

Toward a Model for the Swedish-Norwegian Electricity Certificate Market

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Abstract—This paper explores the Swedish-Norwegian market for Electricity Certificates, which is a support scheme to establish incentives for investments in renewable electricity production. Producers investing in new renewable capacity receive certificates based on their actual production. Retailers of electricity are required to buy certificates for a proportion of their total sales. If a retailer's obligation is not met, a penalty fee is imposed. The certificates are traded both bilaterally and as a financial instrument on the Nasdaq Commodity Exchange. The design and potential success of this multistate support mechanism will be of great interest to policy makers and green investors. The dynamic equilibrium model of Coulon, Khazaei, Powell (2014) is adapted to the Swedish market. It is found to replicate historical long-term trends and price levels well. Sensitivity analyses show that the key drivers of certificate prices are the penalty levels and the discount rate. Further it is shown that a higher rate of certificate price feedback on the investment rate dampens the price fluctuations around the trend line. The rate of feedback is uncertain, but it is assessed to be larger than zero.

Index Terms—Renewable portfolio standards, Tradable Green Certificates, Energy policy, Dynamic equilibrium, Market analysis

I. THE SWEDISH-NORWEGIAN ELECTRICITY CERTIFICATE MARKET

TRADITIONAL environmental policies have usually involved providing subsidies, or imposing obligations on market actors. However, over the last decades, market-based energy policies have grown more popular, as governments have sought to maximize the social surplus while addressing the adverse effects of pollution. The Tradable Green Certificate (TGC) market in Sweden and Norway is an example of such a market-based energy policy, used by governments to promote the development of increased renewable capacity in the electricity grid. The system is flexible and allows regulators to specify which types of renewables should be favored.

In this TGC market, supply is established by letting the *regulator* decide which projects fulfill the requirements for receiving certificates. Once qualified, *producers* of eligible electricity are awarded a number of certificates based on their actual monthly production. Producers are allowed to bank their certificates and may time their certificate sales to maximize profits, i.e. either by selling immediately or by waiting for higher expected prices. Demand is then established by requiring *retailers*

to buy some of these certificates. The requirement imposed on each individual retailer is based on the amount of electricity he has sold to his customers. If a retailer does not fulfill this requirement by holding enough certificates at some specified compliance date, he is fined a penalty fee. Since the required number of certificates is calculated as a proportion of sold quantity, the total demand for electricity certificates is based on *end users'* consumption of electricity. This demand for electricity is typically found to be fairly inelastic, and the total consumption is predictable within seasonal variance.

One might argue who actually pays for these systems. The legislation states that the costs should be charged consumers over their electricity bill [1]. In his paper from 2000, Morthorst, finds that the costs of such a system is in fact carried by the consumers [2]. Since electricity demand is inelastic, an increased electricity price will not cause significant reductions in the quantity of electricity consumed. Bye [3] disagrees with the view of Morthorst. He argues that the costs of TGC markets are actually paid by the producers. As more projects become profitable, production volumes, and hence supply, rise. According to Bye, this will cause lowered retail prices, even though the certificate costs have been added. Thus, the existing producers carry the costs of the system, and consumers benefit from the lowered prices¹.

The Swedish electricity certificate market was opened in 2003, and is planned to last until 2035. From January 2012, the market was extended to include Norway [4]. By legislating the system, the lawmakers seek to add an additional 26.4 TWh of annual renewable capacity to the Swedish-Norwegian power grid. Electricity producers receive one certificate per 1 MWh of generation for their eligible power plants. A power plant declared eligible, will generate certificates during its 15 first years of production. All sources of renewable electricity production are equally entitled to certificates and there are no requirements regarding how this new capacity should be located geographically. This ensures that more profitable projects are realized first. However Swedish taxation rules make investing there favorable, compared

¹Bye notes that the increased consumer surplus is exceeded by the decrease in producer surplus, and hence, the total social surplus experience a net decrease.

to investing in Norway. In a report from 2012, Thema Consulting Group concludes that "up to 5.6 TWh of new renewable electricity in Norway, mainly wind, but also hydro, will be crowded out by more expensive Swedish wind power. The costs of meeting the certificate target of 26.4 TWh will therefore be higher than necessary" [5].

II. PRICE DYNAMICS

A. Price Equilibrium

The formation of certificate price expectations in the market is of major importance. Two conditions explaining the rational formation of expectations are presented.

- 1) The certificate price should equal the difference between the levelized cost of energy (LCoE) of the marginal plant and the electricity price.
- 2) The certificate price should equal the discounted value of the penalty times the probability of having to pay this penalty.

The first condition follows from the way electricity producers make investment decisions. In a TGC market, decisions to invest in renewable electricity capacity will be made on the basis of expected electricity- and certificate prices. Assuming a fixed electricity price, investments are made when the certificate price is at a level that makes a new investment profitable. This happens when the price of certificates is higher than the LCoE of the plant less the price of electricity. Consequently, the renewable plants with the lowest LCoE will be built first, since these are profitable at a lower certificate price. As prices increase, so does the number of profitable investments. Subsequently, investments will be made until the price of certificates is equal to the LCoE of the marginal plant less the electricity price. If the price of certificates never rise above the price level necessary to initiate further capacity investments, the 26.4 TWh goal may never be reached. If this situation occurs, the regulators are likely to implement changes in market design. Such regulatory changes may cause increased volatility and thus an increased required rate of return on investments [6].

Furthermore, the second condition follows from the expected payoff of a certificate. When new certificates are issued, electricity producers are faced with the decision of whether to sell their certificates immediately or bank their certificates to wait for higher prices. Producers will sell their certificates at the current price, unless the present value of an expected future price exceeds the current price. When the present value of a future price is higher, producers will bank their certificates until the willingness to pay among retailers increase to a level at which producers are willing to sell. The retailers' willingness to pay is assumed equal to the expected penalty faced if obligations are not met, times the probability of not being able to meet

these obligations, i.e. a shortage of certificates in the market. Hence, a player acting to maximize profit is likely to sell/bank his certificates such that he reaches an equilibrium where he is indifferent between selling today and selling tomorrow.

To achieve market equilibrium, both of the above conditions should be met at the same time. For modeling purposes, an interesting question is whether fulfilling one of the conditions automatically leads to the fulfillment of the other. For a market in equilibrium, one would expect this to be the case, but this question remains to be answered.²

B. Market Instability

Changes in certificate prices cause some interesting effects. The Swedish-Norwegian market operates with a penalty calculated as 1.5 times the average certificate price of the previous year. This leads to a short term mathematical instability. An increase in price will lead to an increase in the expected penalty, which subsequently will cause the certificate prices to rise even further. Given no intervention from market regulators, this spiral could potentially lead to prices climbing infinitely high or collapsing towards zero, depending on the initial price movement.

Dammed-hydro and bio power could to some extent, benefit from higher prices by increasing production. The percentage share of such "stabilizing renewables" in the mix of certificate eligible electricity, will decide the magnitude of the described instability. In the long run, the market will be able to meet an increase in certificate prices with an increased rate of investment in renewable electricity. This will cause the supply of certificates to increase, which in turns causes prices to decrease. The lead time of new capacity will decide the duration of the time period needed for the system to stabilize at a new equilibrium level.

C. Alternatives to Price Feedback on Investments

Both for the discussion in the previous section and for the example model in section III it is assumed that the level of investments in new renewable capacity is a positive function of the certificate price level. This assumption is logical, as an increase in prices will directly increase the gross profit of a renewable plant. Two extreme cases are considered. In the case of certificate prices moving towards infinity, all investment opportunities will be taken. In the case of prices collapsing towards zero, only investments made without a TGC support scheme will be taken. However, while prices fluctuate within an expected range, the dependency between prices and investment rate is considered uncertain and may vary for the different

²Thanks to Ove Wolfgang for passing this question.

technologies.

Historically, both dammed and run-of-river hydro power have been profitable without subsidies. On the other hand, the profitability of wind and bio power have, with few exceptions, depended largely on subsidies. Assuming that projects waiting to be realized have similar characteristics, one can assess the dependency between investment levels and certificate prices to be less prominent for hydro than for wind and bio. Information from a key producer in the Norwegian electricity market also indicates that their development of new hydro power plants does not depend on prices, but solely on access to capital. Wind and bio power projects will depend on positive certificate prices to be realized. Whether changes in certificate prices affects investment decisions is unclear.

New renewable capacity must be in operation by the end of 2020 to benefit fully from the TGC support scheme. Considering the lead times of the different technologies, investment decisions must soon be done if the new facilities are to be considered certificate eligible. An interesting theory states that the power plants needed to reach 26.4 TWh of new capacity before 2020 have already been planned, since electricity producers have a long planning horizon for future investments. If this is the case, movements in certificate price will be of little to no importance before 2020. Movements in certificate price will thus only affect investments in Sweden after 2020.

D. Expected Prices in the Market

As described in section II-A there are two alternative ways to describe the price equilibrium in a TGC market. However, the market price expected by market players is not necessarily equal to the equilibrium price. Among players, there might be a lack of information and ability to model and forecast prices³. Thus actual price expectations may not be consistent with theoretical prices. For players in the certificate market, price expectation may play a role both in investment decisions and for trading purposes. Today there is a liquid futures market for certificates where contracts can be traded up to five years ahead. The futures market is in contango, with prices increasing with time to maturity. Thus, price expectations seem to be in accordance with the martingale condition⁴. Morthorst argues that a liquid futures market for certificates might increase long-term transparency in pricing while stabilizing expectations [2].

³Some players in the market may utilize advanced forecasts for future prices.

⁴The price in one time step is the discounted expected price at the next time step.

III. EXAMPLE MODEL

This example model is an adaption of Coulon et al.'s modeling of the New Jersey Solar Renewable Electricity Certificate (SREC) market based on the equations described in their paper [7]. The model was chosen due to the promising results it has shown for the New Jersey SREC market. Additionally, to the best of the authors' knowledge, this is the first implementation of such an approach for the Swedish-Norwegian market. The authors are curious of whether Coulon's approach will yield similarly promising results for the Swedish market⁵ as for the New Jersey market.

Minor adjustments to the equations have been made to include the possibility of infinite banking of certificates. Parameters have also been updated to reflect historical values from the Swedish market during the period 2004-2011.

A. Mathematical Formulation

$$b_t = \begin{cases} \max(0, b_{t-1} + \int_{t-1}^t g_u du - R_t) & t \in \mathbb{N} \\ b_{[t]-1} + \int_{t-1}^t g_u du & t \notin \mathbb{N} \end{cases} \quad (1)$$

Eq. (1) keeps track of the accumulated number of certificates, *banking*, in the market at any given time. At any time step t , the currently banked balance b_t is a function of the previous balance $b_{[t]-1}$ and the accumulated issuance since the previous time step, $\int_{t-1}^t g_u du$. If the current time step is part of the set of compliance dates \mathbb{N} , eq. (1) accounts for a reduction in the number of certificates in the market, equal to the requirement R_t at the given date. The balance can never be negative, hence the max statement.

$$p_t = \max_{v \in \{[t], [t]+1, \dots, T\}} e^{-r(v-t)} \pi^v \mathbb{E}_t[1_{\{b_v=0\}}] \quad (2a)$$

$$p_t = e^{-r\Delta t} \mathbb{E}(p_{t+1}) \text{ when } t \notin \mathbb{N} \quad (2b)$$

At a compliance date, the holder of a certificate will avoid the penalty imposed on those who do not comply as he hands in his certificate. Further, if the balance of certificates in the market directly following a compliance date is 0, one can assume that investors would at least have been willing to pay the amount of the penalty fee for one certificate. Eq. (2a) states that at any time t , the value of the certificate p_t is the maximum of the discounted expected future penalty fees it can be used to avoid, discounted at the rate r . Eq. (2b), i.e. the Martingale condition, follows implicitly from (2a) and states that, except at compliance dates, the current price is the discounted expected future price.

⁵From 2003-2011, the electricity certificate market did only include Sweden. Norway did not enter the market until 2012. Hence, the model has been implemented for the Swedish market, to be able to replicate historical price data.

$$g_t = \hat{g}_t(p) \exp(a_1 \sin(4\pi t) + a_2 \cos(4\pi t) + a_3 \sin(2\pi t) + a_4 \cos(2\pi t) + \varepsilon_t) \quad (3)$$

The seasonality of electricity consumption, and hence certificate generation, is accounted for by a stochastic process on the form shown in eq. (3). \hat{g}_t represents the annualized issuance of certificates and is a function of price, p . This is motivated by the assumption that investors are likely to invest more while certificate prices are high. Seasonal changes are modeled by the sine and cosine functions, while a noise term is added to reflect the uncertainty of generation.

$$p_t = \bar{p}_t \quad (4)$$

Bellman introduced the term "the curse of dimensionality", referring to the exponentially increased execution time associated with the introduction of another state variable [8]. While Coulon's generalized model uses a weighted price average to calculate price feedback, it is here assumed, as stated in eq. (4), that the current average price equals the spot price. This is done to reduce dimensionality, and lower runtime. The result of this adjustment is immediate price feedback on generation.

$$\frac{\ln(\hat{g}_{t+\Delta t}) - \ln(\hat{g}_t)}{\Delta t} = a_5 + a_6 \bar{p}_t, \text{ for } a_5 \in \mathbb{R}, a_6 > 0 \quad (5)$$

Eq. (5) accounts for increase in generation. a_6 accounts for the logical effect that producers are likely to invest more as prices rise. a_5 represents the growth of generation not related to price increases. It is an independent term describing the drift in investments over time.

B. Implementation

It is assumed that the requirements and the penalties are known and fixed for each year. The assumption is done for the purpose of computational tractability. Further work will investigate whether it is possible to solve this price model within a reasonable timeframe, without making this assumption.

The solution algorithm proceeds as follows:

- 1) A grid of values for b_t and \hat{g}_t is chosen with lower bounds zero and upper bounds a little above the largest requirement. Time is discretized in monthly steps, matching the frequency of historical generation data.
- 2) The dynamic program is initialized, evaluating the payoff of the certificate at the end of the market's life $t = T$ for every single gridpoint (b_t, \hat{g}_t) . At this point, all information is known and hence, the program yields a digital boundary price surface:
 - a) At grid points where there is a shortage of certificates (i.e. the balance is less than the

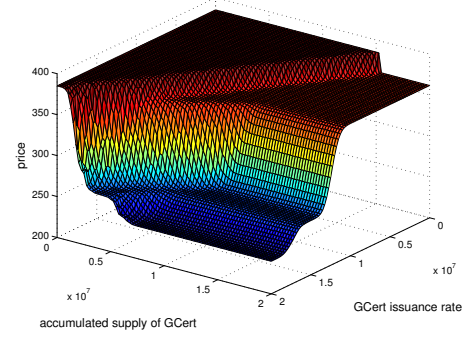


Fig. 1: Price Surface for $t = 55$ (July 2008), $a_6 = 15 \times 10^{-4}$

requirement), investors are willing to pay the penalty, $p_T = \pi^T$, for one certificate.

- b) At grid points where there is a surplus of certificates (i.e. the balance is higher than the requirement), investors are willing to pay $p_T = 0$ for one certificate.

- 3) From the boundary surface at $t = T$, the dynamic program steps backward to $t = (T - 1)$. Here it solves equations 1-5 at every grid point using price information from the price surface at $t = T$. The same procedure is then followed for every time step; information from price surface $t + 1$ is being used to solve equations 1-5 for every grid point of price surface t with Matlab's *fsolve* function [9].

The algorithm provides one price surface for every single time step. The price surfaces show what the price would be at this time step, given a situation (b_t, \hat{g}_t) . An example of the resulting price surfaces is shown in figure 1. In order to compare the modeled prices to historical data, one needs to extract the modeled price for the historical levels of $(b_t$ and $\hat{g}_t)$ for every time step. For the given resolution level, the the runtime is approximately 2.5 hours.

C. Results and Interpretation

Comparing model output to historical prices, it is seen that historical prices are replicated fairly well with modeled and historical prices fluctuating around the same trend line. While the modeled prices capture long term trends quite well, fluctuations are not captured. The model is requiring prices to equal discounted future prices. These future prices are dependent on penalties occurring once a year, thus short term fluctuations will not be captured. This also follows from the frequency of the input data which never exceeds monthly. Between compliance dates, graphs are smooth and increasing due to certificate prices satisfying the martingale condition given by eq. (2a) at all time steps. At compliance dates price drops are sometimes observed. These drops stems from foregone possibilities of using certificates for compliance.

The level of price feedback is determined by regression parameter a_6 . A higher a_6 reflects a greater degree of flexibility among producers of electricity. Producers respond more rapidly to price increases, investing in more capacity to overcome a shortage of certificates in the market. Prices are slightly lower for a greater level of price feedback. Higher feedback levels dampens fluctuations from the trend line.

As risk increases, so does the required rate of return. The higher the required rate of return, the steeper the associated price curves. The sensitivity analysis indicates that a required rate of return of 15% seems to produce the best replication of historical prices. One can argue that this is high. However, not only are investors in the electricity certificate market exposed to price risk. They are also exposed to regulatory risk [6]. This is the risk that changes in regulations will materially impact the certificate price. One reason why such changes might occur is the mathematical instability of certificate prices, mentioned in section II-B.

It is observed that higher (lower) penalty fees yield higher (lower) prices. This is as expected, as the price of a certificate is a positive function of future penalty fees.

Examining the results from the three sensitivity analyses, it is found that the best replication of historical data are produced using a discount rate = 15% with penalty fees at historical levels. For parameter a_6 , the results are inconclusive.

IV. CONCLUSIONS AND FURTHER WORK

The development over the markets first three years indicates that the goal of an additional 26.4 TWh of annual renewable capacity by 2020 is likely to be reached. Due to differences in the tax regimes of Norway and Sweden, some Swedish investment opportunities with higher LCoE are likely to be taken before some of their Norwegian counterparts with a lower LCoE, thus increasing the total social costs of the system. Whether the producers or the consumers are the ones carrying the cost of the system is debatable, however, the system is found to cause a reduction in the total social surplus. From this it is assessed that the system achieves the sought-after effects, but possibly at higher costs than necessary.

The effects of price changes have several important aspects. Due to the spiral dependence between previous certificate prices and penalty fees, it is pointed out that the system is mathematically unstable. However this instability has yet to result in abnormal changes in the certificate price. Further, the degree to which an increase in prices is met by an increased rate of investments in renewable capacity is unclear. However, from the regression done on historical data, this effect is assessed to exist.

The comparison of model output to historical Swedish certificate prices shows that though short-term fluctuations are not captured, long-term trends and price levels are replicated quite well. This indicates that the example model will be a suitable starting point for further work.

From sensitivity analyses done for the penalty fee, discount rate and the feedback effect, results are assessed to be in accordance with the expected behavior. Prices are observed to be positively dependent of the penalty fee, the slope of the price curves increase with the discount rate and an increased feedback effect dampens price fluctuations. Furthermore, the penalty fee and the discount rate seem to be the key drivers of the model.

Some important aspects of the market have yet to be implemented. In contrast to the fixed penalty used here, the penalties in the Swedish-Norwegian market depend on prices observed over the previous year. To include the penalty fee as an endogenous variable requires the introduction of another state variable, leading to a considerable increase in runtime. Generation of electricity, and thus the issuance of certificates depend on electricity prices and weather conditions. Including electricity price forecasts and weather forecasts into the model, allows for better estimates for the issuance of certificates, consequently increasing the quality of the certificate price forecasts. Further investigation in these points will result in a more sophisticated price model for the Swedish-Norwegian electricity market. This will be a useful tool for both investors and regulators.

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