error	Marginal effect	Standard error	Marginal effect	Standard error
Male	0.023	0.025	0.005	0.006	-0.027	0.029	-0.001	0.002
Age (18-75)	-0.001	0.001	0.000	0.000	0.001	0.001	0.000	0.000
Children	-0.014	0.033	-0.003	0.006	0.016	0.037	0.001	0.002
University	0.019	0.027	0.004	0.005	-0.021	0.031	-0.001	0.002
Income (1-12)	0.016***	0.005	0.003**	0.001	-0.018***	0.006	-0.001**	0.000
Left-wing voter	0.049*	0.025	0.010*	0.006	-0.056*	0.028	-0.003*	0.002
Above average emitter	-0.009	0.042	-0.002	0.010	0.011	0.049	0.001	0.003
Trust in politicians	-0.050	0.038	-0.017	0.018	0.063	0.052	0.004	0.004
Environmental concern, not worried	-0.029	0.076	-0.008	0.027	0.035	0.097	0.002	0.006
Environmental concern, neither worried nor not worried	-0.069	0.059	-0.024	0.031	0.088	0.083	0.005	0.006
Environmental concern, worried	-0.132**	0.058	-0.041	0.026	0.163**	0.077	0.010	0.006
Environmental concern, very worried	-0.146**	0.059	-0.044*	0.025	0.179**	0.076	0.011*	0.007
Redistribution rural, basically unfair	-0.105**	0.028	-0.027**	0.011	0.126***	0.034	0.007**	0.003
Redistribution rural, basically fair	-0.167***	0.025	-0.105***	0.031	0.248***	0.045	0.024***	0.009
Redistribution rural, very fair	-0.107**	0.048	-0.061	0.051	0.154*	0.088	0.013	0.011
Redistribution income, basically unfair	-0.149***	0.032	-0.071***	0.026	0.204***	0.050	0.016**	0.007
Redistribution income, basically fair	-0.237***	0.035	-0.082***	0.021	0.297***	0.044	0.022***	0.007
Redistribution income, very fair	-0.261***	0.024	-0.220***	0.037	0.413***	0.040	0.068***	0.020
PCA, not very complex	0.255**	0.107	-0.030	0.039	-0.217***	0.068	-0.008***	0.003
PCA, complex	0.332***	0.095	-0.010	0.026	-0.307***	0.073	-0.015***	0.005
PCA, very complex	0.578***	0.071	0.036	0.024	-0.557***	0.055	-0.058***	0.018

[a] marginal effect is for discrete change in dummy variable from 0 to 1
[b] compared to "Future concern, not worried at all"
[c] compared to "PCA, not complex at all"
[d] compared to "Fairness, don´t agree at all"
[e] compared to "PCA buy additional, very unfair"
* p<0.10; ** p<0.05; *** p<0.01

Appendix II: **Extraction of questions from the survey "The 2007 Climate Barometer"**

	Very little confidence 1	2	3	4	Very strong confidence 5
Question 22. In general, to what extent do you trust Swedish politicians?	☐	☐	☐	☐	☐

	Not worried at all 1	2	3	4	Very worried 5
Question 24. Do you feel worried about what will happen to the global environment in the future?......................	☐	☐	☐	☐	☐

Information about personal carbon allowances

A new environmental policy instrument involving personal carbon allowances is currently being discussed in the UK, and we would like to investigate how the Swedish public feels about a similar system. The system of personal carbon allowances is based on the Swedish Parliament determining a ceiling for the total yearly carbon dioxide emissions due to private car transports, air travel and residential heating. This total amount would be converted to allowances, which would then be distributed to all adult citizens. The emission allowances would be handed out for free and deposited into each person's "carbon dioxide account" at the end of every month.

Each person would receive the same number of allowances. As a person causes carbon dioxide emissions, a corresponding number of allowances would be deducted from his or her carbon dioxide account. Individuals who make an effort to reduce their emissions or who already cause very little emissions will be able to sell their unused allowances to people who need more allowances. In practise, the system would work as follows:

Imagine that you have just put petrol in your car and then gone inside to pay. First you use your carbon dioxide card to 'pay' for the emissions, and then you pay for the petrol. If you have already used up the allotted allowances that month, you can easily buy extra allowances at the petrol station. The same procedure would be used when buying airline tickets or paying the electricity bill.

If this system of personal carbon allowances would be introduced, it would take the place of the current carbon dioxide tax, which means that the petrol price would be reduced by a little over 2 SEK per litre. However, it is important to remember that an abolished tax would mean less public revenue, which in turn would mean that other taxes would have to be increased. The total tax burden would therefore not be changed following an implementation of personal carbon allowance scheme.

As mentioned, the system of personal carbon allowances implies that people who cause high amounts of emissions would have to buy allowances from people who cause less carbon dioxide emissions. This would lead to an economic redistribution among different groups. We will now present a few examples of possible redistributions, and would like to know how you feel about them.

Question 33. People in rural areas commonly need to use a car more than people in urban areas, which means that people in rural areas would need to buy emission allowances from people in urban areas. This means that there would be a redistribution of money from people in rural areas to people in urban areas. Do you feel this would be fair?

☐ Very fair ☐ Basically fair ☐ Basically unfair ☐ Very unfair

Question 36. Low-income earners generally cause less carbon dioxide emissions than high-income earners, which means that high-income earners would have to buy emission allowances from low-income earners. This implies a redistribution of money from high-income earners to low-income earners. Do you feel this would be fair?

☐ Very fair ☐ Basically fair ☐ Basically unfair ☐ Very unfair

Question 39. Do you think that you cause more or less carbon dioxide emissions per person than the average in Sweden?

☐ Far below average Below average ☐ At average ☐ Above average ☐ Far above average

Question 41. Do you think that the personal carbon allowances scheme seems complex?

☐ Very complex ☐ Complex ☐ Not very complex ☐ Not complex at all

Question 42. From what you have learned so far about the system of personal emission allowances, do you think it seems like an overall good or bad suggestion?

☐ Very good ☐ Fairly good ☐ Fairly bad ☐ Very bad

Paper IV

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The stability of electricity prices: Estimation and inference of the Lyapunov exponents ☆

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Abstract

The aim of this paper is to illustrate how the stability of a stochastic dynamic system is measured using the Lyapunov exponents. Specifically, we use a feedforward neural network to estimate these exponents as well as asymptotic results for this estimator to test for unstable (chaotic) dynamics. The data set used is spot electricity prices from the Nordic power exchange market, Nord Pool, and the dynamic system that generates these prices appears to be chaotic in one case since the null hypothesis of a non-positive largest Lyapunov exponent is rejected at the 1 per cent level.

Keywords: Feedforward neural network; Lyapunov exponents; Nord pool; Spot electricity prices; Stochastic dynamic system

1. Introduction

The aim of this paper is to illustrate how the stability of a stochastic dynamic system is measured using the Lyapunov exponents. Specifically, we use a feedforward neural network to estimate these exponents as well as asymptotic results for this estimator to test for unstable (chaotic) dynamics, where a positive exponent is an operational definition of chaos. The data set used is spot electricity prices from the Nordic power exchange market, Nord Pool.

The estimation of the Lyapunov exponents using a feedforward neural network can be found in earlier studies such as Dechert and Gencay [1], Gencay and Dechert [2], McCaffrey et al. [3] and Nychka et al. [4]. The estimation of these exponents has been proved to be quite accurate when applying chaotic series with additive noise in simulations. However, the statistical properties of the Lyapunov exponent estimator were

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unknown until Shintani and Linton's 2004 paper (see Ref. [5]), and without the statistical distribution for this estimator, no statistical conclusion can be drawn on the dynamic structure of the empirical data.

This paper applies the statistical distribution derived in Shintani and Linton [5] to test the stability of spot electricity prices from Nord Pool, and the stochastic dynamic system that generates these prices appears to be chaotic in one case since the null hypothesis of a non-positive largest Lyapunov exponent is rejected at the 1% level.

The rest of this short paper is organized as follows: the Lyapunov exponents are in focus in Section 2, the empirical illustration is carried out in Section 3, and Section 4 concludes the paper with a remark.

2. The Lyapunov exponents

The aim of this section is fourfold: (i) to define the Lyapunov exponents of a stochastic dynamic system; (ii) to motivate why these exponents provide a measure of the stability of a stochastic dynamic system; (iii) to demonstrate how the Lyapunov exponents can be estimated from time series data; and (iv) to demonstrate how hypothesis tests of these exponents can be constructed.

2.1. Definition of the Lyapunov exponents

As argued in Bask and de Luna [6,7], and to be further explained in Section 2.2, the Lyapunov exponents can be used in the determination of the stability of a stochastic dynamic system. Specifically, assume that the stochastic dynamic system, $f : \mathbb{R}^n \to \mathbb{R}^n$, generating, for example, asset returns is

$$S_{t+1} = f(S_t) + \varepsilon^s_{t+1}, \tag{1}$$

where S_t and ε^s_t are the state of the system and a shock to the system, respectively, both at time $t \in [1, 2, \ldots, \infty]$. For an n-dimensional system as in (1), there are n Lyapunov exponents that are ranked from the largest to the smallest exponent:

$$\lambda_1 \geqslant \lambda_2 \geqslant \cdots \geqslant \lambda_n, \tag{2}$$

and it is these exponents that provide information on the stability properties of the dynamic system f in (1).

Now, how are the Lyapunov exponents in (2) defined? Temporarily, assume that there are no shocks to the dynamic system f in (1), and consider how the system amplifies a small difference between the initial states S_0 and S'_0:

$$S_j - S'_j = f^j(S_0) - f^j(S'_0) \simeq Df^j(S_0)(S_0 - S'_0), \tag{3}$$

where $f^j(S_0) = f(\cdots f(f(S_0))\cdots)$ denotes j successive iterations of the dynamic system starting at state S_0, and where Df is the Jacobian of the system:

$$Df^j(S_0) = Df(S_{j-1})Df(S_{j-2})\cdots Df(S_0). \tag{4}$$

Then, associated with each Lyapunov exponent, λ_i, $i \in [1, 2, \ldots, n]$, there are nested subspaces $U^i \subset \mathbb{R}^n$ of dimension $n + 1 - i$ with the property that

$$\lambda_i \equiv \lim_{j\to\infty} \frac{\log_e \|Df^j(S_0)\|}{j} = \lim_{j\to\infty} \frac{1}{j} \sum_{k=0}^{j-1} \log_e \|Df(S_k)\|, \tag{5}$$

for all $S_0 \in U^i - U^{i+1}$. Due to Oseledec's multiplicative ergodic theorem, the limits in (5) exist and are independent of S_0 almost surely with respect to the measure induced by the process $\{S_t\}_{t=1}^{\infty}$.[1] Then, allow for shocks to the dynamic system f in (1), meaning that the aforementioned measure is induced by a stochastic process.

[1]See Guckenheimer and Holmes [8] for a careful definition of the Lyapunov exponents and their properties.

2.2. Motivation of the Lyapunov exponents

The reason why the Lyapunov exponents provide a measure of the stability of a stochastic dynamic system may be seen by considering two different starting values of the system, where the difference is an exogenous shock at time $t = 0$. The largest Lyapunov exponent, λ_1, measures the slowest exponential rate of convergence of two trajectories of the dynamic system starting at these two different values at time $t = 0$, but with identical exogenous shocks at times $t > 0$. Indeed, λ_1 measures the convergence of a shock in the direction defined by the eigenvector corresponding to this exponent. If the difference between the two starting values lies in another direction of $\mathbb{R}^n$, then the convergence is faster. Thus, λ_1 measures the "worst case scenario."[2] In particular, when $\lambda_1 > 0$, the two trajectories diverge from each other, and for a bounded stochastic dynamic system, a positive exponent is an operational definition of chaotic dynamics.

2.3. Estimation of the Lyapunov exponents

Since the actual functional form of the dynamic system f in (1) is not known, it may seem like an impossible task to determine the stability of the system. However, it is possible to reconstruct the dynamics of the system using only a scalar time series, and, then, measure the stability of this reconstructed system. Therefore, associate the dynamic system f in (1) with an observer function, $g : \mathbb{R}^n \to \mathbb{R}$, that generates observed asset returns:

$$s_t = g(S_t) + \varepsilon_t^m, \tag{6}$$

where $s_t \in S_t$ and ε_t^m are the asset return and a measurement error, respectively, both at time t. Thus, (6) means that the asset return series

$$\{s_t\}_{t=1}^N, \tag{7}$$

is observed, which is used to reconstruct the dynamics of the system f in (1), where N is the number of consecutive returns in the time series.

Specifically, the observations in a scalar time series, like the asset return series in (7), contain information about unobserved state variables that can be used to define a state in present time. Therefore, let

$$T = (T_1, T_2, \ldots, T_M)', \tag{8}$$

be the reconstructed trajectory, where T_t is the reconstructed state at time t and M is the number of states on the reconstructed trajectory. Each T_t is given by

$$T_t = \{s_{t+m-1}, s_{t+m-2}, \ldots, s_t\}, \tag{9}$$

where m is the embedding dimension, and time $t \in [1, 2, \ldots, N - m + 1]$. Thus, T is an $M \times m$ matrix and the constants M, m and N are related as $M = N - m + 1$.

Takens [9] proved that the map

$$\Phi(S_t) = \{g(f^{m-1}(S_t)), g(f^{m-2}(S_t)), \ldots, g(f^0(S_t))\}, \tag{10}$$

which maps the n-dimensional state S_t onto the m-dimensional state T_t, is an embedding if $m > 2n$. This means that the map is a smooth map that performs a one-to-one coordinate transformation and has a smooth inverse. A map that is an embedding preserves topological information about the unknown dynamic system, like the Lyapunov exponents, and, in particular, the map induces a function, $h : \mathbb{R}^m \to \mathbb{R}^m$, on the reconstructed trajectory,

$$T_{t+1} = h(T_t), \tag{11}$$

which is topologically conjugate to the unknown dynamic system f in (1). That is,

$$h^j(T_t) = \Phi \circ f^j \circ \Phi^{-1}(T_t). \tag{12}$$

[2] An extensive discussion of the Lyapunov exponents as a measure of the stability of a stochastic dynamic system is provided in Bask and de Luna [6]. For example, it is argued therein that the average of the Lyapunov exponents, $\lambda \equiv (1/n)\sum_{i=1}^n \lambda_i$, is useful as a measure of an "average scenario."

Thus, h in (11) is a reconstructed dynamic system that has the same Lyapunov exponents as the unknown dynamic system f in (1).[3]

Now, to estimate the Lyapunov exponents of the dynamic system generating asset returns, one has to estimate h in (11). However, since

$$h:\begin{pmatrix} s_{t+m-1} \\ s_{t+m-2} \\ \vdots \\ s_t \end{pmatrix} \longrightarrow \begin{pmatrix} v(s_{t+m-1}, s_{t+m-2}, \ldots, s_t) \\ s_{t+m-1} \\ \vdots \\ s_{t+1} \end{pmatrix}, \tag{13}$$

the estimation of h reduces to the estimation of v:

$$s_{t+m} = v(s_{t+m-1}, s_{t+m-2}, \ldots, s_t). \tag{14}$$

Moreover, note that the Jacobian of h at the reconstructed state T_t is

$$Dh(T_t) = \begin{pmatrix} \frac{\partial v}{\partial s_{t+m-1}} & \frac{\partial v}{\partial s_{t+m-2}} & \frac{\partial v}{\partial s_{t+m-3}} & \cdots & \frac{\partial v}{\partial s_{t+1}} & \frac{\partial v}{\partial s_t} \\ 1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & 0 \end{pmatrix}. \tag{15}$$

We use a feedforward neural network to estimate the above derivatives and to derive the Lyapunov exponents in (5) (see Refs. [1–4]). A neural network model with q hidden units, u_{it}, and m inputs, x_{jt}, can be represented as

$$\begin{cases} s_t = \beta_0 + \sum_{i=1}^{q} \beta_i u_{it} + \varepsilon_t, \\ u_{it} = \dfrac{1}{1+\exp(-w_{it})}, \\ w_{it} = \gamma_{0t} + \sum_{j=1}^{m} \gamma_{ij} x_{jt}, \end{cases} \tag{16}$$

where ε_t is a random error, and time $t \in [1, 2, \ldots, N-m+1]$. The input variable x_{jt} in the estimation of a dynamic system are the lagged dependent variables, $s_{t-1}, s_{t-2}, \ldots, s_{t-m}$. The parameters to be estimated in the model are β_i, γ_{ij} and the variance of ε_t, and we use nonlinear least squares to estimate these parameters.

Hornik et al. [13] show that the mapping and its derivatives of any unknown functional form can be approximated by the neural network model in (16). This universal approximation property enables us to apply the estimates of the derivatives from the neural network for the estimates of the derivatives in (15), and the estimation of the Lyapunov exponents in (5) can be derived. In choosing the best model, we use the Schwarz information criterion (SIC) as in Nychka et al. [4] to determine the numbers of hidden units and inputs.

2.4. *Inference of the Lyapunov exponents*

Shintani and Linton [5] derive the asymptotic distribution of a neural network estimator of the Lyapunov exponents. Specifically, given some technical conditions (see Ref. [5] for details), they show that

$$\sqrt{M}(\widehat{\lambda}_{iM} - \lambda_i) \Longrightarrow \mathbb{N}(0, V_i), \tag{17}$$

where $\widehat{\lambda}_{iM}$ is the estimator of the ith Lyapunov exponent, based on the M reconstructed states on the trajectory, V_i is the variance of the ith Lyapunov exponent, and $i \in [1, 2, \ldots, n]$. The stability of a stochastic dynamic system can be measured by the estimates of these exponents, and if the value of the largest exponent is positive, then the system appears to be chaotic.

[3]Since the m-dimensional system h in (11) has a larger dimension than the n-dimensional system f in (1), the number of spurious Lyapunov exponents are $m-n$. This issue is discussed in Dechert and Gencay [10,11] and Gencay and Dechert [12].

To test the stability of a dynamic system, we consider the following null and alternative hypotheses,

$$\mathbf{H}_0 : \lambda_i \leqslant 0, \quad \mathbf{H}_1 : \lambda_i > 0, \tag{18}$$

and the test statistic is

$$\widehat{t}_i = \frac{\widehat{\lambda}_{iM}}{\sqrt{\frac{\widehat{V}_i}{M}}}, \tag{19}$$

where $\widehat{V}_i$ is a consistent estimator of V_i (see Ref. [14]), and $i \in [1, 2, \ldots, n]$. Thus, the null hypothesis is rejected when

$$\widehat{t}_i \geqslant z_\alpha, \tag{20}$$

where the significance level is

$$Pr[\mathbb{Z} \geqslant z_\alpha] = \alpha, \tag{21}$$

where $\mathbb{Z}$ is the standard normal random variable, and $i \in [1, 2, \ldots, n]$.

3. Illustration: stability of electricity prices

The Nordic power exchange market and the data set used are described in Section 3.1, and the empirical results are found in Section 3.2 that also includes a sensitivity analysis of the results.

3.1. Nord Pool and data set used

Nord Pool is a multi-national exchange for trade in power, joining the Nordic countries. Norway was, in 1991, the first of the Nordic countries to deregulate the power market, and Nord Pool ASA was established in 1993, then under the name Statnett Marked AS. Sweden started the deregulation process in 1991, and went step-wise to a deregulated power market. January 1, 1996, was the start-up of the joint Norwegian–Swedish power exchange market, renamed to Nord Pool ASA.

Finland started a power exchange market of its own, EL-EX, in 1996, and joined Nord Pool in 1997. In 1999, Elbas is launched as a separate market for power balance adjustments in Sweden and Finland, giving a fully integrated market between Norway, Sweden and Finland. Denmark Nord Pool Consulting is established in 1998, and western Denmark joins the market in 1999 as a Nordic power exchange price area. When eastern Denmark joins in 2000, the Nordic power exchange market becomes fully integrated.

The data set used is spot electricity prices from Nord Pool. Specifically, it is the daily average of the hourly system price for the period January 1, 1993, to December 31, 2005. The data are analyzed split in parts with the natural breakpoints when a new country is joining the common market. Since the prices are not stationary, we use the returns, which is the logarithm-difference of the prices, in the empirical analysis. See Table 1 for the specific dates in the integration process and for the results of the stationarity tests of the time series.

3.2. Empirical results

For each time series, we estimated the Lyapunov exponents making use of 4, 8 and 12 inputs, respectively, to the feedforward neural network. Moreover, the number of hidden units in the neural network in each case runs from 1 unit to 12 units.[4] In Table 2, the estimates of the Lyapunov exponents that minimizes SIC in each subperiod in the integration process in the power market is reported, including three types of standard errors. The three types of standard errors, $\sqrt{\widehat{V}_i/M}$ in (19), are the heteroskedasticity

[4]We have used NETLE 4, a computer program developed by C.-M. Kuan, T. Liu and R. Gencay, when estimating the Lyapunov exponents (see Refs. [2,15] for details).

Table 1
The Dickey–Fuller unit root test for the system price and the logarithm-difference of the system price (return) at Nord Pool

Countries	Date of entry of new country	Price	Return
Norway	1/1/93	−0.70	−10.67*
Norway and Sweden	1/1/96	−0.44	−9.59*
Norway, Sweden and Finland	12/29/97	−1.30	−8.67*
Norway, Sweden, Finland and western Denmark	7/1/99	−0.36	−6.13*
Norway, Sweden, Finland and Denmark**	10/1/00	−1.19	−15.66*

*Indicates that the t-test is significant at the 1% level.
**Indicates that it is eastern Denmark that joins the power exchange market at this date.

Table 2
Estimates of the Lyapunov exponents (LE) and three standard errors (SE). The top, middle and bottom SEs are the estimates based on the Newey-West, Parzen and Quadratic Spectral kernel, respectively

	1/1/93-12/31/95		1/1/96-12/28/97		12/29/97-6/30/99		7/1/99-9/30/00		10/1/00-12/31/05	
	LE	SE	LE	SE	LE	SE	LE	SE	LE	SE
λ_1	−0.0606	0.00452	−0.0623	0.00776	−0.0421	0.00740	−0.0664	0.00134	−0.0319	0.00568
		0.00473		0.00782		0.00753		0.00321		0.00525
		0.00444		0.00787		0.00685		0.00376		0.00504
λ_2	−0.0743	0.00442	−0.116	0.00840	−0.0588	0.00821	−0.0677	0.00172	−0.101	0.00426
		0.00447		0.00844		0.00840		0.00323		0.00420
		0.00437		0.00858		0.00731		0.00378		0.00431
λ_3	−0.130	0.00661	−0.148	0.0110	−0.0994	0.00495	−0.0988	0.00609	−0.125	0.00439
		0.00664		0.0109		0.00533		0.00539		0.00439
		0.00660		0.0111		0.00556		0.00531		0.00460
λ_4	−0.160	0.00651	−0.183	0.0109	−0.107	0.00508	−0.102	0.00682	−0.157	0.00517
		0.00652		0.0109		0.00558		0.00582		0.00512
		0.00650		0.0109		0.00585		0.00573		0.00520
λ_5	−0.169	0.00709	−0.235	0.0130	−0.124	0.00750	−0.171	NA	−0.176	0.00580
		0.00708		0.0129		0.00741		NA		0.00580
		0.00709		0.0131		0.00732		NA		0.00581
λ_6	−0.199	0.00811	−0.291	0.0151	−0.135	0.00778	−0.174	NA	−0.277	0.00707
		0.00811		0.0149		0.00807		NA		0.00707
		0.00812		0.0153		0.00816		NA		0.00706
λ_7	−0.211	0.00872	−0.423	0.0177	−0.145	0.00790	−0.281	0.00283	−0.323	0.00901
		0.00869		0.0172		0.00789		0.00393		0.00898
		0.00882		0.0178		0.00791		0.00418		0.00903
λ_8	−0.231	0.00847	−1.41	0.0265	−0.166	0.00850	−1.23	0.00480	−1.01	0.0169
		0.00837		0.0312		0.00850		0.00645		0.0166
		0.00865		0.0331		0.00849		0.00707		0.0190
λ_9	−0.253	0.00928			−0.267	0.0135				
		0.00941				0.0132				
		0.00968				0.0141				
λ_{10}	−0.286	0.0112			−0.284	0.00935				
		0.0110				0.0117				
		0.0114				0.0133				
λ_{11}	−0.367	0.0146			−0.290	0.00978				
		0.0145				0.0132				
		0.0148				0.0145				
λ_{12}	−1.07	0.0355			−0.296	0.0139				
		0.0360				0.0139				
		0.0336				0.0140				

NA or "not available" means that the estimated variance is negative. Note that the kernel estimator of a variance may be negative, meaning that the SE does not exist.

Table 3
Estimates of the Lyapunov exponents (LE) and three standard errors (SE)

	1/1/93-12/31/95		1/1/96-12/28/97		12/29/97-6/30/99		7/1/99-9/30/00		10/1/00-12/31/05	
	LE	SE	LE	SE	LE	SE	LE	SE	LE	SE
λ_1	−0.0806	0.00410	−0.0623	0.00776	−0.0215	0.00554	0.0670	0.0169	−0.0386	0.00294
		0.00408		0.00782		0.00548		0.0167		0.00286
		0.00398		0.00787		0.00551		0.0168		0.00306
λ_2	−0.0855	0.00435	−0.116	0.00840	−0.0482	0.00594	−0.0193	0.00852	−0.0775	0.00336
		0.00432		0.00844		0.00600		0.00862		0.00336
		0.00432		0.00858		0.00594		0.00843		0.00336
λ_3	−0.118	0.00545	−0.148	0.0110	−0.0734	0.00663	−0.0451	0.00762	−0.119	0.00400
		0.00544		0.0109		0.00665		0.00769		0.00395
		0.00541		0.0111		0.00665		0.00761		0.00405
λ_4	−0.134	0.00521	−0.183	0.0109	−0.0940	0.00650	−0.0757	0.00811	−0.131	0.00413
		0.00515		0.0109		0.00650		0.00806		0.00408
		0.00550		0.0109		0.00663		0.00822		0.00420
λ_5	−0.176	0.00653	−0.235	0.0130	−0.100	0.00769	−0.130	0.0113	−0.147	0.00468
		0.00648		0.0129		0.00769		0.0114		0.00460
		0.00667		0.0131		0.00769		0.0113		0.00473
λ_6	−0.201	0.00715	−0.291	0.0151	−0.124	0.00724	−0.148	0.0118	−0.170	0.00534
		0.00704		0.0149		0.00717		0.0117		0.00532
		0.00719		0.0153		0.00743		0.0119		0.00537
λ_7	−0.213	0.00789	−0.423	0.0177	−0.143	0.00875	−0.271	0.0195	−0.196	0.00621
		0.00783		0.0172		0.00875		0.0196		0.00617
		0.00793		0.0178		0.00918		0.0197		0.00625
λ_8	−0.237	0.00875	−1.41	0.0265	−0.148	0.00931	−1.12	0.0576	−0.263	0.00679
		0.00860		0.0312		0.00925		0.0589		0.00689
		0.00878		0.0331		0.00944		0.0562		0.00706
λ_9	−0.284	0.00956			−0.175	0.0102			−0.300	0.00768
		0.00943				0.0102				0.00781
		0.00961				0.0103				0.00788
λ_{10}	−0.330	0.00937			−0.206	0.0132			−0.344	0.00863
		0.00982				0.0132				0.00878
		0.0105				0.0134				0.00913
λ_{11}	−0.400	0.0115			−0.319	0.0182			−0.471	0.0108
		0.0121				0.0185				0.0113
		0.0124				0.0188				0.0115
λ_{12}	−1.86	0.0710			−0.506	0.0318			−0.593	0.0165
		0.0675				0.0329				0.0164
		0.0535				0.0278				0.0160

The top, middle and bottom SEs are the estimates based on the Newey-West, Parzen and Quadratic Spectral kernel, respectively. Outliers are eliminated in the estimations.

and autocorrelation consistent estimators based on Newey-West, Parzen and Quadratic Spectral kernels (see Ref. [14]).[5]

Clearly, there is no unstable (chaotic) dynamics in the time series since all estimates of the largest Lyapunov exponent are negative.

When inspecting the time series, it is clear that there are some extreme values, outliers. To see their impact on the result, we eliminated the outliers from the time series and performed the same analysis as above.[6] See Table 3 for the results.

[5]Detailed results of the estimations are available on request from the authors.

[6]The excluded outliers are from February 28, 1994, to March 2, 1994, December 8, 1998, January 24, 2000, February 5, 2001, from December 5, 2002, to January 14, 2003. In total, 44 outliers are excluded.

When eliminating the outliers, the dynamic system appears to be chaotic for the period July 1, 1999, to September 30, 2000, since the null hypothesis in (18) is rejected for the largest Lyapunov exponent at the 1% level. For all other time series, there is no chaotic dynamics.

4. Concluding remark

We should also mention impulse–response functions as another tool to measure the stability of a stochastic dynamic system. Specifically, Koop et al. [16] and Potter [17] extend, in an appealing way, the linear technique of impulse–response functions to the non-linear case, although they show that there is no unique definition of such a function when a non-linear dynamic system is considered. Certainly, impulse–response functions are useful graphical tools in the non-linear case, even if they are less appropriate when inference needs to be performed on a change in the stability. It is, therefore, we recommend the estimation and inference of the Lyapunov exponents to measure the stability of a stochastic dynamic system.

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Market structure and the stability and volatility of electricity prices[☆]

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ABSTRACT

By using a novel approach in this paper, (λ,σ^2)-analysis, we have found that electricity prices most of the time have increased in stability and decreased in volatility when the Nordic power market has expanded and the degree of competition has increased. That electricity prices at Nord Pool have been generated by a stochastic dynamic system that most often has become more stable during the step-wise integration of the Nordic power market means that this market is less sensitive to shocks after the integration process than it was before this process. This is good news.

1. Introduction

During the 1990s, the Nordic countries have gone through an extensive deregulation of their electricity sectors and, at the same time, there has been an evolution from national markets to a multi-national electricity market. Thus, Denmark, Finland, Norway and Sweden have all reformed their electricity sectors and have today access to a common electricity market, which consists of two parts: (i) bilateral trade of contracts between operators; and (ii) the non-mandatory power exchange, Nord Pool.

The step-wise integration of the Nordic power market gives the opportunity to investigate several interesting questions that relate to the relationship between market structure and the behavior of electricity prices. First, because the aim of the deregulation and integration of the electricity sectors was to develop a competitive power market, which would benefit the consumers in the Nordic countries, one might ask whether the degree of competition has increased over time during this process? Bask et al. (2008) examine this question and also find that this, in fact, is the case.

What about the behavior of electricity prices? Has the increased competition at the Nordic power market affected the volatility of electricity prices in a systematic way? This issue is under scrutiny in this paper and using a data set that is similar to the one in Bask et al. (2008), we find that the volatility of electricity prices most often has decreased when the Nordic power market has expanded and the degree of competition has increased (see also Lundgren et al. (2008)). This finding is also consistent with the prediction of McLaren (1999) who presents an oligopoly model for a storable commodity such as water, which to a large extent is used in electricity generation in the Nord Pool area.

The main contribution in this paper is that we take a step further trying to figure out the reason for this change in volatility of electricity prices. Of course, the natural candidate is that the dynamics that govern the evolution of electricity prices have changed, but it could also be the case that the nature of the shocks hitting the Nordic power market has changed. A problem, however, is that we do not know the dynamics that govern the evolution of electricity prices, but as will be clear below (especially in Section 3), this problem is only apparent since we can reconstruct the dynamics using only electricity prices and, thereafter, measure the stability of the reconstructed dynamics.

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Concretely, what we do in this paper is to present (λ,σ^2)-analysis, which is a method to contrast the stability of a stochastic dynamic system (λ) with the volatility of a variable generated by this system (σ^2). Thus, if we focus on the development of Nord Pool, the method contrasts the stability of the dynamics that govern the evolution of electricity prices with the volatility of these prices. What we find is that the dynamic system generating electricity prices most often has increased in stability during the step-wise integration of the Nordic power market.

There are two dimensions of the findings in this paper. The first is theoretical. To the extent that approximating models of the energy sector are developed in an attempt to understand the behavior of energy prices and how they depend on the market structure, the stability of the dynamics that govern the evolution of energy prices should be added as an important dimension in which model and data should be matched. That is, our finding that electricity prices most of the time have increased in stability and decreased in volatility when the Nordic power market has expanded and the degree of competition has increased should be properties of a well-formulated model of the Nordic power market.

The second dimension is welfare. That electricity prices at Nord Pool most often have become more stable during the integration process means that the Nordic power market is less sensitive to shocks after this process than it was before it. This, however, does not mean that electricity prices never can change a lot from one day to the other, but it does mean that such large movements in prices are expected to happen less frequently. This is good news.

This is how the rest of this paper is organized: In Section 2, we first review the literature on the relationship between market structure and the price volatility for a storable commodity. Thereafter, we argue at an intuitive level why (λ,σ^2)-analysis is useful as a tool to contrast the stability of a stochastic dynamic system with the volatility of a variable generated by this system. In Section 3, we formally outline (λ,σ^2)-analysis and, in Section 4, we use this tool to investigate how the step-wise integration of the Nordic power market has affected the stability and volatility of electricity prices. Section 5 concludes the paper with a discussion.

2. Market structure and stability of prices

The aim of this section is to give a careful introduction to the subject of this paper, namely, the relationship between market structure and the stability and volatility of electricity prices. Therefore, in the first subsection, we review the literature on the relationship between market structure and the price volatility for a storable commodity. We do this to have a better idea of how the price volatility might be affected at a market with increased competition.

The second subsection is devoted to the relationship between the stability and volatility of prices or, more correctly, the relationship between the stability of a dynamic system and the volatility of prices generated by this system. We spend some time on this relationship since the techniques that we use to measure stability are not so well-known. Thus, what we do is to the give some intuition behind (λ,σ^2)-analysis that we formally outline in Section 3.

2.1. Market structure and volatility of prices

Since roughly one half of the electricity generated in the Nord Pool area is produced by hydro plants, it is natural to examine what the literature on storable commodities can offer regarding the relationship between market structure and the volatility of commodity prices. However, since most studies within this literature assume perfect competition (see Deaton and Laroque (1992, 1996) and Scheinkman and Schechtman (1983)), this relationship is far from fully understood.

One exception is McLaren (1999) who develops a model in which the price of the commodity decreases in volatility when the degree of competition increases. Specifically, McLaren (1999) presents a model of oligopolistic commodity speculation with an entry barrier in which the speculators perform non-cooperative storage in an infinite-horizon game. The author takes explicit care of the non-negative commodity stock constraint in the analysis and derives a Markov perfect equilibrium of the model in closed form.

McLaren (1999) emphasizes three properties of his model. First of all, there is less storage and more volatile prices than when the commodity market is competitive. Second, the oligopolistic equilibrium converges to the competitive equilibrium when the number of speculators becomes large. Third, an increase in the demand for the commodity lowers storage and increases the volatility of the commodity price.

Another paper is by Thille (2006) who, among other things, investigates the effect of storage on the price volatility under alternative market structures. Specifically, Thille (2006) presents a model of a duopoly in which the firms perform non-cooperative storage in an infinite-horizon game. A difference in this model compared to McLaren's (1999) model is that production no longer is exogenous. Thus, the firms in Thille's (2006) model have market power over both production and storage, and not only over storage as in McLaren's (1999) model. In the latter model, production is modelled as random harvests.

Using numerical analysis, Thille (2006) finds that the relative importance of demand and cost shocks determines whether the price volatility is higher or lower under imperfect competition than under perfect competition. The main findings are that when demand shocks dominate, the price volatility decreases when the degree of competition increases whereas when cost shocks dominate, the price volatility increases when the degree of competition increases. Thille (2006) looks at three market structures in the analysis: monopoly, duopoly and perfect competition.

An early paper that examines the relationship between the degree of competition and the price volatility for a storable commodity, which also should be mentioned, is Newbery (1984). In his random harvests model, the monopolist stores more than firms do in a competitive market, which results in a less volatile commodity price when the commodity demand is linear in the price. However, when the price elasticity of demand is constant, the commodity price is less volatile under competition. Thus, the findings are ambiguous as in Thille (2006). Since Newbery's (1984) model is a random harvests model, the firms have market power over storage only as in McLaren's (1999) model.

To summarize, the small theoretical literature that exists on the relationship between the degree of competition and the price volatility for a storable commodity does not give a unified answer. This should not come as a surprise since the models differ from each other in several respects (see Rui and Miranda (1996), Vedenov and Miranda (2001), and Williams and Wright (1991) for more literature on this topic). But what about the empirical literature? What does it say on the relationship between market structure and the price volatility for a storable commodity?

First of all, there are few empirical studies that measure the degree of market power in the Nord Pool area (see Hjalmarsson (2000) and Vassilopoulos (2003)) and almost none of them studies the effect of market expansion on the degree of market power. One exception, however, is Bask et al. (2008) who investigate how the degree of market power has evolved during the integration process at the Nordic power market using a conjectural variation method and they find that the degree of competition has increased when the common market has expanded. Unfortunately, we are not aware of any empirical study on the effects of market expansion on the degree of market power for some other power market than Nord Pool.

Then, what about the relationship between the degree of competition and the volatility of electricity prices at Nord Pool? Lundgren et al. (2008) take a close look at how the price dynamics have evolved during the integration process at the Nordic power market by estimating not only the price volatility, but also the intensity and size of the price jumps. To be able to accomplish their analysis, they divide their data set into three parts: (i) when only Norway and Sweden participate in Nord Pool; (ii) when also Finland has joined the common market; and (iii) when Denmark too participates in Nord Pool.

If we turn to their results, Lundgren et al. (2008) find that the volatility of electricity prices increased when Finland joined the Nordic power market, but that this increase mainly was driven by an increased size of the price jumps. However, the volatility of electricity prices decreased when Denmark joined the Nordic power market. In other words, Lundgren et al. (2008) do not find a clear-cut relationship between the degree of competition and the volatility of electricity prices. Anyhow, when Finland and Denmark joined the common market, the intensity of the price jumps decreased.

What we do in this paper (see Section 4 below) is that we fit a battery of volatility models to the time series in a data set that is similar to the one in Bask et al. (2008). This means that we are able to draw conclusions regarding the degree of competition at Nord Pool and how this degree is related to the volatility of electricity prices. What we find is that the volatility of electricity prices most often has decreased when the Nordic power market has expanded and the degree of competition has increased.

2.2. Stability and volatility of prices

The main contribution in this paper is that we not only distinguish between the stability and volatility of electricity prices, but that we also present a method that allows us to measure the stability of electricity prices. As will be clear below, more stable electricity prices is not synonymous for less volatile electricity prices. Instead, more stable electricity prices is a sloppy expression for a more stable stochastic dynamic system generating electricity prices.

In fact, what we argue in this paper is that one should contrast the stability of a stochastic dynamic system with the volatility of a variable generated by this system using what we call (λ,σ^2)-analysis. For example, think of macroeconomic models with the purpose of explaining aggregate features of an economy. At the heart of these models (that nowadays are very popular in the literature), there is an impulse-propagation mechanism in which impulses are shocks to the economy, while the propagation mechanism is the means by which these shocks lead to persistence over time. An economy that is less stable is, therefore, associated with a higher persistence of the shocks, meaning that even a small shock to the economy could have a large effect on it.

To further clarify the fundamental idea behind (λ,σ^2)-analysis, let σ^2 denote the conditional variance of a variable generated by a stochastic dynamic system and let λ denote the stability of this system. Then,

$$\sigma^2 = \sigma^2(\lambda, \varepsilon), \tag{1}$$

where ε is exogenous shocks to the dynamic system, meaning that the conditional variance (σ^2) is not only affected by the system's stability (λ), it is also affected by the shocks to the system (ε). Specifically, the conditional variance of a variable increases when the dynamic system decreases in stability, but also when the shocks' amplitude increases in size.

However, because of ε in Eq. (1), there is no one-to-one correspondence between σ^2 and λ, which also motivates (λ,σ^2)-analysis. To better see this claim, imagine a very simple model of how the electricity price, s, is determined at the power market:

$$s_t = \alpha s_{t-1} + \varepsilon_t, \tag{2}$$

where ε is independently and identically distributed shocks with zero mean and finite variance. That is, the model in Eq. (2) is a linear autoregression of order one. If we focus on the deterministic part of the model, it is explosive when $|\alpha|>1$, conservative when $|\alpha|=1$ and stable when $|\alpha|<1$. Further, if we assume that the model in Eq. (2) is stable, we can decompose the volatility of electricity prices as follows (see Bask and de Luna (2002)):

$$\sigma^2 \equiv \mathrm{var}(s_t) = \frac{\mathrm{var}(\varepsilon_t)}{1-\alpha^2} \equiv \frac{\mathrm{var}(\varepsilon_t)}{1-(\exp(\lambda))^2}. \tag{3}$$

Thus, electricity prices are more volatile (σ^2) when the shocks are more volatile (ε), but also when the model is less stable (λ). Be aware that for a stable model, $\lambda<0$ since $\lambda\equiv\log|\alpha|$, meaning that λ approaches zero from below when the model in Eq. (2) decreases in stability.

The stability concept outlined above can in a straightforward way be generalized to linear autoregressions of higher orders than one (see, among others, Bask and de Luna (2002) for a careful demonstration and discussion of this claim). If the model is a linear autoregression of order n, one can characterize the stability of the model by looking at the modulus of the n eigenvalues that solve the eigenvalue problem for the model and this is because the eigenvectors of the model are orthogonal by definition.

First, if the autoregression is stable, the contraction of it in n-dimensional space is dominated by the largest eigenvalue. This also means that the largest eigenvalue can be used when comparing the stability of two linear autoregressions of order n. This, however, is not the only way to compare the stability of two autoregressions. An alternative is to look at the product of the modulus of the n eigenvalues since it describes the rate of contraction of an n-dimensional volume in n-dimensional space. That is, the autoregression with the faster contraction is more stable.

But we do not want to restrict the stability analysis to linear systems such as linear autoregressions. Instead, we would like to have a tool that is able to determine the stability of non-linear dynamic systems. Unfortunately, this also means that we cannot use the eigenvalues in the stability analysis since they are defined over linear systems. Fortunately, Bask and de Luna (2002) argue that the Lyapunov exponents can be used in the stability analysis of non-linear dynamic systems and this is because the Lyapunov exponents for a non-linear system are the non-linear counterpart of the eigenvalues for a linear system.

We save the definition, motivation, estimation and inference of the Lyapunov exponents to Section 3, but a few paragraphs about the use of the Lyapunov exponents in the empirical literature should be spent already here. In the early 1980s, a stream of papers started to emerge on the search for chaotic dynamics in time series data. In the beginning, data were collected from different kinds of systems in the sciences, but later on, time series data in economics and finance were used too when searching for chaotic dynamics (see Urbach (1999) for an extensive although not complete list of papers within this literature).

Two reasons made this stream of papers possible. First, the dynamics that govern the evolution of a variable must be reconstructed since the dynamics are not known. In 1981, Takens (1981) proved that it is possible to reconstruct the unknown dynamics using only a scalar time series. Remarkably, the reconstructed dynamics and the unknown dynamics hidden in the "black box" are equivalent in the sense that the reconstruction preserves topological information about the dynamic system such as the Lyapunov exponents. (Unfortunately, even though the reconstruction theorem by Takens (1981) have made an impact on the sciences, it is still rather unknown in economics and finance.)

However, more was needed than the reconstruction theorem by Takens (1981). Specifically, a method to calculate the Lyapunov exponents from a scalar time series was necessary and the first such method was presented in 1985 by Wolf et al. (1985). Thereafter, several methods have been proposed in the literature. Some of the methods only calculate the largest Lyapunov exponent whereas other methods calculate the whole spectrum of Lyapunov exponents. We will use one of the latter methods in this paper.

To give a general picture of the findings in the search for chaotic dynamics in time series data, these findings have been mixed. To be more precise and if we restrict attention to the findings in economics and finance, most if not all of the early studies demonstrated that several time series could be characterized by chaotic dynamics and that this meant that the predictive ability of these systems were strongly limited. It could be mentioned in this context that Bask et al. (2007) test whether electricity prices from Nord Pool has been characterized by chaotic dynamics, which also is detected in one of the time series in the data set (which is the same data set as in this paper).

However, various limitations in these studies were later on revealed (that, in fact, did not apply in Bask et al. (2007)) and one such limitation was the lack of statistical inference. In other words, that a distributional theory for the Lyapunov exponents was lacking. Further on, it turned out that some of the methods to calculate the Lyapunov exponents suffered from upward bias. Consequently, estimates of the largest Lyapunov exponent that had been reported to be positive in the literature, which is the operational definition of chaotic dynamics, could in fact be negative. Both limitations, especially the lack of a distributional theory for the Lyapunov exponents, had the consequence that the number of new studies within this field diminished over time.

Fortunately, Shintani and Linton (2004) provide a distributional theory for the Lyapunov exponents. Their framework together with the algorithms in Gencay and Dechert (1992) and Kuan and Liu (1995) to calculate the Lyapunov exponents mean that we have an asymptotically normal estimator of the Lyapunov exponents. This estimator is also used in Bask et al. (2007) as well as in this paper (see Section 4 below). However, we do not search for chaotic dynamics in electricity prices as in Bask et al. (2007). Instead, we investigate whether they have changed in stability during the integration process at the Nordic power market.

As we already have pointed out, Bask and de Luna (2002) argue that the Lyapunov exponents can be used in a stability analysis of a non-linear dynamic system. To be more precise, in the same way as the product of the modulus of the n eigenvalues for an n-dimensional linear system describes the rate of contraction of an n-dimensional volume, the average of the n Lyapunov exponents for an n-dimensional non-linear system describes the rate of contraction of an n-dimensional volume. The reason for this is that the Lyapunov exponents for a linear system are the logarithms of this system's eigenvalues.

What we find in this paper (see Section 4 below) is that the stability of electricity prices most often has increased when the Nordic power market has expanded and the degree of competition has increased. Thus, having the Nord Pool experience in focus, increased competition at the power market has been associated with an increasingly stable dynamic system generating decreasingly volatile electricity prices but without having a one-to-one correspondence.

3. Method: (λ,σ^2)-analysis

(λ,σ^2)-analysis is outlined in this section. Specifically, in the first four subsections, we carefully explain how our stability measure (λ) is defined, how it can be estimated and tested from data, but we also motivate why this measure is useful in a stability analysis. The final subsection is about the volatility measure (σ^2).

3.1. Definition of λ

As we have pointed out several times, Bask and de Luna (2002) argue that the (spectrum of smooth) Lyapunov exponents can be used in the determination of the stability of a stochastic dynamic system. Specifically, assume that the dynamic system, $f:\mathbb{R}^n\rightarrow\mathbb{R}^n$, generates

$$S_{t+1}=f(S_t)+\varepsilon^s_{t+1},\tag{4}$$

where S_t and ε^s_t are the state of the system and a shock to the system, respectively. For an n-dimensional system as in Eq. (4), there are n Lyapunov exponents that are ranked from the largest to the smallest exponent:

$$\lambda_1\geq\lambda_2\geq\ldots\geq\lambda_n,\tag{5}$$

and it is these quantities that provide information on the stability properties of the dynamic system f.

Assume temporarily that there are no shocks and consider how the dynamic system f amplifies a small difference between the initial states S_0 and S_0':

$$S_j-S_j'=f^j(S_0)-f^j(S_0')\simeq Df^j(S_0)(S_0-S_0'),\tag{6}$$

where $f^j(S_0)=f(\cdots f(f(S_0))\cdots)$ denotes j successive iterations of the system starting at state S_0 and Df is the Jacobian of the system:

$$Df^j(S_0)=Df(S_{j-1})Df(S_{j-2})\cdots Df(S_0).\tag{7}$$

Then, associated with each Lyapunov exponent, λ_i, i [1,2,…, n], there are nested subspaces $U^i\subset\mathbb{R}^n$ of dimension $n+1-i$ with the property that

$$\lambda_i\equiv\lim_{j\to\infty}\frac{\log_e\|Df^j(S_0)\|}{j}=\lim_{j\to\infty}\frac{1}{j}\sum_{k=0}^{j-1}\log_e\|Df(S_k)\|,\tag{8}$$

for all $S_0\in U^i-U^{i+1}$. Due to Oseledec's multiplicative ergodic theorem, the limits in (8) exist and are independent of S_0 almost surely with respect to the measure induced by the process $\{S_t\}_{t=1}^{\infty}$ (see Guckenheimer and Holmes (1983) for a careful definition of the Lyapunov exponents). Then, allow for shocks to the system, meaning that the aforementioned measure is induced by a stochastic process. The Lyapunov exponents have in this case been renamed to smooth Lyapunov exponents in the literature.

3.2. Motivation of λ

The reason why the spectrum of smooth Lyapunov exponents provides information on the stability properties of a stochastic dynamic system may be seen by considering two starting values of a system, where the only difference is an exogenous shock at time t=0 and that the shocks are identical at times t>0 (see Bask and de Luna (2002) for the origin of this discussion).

The largest smooth Lyapunov exponent, λ_1, measures the slowest exponential rate of convergence of two trajectories of the dynamic system starting at the two starting values at time t=0. In fact, λ_1 measures the convergence of a shock in the direction defined by the eigenvector corresponding to this exponent. If the difference between the two starting values lies in another direction of $\mathbb{R}^n$, then the convergence is faster. Thus, λ_1 measures a "worst case scenario." (When $\lambda_1>0$, the trajectories diverge from each other and for a bounded stochastic dynamic system, this is an operational definition of chaotic dynamics.)

The average of the smooth Lyapunov exponents,

$$\lambda \equiv \frac{1}{n}\sum_{i=1}^{n} \lambda_i, \tag{9}$$

measures the exponential rate of convergence in a geometrical average direction. That is, the convergence of two trajectories of the dynamic system in the geometrical average of the directions defined by the eigenvectors corresponding to the different exponents. Thus, λ measures an "average scenario." We can, therefore, compare the stability of two stochastic dynamic systems via the smooth Lyapunov exponents since a shock has a smaller effect on the dynamic system with a smaller λ than for the system with a larger λ. Since we are dealing with dissipative systems, meaning that $\lambda<0$ by definition, a dynamic system is more stable than another system if λ is more negative.

Potter (2000) too claims that λ_1 can be used not only to categorize a time series as stable or unstable (in the sense it is chaotic), but also that it provides a measure of the convergence speed to (some sort of) equilibrium (see Shintani (2006) who use λ_1 when looking at convergence speeds of exchange rates toward purchasing power parity).

3.3. Estimation of λ

Since the actual form of the stochastic dynamic system f is not known, it may seem like an impossible task to determine the stability of the system. Fortunately, it is possible to reconstruct the dynamics using only a scalar time series and, thereafter, measure the stability of the reconstructed system. Therefore, associate the dynamic system f with an observer function, $g:\mathbb{R}^n\rightarrow\mathbb{R}$, that generates the following scalar time series:

$$s_t = g(S_t) + \varepsilon_t^m, \tag{10}$$

where $s_t \in S_t$ and ε_t^m are an observation in the time series and a measurement error, respectively. That is, the time series $\{s_t\}_{t=1}^N$ is observed, where N is the number of observations.

Specifically, the observations in a scalar time series contain information regarding unobserved state variables that can be used to define a state in present time. Therefore, let

$$T = (T_1, T_2, \ldots, T_M)' \tag{11}$$

be the reconstructed trajectory, where T_t is the reconstructed state and M is the number of states on the trajectory. Each T_t is given by

$$T_t = \{s_t, s_{t+1}, \ldots, s_{t+m-1}\}, \tag{12}$$

where m is the embedding dimension. Thus, T is an $M\times m$ matrix and the constants M, m and N are related as $M=N-m+1$.

Takens (1981) proved that the map

$$\Phi(S_t) = \{g(f^0(S_t)), g(f^1(S_t)), \ldots, g(f^{m-1}(S_t))\}, \tag{13}$$

which maps the n-dimensional state S_t onto the m-dimensional state T_t, is an embedding if $m>2n$ (see below for the intuition behind this condition). This means that the map is a smooth map that performs a one-to-one coordinate transformation and has a smooth inverse. Moreover, a map that is an embedding preserves topological information about the unknown dynamic system such as the smooth Lyapunov exponents and, in particular, the map induces a function, h: $\mathbb{R}^m\rightarrow\mathbb{R}^m$, on the reconstructed trajectory,

$$T_{t+1} = h(T_t), \tag{14}$$

which is topologically conjugate to the unknown dynamic system f. That is,

$$h^j(T_t) = \Phi \circ f^j \circ \Phi^{-1}(T_t). \tag{15}$$

Thus, h is a reconstructed dynamic system that has the same smooth Lyapunov exponents as the unknown dynamic system f. (However, since the m-dimensional system h has a larger dimension than the n-dimensional system f, the number of smooth Lyapunov exponents that are spurious is $m-n$. This issue is discussed in detail in Dechert and Gencay (1996, 2000) and Gencay and Dechert (1996).)

Then, to be able to estimate the smooth Lyapunov exponents, one has to estimate h. However, since

$$h: \begin{pmatrix} s_t \\ s_{t+1} \\ \vdots \\ s_{t+m-1} \end{pmatrix} \rightarrow \begin{pmatrix} s_{t+1} \\ s_{t+2} \\ \vdots \\ v(s_t, s_{t+1}, \ldots, s_{t+m-1}) \end{pmatrix}, \tag{16}$$

the estimation of h reduces to the estimation of v:

$$s_{t+m} = v(s_t, s_{t+1}, \ldots, s_{t+m-1}). \tag{17}$$

Moreover, since the Jacobian of h at the reconstructed state T_t is

$$Dh(T_t) = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ \frac{\partial v}{\partial s_t} & \frac{\partial v}{\partial s_{t+1}} & \frac{\partial v}{\partial s_{t+2}} & \cdots & \frac{\partial v}{\partial s_{t+m-1}} \end{pmatrix}, \tag{18}$$

a feedforward neural network is recommended to estimate the above derivatives to derive the smooth Lyapunov exponents and this is because Hornik et al. (1990) have shown that a map and its derivatives of any unknown functional form can be approximated arbitrarily accurately by such a network.

Having shown how to estimate λ, an intuitive explanation of Takens' (1981) embedding theorem (or reconstruction theorem as we called it in Section 2) is in place. For the sake of the argument, assume that $\mathbf{M}_1 \subset \mathbf{M}$ and $\mathbf{M}_2 \subset \mathbf{M}$ are two subspaces of dimension n_1 and n_2, respectively, where $\mathbf{M} \in \mathbb{R}^m$ is an m-dimensional manifold representing phase space for the reconstructed dynamic system. In general, two subspaces intersect in a subspace of dimension n_1+n_2-m, meaning that when this expression is negative, there is no intersection of the two subspaces. Therefore, and of greater interest, the self-intersection of an n-dimensional manifold with itself fails to occur when $m>2n$ (see Sauer et al. (1991) for generalizations of Takens' (1981) embedding theorem).

A problem in this context is that the dimension of the "true" dynamic system is not known, meaning that the required embedding dimension according to Takens' (1981) embedding theorem is not either known. However, this problem can be solved indirectly by making use of a generic property of a proper reconstruction, namely, that the dynamics in original phase space must be completely unfolded in reconstructed phase space. In other words, if the embedding dimension is too low, the dynamics are not

Table 1
Dates in the integration process at the Nordic power market

Region	Date of entry
Norway	January 1, 1993
Sweden	January 1, 1996
Finland	December 29, 1997
Western Denmark	July 1, 1999
Eastern Denmark	October 1, 2000

completely unfolded, meaning that distant states in original phase space are close states in reconstructed phase space and are, therefore, false neighbors in phase space.

There are at least two methods to calculate the required embedding dimension from a scalar time series: (i) false nearest neighbors; and (ii) the saturation of invariants on the reconstructed dynamics such as the saturation of the Lyapunov exponents. The first method is based on the aforementioned property of a proper reconstruction, meaning that by increasing the embedding dimension enough, the dynamics are completely unfolded when there are no false neighbors in reconstructed phase space (see Kennel et al. (1992)).

The second method, the saturation of invariants on the reconstructed dynamics, is based on the fact that when the dynamics are completely unfolded, the Lyapunov exponents and other invariants (such as entropy and fractal dimension) are independent of the embedding dimension. If,

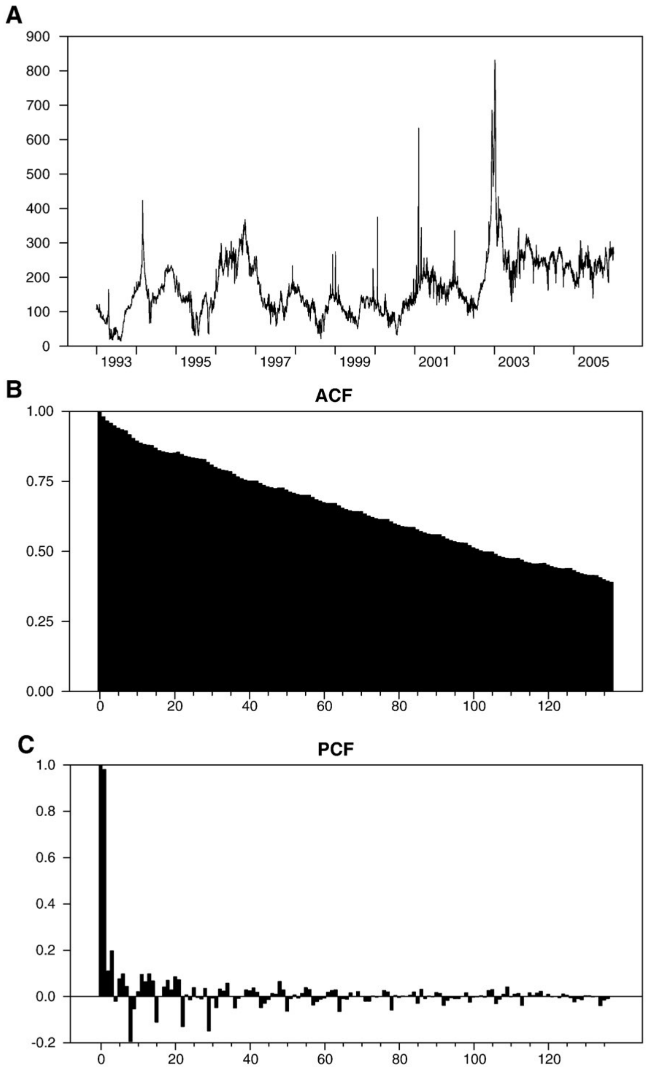

Fig. 1. A) Daily average of the hourly system price during the period January 1, 1993, to December 31, 2005. B) ACF for the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005. C) PCF for the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005.

however, the dynamics are not completely unfolded in reconstructed phase space, these invariants depend on the embedding dimension. Therefore, by increasing the embedding dimension enough, the dynamics are completely unfolded when an invariant stops changing (see Fernández-Rodríguez et al. (2005)) for an example regarding the largest Lyapunov exponent and a statistical test for chaotic dynamics).

3.4. Inference of λ

First of all, we are not aware of any distributional theory for λ. However, Shintani and Linton (2004) show that a neural network estimator of the smooth Lyapunov exponents like the one above is asymptotically normal. Our conjecture is, therefore, that asymptotic normality also holds for a neural network estimator of λ since the eigenvectors corresponding to the smooth Lyapunov exponents are pairwise orthogonal.

An alternative to Shintani and Linton (2004) is to derive an empirical distribution for λ via bootstrapping (see Bask and Gencay (1998) and Gencay (1996) for the case of λ_1). However, as is demonstrated in Ziehmann et al. (1999), this approach is not straightforward for multiplicative ergodic statistics since the limits in (8) may not exist under bootstrapping.

3.5. Measuring σ^2

We will not spend time here on how to measure the volatility of a variable generated by a stochastic dynamic system. The reason is that an extensive literature already exists on this topic. Instead, we will return to this issue when measuring the volatility of electricity prices (see Section 4 below).

4. Nord Pool experience

The Nord Pool experience is in focus in this section. In the first two subsections, we give a short review of the integration process at the Nordic power market as well as provide some descriptive statistics of our data set. In the two final subsections, we use (λ,σ^2)-analysis when examining how the step-wise integration of the Nordic power market has affected the stability and volatility of electricity prices.

4.1. Integration process

Nord Pool is a multi-national power exchange, joining the Nordic countries. Norway was the first of the Nordic countries to deregulate their power market and Nord Pool was established in 1993, but then under the name Statnett Marked AS. Sweden started their deregulation process too in the first half of the 1990s and went step-wise to a deregulated power market. At the turn of 1996, the joint Norwegian–Swedish power exchange market, Nord Pool ASA, was launched.

Finland started a power exchange of its own, EL–EX, in 1996, but joined Nord Pool in 1997. Denmark Nord Pool Consulting was established in 1998 and western Denmark joined the common market in 1999. When eastern Denmark joined in 2000, the Nordic power market became fully integrated. For specific dates in the integration process, see Table 1.

4.2. Data set used and descriptive statistics

The data set used is spot electricity prices from Nord Pool. Specifically, it is the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005. (The price is calculated from a bidding process before any bottlenecks are discovered. Around half of the time, the bidding process price is the price used in the entire region.) The data set is analyzed both as one time series but also split in parts with the natural breakpoints when a new region is joining the common market.

The daily average of the hourly system price is presented in Fig. 1A and basic descriptive statistics of this time series are presented in Table 2.

As is typical with financial time series data, the time series in Fig. 1A does not look stationary and the autocorrelation function (ACF) in Fig. 1B also indicates non-stationary, while the partial autocorrelation function (PCF) in Fig. 1C is harder to analyze. The Dickey–Fuller unit root test in Table 2 shows, however, that the time series qualifies as a stationary time series, but the test statistic is close to the critical value. A positive skewness indicates that the distribution of prices has an asymmetric distribution with a longer tail on the right side and a positive kurtosis indicates a distribution with fat tails.

Instead of using the daily average of the hourly system price in the analysis, we use the logarithmic return of this price. The new time series is presented in Fig. 2A and basic descriptive statistics of it are presented in Table 3. The shape of the time series together with the Dickey–Fuller unit root test in Table 3 and the ACF in Fig. 2B indicate that the time series is stationary (see also the PCF in Fig. 2C). Moreover, a positive skewness and a positive kurtosis indicate that the distribution of logarithmic returns of prices has an asymmetric distribution with a longer tail on the right side as well as fat tails.

We proceed the analysis by dividing the time series into five parts with the natural breakpoints when a new region is joining the common market. See Appendix A for descriptive statistics of each of the five time series.

4.3. Stability of electricity prices

We estimate the smooth Lyapunov exponents for each time series using the algorithm proposed in Gencay and Dechert (1992) and Kuan and Liu (1995) using 4, 8, 12, 16 and 20 inputs to the neural network, respectively, where the number of hidden units runs from 1 unit to 20 units and, thereafter, we calculate our stability measure, λ. It is the λ that minimizes the Schwarz Information Criterion for each time series that we report in Table 4. (We have used NETLE, a program developed by R. Gencay, C.-M. Kuan and T. Liu, when estimating the smooth Lyapunov exponents.) The general picture is that the integration process at the Nordic power market most of the time has been associated with more stable electricity prices. However, we do not test for a change in stability since a distributional theory for λ is lacking.

4.4. Volatility of electricity prices

Since there is no obvious choice of model to fit to our data set to be able to determine whether electricity prices have become more or less volatile during the integration process at the Nordic power market, we fit four time series models to the data set, where all of them belong to the generalized autoregressive conditional heteroskedastic (GARCH) model family (see Bollerslev (1986) and Engle (1982) for the seminal contributions in this area).

The first model that we fit to our data set is the GARCH (1,1) specification (see Enders (2003) and Hamilton (1994) for details on

Table 2
Descriptive statistics of the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005

Statistic	Quantity
Number of observations	4745
Minimum	14.8
Maximum	831
Mean	174
Median	158
Variance	7310
Skewness	1.62
Kurtosis	7.53
Dickey–Fuller unit root test	−4.55***

*** Significant at the 1% level (critical value: −3.44).

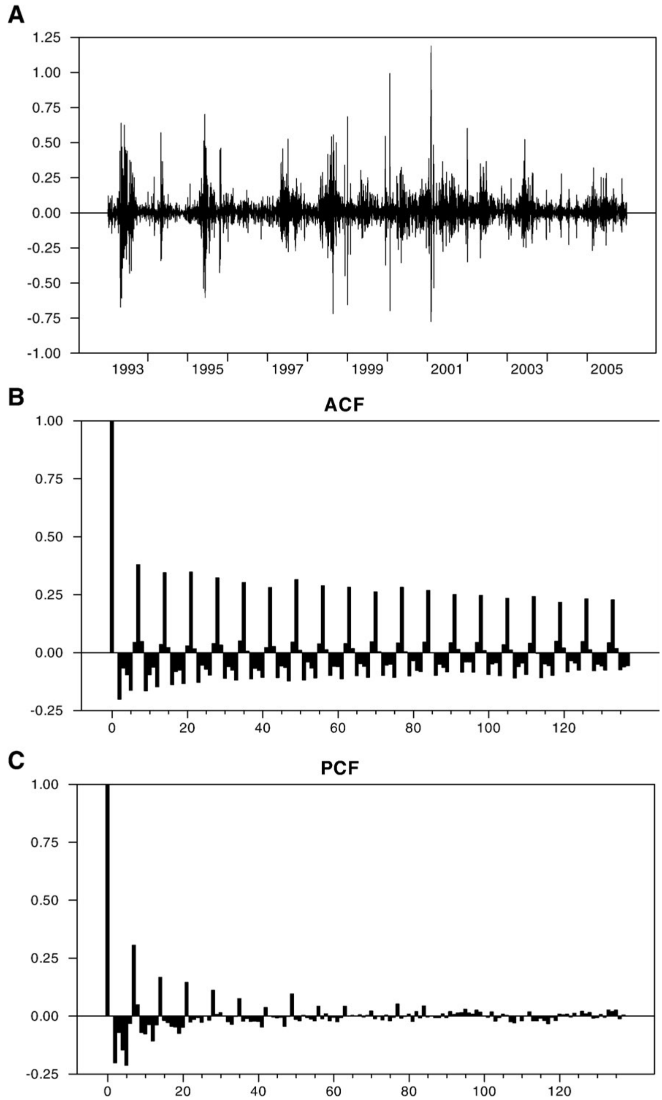

Fig. 2. A) Logarithmic returns of the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005. B) ACF for the logarithmic returns of the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005. C) PCF for the logarithmic returns of the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005.

this and the other three specifications we use when measuring the volatility of a time series):

$$\sigma_t^2 = \beta_0 + \beta_1 \varepsilon_{t-1}^2 + \beta_2 \sigma_{t-1}^2, \tag{19}$$

where σ_t^2 is the conditional and time-varying variance, and ε_t^2 is the squared innovation with $\varepsilon_t = z_t \sigma_t$ and $z_t \sim IID(0,1)$. Our volatility measure is β_2.

However, we are not primarily interested in the volatility level, but, instead, to test whether there has been a change in volatility of electricity prices when the Nord Pool area has expanded in size with a new region. A straightforward way to perform such a test is to fit the following model to two adjacent time series:

$$\sigma_t^2 = \beta_0 + \beta_1 \varepsilon_{t-1}^2 + \beta_2 \sigma_{t-1}^2 + \beta_3 \sigma_{t-1}^2 I_{t \geq t_0}, \tag{20}$$

where $I_{t \geq t_0} = 1$ when $t \geq t_0$ and zero elsewhere, and t_0 is the time point when a new region is joining the common market.

To be more concrete by giving an example, what we do is to fit the specification in Eq. (19) to the time series when only Norway

Table 3
Descriptive statistics of the logarithmic returns of the daily average of the hourly system price during the period January 1, 1993, to December 31, 2005

Statistic	Quantity
Number of observations	4744
Minimum	−0.774
Maximum	1.19
Mean	0.000189
Median	−0.00450
Variance	0.00936
Skewness	0.895
Kurtosis	19.0
Dickey–Fuller unit root test	−23.4***

*** Significant at the 1% level (critical value: -3.44).

participates in what would become Nord Pool and find that $\beta_2=0.258$, which is the volatility of electricity prices during this period. Thereafter, we fit the specification in Eq. (19) to the time series when both Norway and Sweden participate in Nord Pool and find that $\beta_2=0.217$. Finally, to test if there has been a change in volatility of electricity prices when Sweden joined the common market, we fit the specification in Eq. (20) to the joint time series and find that the decrease in volatility is not significant at any conventional significance level. Our findings are reported in Table 5 (that also includes the findings for the other three GARCH specifications). According to the table, there has not been any significant change in volatility of electricity prices during the integration process at the Nordic power market.

The second model that we fit to our data set is the E-GARCH (1,1) specification and the reason is that this model allows positive and negative shocks to have different impact on the conditional volatility (see (Nelson, 1991)):

$$\log\sigma_t^2=\beta_0+\beta_1\cdot\frac{\varepsilon_{t-1}}{\sigma_{t-1}}+\beta_2\cdot\left|\frac{\varepsilon_{t-1}}{\sigma_{t-1}}\right|+\beta_3\log\sigma_{t-1}^2, \tag{21}$$

where β_3 is our volatility measure. Then, if we adopt the same idea as above to test whether there has been a change in volatility of electricity prices when the Nord Pool area has expanded in size with a new region, we fit the following model to two adjacent time series:

$$\log\sigma_t^2=\beta_0+\beta_1\cdot\frac{\varepsilon_{t-1}}{\sigma_{t-1}}+\beta_2\cdot\left|\frac{\varepsilon_{t-1}}{\sigma_{t-1}}\right|+\beta_3\log\sigma_{t-1}^2+\beta_4\log\sigma_{t-1}^2 I_{t\geq t_0}. \tag{22}$$

According to Table 5, the step-wise integration of the Nordic power market is most of the time associated with less volatile electricity prices. However, only one of the changes in volatility is significant (at the 5% level).

However, as discussed, among others, in Dacorogna et al. (2001), there is often a long memory in the volatility of financial time series and since we have no reason to exclude this possibility for electricity prices, the third model that we fit to our data set is the I-GARCH (1,1) specification (see Engle and Bollerslev (1986)):

$$\sigma_t^2=\beta_0+(1-\beta_1)\varepsilon_{t-1}^2+\beta_1\sigma_{t-1}^2, \tag{23}$$

where β_1 is our volatility measure. Then, again, to test whether there has been a change in volatility of electricity prices during the step-wise integration of the Nordic power market, we fit the following model to two adjacent time series:

$$\sigma_t^2=\beta_0+(1-\beta_1)\varepsilon_{t-1}^2+\beta_1\sigma_{t-1}^2+\beta_2\sigma_{t-1}^2 I_{t\geq t_0}. \tag{24}$$

According to Table 5, only one of the changes in volatility of electricity prices is significant (at the 10% level).

The fourth model that we fit to our data set is the Glosten–Jagannathan–Runkle GARCH (1,1) specification (see Glosten et al. (1993)):

$$\sigma_t^2=\beta_0+\beta_1\varepsilon_{t-1}^2+\beta_2\sigma_{t-1}^2+\beta_3\varepsilon_{t-1}^2 I_{\varepsilon_{t-1}<0}, \tag{25}$$

where $I_{\varepsilon_{t-1}<0}=1$ when $\varepsilon_{t-1}<0$ and zero elsewhere, and our volatility measure is β_2. The advantage of the GJR-GARCH (1,1) specification is that it provides a simple way to allow for asymmetries in the

Table 4
Stability and change in stability of the logarithmic returns of the daily average of the hourly system price during the integration process at the Nordic power market

Region	Stability
Norway (1/1/1993–12/31/1995)	−0.268 12 inputs 5 hidden units
	Increase
Norway and Sweden (1/1/1996–12/28/1997)	−0.359 8 inputs 2 hidden units
	Decrease
Norway, Sweden and Finland (12/29/1997–6/30/1999)	−0.168 12 inputs 3 hidden units
	Increase
Norway, Sweden, Finland and western Denmark (7/1/1999–9/30/2000)	−0.273 8 inputs 1 hidden unit
	Increase
Norway, Sweden, Finland and Denmark (10/1/2000–12/31/2005)	−0.275 8 inputs 5 hidden units

Table 5
Volatility and change in volatility of the logarithmic returns of the daily average of the hourly system price during the integration process at the Nordic power market

Region	Volatility GARCH	Volatility E-GARCH	Volatility I-GARCH	Volatility GJR-GARCH
Norway (1/1/1993–12/31/1995)	0.258	0.974	0.230	0.668
	Decrease	**Decrease**	**Decrease**	**Decrease**
Norway and Sweden (1/1/1996–12/28/1997)	0.217	0.935	0.220	0.146
	Increase	**Decrease**	**Increase**	**Increase**
Norway, Sweden and Finland (12/29/1997–6/30/1999)	0.410	0.686	0.612	0.160
	Increase	**Decrease**	**Increase**	**Increase***
Norway, Sweden, Finland and western Denmark (7/1/1999–9/30/2000)	0.765	0.148	0.905	1.02
	Decrease	**Increase****	**Decrease***	**Decrease**
Norway, Sweden, Finland and Denmark (10/1/2000–12/31/2005)	0.198	0.943	0.174	0.0716

** and * Significant change at the 5% and 10% level, respectively.

conditional volatility. Then, to test whether there has been a change in volatility of electricity prices when the Nord Pool area has expanded in size with a new region, we fit the following model to two adjacent time series:

$$\sigma_t^2 = \beta_0 + \beta_1 \varepsilon_{t-1}^2 + \beta_2 \sigma_{t-1}^2 + \beta_3 \varepsilon_{t-1}^2 I_{\varepsilon_{t-1}<0} + \beta_4 \sigma_{t-1}^2 I_{t \geq t_0}. \quad (26)$$

According to Table 5, only one of the changes in volatility of electricity prices is significant (at the 10% level).

Then, which model is the best model? According to the information criteria that are proposed in Brooks and Burke (2003), which are modified versions of the Akaike and Schwarz Information Criteria designed for GARCH models, the best model is the E-GARCH (1,1) specification in (21). (To come to this conclusion, we have fitted all models to the whole and unbroken time series with electricity prices.) Thus, the general picture is that the integration process at the Nordic power market most often has been associated with more stable and less volatile electricity prices, even though a one-to-one correspondence between the stability and volatility measures is lacking. Be aware that the lack of a one-to-one correspondence between these measures motivates (λ,σ^2)-analysis.

5. Discussion

Denmark, Finland, Norway and Sweden have gone through an extensive deregulation of their electricity sectors during the 1990s and, at the same time, there has been an evolution from national markets to a multi-national electricity market. Since the aim of the deregulation and integration of the electricity sectors in these countries was to develop a competitive power market, Bask et al. (2008) examine whether the degree of competition has increased over time during this process and they also find that this, in fact, is the case.

What we have found in this paper is that the step-wise integration of the Nordic power market most of the time also has been associated with less volatile electricity prices. The natural question to pose and answer is, therefore, why these prices have decreased in volatility over time? Of course, the natural candidate is that the dynamics that govern the evolution of electricity prices have changed, but it could also be the case that the nature of the shocks hitting the Nordic power market has changed.

By using a novel approach in this paper, we have found that the increased competition at the Nordic power market most of the time also has been associated with more stable electricity prices. That electricity prices at Nord Pool have increased in stability means that the dynamic system generating these prices has increased in stability during the step-wise integration of the Nordic power market. This, in turn, means that this market is less sensitive to shocks after the integration process than it was before this process. This is good news.

To summarize, what we have learned about Nord Pool regarding the relationship between market structure and the behavior of electricity prices are the following: (i) the degree of competition has increased over time during the integration process; (ii) the volatility of electricity prices has most often decreased over time; and (iii) the stability of the dynamic system generating electricity prices has most often increased over time. For this reason, one might ask: are there any theoretical justifications for these findings?

First of all, there is a small theoretical literature on the relationship between market structure and the price volatility for a storable commodity such as water, which to a large extent is used in electricity generation in the Nord Pool area. One study that our findings are consistent with is by McLaren (1999) who develops an oligopoly model in which the price of the storable commodity decreases in volatility when the degree of competition increases. When it comes to the stability of the dynamics that govern the evolution of commodity prices, the literature is silent on its relationship with market structure and the price volatility.

Anyhow, we argue that when approximating models of the energy sector are developed in an attempt to understand the behavior of energy prices and how they depend on the market structure, the stability of the dynamics that govern the evolution of energy prices should be added as an important dimension in which model and data should be matched. That is, our finding that electricity prices most of the time have increased in stability and decreased in volatility when the Nordic power market has expanded and the degree of competition has increased should be properties of a well-formulated model of the Nordic power market.

To conclude, we believe that the empirical work in this paper has demonstrated that (λ,σ^2)-analysis can be a useful tool in empirical research. It is, therefore, our hope that future research will provide us with more applications of this tool than the Nord Pool experience.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.eneco.2008.11.006.

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