Accepted for publication in Energy, 4 Nov 2017
https://doi.org/10.1016/j.energy.2017.11.013

Tradable Green Certificates for Renewable Support: The Role of Expectations and Uncertainty

Magne Hustveit[a], Jens Sveen Frogner[a], Stein-Erik Fleten[a,*]

[a]Department of Industrial Economics and Technology Management
Norwegian University of Science and Technology, NO–7491 Trondheim, Norway

---

Abstract

This paper analyzes tradable green certificate markets, where producers investing in new renewable capacity receive certificates based on their production. These are sold to electricity retailers, who are required to buy certificates in an amount proportional to their total sales. To assess the performance of such a scheme, we develop a stochastic model based on dynamic programming. The goal is to use the structure and rules of this designed market, together with historical data so far, to model and analyze price dynamics, with a view to policy analysis and future market development. Considering the case of the Swedish–Norwegian electricity certificate market, the main findings include: (i) under the current market structure, prices are expected to start at today's level, while decreasing steadily towards zero when approaching the planned end of the market; (ii) the prices are highly sensitive to changes in electricity consumption and generation; So far, the market has shown ample ability to promote cost-efficient investment in renewable electricity production.

Keywords: Renewable portfolio standards, Tradable green certificates, Energy policy, Dynamic equilibrium, Expectations, Uncertainty

---

[*]Corresponding author. Phone: +47 73 59 12 96.

Email addresses: `magnehustveit@gmail.com` (Magne Hustveit), `jens.frogner@gmail.com` (Jens Sveen Frogner), `stein-erik.fleten@iot.ntnu.no` (Stein-Erik Fleten)

1. Introduction

In recent decades, several energy policies for promoting renewable energy sources have been developed. The tradable green certificate (TGC) market in Sweden and Norway is an example of a market-based energy policy. In contrast to a pure subsidy policy, such as the feed-in-tariffs (FIT) used in several European countries, a TGC market is a quantity-based system relying on market forces to determine the certificate price, whereas the feed-in system is a price-based system with greater involvement from the government. The TGC market can be viewed as a subsidy on green energy production and a tax on energy consumption under the restriction of budget neutrality [2]. Producers of renewable electricity receive subsidies through certificates for their production, while consumers of electricity are taxed through the addition of the certificate cost to the bill from their electricity retailer. However, the introduction of TGC quotas reduces wholesale electricity prices because of an increased supply of electricity with a low short-term marginal cost. Thus, the tax burden is fully or partly redirected to the producers of conventional electricity [3].

Both TGC markets and emission trading markets are "...intrinsically susceptible to unstable prices that can potentially swing rapidly from nearly zero to the penalty level, despite relatively small changes in the underlying supply and demand forces" [1, p. 14]. Understanding the price dynamics is of major importance for stakeholders. Green investors must form certificate price expectations. Retailers need to form price expectations when considering the timing of the certificate purchases needed to meet their obligations. Furthermore, the regulators must understand the dynamics of this price formation in order to design markets that function well and yield the desired effects. Earlier works on equilibrium price formation in similar markets for emission allowances include Montgomery [5] and Rubin [6], the latter providing an analysis of the intertemporal effects of banking and borrowing between time-steps. Carmona et al. [7] suggest that the conditional probability for a deficit of allowance credits, times the penalty, characterizes the equilibrium price. In an early work on TGC markets, Morthorst [8] suggests that the certificate price should equal the cost of renewable generation less the electricity price. Coulon et al. [1] and Wolfgang et al. [9] describe stochastic models for TGC markets. While both assume an equilibrium in prices in accordance with the condition suggested in [7], Wolfgang et al. [9] argue that this should not be seen as contradictory to the price equilibrium suggested by Morthorst [8]. Other works analyzing TGC markets include fundamental equilibrium models [3], system dynamic approaches [10], optimal stopping [12], and econometric studies [13].

Addressing the uncertainty in TGC markets should be of the utmost importance to market regulators, both regarding market and policy risk [14]. The value of flexibility increases with uncertainty; thus, technologies with high variable costs and low fixed costs become more attractive as uncertainty rises [16]. Kildegaard [17] finds evidence for this shift toward the low fixed-cost alternative in case studies for TGC markets in Britain, Sweden, and Texas. Furthermore, he argues that there is an asymmetric risk of overinvestment, resulting in collapsing certificate prices and thus capital losses. Either this will prevent the investor from building new capacity or the investor will require a significant risk premium as compensation. Haas et al. [18] find that their intrinsic stability appears to be a key element in the success of FIT systems. Furthermore, they find that TGC systems are less effective with respect to deployment of less mature RES-E. This view is supported by Bergek and Jacobsson [19]. Agnolucci [20] argues that long-term contracts offered to producers yield more certainty for green investors and thus decrease the price of certificates. Van der Linden et al. [21] discuss cases where retailers are obliged to offer such long-term contracts, resulting in a gradual convergence of the TGC market toward a FIT regime. Amundsen et al. [22] find that banking reduces price volatility significantly and also lowers average prices.

Despite the clear need for a better understanding of the price dynamics in a TGC market, there is a limited amount of research addressing the price volatility and stabilization mechanisms of such markets. This paper contributes to a better understanding of the dynamics in such markets, through a case study on the Swedish–Norwegian electricity certificate market. A flexible way of analyzing this TGC market is proposed, based on stochastic dynamic programming. The model extends the work of Coulon et al. [1] on the New Jersey SREC market, by adding the penalty fee as a state variable and including relationships between green investments, the electricity market, and the cost of such investments. Furthermore, it incorporates all the important features present in a TGC market, such as a price-dependent endogenous green investment rate, an exogenous quota requirement, a penalty level, and stochastic production of eligible electricity. By providing a better understanding of the formation of price expectations, the investment rationale, and the role of uncertainty, this paper contributes to the ongoing debate on the design of energy policies. The proposed approach can also be a supplementary tool for traders, investors, retailers, and regulators.

This paper is organized as follows. Section 2 provides an overview of the dynamics in the market. Section 3 proposes a method for specifying the investors' expectations of electricity prices. Section 4 introduces the electricity certificate model. Section 5 explains the calibration of the model along with the results from the base case. Section 6 provides an analysis of the market for different supply and demand scenarios, different investment rationales, and suggested policy changes. Section 7 concludes.

2. Market Dynamics

This section discusses how price expectations are formed, the effects of a price dependent penalty, and how investment decisions are made in this market. In the Swedish–Norwegian electricity certificate market, the regulators specify a target regarding new annual renewable generation. The regulators decide which projects fulfill the requirements for receiving certificates, thus establishing market supply. Qualified producers receive certificates based on their actual monthly eligible production. New power plants have to be in operation by the end of 2020 to receive certificates. Certificates are then received monthly for a period of 15 years from the time when operations start. 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 established by imposing a requirement on each individual retailer as a proportion of the actual amount of electricity sold to customers. If a retailer does not fulfill this requirement by holding enough certificates at the compliance dates, he is fined a penalty fee. The penalty fee is calculated as 1.5 times the average price over the 12 months prior to the compliance date. At the compliance date, March 31 every year, the required number of certificates are handed in and canceled. Certificates are traded in the spot and futures market, both over-the-counter and on the Nasdaq OMX.

2.1. Price Expectations

The formation of certificate price expectations in the market is of major importance. Demand for certificates is based on consumers' total consumption of electricity. This consumption is exposed to annual variation; thus, the annual demand for certificates is not easily predictable. The supply of certificates depends on actual generation of electricity, which for most renewable sources is affected by weather conditions. It is found to vary between years in addition to having a seasonal variance. For Denmark, it is estimated that the maximum variation in annual wind power generation is approx. ±20%, with a standard deviation of approx. 10% [22]. As the short-term marginal cost of wind energy is close to zero, the production decision is based on weather conditions rather than electricity prices. Thus, volatility in the supply of certificates is expected. The following two conditions for explaining rational formation of price expectations are suggested.

1. The time t certificate price p_t^C should be such that the marginal plant is profitable; i.e., the price should equal the difference between the levelized cost of energy (LCoE) of the marginal plant, L_t^m, and the electricity price, p_t^E.
$$p_t^C = L_t^m - p_t^E \tag{1}$$
2. The time t certificate price should equal the discounted value of the expected penalty, π, times the probability of having to pay this penalty; i.e., the probability of a shortage in the certificate balance, b. Here ϕ is an appropriate discounting factor, and $1_{\{b=0\}}$ a function equal to one if the certificate balance becomes zero.

$$p_t^C = \phi \mathbb{E}_t[\pi] \mathbb{E}_t[1_{\{b=0\}}] \tag{2}$$

The first condition follows from the expected profitability of an investment in a TGC market [8], where decisions to invest in renewable electricity capacity are made on the basis of both expected electricity and certificate prices. We assume that investments are made 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, being profitable at a lower certificate price. If the expected prices increase, so does the number of profitable investments. However, expected prices should at all times be such that the expected marginal plant is profitable. Higher prices than this level indicate that the market is not perfectly competitive, as the price is higher than the long-run marginal cost. One should note that investors might hold a real option mindset, putting a high value on the flexibility achieved by delaying an investment; hence, the required certificate price for making an investment might be higher than the price suggested by (1) [23, 24].

The requirement imposed on the retailers is set such that the investments will add up to the target capacity. Thus, if the market works as planned, combined with perfect foresight of the LCoE of the different investment opportunities, the price level at the end of the investment period is predictable. It is worth mentioning that new investments may cause decreasing electricity prices; thus, a higher certificate price is required for the marginal plant to be profitable. Realistically, the LCoE curve is not known in detail by all players in the market, thus creating slightly different price expectations and more volatile prices. On the other hand, if new investments are less (more) than targeted at the end of the investment period there will be a deficit (surplus) of certificates in the market, and the price of certificates will start rising (falling). Then the regulators are likely to implement changes in market design; e.g., by extending the investment period or reducing the requirement on retailers. Such regulatory changes may cause increased volatility and thus an increased required rate of return [13]. An increased required rate of return results in an increased LCoE; thus, a higher certificate price will be needed for the marginal plant to be profitable.

The second condition follows from the expected payoff of a certificate [1]. When new certificates are issued, electricity producers are faced with the decision of whether to sell their certificates immediately or to bank their certificates and 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 increases to a level at which producers are willing to sell. Hence, a player acting to maximize profit is likely to sell/bank his certificates such that the market reaches an equilibrium where the players are indifferent between selling today and selling tomorrow. Along the lines of Carmona et al. [7], the retailers' willingness to pay is assumed to be equal to the net present value of the penalty that they expect to be imposed if obligations are not met, times the probability of not being able to meet these obligations; i.e., the probability of a shortage of certificates in the market. Predicting these penalty fees is difficult, as they are based on prices observed over the year preceding a given compliance date. Following from this, in a period immediately after a compliance date, no information is available for calculating the penalty fee of the next compliance date. As this compliance date approaches, more information becomes available. The probability of a shortage of certificates is based on the current balance of certificates, the issuance of new certificates, and the requirement imposed on retailers. A lower balance increases expected prices, while a lower requirement level decreases expected prices. As stated in Section 1, both the requirement and the issuance are subject to unpredictable variation on an annual basis. Combined with the unpredictable penalty level, this may, as for the first price condition, cause different price expectations and thus more volatile prices.

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. While this has not been shown empirically, it is natural to assume that the suppliers of certificates ensure the fulfillment of the first condition, and the demand side ensures the fulfillment of the second condition [9].

2.2. Market Instability

The price-dependent penalty has some interesting effects on price expectations and thus prices, and may potentially cause large price increases or decreases. This can be described as a system-inherent instability. An increase in the certificate price will lead to an increase in the expected penalty, which subsequently may cause prices to rise even further. Given no intervention from market regulators, this may result in a spiral that could potentially lead to prices climbing without bound or collapsing toward zero, depending on the initial price movement. As will be discussed below, there seem to be some stabilizing factors in the market, which ensures that spiraling prices do not occur.

For a TGC market in equilibrium, expected increases in demand should be offset by a corresponding increase in expected investment, hence stabilizing the market price. However, following unexpected increases in demand, the lead time of investments create a lag in the increase of generation capacity, causing a mismatch between supply and demand and resulting in a higher price level for some time. The lead time of new capacity will decide the duration of the period needed for the system to stabilize at a new equilibrium level. In the long run, the market will meet an unexpected increase in certificate prices with an increased rate of investment in renewable electricity capacity. This will cause the supply of certificates to increase, which in turns causes falling price expectations and, ultimately, lower prices. Bio power and dammed hydro could to some extent benefit from these periods of higher prices by increasing production. The percentage share of such "stabilizing renewables" in the mix of eligible electricity will decide the magnitude of the described instability.

The percentage share of stabilizing renewable energy sources is low in this market, and investments made after 2020 are not eligible to receive certificates. Hence, other mechanisms are required to avoid the potential market instability [25]. For example, the stabilizing of price expectations will work as such a mechanism. If an initial price movement is not met with a correspondingly large change in penalty expectations and a subsequent change in price expectations, the market will not face upward or downward spiraling prices. Such stabilizing price expectations may stem from a belief among traders that the regulators will act in extreme cases to stabilize the system. This provides an interesting finding about price expectations, particularly that the price expectations are of major importance for observed prices. If prices are expected to remain in a stable range, they most likely will. If prices are expected to change, they may start spiraling upward or downward. Thus, a stable market requires stable price expectations.

2.3. The Investment Decision and Expected Investments

Understanding the rationale behind the investment decision is of major importance when modeling the electricity certificate market [26]. One essential question is whether the regulators' target capacity will be met or whether the total investment will be either lower or higher than the target. Failing to reach the target would again cause prices to rise or fall as described in Section 2.1. Predicting the timing and the level of investment is essential for understanding the rationale behind the investment decision. Three suggested investment rationales are:

1. A given number of investments will be made annually, regardless of the prices and costs.
2. The investment decision is based solely on the certificate price, and a positive feedback from increased prices on the investment level is expected.
3. The investment decision is based on the profit equation for an eligible power plant operating in a TGC market.

The first rationale stems from an assumption that when prices are situated within an expected price range, sufficient profitable investment opportunities exist to reach the capacity target.[1] Thus, all investors who believe their investment opportunities to be among the cheapest will make their investments independent of price movements. In Norway specifically, there are investment opportunities in hydropower that are profitable even if certificates become worthless [27]. Such investments may then be made even if the investor knows this will cause overinvestment and thus a collapse in certificate price. In the opposite case, when the profitability of all investment opportunities depends on the certificate price, it is assumed that investments will not be made if they will cause the total capacity to exceed the target. Additionally, considering the significant lead times of the different technologies, investment decisions must soon be made if the new plants are to be considered eligible. As a result of this, a potential theory could be that all the power plants needed to reach the policy target of new capacity have already been planned. If this is the case, movements in certificate price will be of little to no importance for new investments.

The second rationale suggests that there exist a number of profitable investment opportunities independent of the electricity price and cost structure, and that the number is increasing in increased certificate price.

The third rationale submits that investments will be made if the sum of the electricity price and certificate price minus the LCoE of the invest-

---

[1] Information from a key producer in the Norwegian electricity market indicates that their development of a new hydropower plant does not depend on prices but solely on access to capital.

ment opportunity is greater than zero. If the certificate price is formed according to the first price formation condition presented in Section 2.1, a plant is profitable in the long run if its LCoE is lower than the LCoE of the marginal plant. Furthermore, stemming from this investment rationale, the expected rate of investment will change directly with a change in the expectation of a power plant's marginal profit.

The assumed investment behavior is taken as a combination of the first and third investment rationales; i.e., some investments are a function of time only, while some investments occur if the sum of the expected certificate and electricity price exceeds the LCoE of the investment opportunity. Time-dependent investments are included, as several power plants have already been planned and found to be profitable within a reasonable price range in the studied markets. Other investors are expected to delay their investment decision until their project becomes profitable. These are expected to base their decision on their expectations of certificate and electricity prices. Modeling investments in this way is also expected to capture the downward pressure on prices caused by new investments. The result should be an adequate number of investments, such that the target of new capacity is met, and prices neither climb nor collapse.

3. Electricity Price Simulation

Including a dependency between investments and electricity prices entails a method of assessing and forecasting the investors' long-term expectations of future electricity prices. For this, a Schwartz–Smith two-factor dynamics model [28] has been used:

$$ln(X_t) = \chi_t + \xi_t. \tag{3}$$

Here X_t is the electricity spot price, and χ_t and ξ_t are unobserved state variables representing time t short-term deviations in log prices and time t equilibrium levels for log prices, respectively. Short run deviations (χ_t) are assumed to revert toward zero following an Ornstein–Uhlenbeck process:

$$d\chi_t = -\kappa\chi_t dt + \sigma_\chi dz_\chi, \tag{4}$$

while the equilibrium level (ξ_t) is assumed to follow a Brownian motion process:

$$d\xi_t = \mu_\xi dt + \sigma_\xi dz_\xi. \tag{5}$$

Here κ is the mean reversion coefficient, σ_χ and σ_ξ are the standard deviations, and dz_χ and dz_ξ are correlated standard Brownian motions with correlation $\mathbb{E}[dz_\chi dz_\xi] = \rho_{\chi\xi}$. For the equilibrium level, the drift rate is μ_ξ.

The unobserved state variables are estimated using a Kalman filter process. In typical implementations of the Kalman filter procedure, missing data problems are severe [29]. These known shortcomings have been overcome using the approach of Benth et al. [30] for extracting smooth forward curves from average-based commodity contracts with seasonal variation. The method takes forward contracts with different maturities, observed in the market, and creates smooth forward curves by fitting the contracts to a seasonality function under a maximum smoothness criterion. For any given time to expiry, the resulting forward curves can be interpreted as the future price on a contract with daily settlement. These curves are then used as inputs to the Kalman filter.

Furthermore, following from the output of the Schwartz–Smith two-factor model, the long-term equilibrium level has been used as an input for the electricity certificate model. This is motivated by the assumption that the long-term prices are the ones that are relevant to investors making investment decisions. The expected long-term equilibrium level of the electricity prices is given by Eq. (6), presented in Schwartz and Smith [28]. Here χ_0 and ξ_0 are initial values of short run deviation and equilibrium price, respectively.

$$\begin{aligned} ln(\mathbb{E}[X_t]) &= \mathbb{E}[ln(X_t)] + \frac{1}{2}\mathrm{Var}[ln(X_t)] \\ &= e^{-\kappa t}\chi_0 + \xi_0 + \mu_\xi t \\ +\frac{1}{2}&\left((1-e^{-2\kappa t})\frac{\sigma_\chi^2}{2\kappa} + \sigma_\xi^2 t + 2(1-e^{-\kappa t})\frac{\rho_{\chi\xi}\sigma_\chi\sigma_\xi}{\kappa}\right) \end{aligned} \tag{6}$$

4. Electricity Certificate Model

The electricity certificate model extends Coulon et al. [1] and their equations for modeling the New Jersey solar renewable electricity certificate (SREC) market. Inputs to our model include electricity price dynamics, the quota requirement, parameters characterizing the growth of green electricity generation capacity (typically found by regression analysis of historical data) and information about the levelized cost of energy as a function of accumulated capacity. The objective is to calculate equilibrium (policy) values of the state variables in the stochastic dynamic program: certificate prices, the number of banked certificates over time, expected penalty and the growth of green capacity. The calculated policy allow simulation forward in time, and by changing input parameters we can analyse e.g. the price impact of changes to market rules.

Although similar to the situation in [1], the Swedish-Norwegian market has the notable difference of the penalty being dependent on the electricity price average over the preceding year, rather than being fixed. This characteristic requires the introduction of an additional state variable, the penalty π. Additionally, the model has been extended to include a dependency between investments, the LCoE, and electricity prices, as well as the possibility of infinite certificate banking, present in the Swedish–Norwegian market. All parameters are estimated to reflect historical values from the Swedish market over the period 2004–2011.

4.1. Mathematical Formulation

$$p_t^C = \max_{v \in \{t, t+1, \ldots, T\}} e^{-r(v-t)} \mathbb{E}[\pi_t] \mathbb{E}_t[1_{\{b_v = 0\}}] \tag{7a}$$

$$p_t^C = e^{-r\Delta t} \mathbb{E}(p_{t+1}^C) \text{ when } t \notin \mathbb{N} \tag{7b}$$

The certificate price is modeled in accordance with the second price condition presented in Section 2.1. Eq. (7a) states that at any time t, the value of the certificate p_t^C is the maximum of the discounted expected future penalty fees that it can be used to avoid, discounted at the rate r times the probability of having to pay this penalty. Eq. (7b)—i.e., the Martingale condition—follows implicitly from (7a) and states that, except at compliance dates, the current price is the discounted expected future price. $\mathbb{N}$ notes the set of compliance dates.

$$b_t = \begin{cases} \max(0, b_{t-1} + \int_{t-1}^{t} g_u du - R_t) & t \in \mathbb{N} \\ b_{t-1} + \int_{t-1}^{t} g_u du & t \notin \mathbb{N} \end{cases} \tag{8}$$

Eq. (8) is a standard inventory equation and represents the accumulated number of certificates 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, the equation accounts for a reduction in the number of certificates in the market, equal to the requirement R_t. Negative balance is not allowed, hence the max statement.

$$\begin{aligned} g_t = \hat{g}_t(p_t^C, p_t^E, L_t^m) \exp\,(a_1 \sin(4\pi t) + a_2 \cos(4\pi t) + \\ a_3 \sin(2\pi t) + a_4 \cos(2\pi t) + \varepsilon_t^g) \end{aligned} \tag{9}$$

The seasonality and annual variation in eligible electricity generation, and hence certificate issuance, g_t, is represented in Eq. (9) by a seasonality function and a stochastic process. The state variable $\hat{g}_t$ represents the eligible annual capacity as function of the certificate price, the electricity price, and the LCoE. This is motivated by the assumption that investors are likely to invest more while prices are high. Seasonal changes are specified with the sine and cosine functions, while a noise term, ε_t^g, is added to reflect the uncertainty in generation. The issuance equation describes monthly supply of certificates.

$$\begin{aligned} \frac{ln(\hat{g}_{t+\Delta t}) - ln(\hat{g}_t)}{\Delta t} = a_5 + a_6(\max(0, (p_t^E + \sigma_\xi dz_\xi) \\ + \bar{p}_t^C - L_t^m)) - C_t, \text{ for } a_5 \in \mathbb{R}, a_6 > 0 \end{aligned} \tag{10}$$

As discussed in Section 2.3, the first and third rationale are used as background for modeling new investments. Eq. (10) accounts for the monthly change in eligible generation capacity. The parameter a_6 accounts for the logical effect that producers are likely to invest more as the marginal profits associated with the investment rises. Here $\bar{p}_t^C$ is a "feedback" price function on investment, increasing with higher historical certificate prices. Parameter a_5 represents the growth of generation not related to marginal profit as an independent term describing the drift in investments over time. A noise term $\sigma_\xi dz_\xi$ representing the uncertainty in the equilibrium level is added to the forecast electricity price. C_t represents the monthly phase-out of certificates, occurring when a power plant has received certificates for 15 years.

$$\begin{aligned} \mathbb{E}[\pi_t] = 1.5 \\ \times \begin{cases} \sum_{i=1+max\{1,N|_{\{N<t\}}\}}^{i=t} \frac{p_i^C}{t-max\{1,N|_{\{N<t\}}\}} & t-1 \notin \mathbb{N} \\ (\frac{p_t^C}{2} + \frac{\pi_{t-1}}{2}) & t-1 \in \mathbb{N} \end{cases} \end{aligned} \tag{11}$$

Equation (11) specifies that the expected penalty is a function of all information known in a given month; i.e., the expected penalty equals 1.5 times the average certificate prices since the last compliance date, in accordance with market rules. With an exception for the month directly following a compliance date, where the expected penalty is calculated as 1.5 times the average of the current price and the actual observed penalty from the previous year. This stems from the assumption that agents believe that the prices will remain in a stable range throughout the period, and thus only use the currently available prices to form expectations of the penalty.

$$\bar{p}_t^C = p_t^C \tag{12}$$

To avoid the inclusion of another state variable for the investment decision and preserve computational tractability, we assume that the investment decision is only based on the current price, as the current price captures all future price expectations. Hence, there is an immediate price feedback on eligible generation capacity. This is obtained using Eq. (12). The assumption is justified by Coulon et al. [1], who find that the lead-time of capacity has a modest impact on price forecasts.

4.2. Implementation

The solution algorithm proceeds as follows.

1. A 3-D grid of values for b_t, $\hat{g}_t$ and π_t is chosen. For b_t and $\hat{g}_t$, the lower bounds are zero, and the upper bounds are a little above the largest requirement. For π_t, the lower bound is zero, and the upper bound is a little above the highest expected penalty. Time is discretized in monthly steps, matching the frequency of historical generation data.
2. The dynamic program is initialized, evaluating the certificate payoff at the end of the market's life, $t = T$, at every grid point $(b_t, \hat{g}_t, \pi_t)$. At this point, all information is known, and hence the program yields digital boundary price cubes.
   (a) At grid points where there is a shortage of certificates, investors are willing to pay the penalty, $p_T^C = \pi_T$, for one certificate.
   (b) At grid points where there is a surplus of certificates, investors are willing to pay $p_T^C = 0$ for one certificate.
3. From the boundary cube at $t = T$, the dynamic program steps backward to $t = (T - 1)$. Here it solves eqs. (7)–(12) and finds a price at every grid point using price information from the price cube at $t = T$. The same procedure is then followed recursively for every time step.[2]

The algorithm provides a price cube at every single time step. Starting from the currently observed eligible capacity $\hat{g}_0$, accumulated certificates in the market b_0, penalty level π_0, and time t_0, the state transition equations (7)–(12) are used to obtain the certificate price, p_t^C, the eligible capacity $\hat{g}_t$, the accumulated certificates in the market b_t, and the penalty level π_t for every time step throughout the period. The price cubes show what the price would be at each time step, given a state $(b_t, \hat{g}_t, \pi_t)$. An example of the content of these cubes is shown in Figure 1, plotting the prices obtained for a chosen π_t over the grid $b_t, \hat{g}_t$ for December 2020, the last time step for capacity to be eligible in the Swedish–Norwegian market.[3] As seen in Figure 1, the certificate price is upward restricted by the ex-

---

[2] Solved with the FORTRAN subroutine *nag_roots_withdraw_sys_func_easy (c05nb)* from the NAG Toolbox for MATLAB [31], using the Powell hybrid method.

[3] For the given resolution level, the runtime of this procedure is approximately one hour on an Intel(R) Core(TM) i7-3770 CPU, multithreading at 3.4 GHz on all four available cores. Parallel processing and FORTRAN subroutines have been introduced to keep the model computationally tractable.

pected penalty cost in the highest plateau. This extreme is obtained with the combination of low banking and low capacity, as expected. The price is downward restricted by zero for the opposite. When the level of banking is higher than some threshold, a second plateau is present under low capacity. Further, for the certificate price not taking the value of one of the extremes, capacity and/or banking level must fall within a specific region for each time step.

[Figure 1 about here]

5. Model Calibration and Base Case Results

5.1. Model Input Estimation

The Schwartz–Smith procedure described in Section 3 yields the results shown in Figure 2. The figure shows estimated prices, observed prices, and equilibrium prices. Eq. (6) and parameters obtained by the Schwartz–Smith procedure, shown in Table 1, are used to calculate the long-term equilibrium level shown in Figure 3. This is used as a proxy for investor expectations of the electricity price.

[Figure 2 about here]

[Table 1 about here]

[Figure 3 about here]

The input data for compliance requirements R_t and the LCoE curve are based on numbers from the Norwegian Water Resources and Energy Directorate (NVE) and the Swedish Energy Agency [32, 33, 34].[4] The annual requirement is calculated based on their forecasts of electricity consumption, multiplied by the requirement quotas. Furthermore, all known investment opportunities are sorted based on their estimated LCoE. It is assumed that the least expensive investments are made first. Thus, in every month a certain number of investments are made. The least expensive investment opportunities in the next month will then have similar or higher

---

[4] NVE and the Swedish Energy Agency are the regulators of this certificate market.

LCoEs than those in the current month. Repeating this procedure for every month yields a time-dependent LCoE curve.[5] Cost reductions from technology development are omitted, as the investment period only lasts until 2020. The timing of the phase-out of power plants has been calculated based on data from all 4557 currently eligible power plants, and expected annual investments. The discount rate for the price equation is set to 9.5%, reflecting the required rates of return at which the retail sellers in the Scandinavian electricity market operate.[6] The discount rate assumed in the calculation of the LCoE for investment opportunities in Norway and Sweden has been set to 4% and 8% by the NVE and the Swedish Energy Agency, respectively. Furthermore, the stochastic generation function is calibrated from historical data on issuance of certificates and prices, available from Ref. [35].

$$\begin{aligned} ln(g_t) = a_0 + a_1 sin(4\pi t) + a_2 cos(4\pi t) + a_3 sin(2\pi t) + \\ a_4 cos(2\pi t) + a_5 t + a_6(\max(0, p_t^E + \bar{p}_t^C - L_t^m)) + \varepsilon_t^g \end{aligned} \tag{13}$$

Eq. (13) combines (9), (10), and (12) to allow parameter fitting, where a_0 is an intercept term. The regression of certificate generation yields the coefficients shown in Table 2. The bootstrapped confidence intervals of these coefficients are shown in Table 3. As the regression is nonlinear, the goodness of fit is assessed based on the coefficient standard errors, the coefficient confidence intervals, and a visualization of the regression shown in Figure 4. Testing and concluding whether the relationship between marginal profit and generation—i.e., a_6—is significantly different from zero is difficult. It is, however, likely that the coefficient is positive, because some level of profit feedback is expected.

[Table 2 about here]

[Table 3 about here]

[Figure 4 about here]

---

[5] The LCoE for the relevant period spans from €30/MWh to €46/MWh.

[6] Source: Bjørn Erik Heiberg, Pareto (a financial advisory firm).

The Q-Q-plot of the residuals shown in Figure 5 indicates that the error terms are close to normally distributed, although there are some outliers in the lower left and the upper right corner. It is also noted that the residuals do not show any patterns of autocorrelation. The characteristics of the error term, shown in Table 4, are identified. The residuals demonstrate minor excess kurtosis and negative skewness, but a normal distribution can still be used to simulate noise. Thus, the renewable generation noise term ε_t^g in Eq. (9) is modeled as normal, with zero mean and standard deviation 0.08. For the electricity price stochastic term, $\sigma_\xi dz_\xi$, the standard deviation σ_ξ is obtained from the calibration of the Schwartz–Smith long term factor ξ.

[Figure 5 about here]

[Table 4 about here]

5.2. Model Output for Base Case Scenario

This section presents the base case for the simulation of the certificate market. The model is run for the input described in Section 5.1 from April 2015 until the last compliance date in March 2035. The requirement quota adjustment, suggested by the regulators in the last progress review[7] [34], is included. Figure 6 presents the resulting certificate prices, balance of certificates, eligible investments, and normal annual production of electricity from eligible power plants.

[Figure 6 about here]

Figure 6a shows stable but declining prices. The red line represents the average of 100 model realizations represented by the blue lines. Toward the end of the period, a large difference between scenarios is observed. When the market approaches its planned end in 2035, the modeled prices decline rapidly toward zero, as there is an expected surplus of certificates throughout the market's lifetime. As time passes, the probability of scenarios resulting in a future deficit of certificates decreases. Similar results are found by Wolfgang et al. [9].

---

[7] Progress reviews are scheduled every four years to decide on regulatory adjustments to the market parameters.

Figure 6b plots the accumulated investment in eligible capacity, as forecast by the model, against time. A stable increase in investments is seen until the end of the qualification period in 2020. The parameters estimated in Section 5.1 show the time-dependent term to be substantially larger than the profit feedback term. Thus, the time-dependent term accounts for a large proportion of the expected investments, resulting in a low level of uncertainty in the number of investments. Different scenarios for the investment relation will be further analyzed in Section 6. As seen from the figure, the model expects the policy target of 26.4 TWh of additional capacity from renewable energy sources to be met.

One can surmise that the market is designed so that a small certificate surplus is expected if the policy target regarding green investment is met. This is reflected in Figure 6c. The target is met and a balance surplus is seen throughout the period. The monthly increase in the certificate balance represents the expected monthly production of electricity, which in turn reflects the monthly issuance of certificates. The large annual decreases represent the cancellation of required certificates at compliance dates.

Figure 6d shows the expected level of eligible annual capacity. Until the end of 2020, the eligible capacity is expected to increase from the investments seen in Figure 6b. In 2018, the first power plants declared to be eligible have received certificates for 15 years, and the first phase-out of eligible capacity occurs. In Figure 6d, this is best seen in the decline after 2020, when no new investments receive certificates. In 2035, when the market is planned to end, all the power plants have been phased out.

6. Analysis

This section analyzes and discusses how market changes will impact the market, with basis in the proposal by the regulators in the last progress review. Additionally, changes in certificate supply and demand, different alternatives for the investment decision rationale, and different mechanisms for forming penalty fee expectations are explored. Unless stated otherwise, input parameters are equal to those presented in the base case discussion.

6.1. Changes in Certificate Demand

[Figure 7 about here]

This section investigates the effects of changes in certificate demand, either from changes in electricity consumption or the requirement quota. Figure 7 illustrates three scenarios with varying quota level, compared with the base case. Figure 7a depicts that a lower certificate demand, yields lower prices throughout the period. This is natural, as the probability of scenarios with a shortage of certificates decreases with an increased certificate balance. Correspondingly, a higher demand yields a lower certificate balance and hence higher prices throughout the period. The mechanism is illustrated in Figure 7b, which relates the minimum annual balance to the price level. The effect is noticeable even for small changes in demand. A realistic variance in eligible electricity production is found to cause similar variance in certificate prices. In both cases, extreme scenarios forcing prices to climb without bound or to collapse toward zero can be observed. This illustrates the importance of stability in demand and supply for the formation of stable prices. Market actors report the estimation of consumption as a source of uncertainty [36]. This is supported by the large price changes seen from the model even for slight adjustments of input parameters. The updated forecast for electricity consumption, provided by the Norwegian regulator, shows an annual 3–7% difference compared with the forecast provided at the launch of the market. Thus, such variation in the requirement can be considered to be realistic.

6.2. Regulators' Suggested Market Changes

The regulators' suggestions for the last progress review include four main elements [34]:

1. A slight adjustment of the quota path, to balance the market.
2. Extending the investment period with one year, to the end of 2021, while shifting the quota path upward to compensate for the increasing supply.
3. Increasing the target of additional renewable energy capacity by 2 TWh to 28.4 TWh by shifting the quota path upward.

The suggested adjustment of the quota path is already included in the base case; the other suggested changes are discussed in the following section.

[Figure 8 about here]

The forecasted certificate price and balance, if new investment are to be considered eligible until the end of 2021, are shown in Figure 8. An extension of the investment period lowers the probability of good investments missing out on benefits due to lead-time issues. However, as seen in Figure 8b, some of the investments are not expected to be made until 2021. This leads to a lower issuance of certificates in the preceding years, causing long-term effects on both the certificate balance and the certificate prices. The lowered issuance lowers the balance, and thus higher and more volatile certificate prices are forecast throughout the period. Approaching 2035, large variations between the generated market realizations are observed, following from uncertainty of whether enough certificates will be available to fulfill the certificate obligations. If a deficit of certificates is expected, the prices will start climbing years in advance, and consequently the penalty fee could start spiraling upward. This scenario illustrates the importance of timing new investments. Even for this modest system change, both the expected prices and the volatility increases significantly. The regulators could avoid such effects by making appropriate changes to the requirement quotas.

[Figure 9 about here]

Figure 9 presents the expected prices and balance following an increase of the target to 28.4 TWh. The expected reduction in the certificate price caused by this change is estimated to be €0.91/MWh in 2020. A linear change in requirement quota is assumed to account for the additional issuance of certificates. For the first few years, the prices are slightly higher than in the base case; they do, however, follow a similar path throughout the period.

Common to all the suggested changes in regulations is the risk of investors losing trust in a frequently revised market. This may increase volatility, leading investors to require a higher rate of return. Furthermore, considering a change in market regulations, its effects on supply and demand should be thoroughly assessed, as these are shown to impact prices substantially. Frequent adjustments of requirement quotas are necessary to balance the system when the regulators' electricity consumption forecasts are updated. As mentioned, estimating this consumption has been reported by actors as a considerable source of market uncertainty [36]. An alternative that might ease the formation of market expectations could be to change certificate requirement from being based on consumption of electricity to an absolute number of certificates per year. Thus, the only uncertainty would be in supply, with the stochastic issuance of certificates.

6.3. Penalty Expectations

The expectations of the penalty fee are an important factor in the formation of price expectations. Thus, it is important that Eq. (11) is able to capture future expected prices in the forecast of a given time step correctly. If a more naive price approach is utilized, wherein an actor in the market expects the certificate price over the remainder of the year to equal the certificate price observed at that time step, the model gives identical results to the base case. Such an approach gives more weight to the current price, which imply higher sensitivity to changes in electricity prices should be anticipated. However, as the model yields the same results, this suggests that Eq. (11) captures future expected prices correctly.

6.4. Investment Decision Rationale

The investment equation, Eq. (10), is presented in Section 4.1, with parameter regression in Section 5.1. As seen from Table 2, weak signs of feedback from expected profits or certificate prices on investments are exhibited. This section investigates how a stronger feedback mechanism would influence the market. Figure 10 illustrates market forecast realizations given the investment rationale in (10), for three different levels of profit feedback, a_6, on investments, and a fixed time-dependent drift term. Figure 11 illustrates a scenario given the second investment rationale presented in Section 2.3, formulated in Eq. (14), where the certificate price is assumed to drive investments alone.

[Figure 10 about here]

[Figure 11 about here]

$$\frac{ln(\hat{g}_{t+\Delta t}) - ln(\hat{g}_t)}{\Delta t} = a_7 \bar{p}_t^C, \text{ for } a_7 > 0. \tag{14}$$

Figure 10 illustrates that only small differences in forecasts are observed for medium and high profit feedback on investments. This is because of the downward pressure on certificate prices resulting from new investments. Even for very high feedback, the accumulated investment does not increase substantially, as this is expected by the model to cause a collapse in certificate prices. Thus, the two scenarios turn out to be nearly identical. The scenario with a lower feedback yields higher prices. This stems from the total investments being slightly below the target, thus causing a lower level of certificate issuance and balance throughout the period. Compared with the base case, the resulting prices are lower throughout the period and increasing in the first few years. This stems from more investments in the beginning of the period, decreasing certificate prices, followed by a slightly higher balance throughout the period. We conclude from this that a higher profit feedback on investments yields higher investments, and hence lower prices, until a certain level where further investments are unprofitable because of the low certificate price. Figure 11 presents lower prices throughout the period. This is because of accumulated investment being higher than the target, thus increasing the supply of certificates. This shows that when investments are driven solely by the certificate price scenarios, overinvestment is more likely to occur. Realistically, such scenarios may occur if low-cost investments are made in spite of the capacity target being exceeded, as such investments may be profitable even for low certificate prices.

7. Conclusions

This paper analyzes the characteristics of electricity certificate markets, through a case study of the Swedish–Norwegian market. The purpose is to achieve better understanding of the dynamics of certificate markets, to assess the role of uncertainty and expectations, and to analyze consequences of changes in market structure by regulators. We utilize a stochastic dynamic programming approach that extends the model of Coulon et al. [1], and continues the analysis of Wolfgang et al. [9], by including the price-dependency of penalty cost present in this market.

We find that the certificate price is expected to remain at the current level over the next few years, while steadily declining toward zero when approaching the planned end of the certificate market. This complies qualitatively (but not in numbers) with [9, p. 331] and [1, p. 24]. However, we find that small changes to the market structure or in the levels of electricity generation or consumption produce large shifts in the certificate price. From this, the formation of rational price expectations is challenging and presents the main disadvantage of TGC markets. The investors and retailers in the market report that they want more predictable supply and demand, allowing for better forecasts of market development. We have found that periodic adjustments of the requirement quota are necessary to achieve stable prices throughout the lifetime of the market.

We also find that the price depends largely on the behavior of the market participants. In particular, the possibility of overinvestment constitutes a threat to market stability. Furthermore, we find that the price-based penalty accelerates price changes to a new equilibrium level and causes more volatile prices. Recently, the regulators have suggested several changes to the market design.

Our analysis shows that these may influence the price drastically if the requirement quotas are not changed accordingly. However, it is not obvious how such changes in the quota level should be made. Therefore, it is difficult for market participants to estimate certificate price changes following adjustments in market design and we conclude that investors make investment decisions under substantial uncertainty. Thus, low fixed-cost technologies may be prioritized before high fixed-cost technologies. Improvements made to stabilize the market could be beneficial.

Acknowledgements

The authors are grateful for the valuable input of Ove Wolfgang and the insight provided by Leif Inge Husabø of NVE, as well as the help with preparing the manuscript from Tord Olsen. Further, Fleten acknowledges financial support from the Research Council of Norway through projects 228811 and 268093.

References

[1] Coulon, M., Khazaei, J., Powell, W.B.. SMART-SREC: A stochastic model of the New Jersey solar renewable energy certificate market. Journal of Environmental Economics and Management 2015;73:13–31.

[2] Aune, F.R., Golombek, R., Kittelsen, S.A.C., Rosendahl, K.E.. Liberalizing European Energy Markets: An Economic Analysis. Edward Elgar Publishing Ltd.; 2008.

[3] Unger, T., Ahlgren, E.O.. Impacts of a common green certificate market on electricity and CO2-emission markets in the Nordic countries. Energy Policy 2005;33(16):2152–2163.

[4] Rathmann, M.. Do support systems for RES-E reduce EU-ETS-driven electricity prices? Energy Policy 2007;35(1):342–349.

[5] Montgomery, W.D.. Markets in licenses and efficient pollution control programs. Journal of Economic Theory 1972;5(3):395–418.

[6] Rubin, J.D.. A model of intertemporal emission trading, banking, and borrowing. Journal of Environmental Economics and Management 1996;31(3):269–286.

[7] Carmona, R., Fehr, M., Hinz, J., Porchet, A.. Market design for emission trading schemes. SIAM Review 2009;52(3):403–452.

[8] Morthorst, P.E.. The development of a green certificate market. Energy Policy 2000;28(15):1085–1094.

[9] Wolfgang, O., Jaehnert, S., Mo, B.. Methodology for forecasting in the Swedish—Norwegian market for el-certificates. Energy 2015;88:322–333.

[10] Ford, A., Vogstad, K., Flynn, H.. Simulating price patterns for tradable green certificates to promote electricity generation from wind. Energy Policy 2007;35(1):91–111.

[11] Aune, F.R., Dalen, H.M., Hagem, C.. Implementing the EU renewable target through green certificate markets. Energy Economics 2012;34(4):992–1000.

[12] Benth, F.E., Eriksson, M., Westgaard, S.. Optimal management of green certificates in the Swedish–Norwegian market. Journal of Energy Markets 2017;10(2):1–39.

[13] Fagiani, R., Hakvoort, R.. The role of regulatory uncertainty in certificate markets: A case study of the Swedish/Norwegian market. Energy Policy 2014;65:608–618.

[14] Boomsma, T.K., Meade, N., Fleten, S.E.. Renewable energy investments under different support schemes: A real options approach. European Journal of Operational Research 2012;220(1):225–237.

[15] Boomsma, T.K., Linnerud, K.. Market and policy risk under different renewable electricity support schemes. Energy 2015;89:435–448.

[16] Kallapur, S., Eldenburg, L.. Uncertainty, real options, and cost behavior: Evidence from Washington State hospitals. Journal of Accounting Research 2005;43.

[17] Kildegaard, A.. Green certificate markets, the risk of over-investment, and the role of long-term contracts. Energy Policy 2008;36(9):3413–3421.

[18] Haas, R., Resch, G., Panzer, C., Busch, S., Ragwitz, M., Held, A.. Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources — lessons from EU countries. Energy 2011;36(4):2186–2193.

[19] Bergek, A., Jacobsson, S.. Are tradable green certificates a cost-efficient policy driving technical change or a rent-generating machine? lessons from Sweden 2003-2008. Energy Policy 2010;38(3):1255–1271.

[20] Agnolucci, P.. The effect of financial constraints, technological progress and long-term contracts on tradable green certificates. Energy Policy 2007;35(6):3347–3359.

[21] Van der Linden, N.H., Uyterlinde, M., Vrolijk, C., Ericsson, K., Khan, J., Nilsson, L., et al. Review of international experience with renewable energy obligation support mechanisms. Tech. Rep.; Energy research Centre of the Netherlands ECN; 2005.

[22] Amundsen, E.S., Baldursson, F.M., Mortensen, J.B.. Price volatility and banking in green certificate markets. Environmental & Resource Economics 2006;35(4):259–287.

[23] Linnerud, K., Andersson, A.M., Fleten, S.E.. Investment timing under uncertain renewable energy policy: an empirical study of small hydropower projects. Energy 2014;78:154–164.

[24] Fleten, S.E., Linnerud, K., Molnár, P., Nygaard, M.T.. Green electricity investment timing in practice: Real options or net present value? Energy 2016;116:498–506.

[25] Khazaei, J., Powell, W.B., Coulon, M.. ADAPT: A price-stabilizing compliance policy for renewable energy certificates: The case of SREC markets. Operations Research 2017;In press.

[26] Linnerud, K., Simonsen, M.. Swedish-Norwegian tradable green certificates: Scheme design flaws and perceived investment barriers. Energy Policy 2017;106:560–578.

[27] Fleten, S.E., Ringen, G.. New renewable electricity capacity under uncertainty: The potential in Norway. The Journal of Energy Markets 2009;2(1):71–88.

[28] Schwartz, E.S., Smith, J.E.. Short-term variations and long-term dynamics in commodity prices. Management Science 2000;46:893–911.

[29] Schwartz, E.S.. The stochastic behavior of commodity prices: Implications for valuation and hedging. The Journal of Finance 1997;52:923–973.

[30] Benth, F.E., Koekebakker, S., Ollmar, F.. Extracting and applying smooth forward curves from average-based commodity contracts with seasonal variation. The Journal of Derivatives 2007;15:52–66.

[31] MATLAB, . version 7.10.0 (R2014a). Natick, Massachusetts: The MathWorks Inc.; 2014.

[32] Weir, D.. Kostnader i energisektoren. Tech. Rep.; NVE; 2015. URL `http://publikasjoner.nve.no/rapport/2015/rapport2015_02a.pdf`.

[33] Westin, P., Stenkvist, M.. Produktionskostnadsbedömning för vindkraft i Sverige. Tech. Rep. ER2014:16; The Swedish Energy Directorate; 2014.

[34] NVE, , Energimyndigheten, . Summary of the review of the electricity certificates system. Tech. Rep.; 2014. URL `http://publikasjoner.nve.no/rapport/2014/rapport2014_15.pdf`.

[35] Statnett, . Norwegian Energy Certificate System. Accessed May 24, 2015. URL `http://necs.statnett.no/`.

[36] Regjeringen, . Prop. 97 l (2014-2015). Accessed May 24, 2015. URL `https://www.regjeringen.no/nb/dokumenter/prop.-97-l-2014-2015/id2406493/?docId=PRP201420150097000DDDEPIS&q=&navchap=1&ch=4`.

Figures and tables

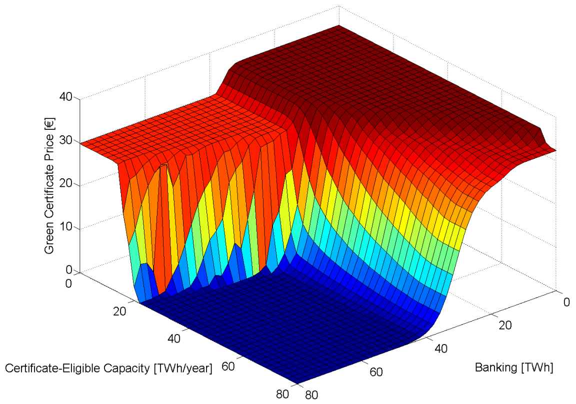


Figure 1: Price surface for t = 69 (December, 2020). Profit feedback (a_6) = 1×10^{-4}

Table 1: Parameters for the electricity price dynamics obtained from the Kalman filter

κ	σ_χ	λ_χ	μ_ξ	σ_χ	$\rho_{\chi,\xi}$	χ_0	ξ_0
5.15	0.84	-1.21	-0.01	0.20	-0.17	3.19	-1.56

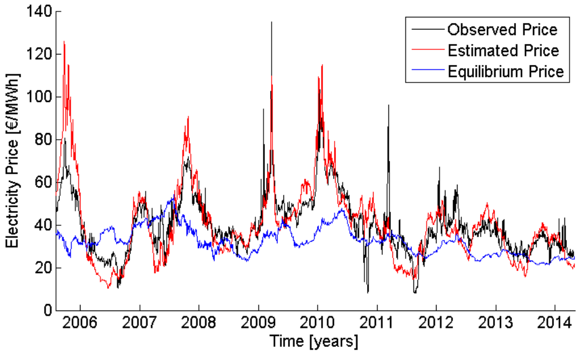


Figure 2: Schwartz–Smith two-factor model output

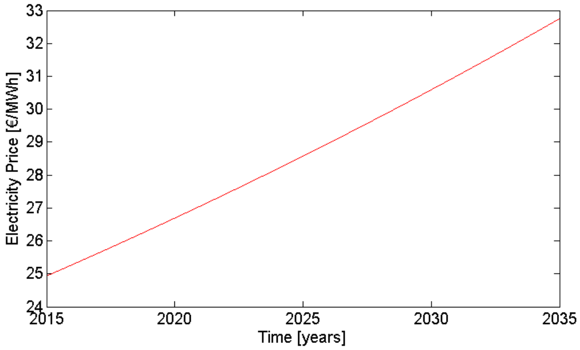


Figure 3: Schwartz–Smith long-term factor

Table 2: Regressed parameters for the certificate issuance seasonality function (13)

a_0	a_1	a_2	a_3	a_4	a_5	a_6
13.627	0.070	0.010	-0.309	0.221	0.087	0.0001

Table 3: Confidence intervals of regressed coefficients

	2.5%	97.5%
a_0	13.58	13.67
a_1	0.046	0.094
a_2	-0.015	0.034
a_3	-0.334	-0.285
a_4	0.197	0.245
a_5	0.007	0.008
a_6	-0.024	0.012

Table 4: Error term characteristics for the renewable generation regression

Mean	Std. Dev.	Skew	Excess Kurt.
0.000	0.080	-0.628	0.106

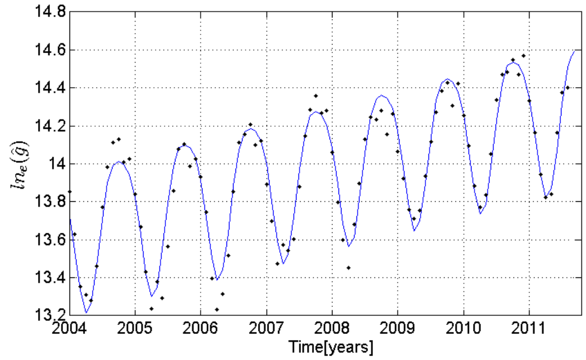


Figure 4: Eligible renewable generation (issuance) and regression fit

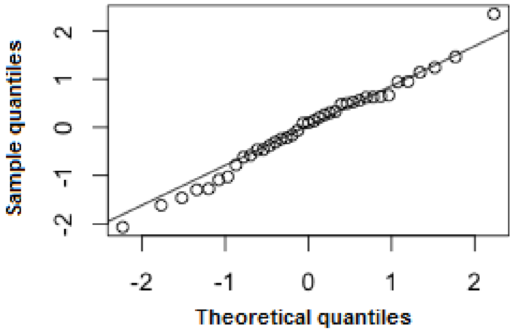
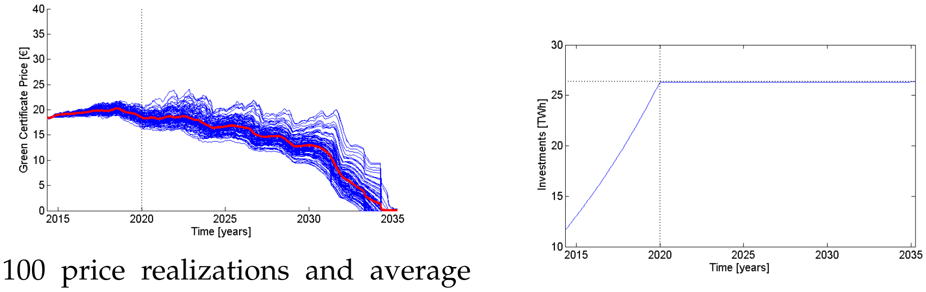
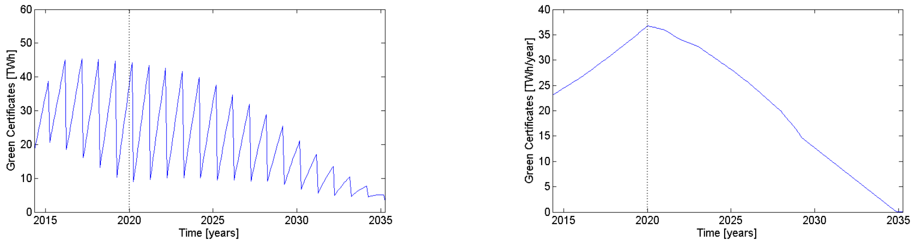


Figure 5: Normal Q-Q plot of standardized residuals



(a) 100 price realizations and average (red curve)

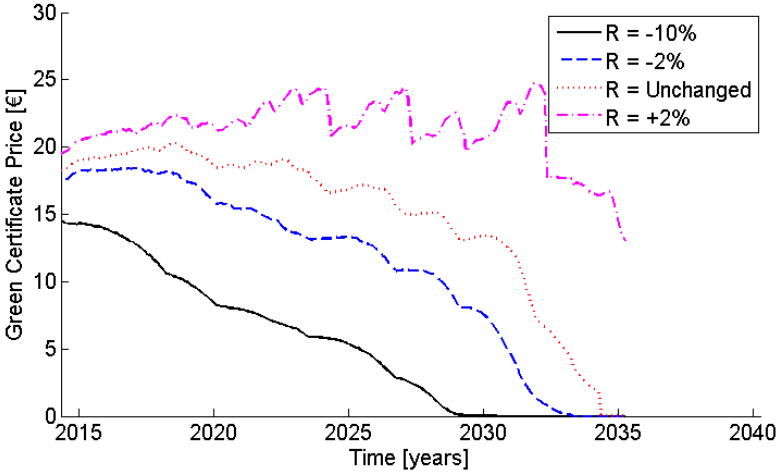
(b) Accumulated investment



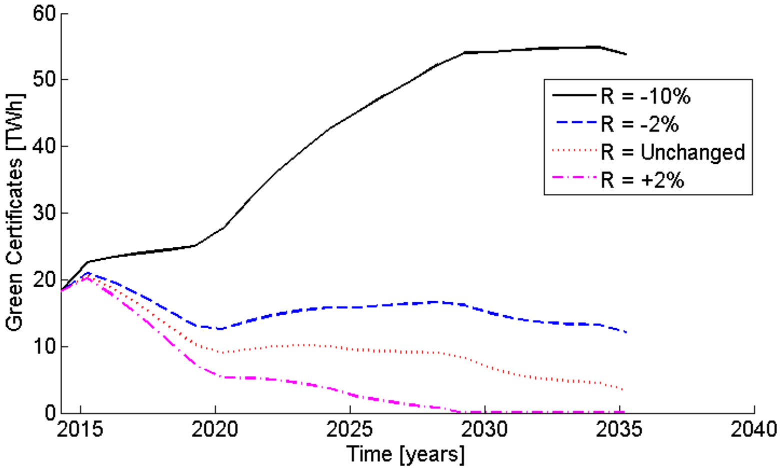
(c) Certificate balance

(d) Annual eligible capacity

Figure 6: Base Case Illustrations

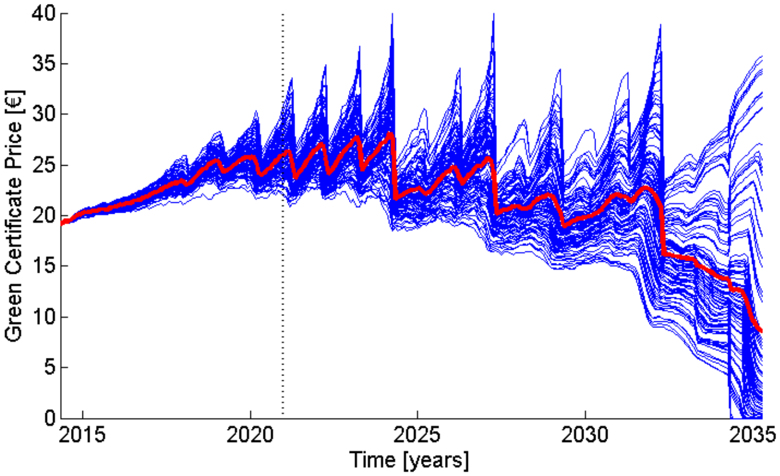


(a) Average of 100 price realizations

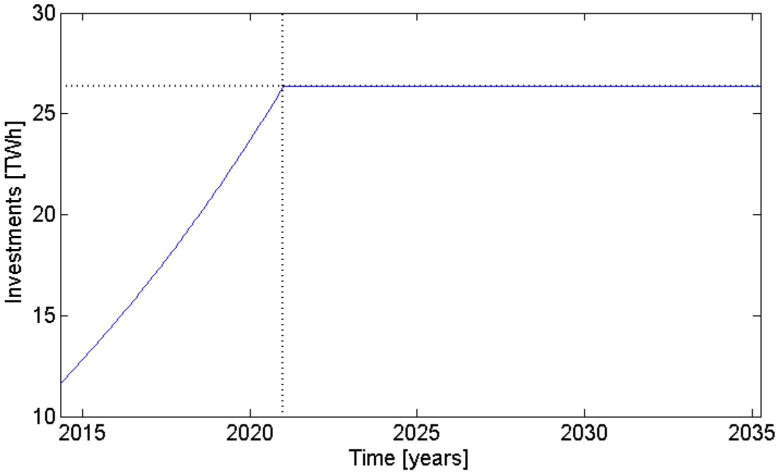


(b) Yearly minimum certificate balance

Figure 7: Varying the quota level *R*

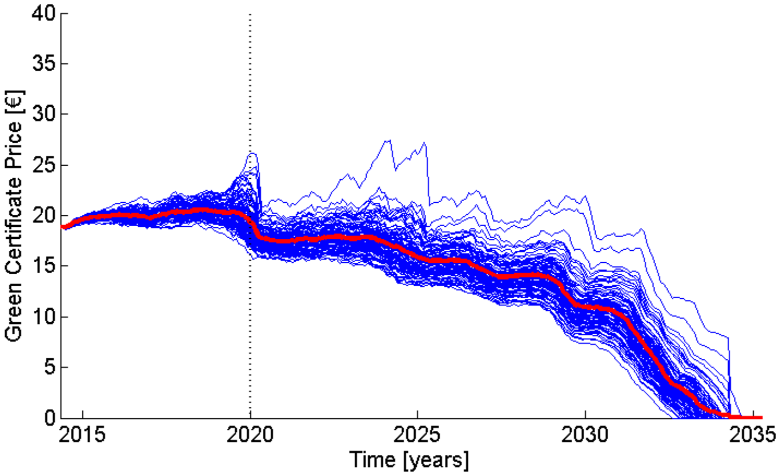


(a) 100 price realizations and average (red curve)

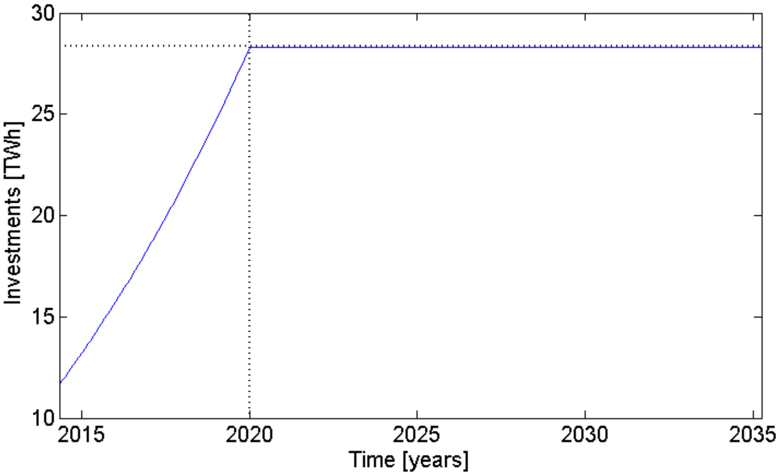


(b) Accumulated investment

Figure 8: Extension of the investment period to the end of 2021



(a) 100 price realizations and average (red curve)



(b) Balance

Figure 9: Increased target capacity to 28.4 TWh

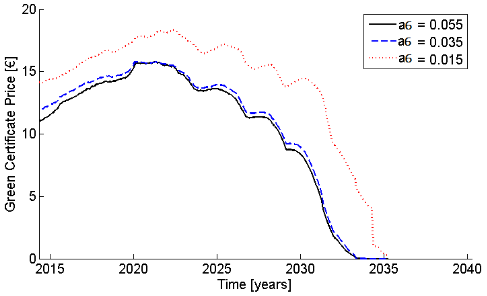


Figure 10: Prices for different levels of profit feedback on investments. The time-dependent drift term (a_5) is 0.072

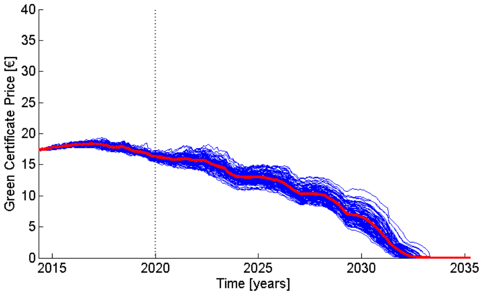


Figure 11: Prices from the model with a modified price-driven investment equation, the feedback parameter (a_7)=0.005