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Abstract

The European Union's Emissions Trading System (EU ETS) and the Swedish-Norwegian Tradable Green Certificate System (Swedish-Norwegian TGC system) are two market-based instruments that have the overlapping goal to mitigate greenhouse gas (GHG) emissions by shifting economies to cleaner energy sources. Understanding the price signals and interactions of these two newly created markets is essential for all decisions makers – regulators and direct market participants – who aim to reach the predefined environmental policy goals in the most efficient manner. The interaction between these policy instruments has been widely examined from the theoretical perspective. This research contributes to the literature by empirically examining the interplay between the prices of three markets: (1) the price of tradable green certificates in the Swedish-Norwegian TGC system, (2) the price of carbon in the EU ETS and (3) the price of electricity in Nord Pool. We use a multivariate vector-autoregression (VAR) approach to take into account the endogenous relationships between these prices. To date, our empirical results do not support the theoretical considerations that the impacts of carbon price on green certificate prices and on renewable electricity production are negative. Contrary, we find that, to date, increases in carbon prices positively affect green certificate prices at least in the short-run.

1 Introduction and Policy Background

In the European Union (EU), the development of policies promoting energy from renewable sources (RES) was kicked off by the European Directive 2001/77/EC (European Parliament and Council, 2001) and kept going with the "20/20/20" climate change and energy sustainability goals in the Europe 2020 strategy (European Commission, 2010). Each EU member state has responded to this by proposing different political devices to contribute its share in reaching a

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reduction of greenhouse gas emissions of 20% compared to 1990, a share of 20% of energy from renewable sources and an increase in energy efficiency of 20%.

On the European level, in 2005, the EU introduced the Emissions Trading System with the goal of reducing GHG emissions by means of a cap-and-trade programme. A "cap" is set on the total amount of certain GHG that can be emitted by the largest GHG emitters in the system. The cap is reduced over time so that total GHG emissions fall. Within the cap, firms receive or buy emission allowances (EUA) which they can trade with one another as needed. The limit on the total number of allowances available in the market ensures that they have a value.

Other national-level policies target the improvement of energy efficiency to lower energy demand or directly aim to increase the share of energy from RES. The implied goal of all these policies is the same as that of the EU ETS's – the reduction of greenhouse gas emissions. Such policies, among many others, include feed-in tariffs and tradable green certificates.[1] However, to date, only few tradable green certificate systems remain in place.

Belgium has a green certificate system that takes slightly different forms in every region of the country (Najdawi and Wevers, 2014). The Netherlands – an early adopter – terminated their green quota system in 2000 and opted for a feed-in tariff in 2003. The UK has had a renewable obligation scheme in operation since 2002, but a proposal is to replace this scheme by a feed-in tariff by 2017 (Department of Energy and Climate Change, 2012). Italy's green certificate system finished phasing over to a feed-in tariff system in 2015 (Gipe, 2012a). Poland moves away from its controversial green certificate scheme and has been trying to put in place a feed-in tariff scheme for the last three years (Gipe, 2012b). This makes the Swedish-Norwegian tradable green certificate system, introduced in 2003, the largest and most comprehensive green quota system in Europe and the only system that has been expanding from a national (Sweden only) to an international system (including its neighbouring country Norway). Since the Nordic countries' electricity market is already an integrated single market, there has been a discussion to expand the Swedish-Norwegian TGC system by integrating Denmark and Finland into it (Unger, 2015). Exploring the functioning of the only TGC system currently in action is relevant in the context of less successful experiences with similar policies in the other EU countries.

Swedish and Norwegian firms have to comply both with the Swedish-Norwegian TGC system as well as with the EU ETS.[2] The TGC system was initiated in Sweden in May 2003. It was joined by Norway in 2012 and it is planned to last until 2035 at the latest. The joint goal of this policy is to increase the electricity production from renewable energy sources by 26.4 TWh between 2012 and 2020. Producers of renewable energy receive one TGC for each MWh produced for a duration of a maximum of 15 years. Electricity retailers and energy intensive industries are obliged to buy a certain share of TGC in relation to their total electricity sales or consumption, respectively. The percentage requirement is given by law for every year until the system ceases (Sveriges Riksdag, 2003). Certificates are traded on an online platform and are surrendered to the regulator on March 31 of each trading year. Each issued green

[1] Some literature also talks about "green quotas", "green certificates" or "electricity certificates." In this study, these terms will be used synonymously with "tradable green certificates."

[2] Norway joined the EU ETS on voluntary grounds in 2008.

certificate is valid until 2036, meaning that both green electricity producers and firms, which should meet their individual certificate quotas, are able to store, trade and surrender certificates at a later point in time.

As both systems – the EU ETS and Swedish-Norwegian TGC – can to a certain degree be regarded as substitutes for each other (Jensen and Skytte, 2003), it is therefore conceivable that the two systems influence each other. Intuition suggests that the carbon price will have a negative effect on fossil-fuel-based energy generation. This will favour the production of energy from RES. However, several theoretical papers suggest that the interaction of these two policy systems might give rather unexpected results: an increase in carbon price might lead to a decrease in renewable electricity generation (see, e.g., Amundsen and Mortensen (2001); Widerberg (2011)).

For the policy goals to be reached the newly created markets have to give the right price signals to investors of RES-based electricity generation. Therefore this work will focus on the prices of the EU ETS, Swedish-Norwegian TGC system and Nord Pool market as the best indicators that incorporate both demand and supply side factors of the affected markets. A better understanding of these prices and their interactions will, on one hand, assist providers of renewable energy capacities in their decision process for building new capacities. On the other hand, it will indicate possibilities for improvements in the legislative framework to adapt to the economic realities of the TGC market.

In contrast to the few existing empirical analyses that examine short- and long-run dynamics between certificates prices and several macroeconomic variables (Fagiani, 2014, chap. 7) or TGC price volatility (Fagiani and Hakvoort, 2014), our study contributes to the empirical literature by applying a vector-autoregressive model that acknowledges the interactive nature between the variables of interest. In particular, the paper's objective is to investigate the interplay between the prices of three markets – the price of tradable green certificates in the Swedish-Norwegian TGC system, the price of carbon in the EU ETS and the price of electricity in Nord Pool – with a particular attention towards the postulated interaction of green certificate and carbon markets. While each policy was introduced with its own goal in mind, each policy's performance should depend on the other one. If the markets are related, we hypothesise that the EU ETS counteracts the goals of the Swedish-Norwegian TGC system by leading to lower TGC prices and consequently to lower supply of renewable electricity. If the EU ETS is exogenous to the Swedish-Norwegian TGC system we do not expect to find such an interaction. To date, we find no indication that the impacts of carbon price on green certificate prices and on renewable electricity production are negative. Contrary, we find that increases in carbon prices positively affect green certificate prices at least in the short-run. This result implies that the goals of the EU ETS do not undermine the goals of the Swedish-Norwegian TGC system.

The remainder of the paper is organised as follows. Section 2 reviews the theoretical and empirical literature on the interaction of tradable green certificates and carbon markets. In Section 3, we first introduce our empirical model and briefly discuss the econometric strategy, then, we present the data and its sources. Section 4 summarises and discusses the main results.

Finally, in Section 5, we conclude the paper and provide several policy implications.

2 Literature Review

2.1 Theoretical studies

The theoretical scope of whether and how the the price of carbon affects renewable electricity provision and green certificate prices have been researched amply. A theoretical base model for an electricity market that includes both a green certificate market and a carbon market has been developed by Amundsen and Mortensen (2001). Their model shows that, under the assumption of electricity independence from other countries, increases in carbon prices do not have a positive impact on RES-based power production in the long-run. If carbon prices increase, generation costs of electricity from non-renewable sources become more expensive relative to electricity based on RES. Therefore non-renewable electricity generation will be substituted by electricity from RES. The larger production of electricity from RES will supply more green certificates and decrease green certificate prices. In the long-run, this will lead to fewer investments into RES capacity and reduce additional generation of RES-based electricity. Widerberg (2011) expands Amundsen and Mortensen's model with more explicit assumptions. In the short-run, she assumes the marginal cost of RES-based electricity production to be constant and zero and the change of non-renewable electricity generators in response to a change in carbon prices to be zero since generation technologies cannot be adapted in the short-run. In the long-run, she assumes that price elasticity for demand for carbon emissions is inelastic and that production shifts towards non-renewable electricity generation with lower emission density. Irrespective of the assumptions, the resulting impact of increases in carbon price on electricity generation in the domestic market is the same – both electricity generated from RES and from non-renewable sources decrease, though the former is affected to a smaller degree. These two studies suggest that the EU ETS seems to work against the TGC system's aim of increasing the share of renewable energy sources in electricity generation, even if the primary goal of reducing emissions from non-renewable generation is reached.

If there is an electricity market with an external trader who is neither part of the certificate market nor part of the carbon market, Amundsen and Mortensen (2001)'s model predicts that the negative effect of carbon price on certificate price disappears and certificate prices are expected to stay the same in the long-run. For the Swedish-Norwegian TGC system, trade in electricity with the other Nordic countries via Nord Pool electricity market has been an option throughout its operation. But the TGC market itself was a closed Swedish market up until 2012 when Norway was added. Amundsen and Nese (2009) clarify in a later paper that the effect of increased carbon permission prices will be the same: no matter whether a country establishes the TGC system independently, whether trade in electricity, or trade in electricity and certificates is allowed, an increase in carbon permission prices will unfailingly shift marginal costs and eventually consumer price of electricity upwards, which leads to both lower black and green electricity generation.

When considering market extension of the TGC market, Widerberg (2011) takes the prices of electricity and emission allowances to be exogenous since Sweden and Norway are part of the respective larger markets. She assumes two different scenarios, one in which TGC price decreases because of surplus production from Norwegian hydro power plants, and one in which the opposite, a too scarce allocation of TGC, leads to higher TGC prices than in the single market. The exogeneity assumption might be true for the emission allowances market, but not for the electricity market. Norway and Sweden are part of Nord Pool market, which also comprises Denmark, Finland, the Baltic states, Germany and the UK. However, the largest volumes of electricity in this market are bought and sold by Sweden and Norway (Nord Pool Spot, 2015). It is therefore reasonable to assume that the amount and type of electricity generation with their different marginal production costs in those two countries drive electricity prices in the Nord Pool market. Apart from that, electricity transmission in both countries is subject to transmission capacity constraints and, as shown in Brännlund et al. (2012), these bottlenecks also influence electricity price.

Energy production from RES, such as wind and solar power, is fluctuating and so is the number of issued tradable green certificates and their market price. A TGC system that allows banking of certificates can transform a random certificate price series into a positively correlated price series (Amundsen et al., 2006). If banking is allowed, extreme TGC price peaks are much rarer and also the standard deviation of TGC price is much lower since in bad wind-years price peaks are evened out by using banked certificates from previous good wind-years

Market power is another factor that could undermine efficiency of TGC markets. Few RES-electricity producers in the market can artificially limit the supply of TGC, which will increase TGC price. Opening the market to allow trading in green certificates between countries, in which firms exercise market power, should lower prices of green certificates in both countries (Amundsen and Bergman, 2012).

Black and green quota effects on electricity price have been analysed by Jensen and Skytte (2003) and Rathmann (2007). The TGC system's direct effect on electricity price results from the reduced marginal cost in the merit order when the increasing generation from RES replaces generation from non-renewable sources. Jensen and Skytte (2003) find that the consumer price of electricity does not unambiguously decrease or increase with the introduction of a TGC market. The price for power will decrease if renewable electricity is subsidised by a green quota system, but with an increasing quota demand for TGC increases thereby increasing TGC price. Depending on whether these increased TGC costs are smaller or larger than the saved costs from the lower electricity price, consumer electricity price may decrease or increase (Jensen and Skytte, 2002).

The EU ETS directly increases costs of electricity generation and therefore increases wholesale electricity prices (Rathmann, 2007). But Rathmann also describes the indirect effect of carbon price on electricity price.[3] Substitution of non-renewable electricity generation by RES-based electricity generation reduces carbon emissions, lowers the demand and hence the price

[3]Although Rathmann (2007) describes RES-based electricity support schemes in general, his conclusions are valid for both feed-in tariffs and quota systems.

of carbon. These reduced costs are reflected in changes in the merit order and eventually in reduced wholesale electricity price. Böhringer and Rosendahl (2010)'s similar model, in which a green quota is introduced on top of an existing black quota, adds that green quotas lower profitability of conventional power which therefore reduce their production. While keeping the carbon emission cap, subsequently this reduced production will lead to lower carbon prices. From this the most emission-intensive electricity generation technologies naturally benefit most and they will substitute for generation from lower-emission conventional electricity generation. Therefore, production and emissions from the dirtiest technology will actually increase if a green quota is imposed on top of a carbon emissions trading scheme. However, Böhringer and Rosendahl model carbon allowances and green quotas in a closed system where the demand of power generators for carbon allowances influences the price of carbon allowances. This is unlikely in the present EU ETS where the price of carbon is determined by the demand for and supply of allowances by all 31 participating countries meaning that small players like Sweden and Norway will only be able to influence the price of carbon allowances to a very small degree. Furthermore, their model covers the exact opposite of the Swedish case, where the TGC system was already in place when the carbon market was introduced.

2.2 Empirical studies

Turning to the recent empirical literature on price determination in the EU ETS market, Aatola et al. (2013) find a clear and stable relationship between market fundamentals (German electricity prices, gas and coal prices) and prices of EU emission allowances. Koch et al. (2014) quantify the impact of the explanatory variables on EUA prices and find that variations in economic activity are the most important determining factors as well as increasing deployment of renewables which is associated with decreasing EUA prices. Brännlund et al. (2012) analyse factors that have historically influenced electricity price development in the Nordic market (1970-2010). The most important determinants for electricity price are market fundamentals of electricity demand and supply of the current and previous periods (temperature, coal price, GDP, nuclear power production), plus previous electricity price and the existence of electricity transmission bottlenecks. On top of that they find that precipitation has a negative effect on electricity price levels in the following year, since the loaded hydro reservoirs can generate baseload electricity at low marginal cost. Among others, they find a structural break in 2005-2006 which they explain by the introduction of the EU ETS which increased electricity prices. Freitas and Silva (2015) find a long-run relationship between EUA prices and electricity prices in the Spanish electricity market, taking also into account coal and natural gas prices and climate variables. Weather variables are important for short-run changes in electricity price.

To the best of our knowledge, the only econometric studies on the interaction of carbon, green certificate and electricity markets have been conducted by Fagiani (2014, chap. 7) and Fagiani and Hakvoort (2014) for Sweden, Norway and the UK. In the first study, Fagiani uses a vector error correction model to estimate short- and long-run dynamics of energy prices, economic activity and TGC price in the Swedish-Norwegian and the UK markets. The results indicate that in the Swedish-Norwegian TGC system TGC price is cointegrated with natural gas, coal, carbon prices and equity index prices. In the UK TGC system, a long-run relationship exists between TGC price and the industrial production index. In the second study, Fagiani and Hakvoort (2014) use a GARCH model with structural break tests to verify that TGC price volatility in the Swedish-Norwegian TGC system increased during the negotiation period for market expansion to include Norway and not completely returned to volatility rates experienced before the market enlargement. These results indicate that changes in the regulatory framework that lead to market uncertainty might actually counteract the stabilising effect expected from the competition created by the larger market.

Table 1 summarises the theory- and empirics-based direct expected effects of market fundamentals on electricity price and TGC price. Temperature and industrial production affect the demand for and price of electricity negatively and positively, respectively. Fossil fuel prices, such as the prices of coal, oil or gas, increase production costs of thermal electricity generation and increase electricity price. EUA price increases electricity price. However, EUA price could have a negative effect on TGC price since higher EUA prices increase generation of RES-based electricity generation as well as the supply of green certificates. Renewable electricity generation has lower marginal costs of production than thermal-based electricity generation and therefore IT affects electricity price negatively. The number of banked green certificates signifies the oversupply of renewable electricity and has therefore a negative effect on TGC prices. Increases in electricity price will reduce the demand for electricity as well as the demand for green certificates, which will lead to lower TGC price.

Table 1: Summary of the short-run theory- and empirics-based expected direct effects of market fundamentals on electricity and TGC prices.

Factor	Effect on electricity price	Effect on certificate price
Temperature	−	
Industrial production	+	
Fossil fuel prices	+	
EUA price	+	−
Renewable electricity supply	−	−
Banked TGCs		−
Electricity price		−

3 Methodological Issues and Data

3.1 Methodological issues

In this empirical study we aim to capture the interplay between the prices of three markets: the Swedish-Norwegian TGC system, the EU ETS and Nord Pool. Based on the literature, it can be hypothesised that these prices are closely related to and influence each other in a circular way. Moreover, these market prices capture fluctuations of other determining factors. The theoretical literature summarised in Section 2 shows that none of our considered prices can be labelled as dependent or independent. Since we cannot assume otherwise, we perform a standard VAR analysis that takes into account the interrelationships between the selected variables by treating them symmetrically. In our VAR model, each variable is expressed as lags of all variables in the system. This approach allows us to test for the endogeneity of all our considered prices and to understand their short-run dynamics by analysing the responses of these prices to price shocks in the considered markets. In this paper we estimated the following VAR model:

$$y_t = \sum_{i=1}^{p} A_i y_{t-i} + c + u_t,$$

where y_t is the (3×1) vector of endogenous variables (TGC price, electricity price, and EUA price); A_i are (3×3) coefficient matrices for lag $i = 1, \cdots, p$; u_t is the error term with zero mean and time invariant covariance; and c is the (3×1) vector of constants.

Initially, we estimated two VAR models. The first one controls for the compliance month (March) when regulated firms have to surrender certificates to the regulator in order to be compliant with their individual percentage requirements and for the expansion of the Swedish TGC system by the Norwegian membership. This model includes two exogenous dummy variables: the first one is equal to one in 2011 and 2012 to control for market expansion and the second one is equal to one in March of every year to control for compliance month. These exogenous variables turned out to be insignificant. In the case of compliance month this can be attributed to banking of certificates that reduce TGC price volatility when the demand for certificates increases. Since these exogenous variables were insignificant, they were dropped in the second VAR model estimation to save degrees of freedom. In Section 4, we report the results only from the estimation of this model.

Our empirical analysis consists of two stages. The first step is to verify the order of integration of the variables. Initially, we use the augmented Dickey-Fuller test to test for the presence of a unit root (Dickey and Fuller, 1981). A well-known weakness of the Dickey-Fuller style unit-root test is its potential confusion of structural breaks in the series as evidence of nonstationarity. To address this problem, additionally, we use the test proposed by Clemente et al. (1998) that allow for two breaks within the observed history of a time series. In our analysis, we allow for the double-break innovational outliers (a gradual shift in the mean of the series).[4]

The second step involves estimation of the VAR model. To determine the appropriate lag length of the VAR model we rely on several sets of information criteria. Next, we perform a number of diagnostic tests including serial correlation, ARCH, normality and VAR model stability. Finally, the orthogonalised impulse response functions and the orthogonalised variance decompositions are employed to analyse the short-run dynamics of the selected variables. The

[4] A second step could be to test for cointegration between integrated variables. But since we are not interested in the long-run relationship but in the short-run shocks, we will forego this step.

purpose of this analysis is to explore how each variable responds to shocks by the other variables in the system to eventually confirm or refute theoretical assertions. The orthogonalised impulse responses provide an estimate of the response of a variable in the case of innovation in another variable.[5] Forecast error variance decompositions reveal the proportion of movement in a variable due to its previous values and the proportion that can be attributed to some other variable.

3.2 Data

This study uses the weekly price series of tradable green certificates in the Swedish-Norwegian TGC system, of electricity in Nord Pool and of carbon allowances in the EU ETS. Table 2 and Table 3 present the sources of the data and their descriptive statistics, respectively.

Table 2: Data sources

Variable	Source	Period	Frequency
TGC Spot Price	SKM - Svensk Kraftmäkling	2005-2015	Weekly
Average Electricity Spot Price	Nord Pool	2005-2015	Weekly
EUA Futures Price	ICE Futures Europe	2005-2015	Weekly

Table 3: Descriptive statistics of the price series in SEK

	N	Min	Max	Mean	Median	Std. dev.	Unit
TGC price	558	136.8	376.0	214.2	194.3	61.7	SEK/Certificate
Electricity price	558	69.9	966.0	356.5	335.4	129.8	SEK/MWh
EUA price	558	28.4	298.1	122.6	116.0	63.9	SEK/EUA

The weekly series of TGC prices in the Swedish-Norwegian TGC system were taken from the Nordic brokerage firm SKM. It covers the period from 2005 until December 2015. This price is the result of TGC supply and demand factors. The demand side comprises the exogenous effect of the percentage requirement, that is the share of the domestic electricity consumption produced by renewable sources. This requirement raises the demand for green certificates, which increases TGC price in the short-run but decreases it in the long-run once capacities have been built to meet the requirement. Together with the percentage requirement the supply of electricity directly determines the demand for green certificates. TGC supply is determined by the number of issued green certificates. Issued TGC in turn are directly and positively related to the generation of electricity from renewable power plants. Banked certificates will increase the supply of TGC in the following years and reduce both TGC prices and their fluctuations.

Figure 1 shows issued TGC for each renewable energy technology (in different shades of grey), cancelled TGC (in hatched bars) and accumulated banked TGC (black line) for each year. For instance, for the trading year 2015, the number of banked certificates almost equaled

[5] The orthogonalised impulse response function will give the same results as the generalised impulse response function since innovations of the fitted model are uncorrelated (see Table A5).

the number of newly issued certificates indicating the significant surplus of green certificates in the system. The surplus of accumulated banked TGC to some extent has been reflected in TGC price. Figure 2 shows the dynamics of TGC spot price for the period 2005-2015. TGC price was slightly falling until 2006, but from 2007 to 2008 it was rising, plateauing at just above SEK 300 in 2009.[6] In 2010 TGC price started falling again and has been moving between SEK 150 and SEK 200 ever since. The mean price for the entire period is at around SEK 215.

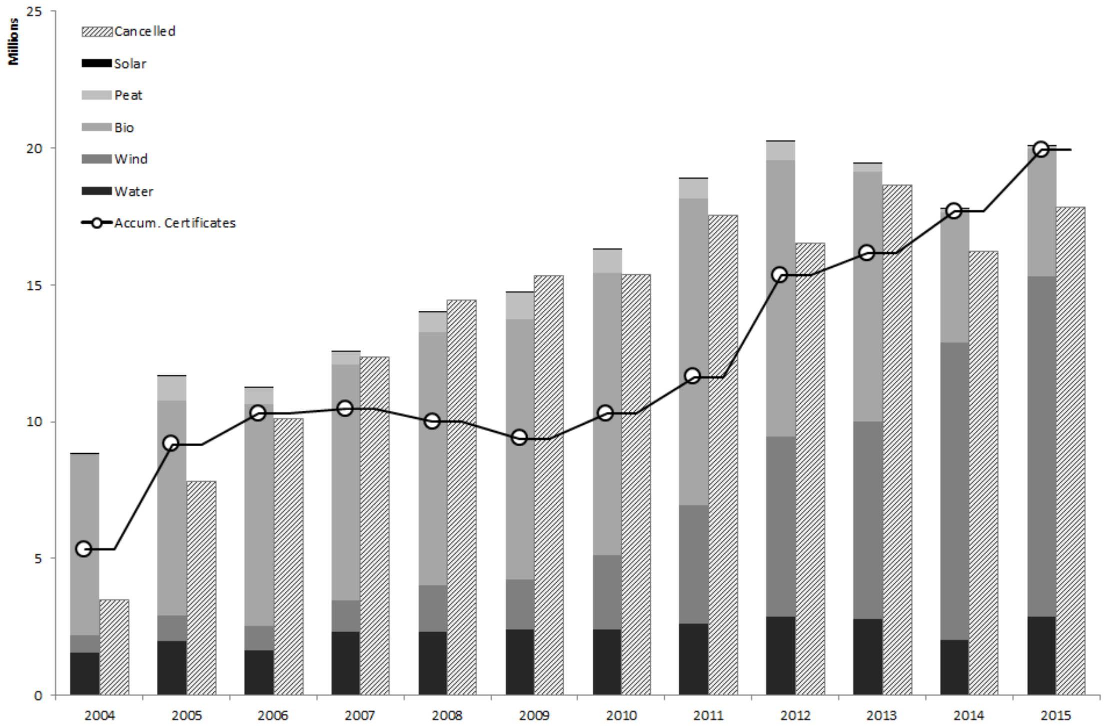

Figure 1: TGC issued, cancelled and banked, 2005-2015

Notes: TGC issued are shown as stacked bars in different colors for each renewable energy technology. TGC cancelled every April are shown as light grey bars. Accumulated certificates that were not cancelled are presented as overlying line. Each year denoted here is a TGC trading year from April of the preceding year until March of the specified year. The numbers of issued and cancelled certificates were retrieved from the Swedish Energy Agency's electricity certificate register Cesar (Accessed: 10 January, 2016).

Since many explanatory variables used in the econometric studies on TGC prices are strongly correlated with electricity price (see our literature review in Section 2), in our empirical analysis, we choose to include electricity price as its determination in the market already captures movements of electricity supply and demand factors. The spot price of electricity was taken from Nord Pool and it is the average price of all bidding zones in Sweden, and subsequently Norway. The price has been meandering around a mean of SEK 350 with four price peaks from 2005 to 2015 (see Figure 2). Electricity demand and supply determine electricity price. Main supply boosting factors include economic activity and temperature, which have been shown to have a stable relationship towards electricity price development (Brännlund et al., 2012). Fuel costs of conventional electricity generation, such as costs of coal, gas or oil, also drive electricity price. On top of fuel costs, carbon prices have the same impact on electricity price.

[6]The average exchange rate for 2015 was SEK 100=EUR 10.60

Furthermore, electricity price captures the volatility of electricity production based on variable electricity from RES.[7] Variable renewable energy capacity is responsible for short-term volatility in electricity prices since a large share of renewable electricity production means that the natural variability of renewable energy is transmitted into electricity production.

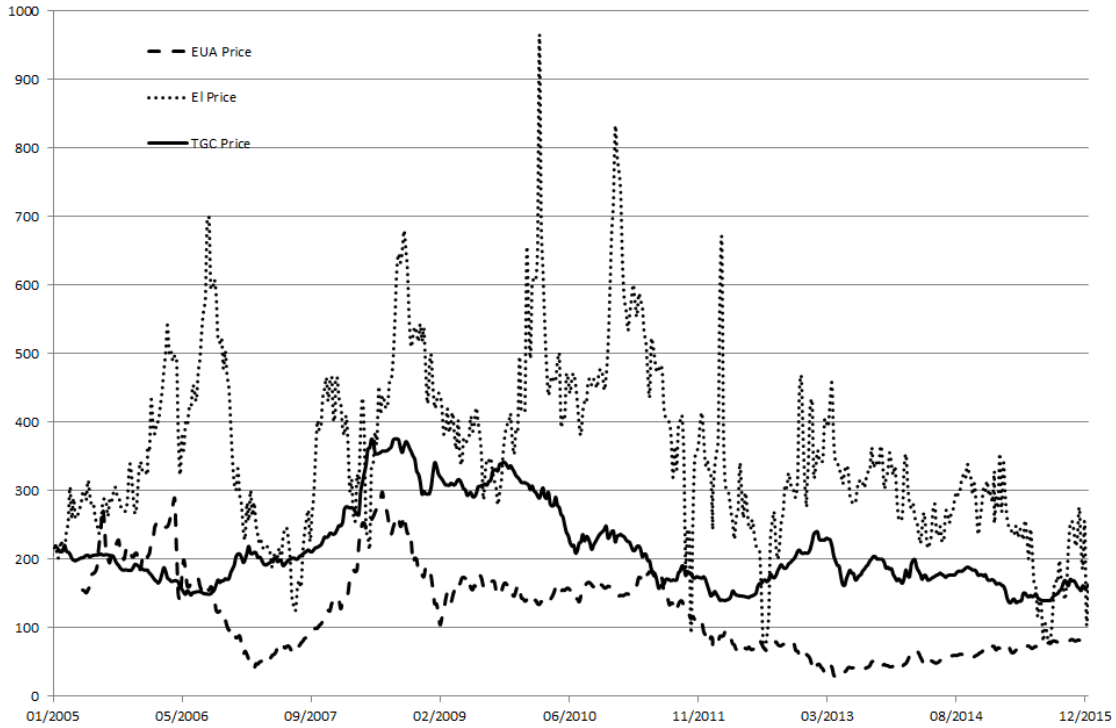

Figure 2: Weekly average prices of TGC (SEK/certificate), electricity (SEK/MWh) and EUA (SEK/EUA), 2005-2015.

The series of EUA prices was retrieved from the ICE Futures Europe as the continuous daily series of forward contract prices of all maturities. Figure 2 shows that a year after the launch of the EU ETS, EUA prices started to drop. By the middle of 2007 when the first phase of the EU ETS moved towards its end and the start of phase II in 2008 drew closer, EUA prices increased to just over SEK 200 but then gradually decreased to stay at around SEK 70 since 2013. The mean price for the whole period from 2005 to 2015 is SEK 120.

The empirical analysis is carried out using weekly data from the last week in April of 2005 to the last week in December of 2015. All data series are not seasonally adjusted as seasonal patterns could not be observed in any of the data series. No further transformations of the data were performed.

4 Results and Discussion

4.1 VAR Model Specification and Diagnostics

Table A1 and Table A2 in the Appendix present the augmented Dickey-Fuller and Clemente-Montañés-Reyes tests for the three price series used in the empirical analysis: TGC price, EUA

[7]Variable renewable energy sources are mainly wind power and solar power.

price and electricity price in levels and first differences. The test results are presented for a lag length of six, but they are robust to changes in lag length. The augmented Dickey-Fuller test's statistics for both specifications (with trend and intercept and only with intercept) indicate that TGC price and EUA price are integrated of order one, $I(1)$, whereas the first differences of EUA price, TGC price and the level of electricity price are integrated of order zero, $I(0)$ (cf. Fagiani, 2014). Therefore, the hypothesis that the price series contain a unit-root process is accepted for all variables except for the price of electricity.

Finally, the Clemente-Montañés-Reyes test's statistics with two innovational outliers in each variable suggest that, despite the double structural breaks in each price series, we cannot reject the null hypothesis of a unit root in TGC price and EUA price series. However, the first differences of EUA price, TGC price and the level of electricity price are stationary. Therefore, the combined results from both unit-root tests suggest that all price series except the price of electricity appear to be $I(1)$ processes.

Although aware of the nonstationarity of the data, we estimate our VAR model in levels, as this is the relationship that interests us. The results of the differenced model also support our main findings.[8] Enders (2010, p. 301) argues that differencing of time series "throws away information concerning the comovements in the data" and would reduce the chances of finding effects of price shocks. Sims et al. (1990) show that most standard asymptotic tests are still applicable for a VAR model estimated in levels. Moreover, standard inference on impulse responses based on VAR models in levels will remain asymptotically valid. Inference also is asymptotically invariant to the possible presence of cointegration between our considered price series (Lütkepohl and Reimers, 1992).

Lag length tests indicate that, according to Schwartz Information Criterion and Hannan-Quinn Criterion, two or, according to Akaike Information Criterion and Akaike's final prediction error, maximum three lags should be used (see Table A3). However, the VAR model with three lags showed signs of serial correlation. Adding six lags removes serial correlation and is a more reasonable specification given the weekly price series. The inclusion of more than six lags did not improve overall model stability or parameter significance.

The results of the various diagnostics tests of our VAR model can be found in the Appendix. Table A4 shows p-values of serial correlation, normality and ARCH tests for the VAR model in levels. For serial correlation the Breusch-Godfrey test was chosen since lagged dependent variables are included. The results of this test show that we can reject the null hypothesis of no serial correlation if we include six lags. The normality test suggests that the VAR model's disturbances are not normally distributed, but this does not interfere with the interpretation of the VAR model's results. The ARCH test for autoregressive conditional heteroskedasticity in the residuals was not passed, however, the visual inspection of the residuals over fitted values suggests that the departure from homoskedasticity is not substantial[9] (see Figure A1). A stability test shows that the estimated VAR model is stable since the whole sum of recursive errors lies between the critical values (see Figure A2). Moreover, the residuals of our VAR

[8]The full set of results can be obtained from the authors upon request.

[9]Estimators will still be consistent, unbiased and asymptotically normally distributed.

model are not correlated at any common significance level (see Table A5).

4.2 Impulse Response Functions and Variance Decomposition Analysis

The detailed results of the estimated VAR model are presented in Table A6. We investigate the interplay of the three prices through the estimation of the orthogonalised impulse response functions and the orthogonalised variance decomposition analysis to investigate the dynamic properties of the VAR system.

The orthogonalised impulse response functions for TGC price, electricity price and EUA price from one-standard deviation shock to TGC price, electricity price and EUA price for a horizon of 52 weeks (one year) are presented in Figure 4, Figure 5 and Figure 6, respectively. Figure 4 shows the impulse responses for electricity price and EUA price from a positive one-standard deviation shock in TGC price. Such a shock can arise from a reduction in the supply of green certificates or an increase in the demand for green certificates in the market. For example, if weather conditions cause low production of electricity from hydro power or if changes in the regulative framework increase the demand for green certificates. It can be seen that with a delay of two weeks a TGC price shock has a negative though insignificant impact on electricity price that becomes positive and significant after week 20 (see Figure 4). This small positive effect of TGC price on electricity price could be explained by the characteristics of the Swedish and Norwegian energy markets. For a number of years, both markets have been relatively independent of carbon-intensive energy generation. In Sweden, about 40% of electricity generation comes from hydro power and about 40% comes from nuclear power. Electricity generation from conventional thermal and other renewable energy sources contribute just about 10% in total electricity generation (Statistiska Centralbyrån, 2016). In Norway, consistently more than 95% of electricity is generated by hydro power (Statistisk Sentralbyrå, 2016). This suggests that renewable power generation induced by the recently created TGC system is relatively small and that, to date, it has had a very negligible impact on the price of electricity in Nord Pool market.[10] This could change when there is more new renewable electricity generating capacity brought to the system.

A shock in TGC price has a fairly small positive effect on EUA price that is not significant for the major part of the horizon. This result could be explained by the relatively small size of the Swedish-Norwegian TGC market compared to the EU ETS meaning that volatility in TGC price barely affects EUA price.

Figure 5 presents the impulse responses for TGC and EUA prices from a positive one-standard deviation shock in electricity price. Such a shock can arise with demand shocks, e.g. very low temperatures that require more heating, or supply shocks, e.g. (temporary) closure of power plants or dry summers that reduce generation of hydro power. A one-standard deviation shock to electricity price has a negative effect on TGC price that is insignificant

[10] Note that this result does not reflect the effect of TGC price on final consumer electricity prices charged by electricity suppliers. Normally, TGC prices should be fully passed through into final consumer electricity prices.

for all horizon. This result might be expected as increases in electricity price will reduce the demand for electricity as well as the demand for green certificates, which will lead to lower TGC price. The same shock has an initial positive and insignificant effect on EUA price that becomes significant and negative after 18 weeks. This later result can be also explained by lower demand for electricity and hence lower demand for more carbon-intensive off-peak electricity generation that lowers the demand for carbon allowances as well as their prices.

Figure 6 shows the impulse responses for TGC price and electricity price from a positive one-standard deviation shock in EUA price. EUA price shocks can arise when economic recessions lower energy demand and thereby reduce demand for carbon emission allowances. A shock in EUA price has a positive impact on electricity price with a delay of one week. It turns insignificant after three weeks and becomes again significantly positive after week 10. This result is expected as increases in EUA price are associated with higher demand for carbon allowances, which could be explained by higher demand for electricity which is met by more carbon-intensive and more expensive off-peak electricity generation.

A disturbance in EUA price has a small positive but significant impact on TGC price that turns out insignificant 15 weeks after the initial shock. In the context of the Swedish-Norwegian TGC system, this result can be explained as follows. EUA prices are high when the demand for carbon allowances is high. This is the case when the increasing demand for electricity is met by more carbon-intensive electricity generation. Since the required share of renewable electricity consumption in total electricity consumption has to be met, higher demand for electricity leads to higher demand for green certificates. This drives TGC price upwards. The delay and relative small size of EUA price impact on TGC price could be interpreted as a result of green certificate banking. As Amundsen et al. (2006) have shown, banking serves as a form of insurance against sudden price peaks or drops. As discussed above, in the Swedish-Norwegian TGC system, the number of banked certificates has kept increasing and in 2015 it almost equalled the number of newly issued certificates in 2015 indicating the significant surplus of green certificates in the system. In response to this, the Swedish Energy Agency increased the required share of the domestic power consumption produced by renewable sources for the period 2016-2035 (Figure 3). In 2020, almost 30% of electricity consumption in Sweden and Norway should be produced from RES.

An alternative way to obtain the information regarding the relationships among the three market prices is trough the variance decomposition analysis. This analysis supports the results from the estimation of the impulse response functions. It suggests that each of the prices used in the empirical analysis can be explained by the disturbances in the other market prices and that the share of the variance that can be attributed to these disturbances increases with time. Figure 7 shows that, in the first weeks, most of the variability in each price is explained by its own innovations. After almost 1 year, the contribution of shocks in the respective other prices increases but reaches only about 5 to 10%. This implies that on a week-to-week basis, price variations in, for example, TGC price can be mainly explained by its own innovations. Even after almost 1 year, about 90% of the variability in TGC price is explained by shocks in

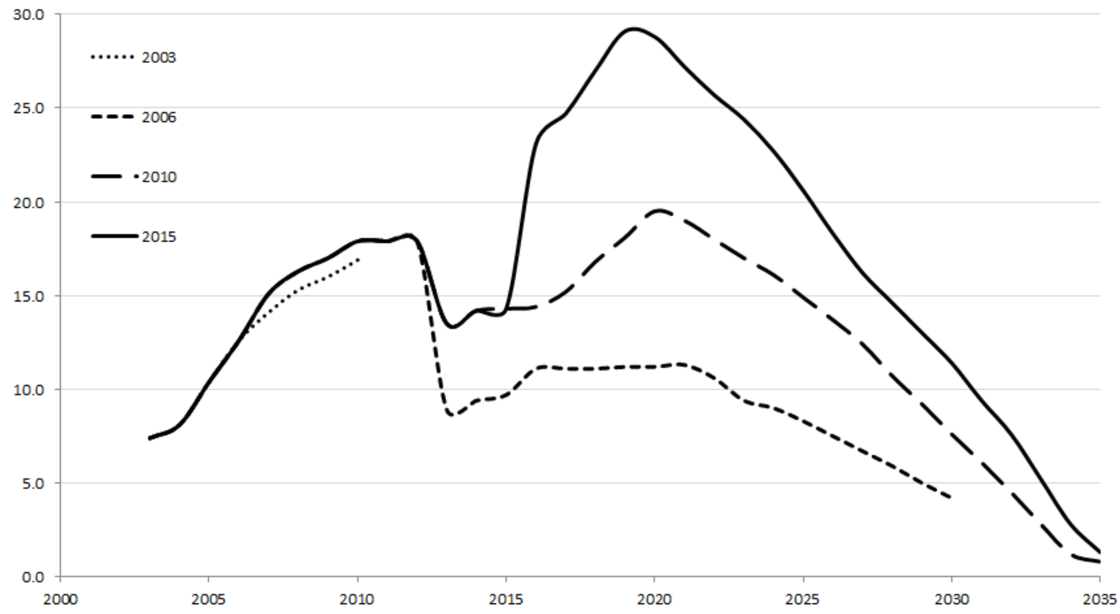

Figure 3: Required share of power consumption from RES since the implementation of the TGC system and the subsequent changes in the regulation in 2006, 2010 and 2015

TGC price. Similarly for electricity price variations: its own innovations explain most of the variability in the first weeks, but with a horizon of a year, about 15% and 10% can be explained by EUA price shocks and TGC price shocks, respectively.

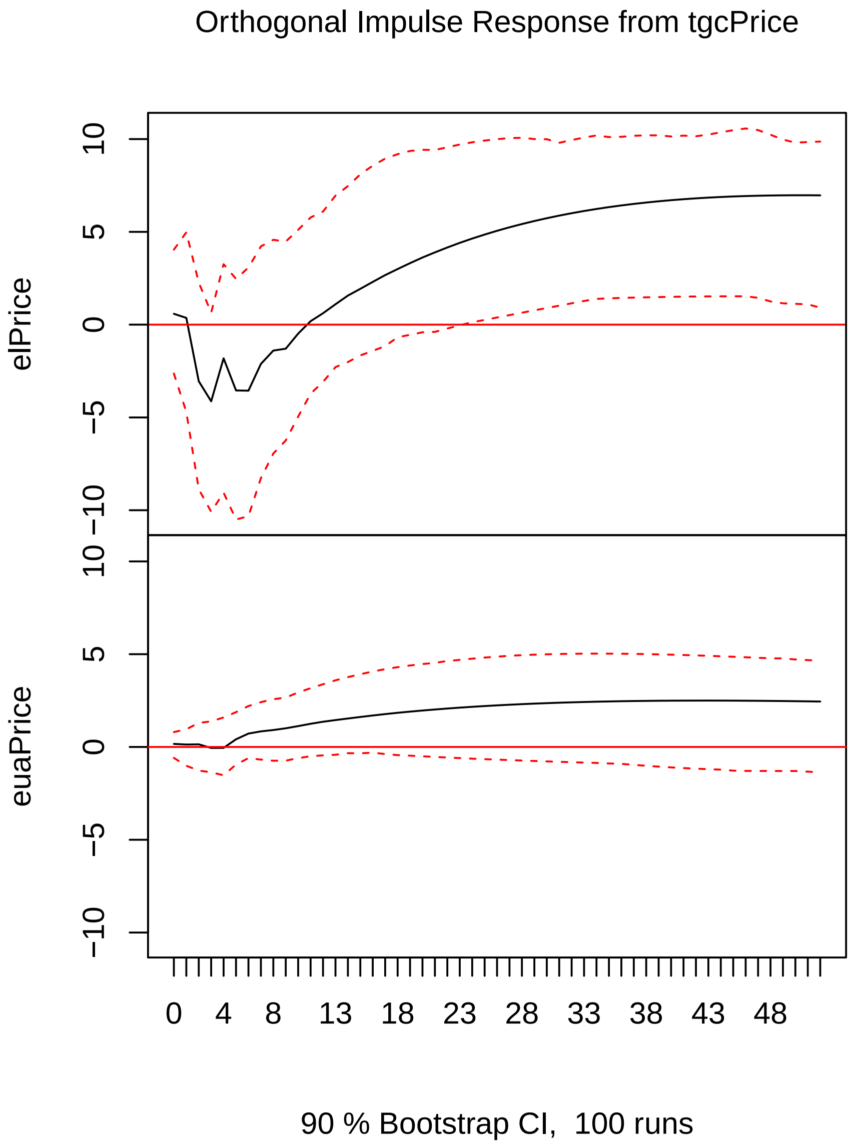

Figure 4: Orthogonalised impulse responses for TGC price and EUA price from one-standard deviation shock to TGC price for a horizon of 52 weeks with one standard error confidence intervals.

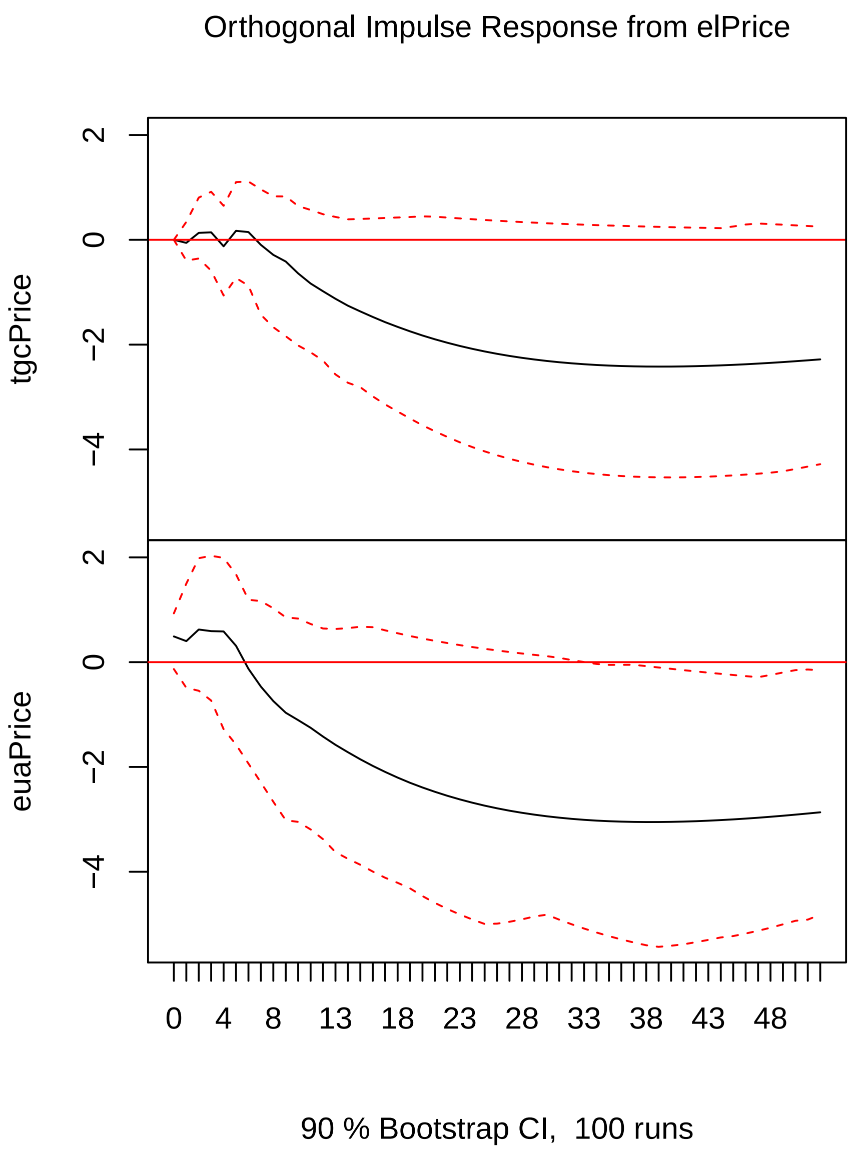

Figure 5: Orthogonalised impulse responses for TGC price and EUA price from one-standard deviation shock to electricity price for a horizon of 52 weeks with one standard error confidence intervals.

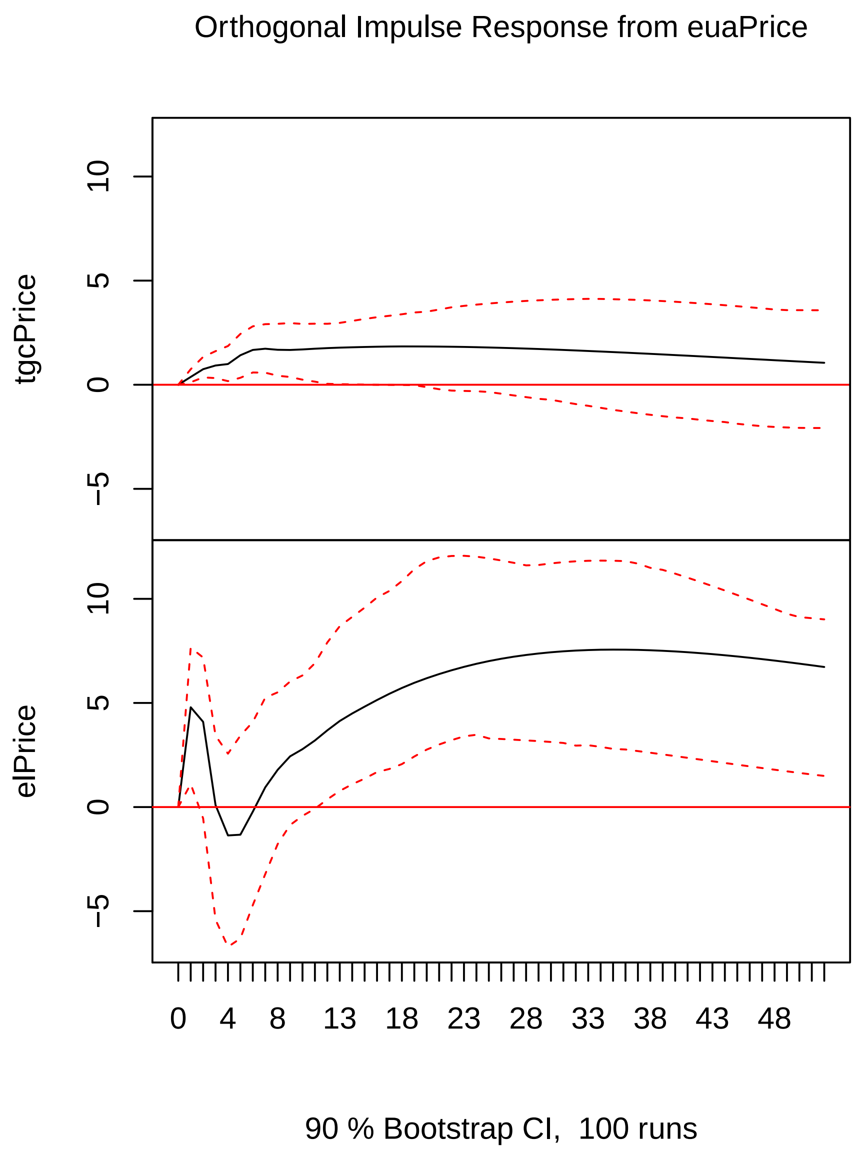

Figure 6: Orthogonalised impulse responses for TGC price and electricity price from one-standard deviation shock to EUA price for a horizon of 52 weeks with one standard error confidence intervals.

5 Conclusion

In this study we empirically examined the interplay between the prices of three markets: (1) the price of tradable green certificates in the Swedish-Norwegian TGC system, (2) the price of carbon in the EU ETS and (3) the price of electricity in Nord Pool. We placed a particular attention towards the postulated interaction of green certificate and carbon markets with the aim to test the hypothesis that the EU ETS counteracts the goals of the Swedish-Norwegian TGC system by leading to lower TGC prices and consequently lower supply of renewable electricity. For this purpose we performed the standard VAR analysis that takes into account the interrelationships between the selected three market prices.

We found no indication that the impacts of carbon price on green certificate prices and on renewable electricity production are negative. Contrary, our results show that increases in carbon prices positively affect green certificate prices at least in the short-run. This finding could be inherent to the specific features of the Swedish-Norwegian TGC system in which the targeted share of renewable electricity is met trough the percentage requirement. This implies that demand for TGC is a derived demand stemming from demand for electricity meaning that any factors potentially affecting demand for TGC are already captured by demand for electricity.

An immediate policy implication from our finding is that, to date, the EU ETS and the Swedish-Norwegian TGC system do not interfere with each other's prices formation. When it comes to price signals, the two systems do not obstruct the goal to reduce GHG emissions and increase the share of renewable electricity. For producers aiming to expand the capacity of renewable electricity or for new producers aiming to enter the market our results imply that these markets support investment into renewable electricity. In the near future, these kind of investment should be further supported by the tighter cap on the EU's GHG emissions and the increasing targeted share of renewable electricity.

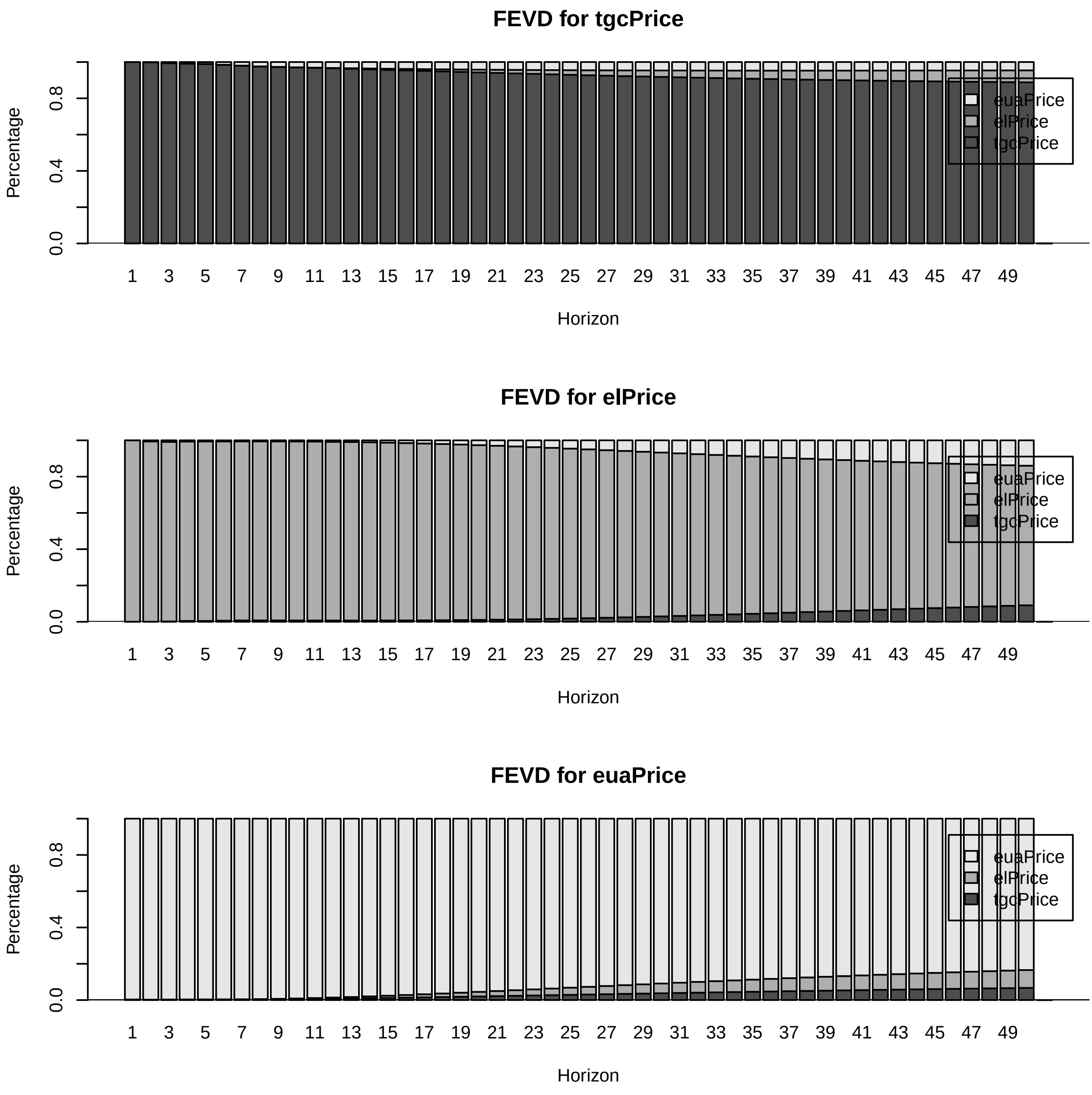

Figure 7: Forecast error variance decompositions.

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A Appendix

Table A1: Augmented Dickey-Fuller unit-root test

	Level		First Difference	
	trend & intercept[a]	intercept[b]	trend & intercept[a]	intercept[b]
TGC price	-1.73	-1.45	-8.45	-8.44
Electricity price	-3.37	-2.97	-10.51	-10.50
EUA price	-2.43	-1.89	-8.93	-8.94

[a] The 95% critical value is -3.41.
[b] The 95% critical value is -2.86.

Table A2: Clemente-Montañés-Reyes unit-root test with double mean shifts

	Level	First Difference
TGC price	-4.72	-19.10
Electricity price	-5.55	-14.70
EUA price	-4.17	-11.63

The 95% critical value is -5.49.

Table A3: Lag order selection

Lag	AIC	HQ	SC	FPE
1	15.47	15.51	15.57	5227087.28
2	15.37	15.44[a]	15.54[a]	4756402.67
3	15.36[a]	15.6	20.77	4701698.9[a]
4	15.37	15.49	15.68	4740974.82
5	15.39	15.54	15.78	4844503.64
6	15.39	15.57	15.85	4845124.28
7	15.39	15.6	15.92	4835441.23
8	15.41	15.64	16	4906220.46
9	15.41	15.67	16.08	4919835.56
10	15.42	15.71	16.16	4962643.85
11	15.42	15.74	16.24	4993433.91
12	15.44	15.78	16.32	5068685.68

AIC: Akaike Information Criterion.
HQ: Hannan-Quinn Information Criterion.
SC: Schwartz Information Criterion.
FPE: Final prediction error.
[a] indicates chosen lag order.

Table A4: P-Values of diagnostic tests

Model	Serial Correlation Test[a]	Normality Test[b]	ARCH Test[c]
with 3 lags	0.16	0.00	0.00
with 6 lags	0.01	0.00	0.00

[a] The null hypothesis of the serial correlation test is that there is no serial correlation.
[b] The null hypothesis of the normality test states that skewness is zero and excess kurtosis is zero, i.e. the data is from a normal distribution.
[c] The Null hypothesis from the ARCH test is that there are no ARCH effects.

Table A5: Residual Correlation of VAR model

	TGC price	Electricity price	EUA price
TGC price	1.00		
Electricity price	0.01	1.00	
EUA price	0.02	0.05	

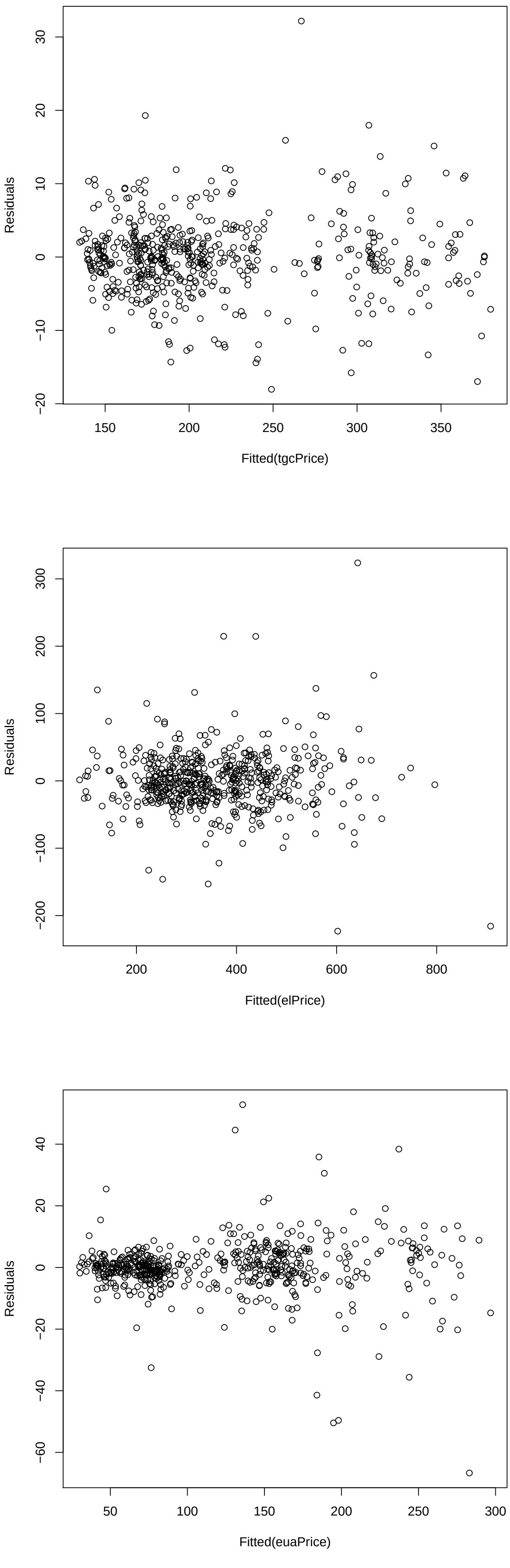

Figure A1: Residuals over fitted values of the VAR model

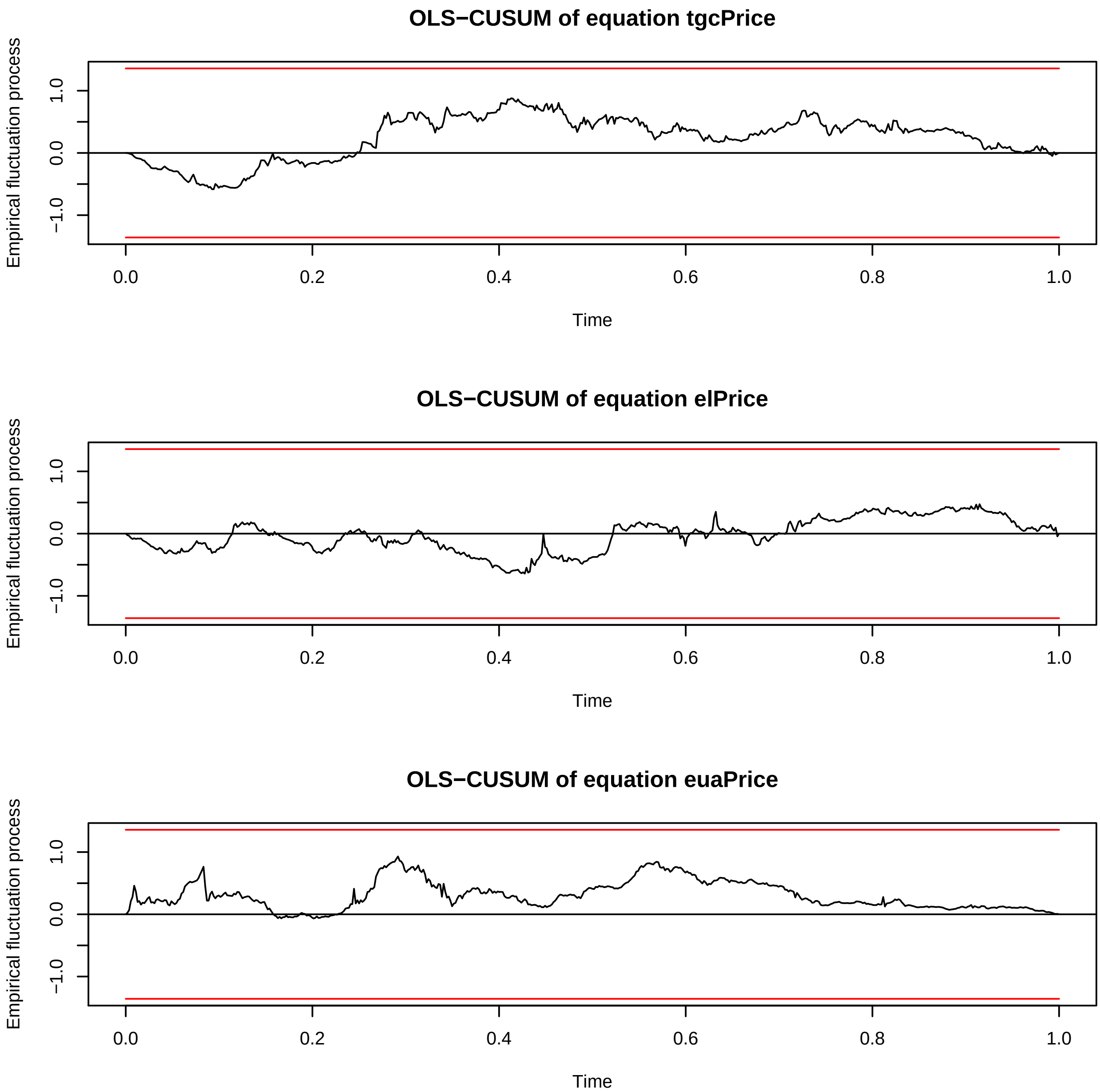

Figure A2: Stability test of the VAR model (cumulative sums of residuals)

Table A6: VAR model results

	tgcPrice	elPrice	euaPrice
tgcPrice.l1	1.2855***	-0.0495	-0.0106
tgcPrice.l2	-0.3000***	-0.5520	0.0191
tgcPrice.l3	0.0319	0.5279	-0.0463
tgcPrice.l4	0.0593	0.4676	0.0592
tgcPrice.l5	-0.1439**	-0.8208	0.0602
tgcPrice.l6	0.0620	0.4926	-0.0687
elPrice.l1	-0.0018	0.9244***	-0.0038
elPrice.l2	0.0062	-0.1123*	0.0101
elPrice.l3	-0.0057	0.1525**	0.0069
elPrice.l4	-0.0042	-0.0831	0.0025
elPrice.l5	0.0126*	-0.0504	-0.0082
elPrice.l6	-0.0102**	0.0738*	-0.0022
euaPrice.l1	0.0412	0.5278**	1.1643***
euaPrice.l2	-0.0178	-0.6497**	-0.2773***
euaPrice.l3	-0.0175	-0.1312	-0.0115
euaPrice.l4	0.0037	0.2043	0.0690
euaPrice.l5	0.0420	0.0318	0.0940
euaPrice.l6	-0.0478*	0.1099	-0.0477
const	1.7296*	8.2178	-1.2054
N	552	552	552
Adj. R^2	0.993	0.885	0.98

*, **, *** denote statistical significance at the 10%, 5% and 1% level respectively.