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METHODOLOGY FOR FORECASTING IN THE SWEDISH-NORWEGIAN MARKET FOR EL-CERTIFICATES

Ove Wolfgang, Stefan Jaehnert, Birger Mo

SINTEF Energy Research, Sem Saelands v. 11, NO 7034 Trondheim, Norway.

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Abstract: In this paper we describe a novel methodology for forecasting in the Swedish-Norwegian el-certificate market, which is a variant of a tradable green certificate scheme. For the forecasting, the el-certificate market is integrated in the electricity-market model EMPS, which has weekly to hourly time-step length, whereas the planning horizon can be several years. Strategies for the certificate inventory are calculated by stochastic dynamic programming, whereas penalty-rates for non-compliance during the annual settlement of certificates are determined endogenously.

In the paper the methodology is described, and we show the performance of the model under different cases that can occur in the el-certificate market. The general results correspond to theoretical findings in previous studies for tradable green certificate markets, in particular that price-scenarios spread out in such a way that the unconditional expected value of certificates is relatively stable throughout the planning period. In addition the presented methodologies allows to assess the actual dynamics of the certificate price due to climatic uncertainty. Finally, special cases are indentified where the certificate price becomes excessively high respectively zero, due the design-specific dynamics of the penalty rate.

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Key words: El-certificates, TGC, electricity, forecasting, RES-E, stochastic dynamic programming, power market

1. Introduction

A variety of support schemes for renewable electricity are in operation in Europe, including market-based instruments such as tradable green certificates (TGCs). In 2006, TGC schemes were in operation in eight EU-countries [1]. Similar solar renewable energy certificate (SREC) markets have emerged in a number of states in USA [2]. The Swedish market for TGCs started in 2003, and from 2012 there is a common market for Sweden and Norway called the el-certificate market. Translations of the Norwegian act and regulations on el-certificates, as well as the Swedish-Norwegian treaty, can be downloaded from [3].

In the el-certificate market, producers obtain 1 el-certificate on their el-certificate account per MWh electricity produced from renewable sources during the first 15 years of operation. On the other side, power suppliers have to purchase a number of el-certificates given by the certificate share for that year multiplied with the number of MWh electricity supplied to end-users that are included in the el-certificate system. Power-intensive industry and a number of other consumers are exempted from requiring el-certificates. If suppliers have too few certificates on their account during the annual

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settlement for the previous year at April 1st, they have to pay a penalty for the deficit. The penalty rate is set to 150 % of the average certificate price for the previous year. This creates a demand for certificates. Certificates can be stored from one year to the next, which is important for stabilizing prices. The certificate shares for consumers are increased year by year until 2020. Afterwards certificate shares are reduced again till the planned end of the system in 2035

The certificates traded in the Swedish-Norwegian el-certificate market shall provide an incentive to invest in new generation assets for renewable energy sources. As a result the certificate system are expected to provide annually 26.4 TWh extra electricity from renewable energy sources in sum for Norway and Sweden by 2020. In order to take investment decision for such generation assets, stakeholders need to know respectively estimate the future certificate price. As this price is not set, but determined through a cap and trade system with an inherently set penalty price advanced forecasting methodologies are required.

In this paper we propose a methodology for forecasting in the common el-certificate market for Norway and Sweden. We present an integrated model for electricity markets and el-certificates markets where the value of certificates is calculated from stochastic dynamic programming with a weekly time-resolution and with endogenously determined penalty-rates. The objective is to provide a forecast for the el-certificate price for a short to medium-term horizon (a number of years), taking into account climatic uncertainties, such as the annual inflow to the hydropower system or the annual wind speeds. These uncertain values will have a significant impact on the power production from the renewable energy sources as well as the availability of el-certificates.

The proposed methodology is implemented in the exisiting power market modeling tool EMPS, as it is well suited to determine optimal storage strategies in case of climatic uncertainties. The proposed stochastic dynamic programming methodology is already used in EMPS to address the challenge of calculating water values. Furthermore, EMPS is a well known and applied model throughout the power sector in the Nordic region.

The paper is organized as follows. In Section 2 we give a brief description of the EMPS model, which is the electricity market model we build upon. The implementation of the el-certificate market is described in Section 3. In Section 4 we show how the model performs for different situations that may occur in the el-certificate market. Conclusions are provided in Section 5.

2. Literature review

There are numerous studies of TGC markets. An early study [4] shows that the equilibrium price for certificates (P^{cert}) will be the production costs for renewable generation (C^{ren}) minus the electricity price (P^{el}).

$$P^{cert} = C^{ren} - P^{el}$$

The cost for renewable generation (C^{ren}) and hence the certificate price will be impacted by the ambition level for renewable generation. Many studies utilize static equilibrium models to derive market equilibrium conditions for TGC schemes. For instance, [5] shows that the impact on end-user prices for electricity is ambiguous. The interaction between markets for electricity, TCGs and emission permits is studied in [6], whereas cost-reductions because of international TCG trade are studied in [7].

Several numerical energy-system models have been adopted to include TGC markets. In optimization models such as MARKAL [8,9] this is typically done by including the effect of such a market. This mean an extra constraint is implemented, requiring that power generation from renewable energy sources shall be at least a given quantity or a share of electricity consumption. The shadow price of such a constraint can provide a good estimation for a certificate price. However, when such models are run separately for several years in a sequence, prices will not reflect the possibility of storing certificates from one year to the next. In agent-based competitive equilibrium models for a given year such as LIBEMOD [7], a new equilibrium condition for the renewable market can be included. The PRIMES model [10] is a deterministic dynamic model for many years including within-year periods. Since it is deterministic, the TGC price can be calculated, which is sufficient for reaching policy-goals for renewable generation. However, there is no uncertainty in the availability of certificate and hence certificate prices or within-year price variation.

The storage of TGCs from one year to the next is called banking. The possibility of banking TGCs has a major effect on prices, as certificates can be stored in years with ample supply to years with scarcity. Such effects can only be analyzed in dynamic models, and preferably with including the stochastics the generation from renewable energy sources. In [11], a competitive market equilibrium with and without banking is derived. In the case of banking, the speculation in TGCs as a financial commodity leads to equilibrium prices such that no expected profits can be made by an arbitrage between different time-steps. While certificates that exist today are perfect substitutes for certificates in the future, the opposite is not true. A certificate cannot be utilized in any settlement before it has been issued. Thus, the expected price for certificates can descend. However, if some certificates are banked from one time-step to the next, the competitive certificate price in the current time-step (P_t^{cert}) must equal the discounted (*β*) expected value in the next time-step $E[P_{t+1}^{cert}]$.

$$P_t^{cert} = \beta E\left[P_{t+1}^{cert}\right]$$

This should not be regarded as a contradiction to the study [4]. Instead one should think of [4] giving the general required certificate price-level for the aggregated market over several years, while [11] provides the expected value for the stochastic price development from one time-step to the next.

Furthermore, the specific design of a TGC market will also influence prices. TGCs have a certain value because there is a probability for certificate deficit and a corresponding penalty during future settlements. If one extra certificate is at disposal in a given settlement-week (*s*), then the expected avoided penalty during this settlement is the penalty rate (P^{pen}) multiplied with the probability for certificate shortage (q_s). As certificates can be stored to future years, the price of certificates in any given week must be equal to the highest of discounted expected-value for all future settlements, cf. [12].

$$P_t^{cert} = \max_s \left\{\beta_s q_s P^{pen}\right\}$$

The model in [12] is developed for the New Jersey SREC market. The interaction with the electricity market is not included as generation from existing solar-power capacity is assumed to be unaffected by electricity prices, and the share of solar-power is small in the electricity market. This, however, is different in the Swedish-Norwegian el-certificate market since production from hydro and bio can be adjusted in response to changes in power prices. Other approaches for analyzing TGC markets include i.a. system-dynamic approaches [13], experiments [14] as well as econometric studies [15].

Resulting from the literature review no numerical simulation model could be found, which analyses the electricity market as well as a green certificate market in an integrated way, including the banking of certificates. In addition, one important feature of the Swedish-Norwegian, the endogenous determined penalty price, has to be addressed. The methodology proposed in this paper should fill this knowledge gap.

3. EMPS model

3.1. General

The EMPS model [16] is a partial model for electricity markets, which is used by producers, regulators and system operators throughout Scandinavia. Especially hydropower is represented in detail, as well as the uncertainty of climatic variables.[1] The model calculates the optimal strategy for the utilization of hydropower reservoirs. Subsequently, the market equilibrium is calculated for each time-step, area and stochastic climate scenario. The model can run in an operational mode, i.e. with predefined capacities for production and transmission, or in investment mode [18]. The el-certificate market is implemented for the operational mode of the model. The aim is to develop a tool for short to medium-term forecasting of el-certificate prices. In the following we give a brief overview of the EMPS model before focusing on the extensions done for the integration of an el-certificate market. See [16] and further references therein for a more comprehensive description of the EMPS model and applied methodologies. Figure 1 shows an example of the geographic spread of a simulated power system.

3.2 Strategy calculation for hydropower

In a first step, an optimal strategy is calculated for the hydropower operation in each of the defined areas. The objective is to maximize the expected profits in the planning period, taking into account the value of water at the planning horizon. The time-resolution is one week. In (1) the area-index is omitted since strategy-calculation is carried out for each area separatly[2]. Each individual hydropower producer is assumed to be a competitive price-taker, which treats future inflow and prices as stochastic variables. All symbols are explained in Appendix A.

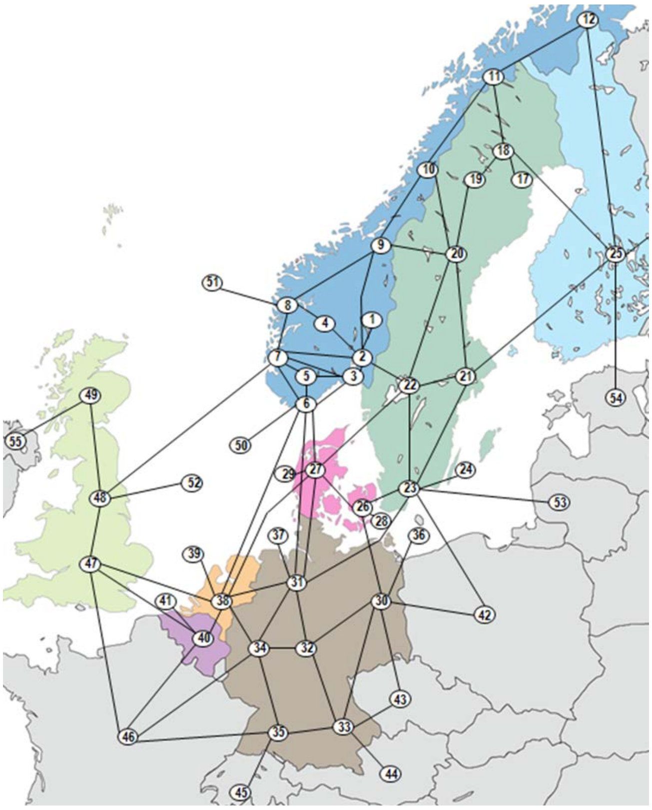

Figure 1 Example of simulated system

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[1] In the context of the EMPS model climatic variables comprise the precipitation (inflow to hydro reservoirs), wind speeds, solar radtion as well as temperatures.

[2] This is the version of the objective function without discounting of future incomes. However the model can also be run with discounting of future incomes as will be shown in Section 4.

$$W_t\left(x_t, u_t^{inflow}, p_t\right) = \text{maximize } \left\{ E_{\left\{u_\tau^{inflow}, p_\tau\right\}} \left[\sum_{t \le \tau \in T} p_\tau \cdot y_\tau + Z\left(x_T\right) \right] \right\} \tag{1}$$

This multi-period problem is transformed to a sequence of two-period problems in (2), i.e. the Bellman-formulation for dynamic problems. The transformation in (2) is based on the premise that the current-week realization of stochastic variables can be observed in the current week.

$$\begin{aligned} W_t\left(x_t, u_t^{inflow}, p_t\right) &= \text{maximize}\left\{ p_t y_t + E_{\left\{u_\tau^{inflow}, p_\tau\right\}} \left[\sum_{t \le \tau \in T} p_\tau y_\tau + Z\left(x_{,t^{final},}\right) \right] \right\} \\ &= \text{maximize}\left\{ p_t y_t + E_{\left\{u_{t+1}^{inflow}, p_{t+1}\right\}} \left[W_{t+1}\left(x_{t+1}, u_{t+1}^{inflow}, p_{t+1}\right) \right] \right\} \end{aligned} \tag{2}$$

The main decision in this problem is to balance the use of reservoir water for production in the current week against saving water to the next week.

$$x_{t+1} = x_t + u_t^{inflow} - y_t - s_t \quad \left(\mu_{t+1}\right) \tag{3}$$

In the strategy calculation water is measured in energy-units and not cubic meters of water. However, efficiencies and head-of-water effects are accounted for iteratively when the problem is solved. Additional constraints in the strategy calculation include production capacity, reservoir capacity, and minimum constraints for reservoir levels and production. In the special case where (3) is the only binding constraint, it is easy to show that combining first-order conditions for y_t and x_{t+1} and applying the envelope theorem gives:

$$\frac{dW_t\left(x_t, u_t^{inflow}, p_t\right)}{dx_t} = E_{\left\{u_{t+1}^{inflow}, p_{t+1}\right\}} \left[\frac{dW_{t+1}\left(x_{t+1}, u_{t+1}^{inflow}, p_{t+1}\right)}{dx_{t+1}} \right] = p_t \tag{4}$$

The first equality is the hydropower reservoir equivalent to the competitive market equilibrium in trade of the TGC inventory as derived by [11]. However, here it refers to hydropower-producers that carry out arbitrage between weeks if possible with their own reservoir. The second equality shows that the expected marginal value of water in the next time-step shall be equal to the power price in the current time. The hydropower producer is a price-taker, but in the model the power price is determined by the residual demand curve for hydropower.

$$p_t = F_t\left(y_t, u_t^{res}\right) \tag{5}$$

The residual demand curve is the total demand minus supply from other technologies than hydropower as well as the trade possibilities with other areas. In the model, heuristic methods are applied to calculate the residual demand allocated to be used for each hydropower area. This methodology greatly reduces computational time because the strategy calculation can be carried out for each area separately. On the other hand the model must be calibrated on basis of the outputs from simulations.

The right hand side of the first equality in (4) represents the water-values, which is the output from the strategy calculation part of the model. Since the equilibrium condition in (5) also will apply for *t+1*, the equilibrium strategy for hydropower is:

$$E_{\left\{u_{t+1}^{inflow}, u_{t+1}^{res}\right\}} \left[\frac{dW_{t+1}\left(x_{t+1}, u_{t+1}^{inflow}, F_{t+1}\left(y_{t+1}^{*}, u_{t+1}^{res}\right)\right)}{dx_{t+1}} \right] = E_{\left\{u_{t+1}\right\}} \left[\frac{dV_{t+1}\left(x_{t+1}, u_{t+1},\right)}{dx_{t+1}} \right], \tag{6}$$

where

$$V_{t+1}\left(x_{t+1}, u_{t+1}\right) \equiv W_{t+1}\left(x_{t+1}, u_{t+1}^{inflow}, F_{t+1}\left(y_{t+1}^{*}, u_{t+1}^{res}\right)\right), \tag{7}$$

In the water-value calculation, the right and side in (6) is calculated in practice. The calculation of water-values starts at the final time-step in the horizon, where all uncertainty has been revealed. The optimization is then to utilize water in the final time-step, or to save it at a defined end-value. The expected value of saving more water to this time-step can therefore be calculated for a set of reservoir levels, which are evaluated for a set of realizations for stochastic variables in the final time-step. When water-values have been calculated for the final time-step, the same calculation can be carried out for the previous time-step, expect that the water-value function for the final week is utilized instead of the end-value function. In this way, the two-period problems are solved recursively step by step. This solution methodology is a variant of stochastic dynamic programming (SDP) called the water-value method, see [17] for an early reference.

3.3 System simulation

From standard microeconomic theory we know that well-functioning markets maximize the total economic surplus, see e.g. [19]. Therefore, many models carry out a total system optimization to calculate the market equilibrium. Likewise, in the EMPS model, total costs in the simulated system are minimized in a linear problem formulation (LP) for each time-step (minimum 1 hour) and stochastic scenario. Stochastic scenarios are typically derived from statistical information about weather variables in a set of historical years. For each climatic year, time series for inflow, temperatures, wind- and solar power are specified. In the system simulation, each climatic year or sequence of several years are simulated with the calculated strategies for hydropower in each area. In (8) we show total costs for one given week in the case of weekly time-resolution during simulations. Since this calculation is carried out for each scenario separately, we have omitted the scenario index.

$$C_t = \text{minimize} \left\{ \sum_{j \in J, i \in I} c_{ti} m_{ti} + \sum_{j \in J} c_{tj}^{h} y_{tj} \right\} \tag{8}$$

The marginal cost for hydropower production c_{tj}^{h} is the calculated water value for this week, cf. (6). In one given LP-solution of the problem it is a parameter, but the value is updated i.a. on basis of the amount of water saved to the next time-step in the previous iteration when calculating a numerical solution in in the model. The cost elements represented by c_{tj} includes thermal power generation costs, costs of reducing demand, curtailment costs and cost of net import from the outside of the simulated system. Constraints in the system simulation part of the model include power balances for each area, production capacities, transmission capacities and hydropower constraints for reservoirs and production.

2.4 Draw-down model

The LP problem described in Section 2.3 calculates optimal hydropower generation for each aggregated area, time-step and stochastic scenario. This is input to the draw-down model, which allocates area-production to individual hydropower stations through rule-based heuristics.

$$y_{tj} = \sum_{i \in I_j^{hyd}} y_{ti}^{hydro} \tag{9}$$

From the corresponding operation of individual plants y_{ti}^{hyd}, efficiencies are calculated and constraints for individual plants and reservoirs are checked. If constraints are violated or efficiencies changed compared to the previous iteration, the LP problem formulation for the area is updated, and then the system simulation (optionally also strategy calculation) is carried out again.

4. Implementing el-certificate market

4.1 Overall approach

The el-certificate market is implemented as one additional area in EMPS. The corresponding "reservoir level" for this area is the el-certificate inventory. In this way, the embedded stochastic dynamic optimization for the strategy-calculation in EMPS is likewise applied to the el-certificate inventory (certificate storage).

4.2 Reservoir equivalent: Inflow, residual demand and iterative updates

The inflow to this inventory are certificates issued to power generation from renewable energy sources, including wind power, and hydropower generation from individual plants. The residual demand for certificates in a given time-step is the difference between the total certificate obligations for electricity consumption and certificates issued to bio-based (dispatchable) power generation. Electricity prices in the previous iteration of the model are accounted for when calculating the residual demand for certificates as a function of certificate prices, as electricity prices affect bio-based power-generation and demand.

4.3 Strategy calculation for certificates

The penalty rate for non-compliance of the certificate obligation is 150 % of the average price of certificates in the previous year. Certificate prices in past weeks within the current year affect the expected penalty rate for the next settlement, and hence also the value of certificates in the current week. The average price so far in the current year could in principle be implemented as an extra state in the SDP calculation of strategies for the certificate area. However, due to the complexity of including an extra dimension in the strategy calculation part of the model, a different approach was chosen. During the strategy calculation, the penalty rate is treated as a known parameter $p_k^{penalty}$. The calculated marginal values for certificates are shown in (10).

$$E_{\{u_{t+1}\}}\left[\frac{dV_{t+1}\left(x_{t+1},u_{t+1},p_k^{penalty}\right)}{dx_{t+1}}\right] \tag{10}$$

The strategy is calculated for different penalty values. However, since the future penalty rate is unknown during simulations, a forecast is applied instead. This is further discussed in Section 3.4

4.2 Adjustments for system simulation

New objective function

The original objective function before the implementation of a certificate market is described in (8). The new objective function is:

$$\begin{aligned}
&\text{For } t \notin S: \quad C_t\text{=minimize}\left\{\sum_{j\in J,i\in I_j} c_{tij}m_{tij} + \sum_{j\in J} c_{tj}^h y_{tj} + c_t^g y_t^{out}\right\} \\
&\text{For } t \in S: \quad C_t\text{=minimize}\left\{\sum_{j\in J,i\in I_j} c_{tij}m_{tij} + \sum_{j\in J} c_{tj}^h y_{tj} + c_t^g y_t^{out} + p_t^{pen} y_t^{pen}\right\}
\end{aligned} \tag{11}$$

The product $c_t^g y_t^{out}$ represents the cost of withdrawing el-certificates from the inventory. For settlement weeks, the term $p_t^{penalty} y_t^{pentaly}$ represents the total penalty for missing certificates. The term c_t^g is a constant parameter given by the strategy evaluated for the current week and scenario before solving the LP model, while the value for the penalty rate p_t^{pen} is known in a settlement week.

Extra constraints

The consumption of certificates in any given week and scenario is the fixed demand minus utilization of demand reduction options, multiplied with corresponding certificate obligation shares.

$$y_t^{cons} = \sum_{i\in\bigcup_{j\in J} I_j^{con}} a_{ti}\left(M_{ti} - m_{ti}\right) \tag{12}$$

Certificates issued to thermal power generation, i.e. bio-based power, are given by the produced amount multiplied with corresponding certificate shares.

$$y_t^{therm} = \sum_{i \in \bigcup_{j \in J} I_j^{therm}} a_{ti} m_{ti} \tag{13}$$

The inflow to the certificate storage is certificates issued to wind power and hydropower.

$$y_t^{in} = \sum_{i \in \bigcup_{j \in J} I_j^{hydro}} a_{ti} y_{ti}^{hydro} + \sum_{i \in \bigcup_{j \in J} I_j^{wind}} a_{ti} y_{ti}^{wind} \tag{14}$$

For wind power values are given by energy-series that are an input to the model. Values for hydropower are taken from a previous solution of the draw-down model, cf. (6). Hence, they are parameters in the system simulation part of the model.

In each week, the outtake from the storage plus certificates issued to bio-based power generation must be equal to the consumption of certificates. The weekly price for el-certificates is given by the dual-variable for this certificate balance.

$$y_t^{out} + y_t^{therm} = y_t^{cons} \qquad \left(p_t^{cert}\right) \tag{15}$$

The development of the certificate storage is the net of inflow and outtake. In settlement-weeks, penalty taken can provide an additional inflow.

$$\begin{aligned} &\text{For } t \notin S: \quad x_{t+1}^g = x_t^g + y_t^{in} - y_t^{out} \\ &\text{For } t \in S: \quad x_{t+1}^g = x_t^g + y_t^{in} - y_t^{out} + y_t^{pen} \end{aligned} \tag{16}$$

During a year, the net certificate balance can be negative. However, a penalty must be taken if too few certificates are available during a settlement. This mechanism is modelled as a non-negative constraint for the certificate storage at the end of the settlement-week.

$$\text{For } t \in S: \quad x_{t+1}^g \geq 0 \tag{17}$$

If a penalty is taken during a settlement $\left(y_t^{pen} > 0\right)$, the corresponding penalty rate in (11) is 150 % of the average certificate price in the previous year. :

$$p_t^{pen} = 1.5 \sum_{\tau \in R_t} \theta_\tau p_\tau^{cert} \tag{18}$$

The parameters θ_τ identify the share of the certificate turnover that occurs in each individual week. Since certificates are financial assets, there is no guarantee that the turnover in different weeks will be based on production or consumption values.

4.4 Estimating the first occurring penalty rate

Forecast for expected penalty rate

Whereas the strategy for the certificate inventory is defined for different penalty values, cf. (10), this is an unknown parameter during simulations. Instead we apply a forecast for the first occurring penalty value. The probability that any given future settlement week will be the first occurring deficit seen from any given week *t* is defined by (19).

$$v_{t\tau} = q_{t\tau} \prod_{\substack{t < r < \tau \\ r, \tau \in S}} \left(1 - q_{tr}\right) \tag{19}$$

The expected value for the first occurring penalty rate is calculated by (20). The expected penalty rate in each future settlement week is weighted by the probability that this is the first occurring deficit, whereas the weight for the final year is set to the probability that no deficits occurred before the final settlement-week.

$$p_t^{first} = \sum_{t \leq \tau \in S} v_{t,\tau} p_{t\tau}^E + \left(1 - \sum_{t \leq \tau \in S} v_{t\tau}\right) p_{t,'s^{fin}}^E, \tag{20}$$

During simulations the value of p_t^{first} is inserted instead of $p_k^{penalty}$ in (10), in order to calculate the value of certificates. A linear interpolation between certificate values calculated for the two closest values for $p_k^{penalty}$ is applied. However, to estimate (20) we need forecasts for all of the values $q_{t,\tau}$, $p^E_{t,\tau}$.

Expected penalty rates

The penalty rate for any given settlement week is given by (18). In any given week t, the expected value for the penalty rate in a future settlement week τ is given by (21).

$$p^E_{t\tau} = 1.5\sum_{i\in R_\tau} \theta_i E\left[p_i^{cert}\right]_t \qquad (21)$$

For a well-functioning market with risk-neutral players the expected (discounted) price in future weeks must be equal to the current price, or lower for weeks after a deficit has occurred. See e.g. [6] for a further discussion. When calculating the expected penalty rate, our estimate for expected future certificate prices for the rest of the current year and the next year are therefore set equal to the price in the current week. For distant future years, unconditional expected values can be reasonable approximations for expected values in individual scenarios. For prices beyond the end of next year, the expected price is therefore estimated by average prices from the previous iteration. The expected price for any given week *i* is then estimated by (22).

$$E\left[p_i^{cert}\right]_t = \begin{cases} p_i^{cert} & | \quad t > i \\ p_t^{cert} & | \quad t \le i \in N_i \\ \overline{p_\tau^{sim}} & | \quad else \end{cases} \qquad (22)$$

Probability for deficit

The value $q_{t\tau}$ in (19) represents the probability of certificate deficit in a future settlement week. In order to determine these probabilities, the trajectories of the certificate storage from the current week to the according settlement-weeks are calculated. These trajectories are calculated based on the last iteration. Figure 2 illustrates these probabilities. It shows the share of scenarios for the certificate balance development that lead to deficit when starting at the certificate storage level. At the point labelled "A", the probability for deficit in the first settlement is zero, while the probability for deficit in the two next settlements is below 12.5 percent for each of them. The probability curves are updated before every new solution of the formal LP part of the model.

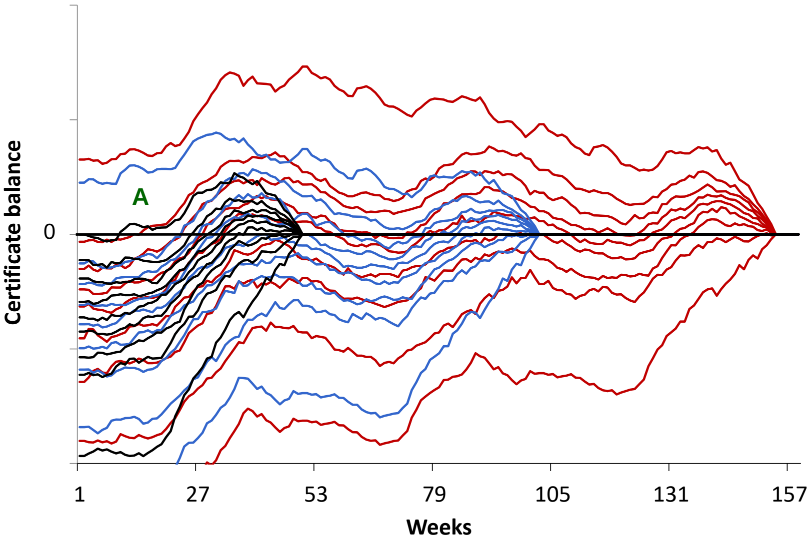

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Figure 2 Example of estimated percentiles for the certificate deficit-probability in the 3 next settlements.

The first occurring penalty rate in (20) is then estimated by applying estimates for future prices and the probability for deficit in future settlements, which then identifies estimates for expected future prices and probabilities for deficits, the first occurring penalty is estimated. This expected penalty rate is then used to pick the corresponding strategy in (10), applying linear interpolation between the according certificate value tables from the strategy calculation.

Excess penalty taken

In the strategy-calculation, the penalty rate is the upper bound for the value of certificates. However, the expected future value of certificates can in principle be higher than the penalty rate in a given year. In such cases a penalty should be taken in the first settlement even if it could be avoided, as arbitrage is utilized between time-steps, when possible. In the model this mechanisms is implemented by setting the penalty rate in (10) during settlements to the highest value of the actual penalty rate, and the expected value for the first penalty that must be taken in future years, i.e. (20) evaluated for $q_{t,t} = 0$.

5. Case studies

5.1 Inputs and cases

The performance of the model for different cases and situations that may occur in the el-certificate market is discussed in the following. In these test cases there are two areas defined: NO and SE. Even though several parameters have been tuned to roughly fit Norway and Sweden, it has not been the intention to make a realistic forecast or carry out back-testing of the common certificate market for Norway and Sweden. The system is simulated week-by-week from week 1 to week 520 for 75 different realizations for climate variables. The annual settlement for certificates is in week 14 of each year, and the penalty-rate for missing certificates is 150 % of the average price of certificates in the previous year.

Table 1 shows capacities and costs in the simulated system, in addition to the share of the capacity eligible to el-certificates. Other inputs to simulations include:

- Average certificate price in the previous year: 3.5 Eurocent/kWh
- End-value of certificates at the planning horizon: 3.0 Eurocent/kWh
- Initial certificate balance: 1 TWh

Table 1 Capacities, costs and certificate shares in year 1.

Area	Type	Capacity (GW)	Marginal cost (€cent/kWh)	Storage (TWh)	Share (%)
NO	Hydro	27.5		87.5	2
"	Gas	0.8	4.0		
"	Wind	0.6			100
SE	Hydro	14.1		44.1	
"	Nuclear	9.0	1.0		
"	Wind	1.5			40
"	Coal	1.0	3.5		
"	Gas	1.0	4.2		

"	Oil	1.0	10.0	
"	Bio	0.3	[8-10]	100
NO-SE	Transmission	3.5		

Table **2** shows the simulated outcome with respect to the annual electricity balance for NO and SE, and the balance for the common el-certificate market. On average, there is approximately 2 TWh export of electricity from SE to NO. In the el-certificate market, the el-certificate obligation is on average 0.1 TWh higher than the supply of certificates in the 10-year period, which correspond to 1 TWh initial storage. El-certificate prices are adjusted so that there is an aggregated balance, where bio-based power generation is the flexible technology. However, there is considerable variation within years, throughout the 10-year period and between different realizations of the climate variables. The variability for inflow to reservoirs and wind power in NO is illustrated for the first year in Figure 3.

Table 2 Annual balance (TWh). Average values for 75 stochastic scenarios over 10 years.

Area	NO	SE	Certificates
Hydropower	117.6	67.3	2.4
Wind power	1.7	4.5	3.5
Nuclear		76.8	
Oil			
Gas	5.5	6.1	
Bio		1.8	1.8
Production	124.9	163.6	7.8
Consumption	126.9	161.6	7.9
Balance	-2.0	1.9	-0.1

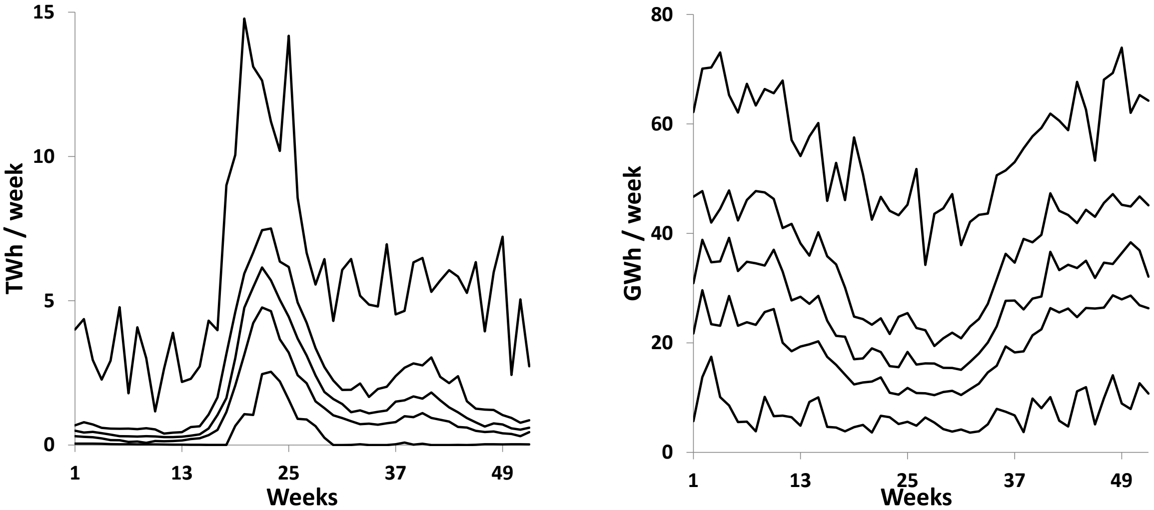

Figure 3 Week-by-week percentiles (0 %, 25 %, 50 %, 75 %, and 100 %) for the inflow to reservoirs (left panel) and wind power (right panel) in NO.

There is a slight increase in wind power generation and increasing certificate shares for consumption during the 10-year planning period. Apart from this, the specified system is stable from year to year.

In principle, a maximum penalty rate for the certificate market does not exist. However, for our simulations a technical maximum on 1 €/kWh is specified to make sure that there always exists a numerical solution.

Table 3 gives an overview of all simulated cases. The inputs for the Base case have been described previously in this Section. In cases 2 – 5 we study the effect of altering the el-certificate balance, in case 6 we show and explain why there in many cases exists a second possible solution, while the effect of interest rate is studied in case 7.

Table 3 Simulated cases.

No	Case	Certificate share NO hydropower	Comment
1	Base case	2.0 %	
2	Unexpected imbalance	1.5 %	
3	Scarcity	1.5 %	Start in week 15
4	Deficit	0.5 %	Start in week 15
5	Surplus	2.0 %	
6	Degenerated solution	"	End-value: 0 cent/kWh
7	Interest rate 10 %	"	End-value: 0 cent/kWh, 10 % interest rate.

5.3 Base case

As shown in Table 2, the certificate market is roughly in balance in the Base case over the 10-year period. However, in the first year there is a build-up of certificates because the certificate share for consumption is low. Figure 4 shows simulated values for the certificate prices and the certificate balance in the first year in each of the 75 stochastic scenarios. The average over all scenarios is plotted in red.

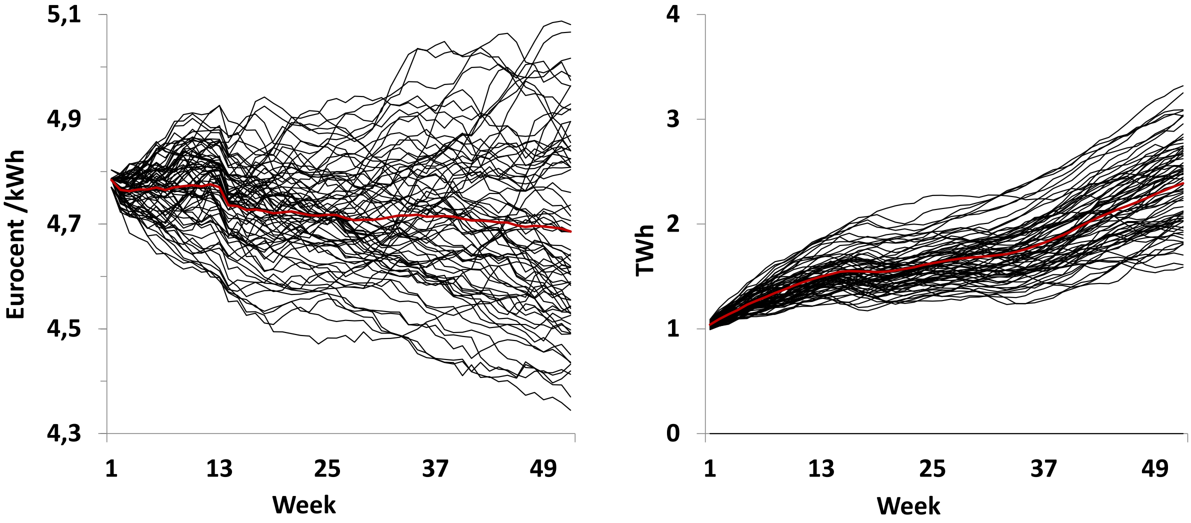

Figure 4 Base case results for certificates, week 1 - 52.
Left panel: certificate prices. Right panel: certificate storage.

The certificate price in week 1 is approximately 4.8 Eurocent/kWh. Thereafter, prices develop different in each scenario depending on realizations for wind power production and the inflow to the hydropower system. In any given week and scenario the certificate price reflects the expected future value. The average price is drops by less than 0.1 cent/kWh during the year, which is fairly stable. However, the curve representing the average price is not a straight line as the average price is not a variable in the model. The average prices are calculated after the simulation of all stochastic scenarios. Small deviations between what could be expected from theory and numerical simulations can occur due to the model, which is used for the multivariate probability distribution in the strategy calculation part. This does not perfectly embed all correlations in the applied stochastic scenarios. Moreover, 75 stochastic realizations are not sufficient for eliminating the effect of sampling error. As a consequence, the average value for simulated certificate prices during simulations will not be constant from week to week. The small change in average price in week 15 is caused by a rolling annual update of the function describing the expected future penalty.

Prices and balances for certificates for all weeks in the 10-year planning period, all stochastic scenarios, and all simulated cases are shown in Figure 5. In the Base case, differences in prices between different scenarios are increasing from the start week since the certificate storage and price history develops differently from scenario to scenario. The difference between the highest and lowest average price is about 0.5 from week 1 to week 425. Thereafter, the average price drops before the final settlement. After the final settlement prices are typically are either equal to the end-value for certificates (in 54 of 75 scenarios) or equal to the penalty-rate for the respective scenario. In general, the average price typically drops after a settlement if there is deficit in some of the scenarios. The reason is that prices can drop just after the settlement if a penalty is taken in the scenario. The first occurring deficit is the settlement in week 326, but 83 % of the total deficit occurs in the final settlement. After the final settlement, prices drop to the end-value for certificates. The highest simulated prices are above 11 Eurocent/kWh, which reflects both the probability for deficit and the expected penalty-rate for those scenarios.

5.4 Unexpected imbalance

In the Base case, the simulated price in the first week is only 0.45 cent/kWh below the penalty rate at the first settlement. Now, in the Unexpected imbalance case the certificate share for hydropower is reduced, which leads to higher certificate prices, see Figure 5(b). Thus, prices in the first weeks do not stay well below the penalty rate for the first settlement. Such price-increases from one year to the next can occur because of unexpected events, such as new information about investment plants for renewable power generation, or unfortunate climate conditions during the previous year. If no penalty had been taken in the first settlement for this case, the expected price after the settlement would have jumped up to a value above the penalty rate. However, this is not consistent with an equilibrium, since certificate owners would rather pay the penalty for deficit and keep the certificates. Hence, a penalty is taken in the first settlement even though there are sufficient certificates to avoid deficit. In Figure 5, the penalty taken is seen as an upward step in the net certificate balance. The height of the step is the amount of extra certificates, which is necessary to balance the expected future value of certificates towards the current penalty rate.

5.5 Scarcity

Inputs for the cases Scarcity and Unexpected imbalance are the same, except that the simulation for the Scarcity case starts in week 15, just after the settlement. Thus, a penalty cannot be taken at a moderate cost[3] in week 14. As a consequence, a higher future certificate price compensates for 0.6 TWh fewer certificates issued to hydropower compared to the Base case. The price in the first

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[3] The reason for that there is no possibility to take a penalty at a moderate cost is due to the calculation of the penalty rate (150% of the certificate price in the previous year). Hence, starting in week 1 (Unexpected imbalance case), the penalty rate for the next settlement is already set to a certain (moderate) level by historic certificate prices. However, when starting in week 15, the penalty rate for the next settlement is not definetly set, but will also be affected by present and future certificate price. Thus, a higher certificate price will increase the penalty rate, so that taking a penalty is not profitable anymore.

simulated week goes up to 8.6 Eurocent/kWh, as shown in Figure 5(c). Higher prices lead to 0.5 TWh extra bio-based power generation on average. A higher average utilization of bio-based generation capacity results in reduced remaining flexibility in the system, and higher price volatility. Hence, the highest simulated prices are close to 40 Eurocent/kWh.

5.6 Deficit

In the Deficit case the share of hydropower obtaining certificates is reduced further so that a balance for the el-certificate market is unattainable even if all bio-based power generation capacity is utilized at maximum. If the simulation had been started in week 1, the model would have solved the deficit by taking a major penalty in the first settlement. However, this would not be possible at moderate prices if the deficit already was expected in the previous year. To simulate how the market would react to an expected unavoidable deficit, the simulation starts just after the first settlement, i.e. in week 15. The simulation results in Figure 5(d) show that prices for this case converge towards the technical ceiling that is specified within the model. The reason can be understood within a market-context: In the beginning of the year, everybody knows that there will be a deficit. Hence, the market price will be equal to the penalty rate. However, the penalty rate is set to 150 % of market-prices. This gives an upward spiral for prices and penalty. If the initial price is 10, the penalty will be 15. This penalty rate pushes the market price up to 15, as everybody knows that there will be a deficit and a certificate price equal to 15 at the next settlement. That in return pushes the penalty-rate up to 22.5, and so on. In the model this spiral is stopped by the upper ceiling for the penalty rate.

5.7 Surplus

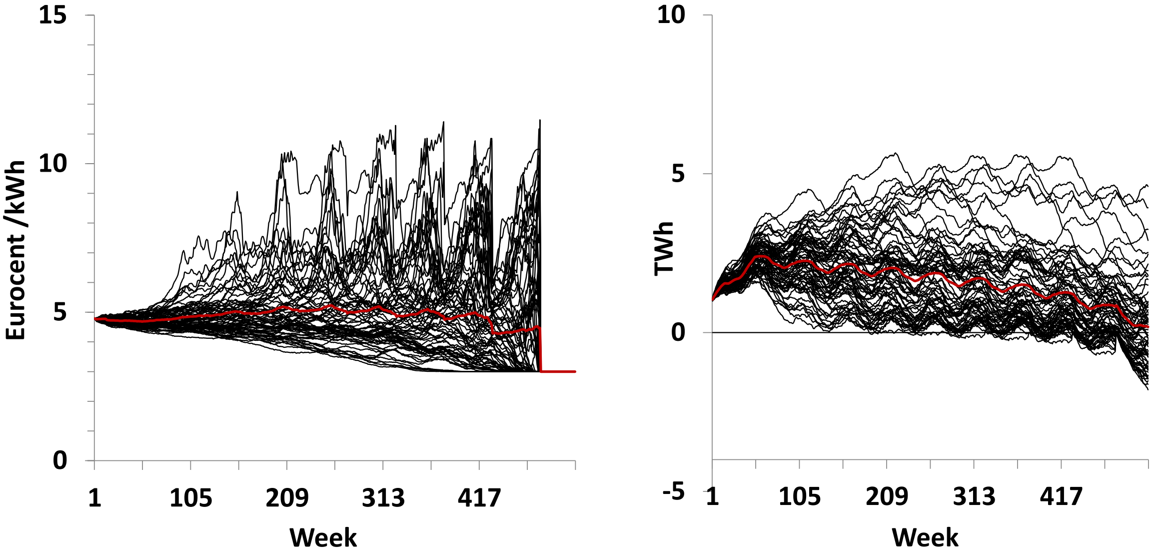
In this case the certificate share for hydropower is increased to 3.5 per cent. As a consequence, the amount of certificates stored is increased week by week in all of the scenarios. Hence, there is no probability for deficit, and therefore the certificate price is constant equal to the defined end-value at 3 cent/kWh, see Figure 5(e).

5.8 Degenerated solution

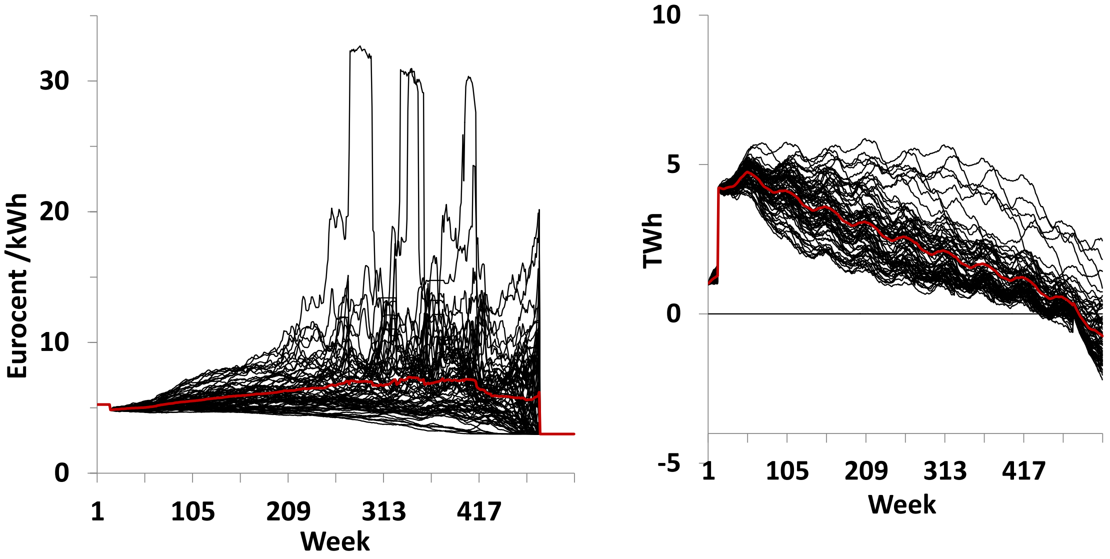
For many cases there exist at least two solutions for the problem, where in one of the solutions all prices are zero, see Figure 5 (f). The only requirement for the existence of the zero-price solution is that it can be guaranteed that there is no deficit in the next settlement and the end-value of the certificates is zero. This can be the case towards the end of a given calendar year given a sufficiently large number of available certificates. If prices are zero in all weeks from this point on, then the penalty for possible deficits after the first occurring settlement will be zero too since 150 % of zero is zero. This has the same effect as an infinite supply of certificates at a price equal to zero, which is consistent with the initial assumption of zero prices. The technical requirement that the end-value of certificates are zero will be the case if the system is terminated at a given date as it is actually planned for the Swedish-Norwegian system.

5.9 Interest rate 10 %

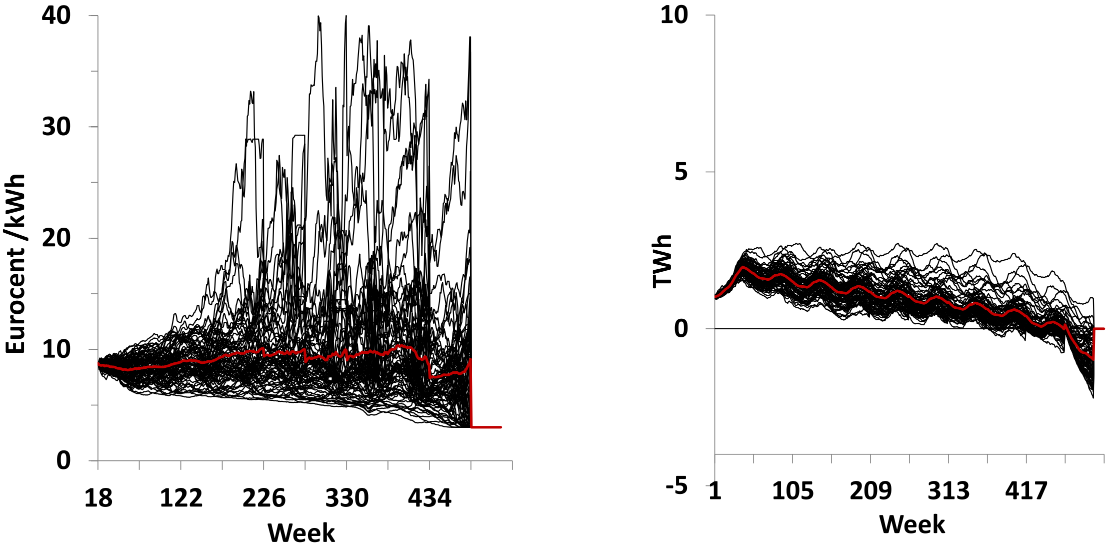
For the upper presented cases we have applied 0 % interest rate, as the overall goal has been to develop a tool for more short-term forecasting. In this case 9 the interest rate is set to 10 % per year. The additional curve in Figure 5 (g) shows a 10 % increase in the price per year starting from week 1. Simulated prices coincide well with this curve before a deficits occurs, including a subsequent price drop, which correspond well with theoretical findings in [6] and [12].



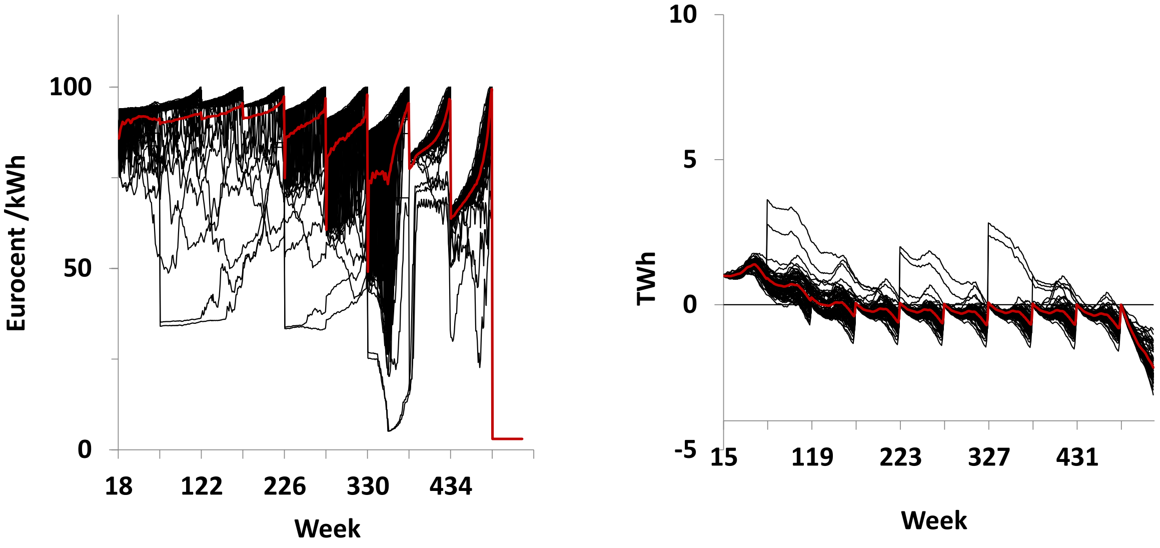
(a) Base case



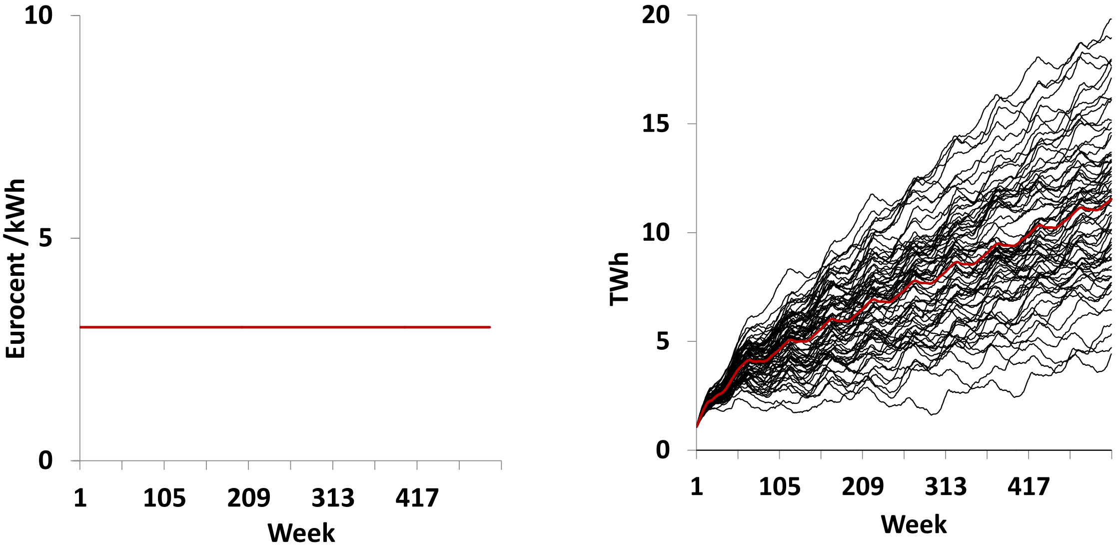
(b) Unexpected imbalance



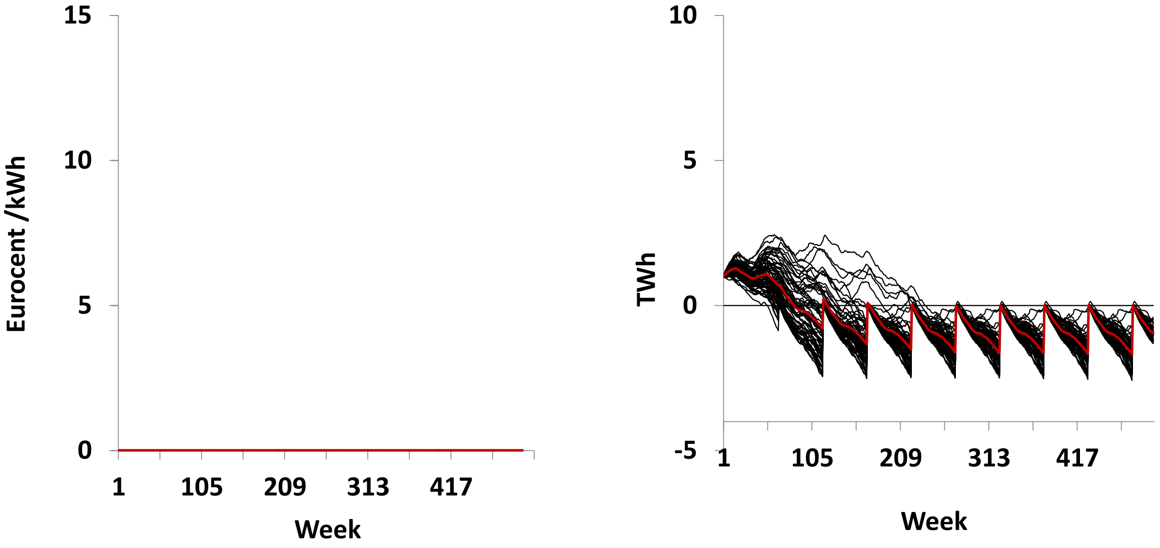
(c) Scarcity



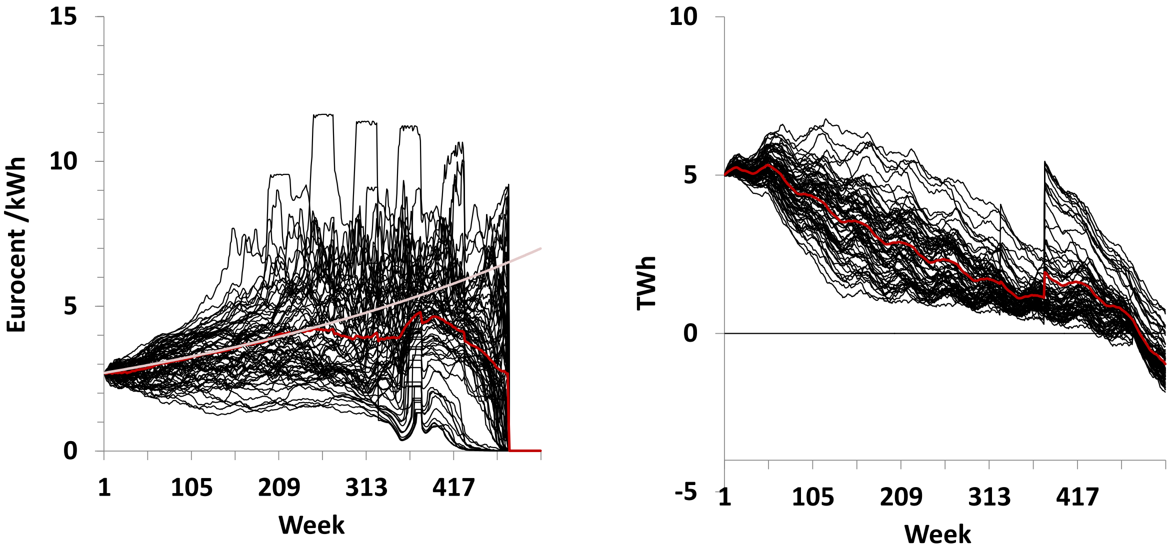
(d) Deficit



(e) Surplus



(f) Degenerated solution



(g) Interest rate 10 %

Figure 5 El-certificate prices (left panel) and el-certificate balance (right panel) for all 520 weeks, 75 scenario and average (red curve), for all cases.

6. Summary and concluding remarks

By means of the Swedish-Norwegian el-certificate market an extra annual 26 TWh of electricity from renewable energy sources shall be provided until the end of 2020. The incentive to invest in new generation assets for renewable energy sources is provided through the el-certificates. To take an investment decision for such generation assets, stakeholders need to know respectively estimate the future price for el-certificates. However, as this price is not defined ex ante, but determined through a market-based system with an endogenously set penalty price, advanced forecasting methodologies are required. To address this challenge, a novel methodology for forecasting in the Swedish-Norwegian el-certificate market is described in this paper.

The presented model integrates the markets for electricity and for el-certificates. The certificate market can comprise one, some or all areas and countries included in the electricity market. The optimal strategy for the el-certificate inventory is calculated by stochastic dynamic programming for a set of possible penalty-rates. However, the penalty-rate is not known before after the market simulation. Hence, a rolling forecast for the expected penalty is applied, using an iterative approach. The resulting performance of the model for different situations that can occur in the el-certificate market is illustrated by a case study.

The findings of the case studiy correspond broadly to theoretical findings in previous studies for tradable green certificate markets. In addition to those findings, in this case study the short-terrm dynamics of the certificate price are assessed. It is shown, that the price-scenarios spread out in such a way that the unconditional expected value of certificates is relatively stable as long as there are no or few occurrences of deficit in the simulated scenarios. Within the case studies the effect of climatic uncertainty is illustrated as well as the significant consequences of the endogenously determined penalty rate. In addition special cases are identified, where certificate prices become excessively high or zero respectively, due to this design-specific dynamics for the penalty-rate.

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Appendix A. Nomenclature.

Units

All electricity quantities are measured in MWh, while monetary units are in Euro/MWh. Each el-certificates represent 1 MWh renewable generation. Certificates are therefore measured in number of certificates / MWh. The current week is denoted *t*, while any given week is τ .

Variables and parameters

In a model such as the EMPS model where the total is not solved in one big optimization but rather divided into sequences, a variable can be an output from one part of the optimization (e.g. the strategy calculation) but an input to another part of the model (e.g. the weekly simulation). In the following variables and parameters are classified on basis of their status in the part of the model where they enter in the description.

Sets

J	Areas
I	All flexibility options, $I = \bigcup_{j \in J} I_j$.
I_j	All flexibility options in area $j \in J$, including thermal power generation, demand reductions, curtailment and trade with the outside of simulated system.
I_j^{con}	Flexible power demand options in $j \in J$, $I_j^{con} \subset I_j$.
I_j^{therm}	Thermal power generation units in area $j \in J$, $I_j^{\sup} \subset I_j$.
I_j^{hydro}	Hydropower modules.
I_j^{wind}	Energy series for wind- and solar power.
K	Penalties strategies are calculated for.
R_t	The set of weeks that constitutes one full 52-week year, for the year previous to any given settlement week *t*.
N_i	For any given week *i* this is the set of weeks from the current week to the first settlement, plus one full year.
S	Settlement weeks, $S \subset T$. The final settlement week is s^{fin}.
T	Weeks in planning period.

Decision variables

m_{ti}	Utilization of flexibility option.
s_t	Spillage from reservoir.
x_{t+1}	Reservoir level at the start of next week.
x_{t+1}^g	Net certificate balance at the start of next week.
y_t	Hydropower generation for an area in strategy calculation. The optimal value is y_t^*
y_t^{out}	Outtake of certificates from certificate storage.
y_t^{con}	Consumption of certificates.
y_t^{pen}	Deficit during a settlement.
y_t^{therm}	Certificates issued to thermal power generation.
$y_t^{\sup}$	Supply of certificates.

Dual variables for constraints

p_t^{cert}	Price for el-certificates.
λ_t	Electricity price.
μ_{t+1}	Value of saving additional water to next week.

Functions

C_t	Minimum cost in a given week during simulations
$F_t(.)$	Residual demand curve for an area.
$W_t(.)$	Minimum cost in planning horizon during strategy calculation for an area
$V_t(.)$	Minimum cost in planning horizon during strategy calculation for an area
$Z_T(.)$	End-value function for storage

Iteratively updated parameters

c_t^g	Certificate value during simulations.
c_{tj}^h	Water-values during simulations.
$E\left[p_i^{cert}\right]_t$	Expected certificate price in week *i*, seen from week *t*.
p_t^{pen}	The applied penalty in any given settlement week. Value is calculated by model based on book-keeping of certificate prices, and not a direct decision variable during simulations.
$p_{t\tau}^E$	Forecasted penalty-rate for missing certificates in any given future settlement-week $\tau \in S$.
p_t^{first}	Forecasted penalty-rate for first occurring el-certificate deficit during settlements.
$\overline{p_\tau^{sim}}$	Average of simulated certificate-prices for a given week in previous iteraton.
$q_{t\tau}$	Forecasted probability for certificate deficit in any given future settlement-week $\tau \in S$.
$v_{t\tau}$	Probability that the first occurring deficit seen from week *t* will be in week τ.
y_t^{in}	Inflow of certificates to certificate storage.
y_{ti}^{hyd}	Hydropower generation from individual modules within areas.

Parameters

a_{ti}	Certificate share assigned to production and consumption units.
$c_{\tau i}$	Constant marginal cost for flexibility option.
M_{ti}	Initial demand, i.e. demand if no demand reduction options are utilized.
$p_k^{penalty}$	A given penalty applied during strategy-calculation for el-certificates, $k \in K$.
t^{final}	Final week in planning period.
θ_τ	Share of annual turnover for el-certificates in week *t*.

Stochastic variables

p_τ	Electricity prices.

u_t^{inflow}	Inflow to reservoirs in aggregated area.
u_t^{res}	A vector of uncertain variables affecting the probability distribution for residual demand in a given area and week, e.g. temperatures, wind power and solar power.
u_t	A vector for all stochastic variables, i.e. $[u_t^{res^T} u_t^{inflow}]$.
y_{ti}^{wind}	Varying renewable power generation such as wind power and solar power. For each series, week and stochastic scenario, values are fixed input to the model.