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Report

El-certificates in EMPS model

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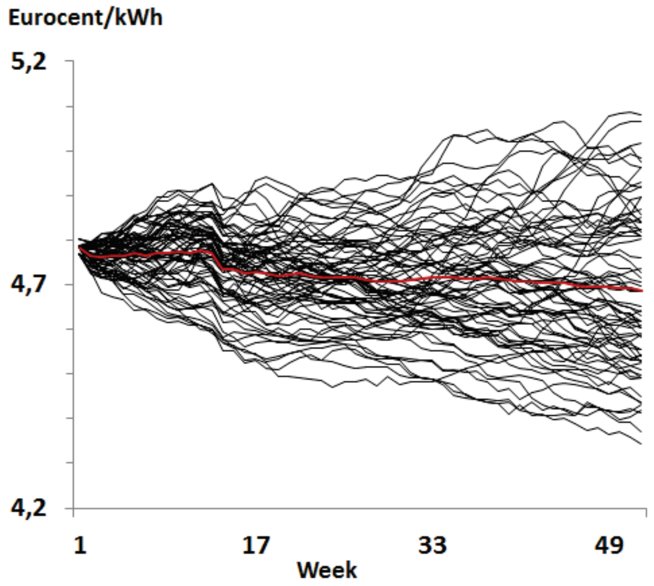

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ABSTRACT
This report documents how the el-certificate market has been implemented in EMPS as one extra area in the model. The reservoir storage for the new area represents the net balance for the certificate market. In this way, the existing methodology for strategy calculation in EMPS is utilized for the certificate inventory. Our model for forecasting in the certificate market:

- Is an integrated model for el-certificates and electricity
- Carry out a week-by-week dynamic simulation for several constitutive years
- Includes uncertainty for climate variables
- Apply a stochastic-dynamic strategy for the certificate inventory
- Calculate the penalty rate endogenously

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1 Introduction

1.1 Project and status

In 2013 – 2014 SINTEF Energy Research carried out the Research Council EnergiX-project "Modellering av marked for elsertifikater i Samkjøringsmodellen". Energy Norway was the applicant, and industrial participants were NVE, Statkraft, Statnett and SKM Market Predictor. The goal of the project was to develop a model for forecasting in the common Swedish-Norwegian market for el-certificates based on the EMPS model (no: Samkjøringsmodellen).

In the project we have managed to implement a market for el-certificates in EMPS. Basically we have implemented the el-certificate market as one extra area that is created automatically, where the reservoir storage for the new area represents the net balance for the certificate market. In this way, the model is calculating an optimal strategy for the certificate inventory based on stochastic dynamic programming. To our knowledge, there are currently no other models which have all of the following characteristics:

- Integrated markets for certificates and electricity
- Week-by-week dynamics for several constitutive years
- Stochastic climate variables
- A stochastic-dynamic strategy for the certificate inventory
- Model-determined penalty rate

The parameters for the certificate market are specified in a new input-file. Outputs for the certificate market are extracted by standard result-programs for the EMPS model, such as PCKURVETEGN. As far as possible, we have treated the certificate area as a standard area, and in this way utilized existing structures in the model.

The most challenging issue has been to deal with the penalty for missing certificates during settlements. This penalty is 150 % of average prices for the previous year. Therefore, the value of certificates will be affected by historical prices within the current year. This constitutes a new state-variable for the model, and the value of certificates needs to be calculated with one extra dimension during strategy-calculation. In practice we have calculated the strategy for different penalty-levels separately. The penalty-rate is unknown during simulations, and instead we utilize an estimated expected value for the first occurring penalty that is calculated in every week and scenario.

Results from tests on a small dataset have been promising. Apparently the model is functioning as intended, and simulation results correspond well with theory and expected qualitative characteristics in different cases. The starting point for model development was a version of the EMPS model between 9.2 and 9.3. During the project new versions of the EMPS model has been developed, and by Oct-14 the latest official version is 9.6. This has created a barrier for the industry's testing in the project. Still, industry's testing with larger datasets revealed needs for several adjustments and corrections we have implemented during the project. There is a need for additional testing with large datasets and more functionality, as well as an update to the latest version of EMPS.

1.2 Structure of report

This report is organized as follows. Chapter 2 is a draft for a manuscript to a journal paper. A revised version will be submitted to the Elsevier journal Energy. The draft paper includes descriptions of existing literature about markets for tradable green certificates, how we have implemented the el-certificate market in EMPS, and simulation results for a set of cases. Chapter 3 is the user-manual for the el-certificate functionality, while Appendix gives some additional information about the implementation. Suggestions for further developments are in Chapter 4.

2 Methodology for forecasting in the Swedish-Norwegian market for el-certificates

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

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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 included in the electricity-market model EMPS, which has weekly to hourly time-step length, and a planning period of 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. Results correspond broadly 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. We also identify special cases where certificate prices become excessively high respectively zero, due the built-in dynamics of the penalty rate.

Acknowledgements: The authors gratefully acknowledge financial support from the Research Council of Norway in the ENERGIX program, and from NVE, Statkraft, and Statnett. We are also grateful for participation from SKM Market Predictor and Energy Norway in the research project.

Key words: El-certificates, TGC, electricity, forecasting, RES-E

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. In the paper we present a novel methodology for forecasting prices in this 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 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. It is expected that the system will provide annually 26 TWh extra electricity from renewable sources in sum for Norway and Sweden by 2020.

There are numerous studies of TCG 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 therefore 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 TCG 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 TCG markets. In optimization models such as MARKAL [8,9] this is typically done by including the extra constraint that renewable power generation shall be at least a given quantity or a share of electricity consumption. When such models are run separately for several years in a sequence, prices will not reflect the possibility of saving 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 TCG price which is sufficient for reaching policy-goals for renewable generation can be calculated. There is however no uncertainty in 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 influence on prices, as certificates can be saved in years with ample supply to years with scarcity. Such effects can only be analyzed in dynamic models, and preferably with stochastic renewable generation. In [11], a competitive market equilibrium with and without banking is derived. In the case of banking, speculation in TGCs as a financial commodity leads to equilibrium prices such that no expected profits can be made by 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 give settlement before it has come into existence. Therefore, the expected price for certificates could go down. 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 therefore 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 price-level for the aggregated market over many years, while [11] provides the expected value for the stochastic price development from one time-step to the next.

The specific design of the TGC market will also influence prices. TGCs have a value because there is a probability for deficit and 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). Because 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 [12].

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

The model in [12] is made for the New Jersey SREC market. The interaction with the electricity market is not included because generation from existing solar-power capacity is unaffected by electricity prices, and the share of solar-power is small in the electricity market. This is different in the 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], and econometric studies [15].

In the following we will present a methodology for forecasting in the common el-certificate market for Norway and Sweden. To our knowledge, this is the first 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 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 EMPS model

2.1. 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 can be represented in detail, and uncertainty in weather variables are taken into account. The model calculates strategies for utilization of hydropower reservoirs, and thereafter market equilibriums are calculated for each time-step, area and stochastic climate scenario. The model can run in operational mode, i.e. with predefined capacities for among others production and transmission, or in investment mode [18]. The el-certificate market is implemented only for the operational mode of the model. The aim has been to make a tool for short-term forecasting of el-certificate prices. In the following we give a brief overview of the EMPS model before focusing on the adjustments done for the implementation 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 a simulated system.

2.2 Strategy calculation for hydropower

Firstly, a strategy is calculated for the hydropower operation in each area. 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 separately.[1] 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.

[11] 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.

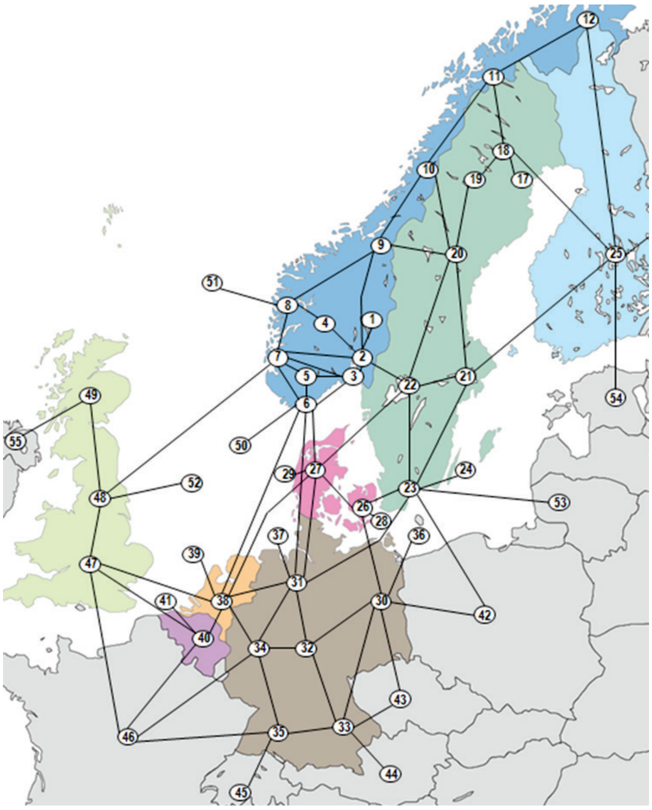


Figure 1 Example of simulated system

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

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.

2.3 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.

3. Implementing el-certificate market

3.1 Overall approach

The el-certificate market has been implemented as one additional area in EMPS. The corresponding "reservoir level" for this area is the el-certificate inventory. This way, the embedded stochastic dynamic optimization for the strategy-calculation in EMPS is applied for the el-certificate inventory.

3.2 Reservoir equivalent: Inflow, residual demand and iterative updates

The inflow to the certificate storage are certificates issued to variable power generation, including wind power, and hydropower generation from individual plants as calculated by the draw-down model in the previous iteration. 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 because electricity prices impacts bio-based power-generation and demand.

3.3 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 therefore 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

3.2 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:

$$\begin{aligned} &\text{For } t \notin S: \quad C_t = \text{minimize}\left\{ \sum_{j\in J, i\in I_j} c_{tij} m_{tij} + \sum_{j\in J} c^h_{tj} y_{tj} + c^g_t y^{out}_t \right\} \\ &\text{For } t \in S: \quad C_t = \text{minimize}\left\{ \sum_{j\in J, i\in I_j} c_{tij} m_{tij} + \sum_{j\in J} c^h_{tj} y_{tj} + c^g_t y^{out}_t + p^{pen}_t y^{pen}_t \right\} \end{aligned} \tag{11}$$

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 hydro-power 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.

3.4 Estimating the first occurring penalty rate

<u>Forecast for expected penalty rate</u>
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.

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

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 $q_{t,\tau}$, $p_{t,\tau}^E$.

<u>Expected penalty rates</u>
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).

$$p_{t\tau}^E = 1.5 \sum_{i \in R_\tau} \theta_i E\left[p_i^{cert}\right]_t \tag{21}$$

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).

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

<u>Probability for deficit</u>
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 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.

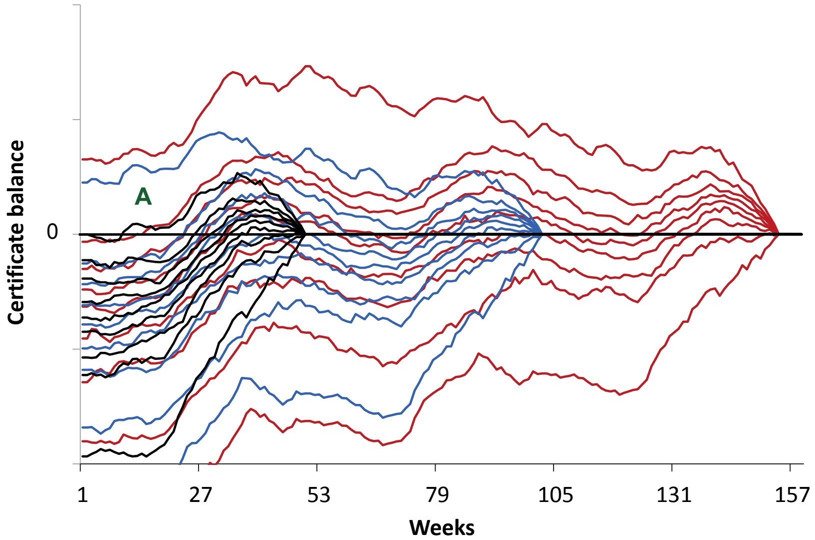


Figure 2 Example of estimated percentiles for deficit-probability in the 3 next settlements.

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.

<u>Excess penalty taken</u>

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 $q_{t,t} = 0$.

4. Case studies

4.1 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

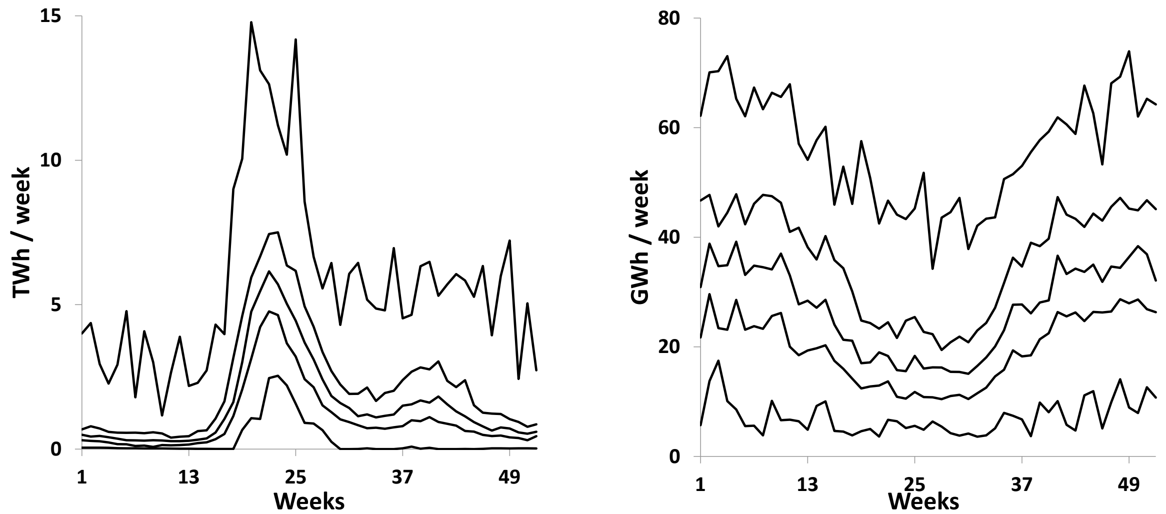


Figure 3 Week-by-week percentiles (0 %, 25 %, 50 %, 75 %, and 100 %) for inflow to reservoirs (left panel) and wind power (right panel) in NO.

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.

4.3 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 balance and certificate prices in the first year in each 75 stochastic scenarios. The average over all scenarios is plotted in red.

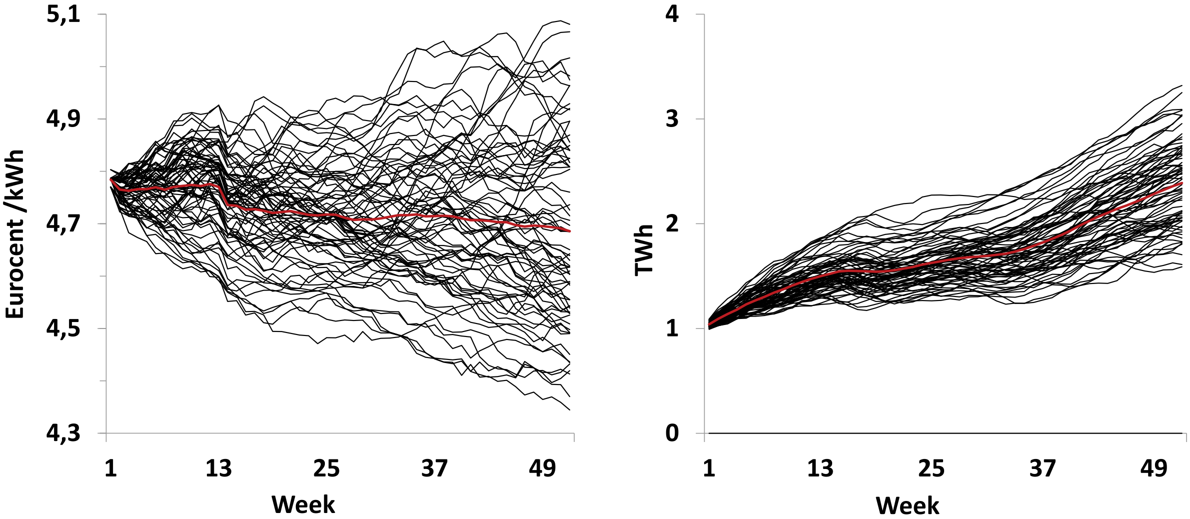


Figure 4 Base case results for certificates, week 1 - 52. Left panel: prices. Right panel: storage.

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 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 reduced 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. Average prices are calculated after the simulation of all stochastic scenarios. Some small deviations between what could be expected from theory and numerical simulations can occur e.g. because the model for the multivariate probability distribution used in the strategy calculation part of the model does not perfectly embed all correlations in the applied stochastic scenarios. Also, 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 a bit before the final settlement where 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 in most cases drop just after the settlement if a penalty is taken. The first occurring deficit is the settlement for 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.

4.4 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. As a consequence, prices in the first weeks are not kept 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. This is not consistent with equilibrium, since certificate owners would rather pay the penalty for deficit and save 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 that balances the expected future value of certificates towards the current penalty rate.

4.5 Scarcity

Inputs for the cases Scarcity and Unexpected imbalance are the same, except that the simulation starts in week 15 for Scarcity. Thus, a penalty cannot be taken at a moderate cost in week 14. As a consequence, a higher future price is needed to compensate for 0.6 TWh fewer certificates issued to hydropower compared to the Base case. The price in the first simulated week goes up to 8.6 Eurocent/kWh. 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. The highest simulated prices are close to 40 Eurocent/kWh.

4.6 Deficit

In the Deficit case the share of hydropower obtaining certificates is reduced so far 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. Simulation results show that prices for this case converge towards the technical ceiling that is specified. 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. But this pushes the market price up to 15, as everybody knows that there will be a deficit and a price equal to 15 at the next settlement. This 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.

4.7 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. There is no probability for deficit, and therefore the certificate price is constant equal to the defined end-value at 3 cent/kWh.

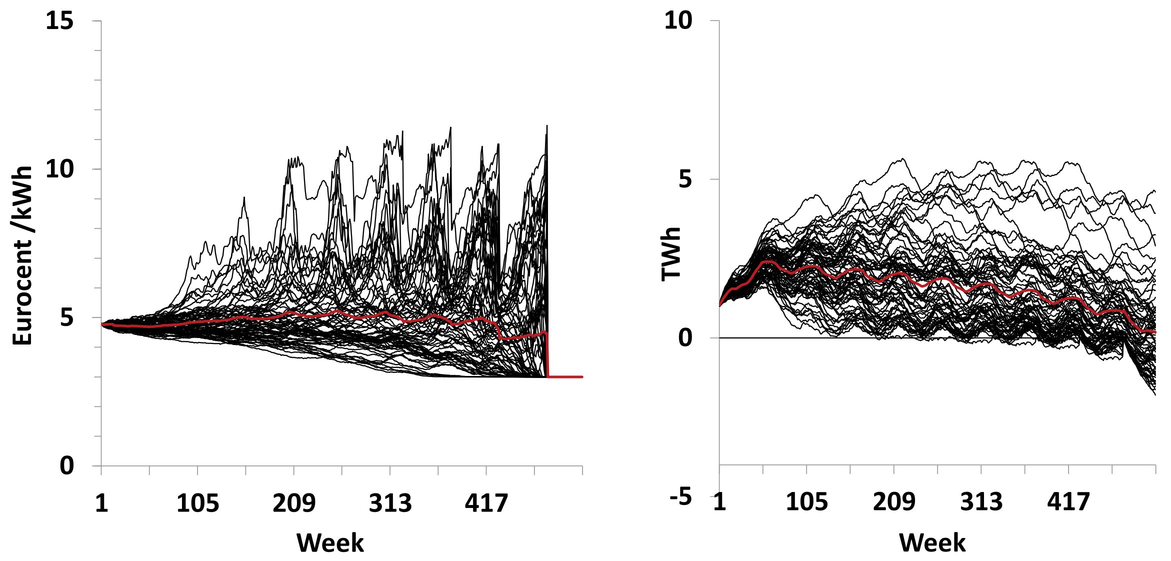
4.8 Degenerated solution

For many cases there exist at least two solutions for the problem, where in one of the solutions all prices are zero. The only requirement for the existence of the zero-price solution is that it can be guaranteed that a deficit is avoided in the next settlement. This will often be the case, e.g. towards the end of a given calendar year. 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.

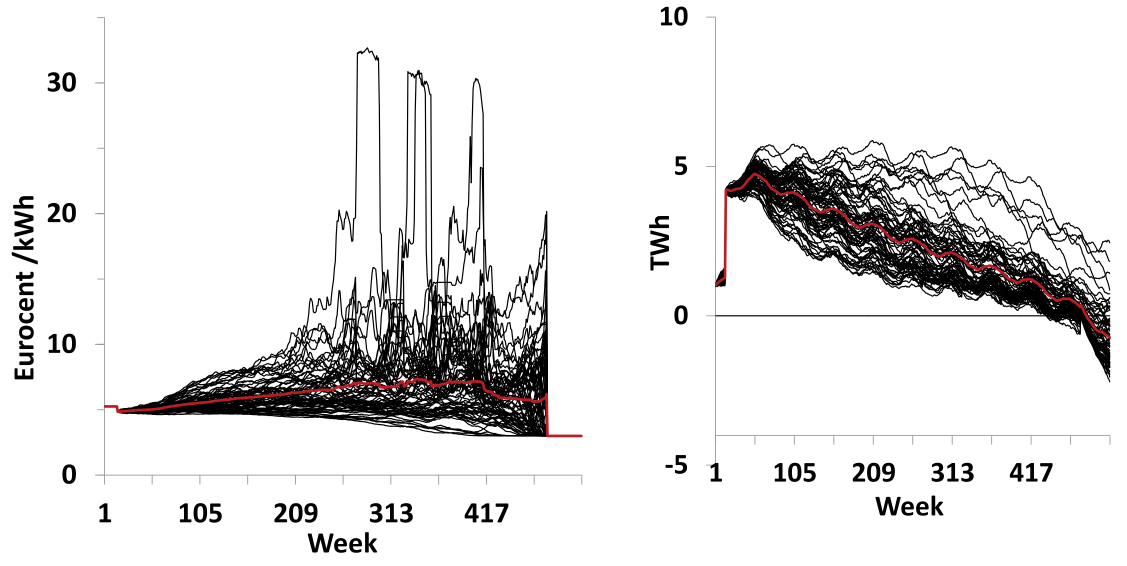
Technically it is also a requirement that the end-value of certificates are zero, which will be the case if the system is terminated at a given date as it is planned for the Swedish-Norwegian system.

4.9 Interest rate 10 %

For the other cases we have applied 0 % interest rate because the overall goal has been to develop a tool for short-term forecasting. In this case the interest rate is set to 10 % per year. The additional curve in Figure 5 shows a 10 % increase in the price per year starting from week 1. Simulated prices coincide well with this curve before there are occurrences of deficits, which correspond with theoretical findings in [6].



(1) Base case



(2) Unexpected imbalance

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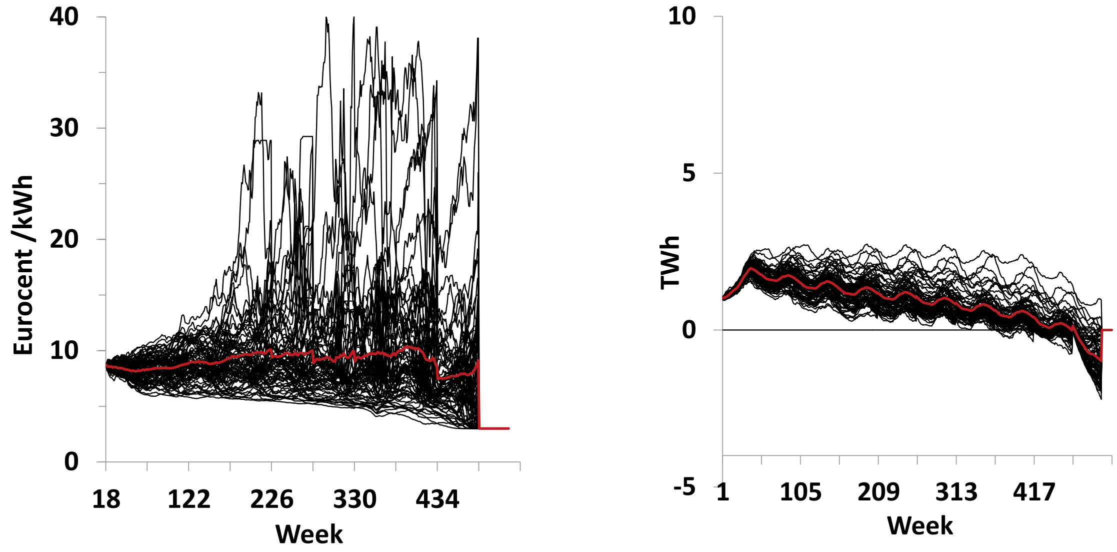
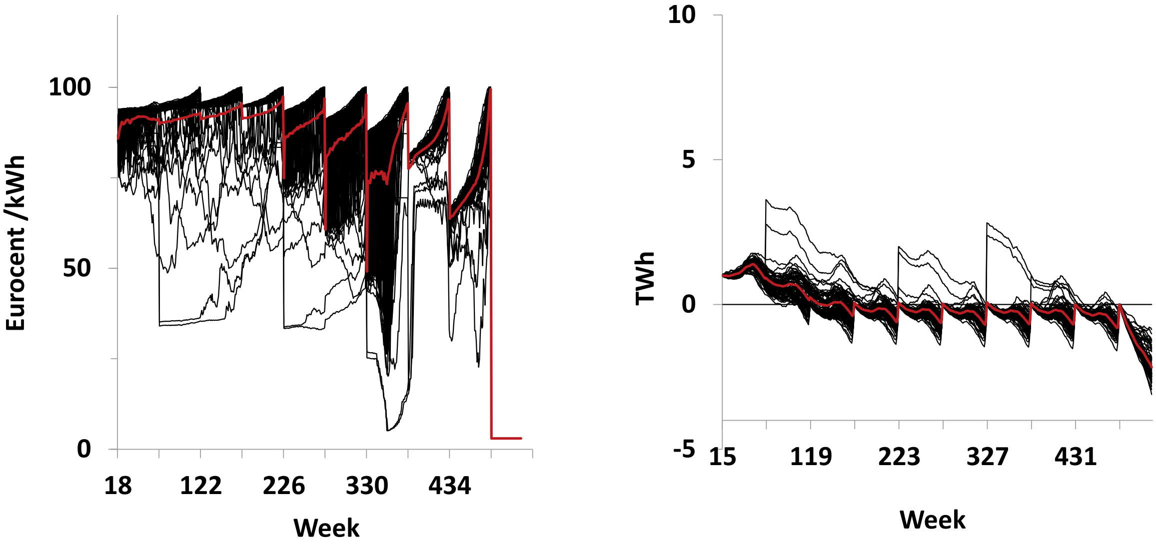
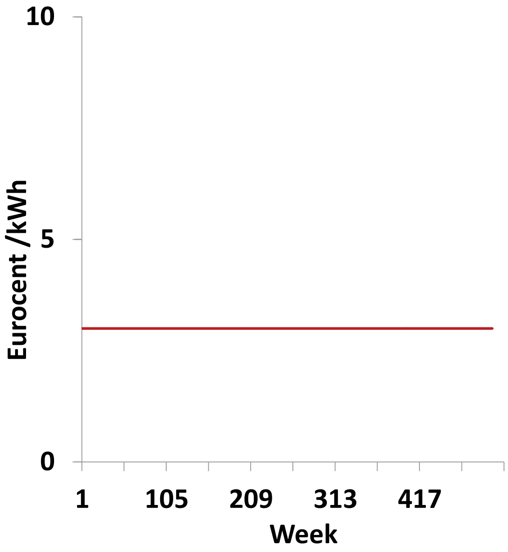
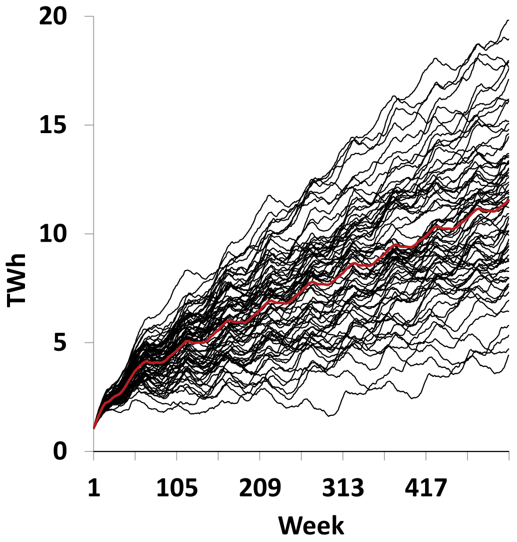


(3) Scarcity

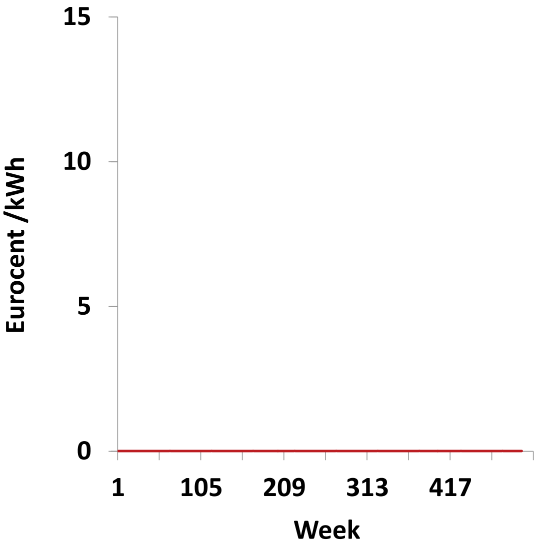


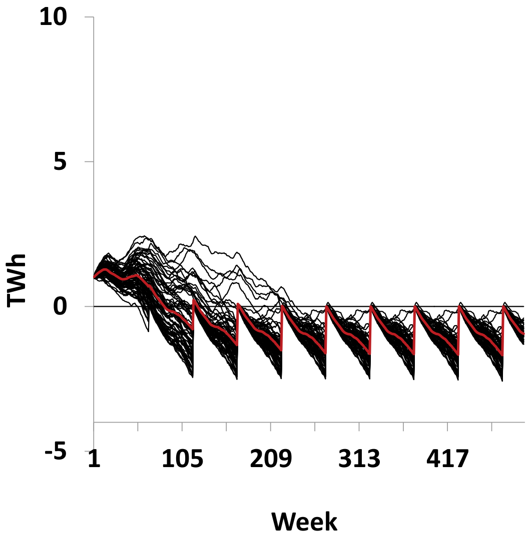
(4) Deficit



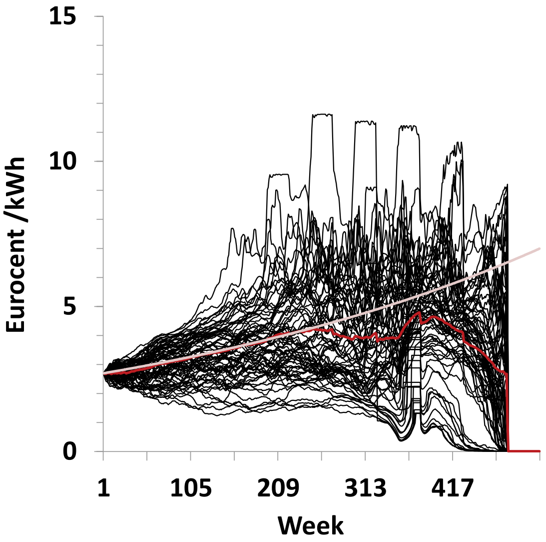


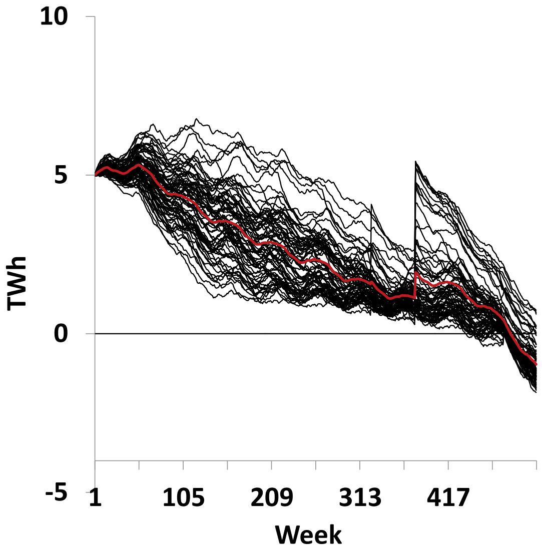
(5) Surplus





(6) Degenerated solution





(7) 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.

5. Summary and concluding remarks

In this paper, a novel methodology for forecasting in the Swedish-Norwegian el-certificate market is described. The applied model includes 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. A strategy for the el-certificate inventory is calculated by stochastic dynamic programming for a set of possible penalty-rates. The penalty-rate is however not known during simulations. Instead a rolling forecast for the expected penalty is applied, in an iterative way. The performance of the model for different cases that can occur in the el-certificate market is illustrated. Results correspond broadly to theoretical findings in previous studies for tradable green certificate markets. In particular, 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. In addition special cases are identified, where certificate prices become excessively high or zero respectively, due to the built-in 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.

3 User manual

3.1 Introduction

Content of document

This is the user-manual for the el-certificate market in the EMPS model, which is developed within the IPN-project "Modellering av marked for elsertifikater i Samkjøringsmodellen". The document describes how to prepare the inputs, start an integrated simulation for the el-certificate- and power-market, and extract simulation results for the certificate market. The overall methodology is not described in this document.

A new area is created automatically

The handling of the green certificates is done within a dedicated area, which is created automatically, when running with the option for green certificates. The area is added as new area at the end of all other areas. This means if the power system model consists of 3 areas, a new area with the number 4 (the green area) will be added. The area contains a storage for green certificates, which is modelled as aggregated reservoir. In addition several other production and consumption assets are included, which are in accordance with the production / consumption assets, which receive respectively require green certificates.

Environment variable

A new environment variable has to be set to run the el-certificate functionality: `LTM_MPS_ELSERT`
All letters are capital.

Parallel simulation

The el-certificate market simulation has been developed for a **parallel simulation**, i.e. a simulation that starts e.g. in the current week with known reservoir levels and known net certificate balance. The other option in the EMPS model is series-simulation. Do not apply this option when running a simulation for the certificate market.

3.2 Input file

There is one new input file required for the green certificate options, called *grsert.csv*. This is a text-file with columns separated by semicolons. The file can be edited in Excel. In the following an overview of the file is given (as defined in Excel). The example of a whole file is shown in the appendix.

The first line has to include a file identifier that will be utilized internally in the model. Use only English letters, e.g.:

	Groenne sertifikater	

The further definitions are defined in blocks, in which the first line contains the number of rows in the block, as well as the name of the block.

3.2.1 Parameter

In the first block several simulation parameters can be set. All of these parameters are optional. The formatting and the default values of the parameters are shown in the following.

	Sertifikatparameter					
	Oppgjoeruke	Start sertifikat lagerbeholdning (GWh)	Maximal sertifikat pris	Maximal sertifikat lager (GWh)	Null magasin level (%)	Antall straff scenarier
	14	0	150			

The week-number for the first settlement is specified. If week 14 is specified, the model will include settlements in week 14, 66, 118 and so on for the whole planning period.

The initial storage of certificates is the net balance of certificates in the system the first simulated week. If e.g. the simulation start in week 34/2014, then one should provide the net balance at the start of this week also accounting for built-up certificate obligation during 2014 to be settled in 2015.

The maximum certificate prices should be set in the same monetary unit as the rest of the data-set. So if the prices are calculated in ore/kWh, then the maximum price should be in ore/kWh too. A maximum-price for certificates equal to 150 ore/kWh correspond with 1500 NOK/MWh (or NOK1500 per certificate).

The next 3 columns can be left blank, and then the default values are used. Below we provide a brief explanation to each of them. A further discussion of the separate parameters is given in section 5.

The maximum storage of certificates is in reality infinite, but the model needs a maximum to tune the evaluation points for the water-value calculation. However, a reasonable default-value for this is calculated automatically.

The reference level is a similar parameter specifying the 0 GWh point in the full reservoir that actually must allow both positive and negative values during a year. A default-value is calculated automatically.

The number of penalty-scenarios is number of strategies that are calculated for the certificate storage (one strategy is calculate for each penalty scenario). The default number 9. If a lower number is provided the calculation of certificate values will be less accurate, but computational time will decrease.

3.2.2 Historic certificate prices

The penalty price for el-certificate shortage is based on the certificate prices of the previous year. If the first simulated week is before the settlement-week for the current year, one therefore has to specify certificate prices for the previous year. In addition, one has to specify certificate prices for past weeks in the current year.

2	Sertifikatpriser	
Loepenr.	Sluttuke	Pris (ore/kWh)
1	0	12
2	9	10

In the example above, the simulation starts in week 10. The average price of certificates was 12 in the previous year. This specified by providing the value 0 on "Sluttuke" and "Pris" equal 12. The average price for the first 9 weeks of the current year is 10. It is possible to specify different prices for individual or smaller intervals of weeks.

Certificates are financial assets that can be traded by different parties at any time. Therefore, the trades do not have to coincide with issuing or certificates or build-up of certificate-obligation for the next settlement. In the current version of the model each weekly price gets the weight 1/52. In future versions this will be the default-value, but the user shall be able to specify different weights.

3.2.3 Final certificate value (optional, but suggested)

If no end-value is specified for certificates at the planning horizon, the model will apply the same methodology that is applied for hydropower. Tis will result in an end-value function that is consistent with a problem where the final year is repeated (infinite) many times.

It is however possible and suggested to specify a final value for the green certificates. A constant value or a variable value depending on the amount of stored certificates can be specified. In general, a piecewise linear function is specified by giving a set of points. In the example below, the certificate value is constant at 10 for values below zero. Above zero the value start at 10 and is linear decreasing to zero at 11 TWh.

3	Sluttverdi	
Loepenr.	Magasinlevel (GWh)	Sertifikatverdi (ore/kWh)
1	-5000	10
2	0	10
3	11000	0

3.2.4 Defined penalty values (optional)

In the Norwegian-Swedish certificate market, penalties for missing certificates are 150 % of prices in the previous year. This has been implemented in the model, and will be applied if the penalty-value table is not present or empty, cf. the left table below.

0	Straffverdi	
Loepenr.	Sluttuke	Verdi (ore/kWh)

2	Straffverdi	
Loepenr.	Sluttuke	Verdi (ore/kWh)
1	66	7.5
2	222	15

However, it is also possible to run the model with fixed penalty-rates specified in the input. To apply this option, the penalty rates must be specified for the settlement weeks. In the example in the right table above, the penalty price is equal to 7.5 for settlements in week 66 or before, and equal to 15 for settlements in weeks after week 66 and till week 222.

3.2.5 Weighting of weeks

When calculating the penalty price for a settlement of certificates, the average price of certificates for the previous year is used. To be able to take into account the date of the turnover of the certificates, weighting factors for the weeks can be given. The weighting factors can be in any format, such as percent or turnover per week. Again, the final week of a certain factor and its value have to be given.

2	UkePrisVekt	
Loepenr.	Uke	Vekt
1	26	1
2	52	1

3.2.6 Thermal production

Thermal power plants, which receive el-certificates because production is based partly or fully on biomass, are defined by the area they are situated in, as well as their according number within the area. Furthermore the percentage of el-certificates, which the production asset receives, has to be defined in the last column (in percent). As this share can change during the simulation, several steps can be defined for each power plant. Thereby the final week for which this step is valid has to be given, as shown in the example below. It is optional to provide a name.

2	Produksjon				
Loepenr.	Delomraade	Typenr.	Navn	Sluttuke	Andel (%)
1	1	12	Ny bioenergi	52	75
2	1	12	Ny bioenergi	260	50

3.2.7 Wind power production

Wind power production assets, which receive el-certificates, are identified by the area number, as well as the number of the energy series (in case several series are defined in one area). Again several steps for the share receiving certificates can be defined, where the final weeks have to be given.

2	Vindkraft				
Loepenr.	Delomraade	Serienr.	Navn	Sluttuke	Andel (%)
1	1	1	NO.V30	260	100
2	2	1	SE.V30	260	100

3.2.8 Hydro power production

Hydro power production, which receives el-certificates, has to be defined on the basis of modules. Then the according modules are defined by their area number and the module number. The share of certificates is defined as follows:

1	Vannkraft				
Loepenr.	Delomraade	Modulnr.	Navn	Sluttuke	Andel (%)
1	1	101	NO	260	10

3.2.9 Firm consumption ("Fastkraft")

For historical reasons, consumption can be specified as firm-power ("Fastkraft") or accidental power ("Tilfeldig kraft") in the EMPS model. The inputs provided and characteristics are somewhat different for the two, but both types can respond to prices.

The firm-power consumption, which requires el-certificates, is defined by the area number as well as the number of the specific consumption within the area. However, the power-suppliers do not have to buy certificates e.g. for deliveries to power-intensive industry. Also, a given consumption entity in EMPS may consist of several consumption types. For each consumption-entity in the model one therefore has to specify the share of the consumption that requires certificates. If all consumption represented by an entity is ordinary demand, then the share should be 100 %. The name provided in the table is optional.

1	Fastkraft				
Loepenr.	Delomraade	Dellastnr.	Navn	Sluttuke	Andel (%)
1	1	1	NO	260	21

The number of certificates that must be obtained for a given power-delivery e.g. to ordinary demand varies from year to year. The certificate-quota is specified in "Elsertifikatloven, §17". This information has to be translated into weekly certificate-quotas in the model. The annual certificate quota is set in a separate block, defining the final week for each of the quotas in each of the areas.

3	Kvoteplikt		
Loepenr.	Sluttuke	Kvote Delomr. 1 (%)	Kvote Delomr. 2 (%)
1	52	4,9	2,3
2	156	6,9	3,5
3	260	8,8	4,2

3.2.10 Flexible consumption ("Tilfeldig kraft")

This is the consumption-units that are specified along with thermal power generation. The needed input is shown below. In the example, one have to buy certificates to only 10 % of the consumption for all weeks till week 260. The remaining 90 % is exempted. The name is optional.

1	Forbruk				
Loepenr.	Delomraade	Typenr.	Navn	Sluttuke	Andel (%)
1	1	30	Flex Forbruk	260	10

For accidental power we have implemented the corresponding need for certificates for the categories "Salg" and "REFER". So far we have not done the implementation for the third category "GJENKJ", which normally created to account for the price-elasticity in firm-power when a dataset is converted from version 8 to 9. However, price-elasticity can be directly defined for the firm-power, and that certificate-consumption will be adjusted accordingly.

The whole file is presented in the appendix.

3.3 EMPS run with green certificates

To start EMPS with the el-certificate option, the previously explained file *grsert.csv* has to be present in the model folder. Then the program SAMINN has to be started with the option GRS:

```
SAMINN GRS
```

Exogenous prices can be applied together with the el-certificate modelling (LTM_MPS_EKOSGEN_PRISNIV). However, only one set of water-values will be calculated. If exogenous prices are applied when running a simulation for the el-certificate market, an extra argument must be provided when running SAMINN:

```
SAMINN GRS ELEKS
```

When running through SAMINN, the area handling the el-certificates is created automatically. There will be an output reporting a couple of internally calculated parameters, such as the size of the certificate storage.

```
Navn p} verk/delomr}der som skal inng} i simuleringene.
-------------------------------------------------------------
Delomr.: Navn p} delomr}de    : Navn p} linjebildefil hvor  :
nummer :                      : enmagasindata er lagret.    :
-------------------------------------------------------------
   1   :                   NO :                 NO.ENMD     :
   2   :                   SE :                 SE.ENMD     :

Er data ok ? ........................................... : j

Vil du gruppere delområder til Samkjøringssystem ? ..... : n

Bygger naa groent omraade => GROENN.ENMD

The boundaries for the certificate storage are:
Upper: 10978.10 GWh
Lower: -5407.12 GWh


Delomr}de nr:  1. Navn:                   NO
--------------------------------------------

Delomr}de nr:  2. Navn:                   SE
--------------------------------------------

Delomr}de nr:  3. Navn:               GROENN
--------------------------------------------

Starter sammenlagring av alle preferansefunksjonene.
```

When running STFIL, one has to be aware, that running with green certificates requires running the detailed drawdown model, if some of the hydro power receives green certificates. No other special options have to be chosen.

3.4 Result analysis tools

For the analysis of the results, the KURVETEGN / PCKURVETEGN, SAMUTSKRV and VVTEGN/VVPRINT can be used. So far we have not tested AVREGN or SAMOVERSKUDD.

The area in which the green certificates are handled is the area with the highest area number. When extracting results for the certificate-market, this area has to be chosen. The table below shows the mapping of the results is done for that area. Example: If the certificate-area is selected, and one selects hydropower production, then the provided values are actually the certificates generated from hydropower.

In the result programs	Description
Hydro power	Certificates generated from hydro power
Wind power	Certificates generated from wind power or accordingly defined energy series
Consumption	Certificates required for consumption
Internal market - Purchase	Certificates generated from thermal power plants (or similar)
Internal market - Sale	Certificates required for flexible consumption
Regulated inflow	Certificates issued due to penalty
Reservoir level	Net balance of certificates
Power price	Certificate price
Water value	Certificate value

3.5 Additional simulation parameters

There is a set of parameters that are optional to define for the simulation. These are:

- The reference reservoir level (default: 33%) - It defines the zero level for the certificate storage in the underlying hydro reservoir. It should be considered to be changed in cases the boundaries of the certificate storage are hit during the simulation.
- The maximum certificate storage (default: automatically determined) - It defines the size of the certificate storage. It should be considered to be changed in cases the boundaries of the certificate storage are hit during the simulation.
- Number of penalty scenarios (default: 9) - Defines the scenarios of different penalty prices for which the strategy is calculated. Can be changed, when the strategy calculation is to time intensive.

3.6 Example of grsert.csv

```
;Groenne sertifikater;
;
;Sertifikatparameter;
Oppgjoeruke;Start sertifikat lagerbeholdning (GWh);Maximal sertifikat pris
(ore/kWh);Maximal sertifikat lager (GWh);Null magasin level (%);Antall straff scenarier
14;0;150;
;
2;Sluttverdi;
Loepenr.;Magasinlevel (GWh);Sertifikatverdi (ore/kWh);
1;-5000;0;
2;0;0;
;
2;Sertifikatpriser;
Loepenr.;Uke;Pris (ore/kWh);
1;0;12;
2;15;15;
;
2;UkePrisVekt;
Loepenr.;Uke;Vekt;
1;26;1;
2;52;1;
;
2;Produksjon;
Loepenr.;Delomraade;Typenr.;Navn;Sluttuke;Andel (%)
1;1;12;Ny bioenergi;52;75
2;1;12;Ny bioenergi;260;50
;
1;Forbruk;
Loepenr.;Delomraade;Typenr.;Navn;Sluttuke;Andel (%)
1;1;30;Flex Forbruk;260;10
;
3;Kvoteplikt;
Loepenr.;Sluttuke;Kvote Delomr.1 (%);Kvote Delomr.2 (%);
1;52;22;11;
2;104;24;12;
3;260;26;13;
;
1;Fastkraft;
Loepenr.;Delomraade;Dellastnr.;Navn;Sluttuke;Andel (%)
1;1;1;NO;260;21
;
2;Vindkraft;
Loepenr.;Delomraade;Serienr.;Navn;Sluttuke;Andel (%)
1;1;1;NO;260;100
2;2;1;SE;260;100
;
1;Vannkraft;
Loepenr.;Delomraade;Modulnr.;Navn;Sluttuke;Andel (%)
1;1;101;NO;260;1
;
```

3.7 Calibration of certificate area

About calibration in the EMPS model
EMPS model utilizes a combination of stochastic dynamic programming (SDP), linear programming (LP), and heuristic methods that reduces computational time a lot. Examples of heuristic methods are

- Water-value calculation is carried out for each area separately by the creation of a residual demand curve for each hydropower area.
- Allocation of hydropower generation per area is allocated to specific plants through a rule-based methodology in the draw-down model (no: Tappefordelingsmodell).

However, the water-value calculation per area is adjusted on basis of simulation results in the previous iteration. In this way, the final water-values do take into resulting simulated prices in other areas. Still, the EMPS model needs to be calibrated either manually, on basis of a set of criteria, or in an automatic procedure that e.g. can be set up to maximize total economic surplus.

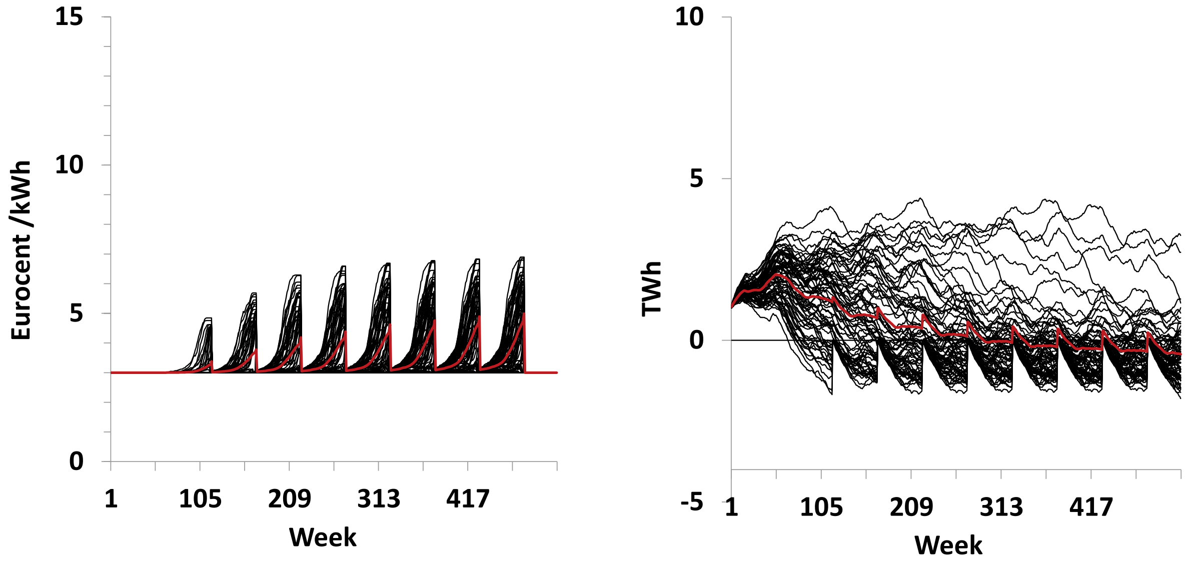
For the certificate-market, all production or consumption that affects either demand or supply in the market is represented in the residual demand curve or as inflow to the certificate storage. Therefore, it is so obvious why the certificate market needs calibration. Basically, the explanation is that the calibration part of the model also compensate for other simplifications that are done in the model to be able to solve the full problem at acceptable computational times. For instance, the applied probability distributions for stochastic variables during strategy calculation are unconditional and not affected by realizations prior to the current week. Some autocorrelation is probably represented in the simulated scenarios. For the certificate market specifically, we apply an estimate for the expected first penalty to decide the strategy during simulations, while strategies are calculated for given (known) penalties. The calibration process compensate for the imperfect elements in the model.

SINTEF experience with calibration of the el-certificate area
SINTEF's experience so far is that calibration of the certificate market is necessary, and that results are good after calibration. Typically, it is also relatively clear from simulated results for prices and the certificate balance if there is a need for adjusting the calibration. In the following we will show and explain this in examples.

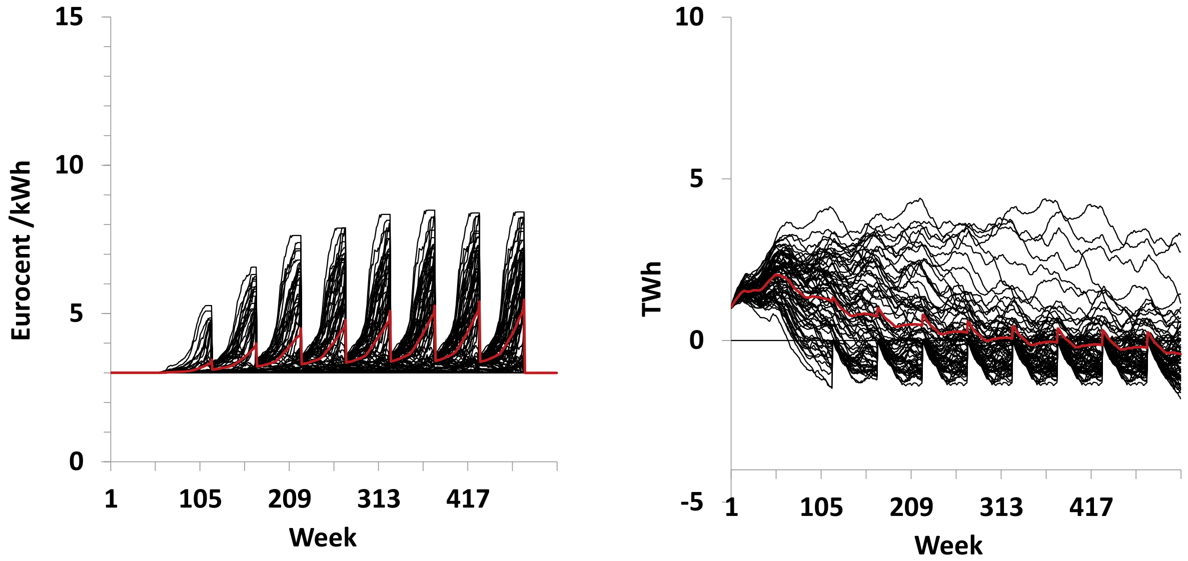
In the EMPS model there are several calibration factors for each area. These factors can be accessed by writing KOPL at the right place in the sequence when running STFIL (or SAMINN if STFIL is called directly). This is shown in Figure 3.1. The total firm demand (no: fastkraft) as seen by the model in strategy-calculation is adjusted by the feed-back factor (no: Tilbakekoblingsfaktor). We have only adjusted this parameter when running test-cases for the el-certificate market. In Figure 3.2 we have showed simulated prices and certificate storage development for 8 different calibrations for a given case. Note that the best calibration varies for case to case. In the following we will discuss each of those calibrations.

```
Command Prompt - stfil
Siste simuleringsuke  (520) ............................ :

Skal vannverdiberegning utføres (JA) ................... :

Skal det simuleres med tappefordeling (NEI) ............ : j

                I N N L E S T E   O M R ] D E M A G A S I N E R

Delomr>de  1, NO                                50.00 %    43793.8 GWh
Delomr>de  2, SE                                60.00 %    26510.3 GWh
Delomr>de  3, GROENN                            86.60 %    19388.1 GWh
-------------------------------------------------------------------
Sum                                             58.18 %    89692.2 GWh

Ønskes oppdatering av startmagasinene (NEI) ............ :

Tast utførelseskode eller RETURN ....................... : ??

Utf¦relseskoder  :  Forklaring

          NUTV    :  Tilbakekoplingsparametre f>r default-verdier
          SIM]R   :  Endring av hvilke >r som skal simuleres eller
                     simulering med prosenter av middeltilsiget
          KOPL    :  Korrigering av parametre som p>virker fastkraftniv>
                     og fastkraftfordeling ved vannverdiberegningene for
                     hvert delomr>de. Korreksjonsfaktor for
                     preferansefunksjon.
          VVMINP  :  Minimumsproduksjon for vannverdiberegning
          GRENS   :  Endring av konvergensgrenser
          GINT    :  Gasskraft med integralkrav
          FIVA    :  Fastkraft brukt i vannverdiberegningen

Tast utførelseskode eller RETURN ....................... : kopl

-----------------------------------------------------------------
: Omr>de  :  Navn p> omr>de        : Tilbake- : Form-   : Elasti-
: nummer  :                        : koplings-: faktor  : sitets-
:         :                        : faktor   :         : faktor
-----------------------------------------------------------------
:     1   : NO                     :   1.546  :  1.059  :   1.000
:     2   : SE                     :   1.447  :  0.901  :   1.000
:     3   : GROENN                 :   0.950  :  1.000  :   1.000

Er data i orden (JA) ................................... :
```

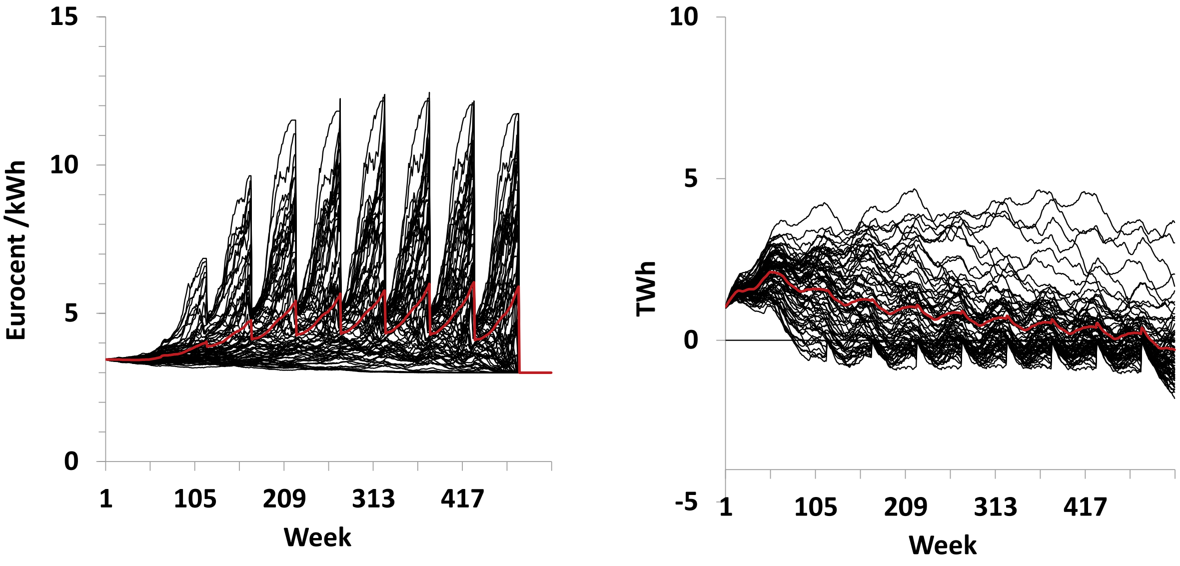
Figure 3.1 Accessing calibration factors


15
10
5
0
Eurocent /kWh
1
105
209
313
417
Week
10
5
0
-5
TWh
1
105
209
313
417
Week

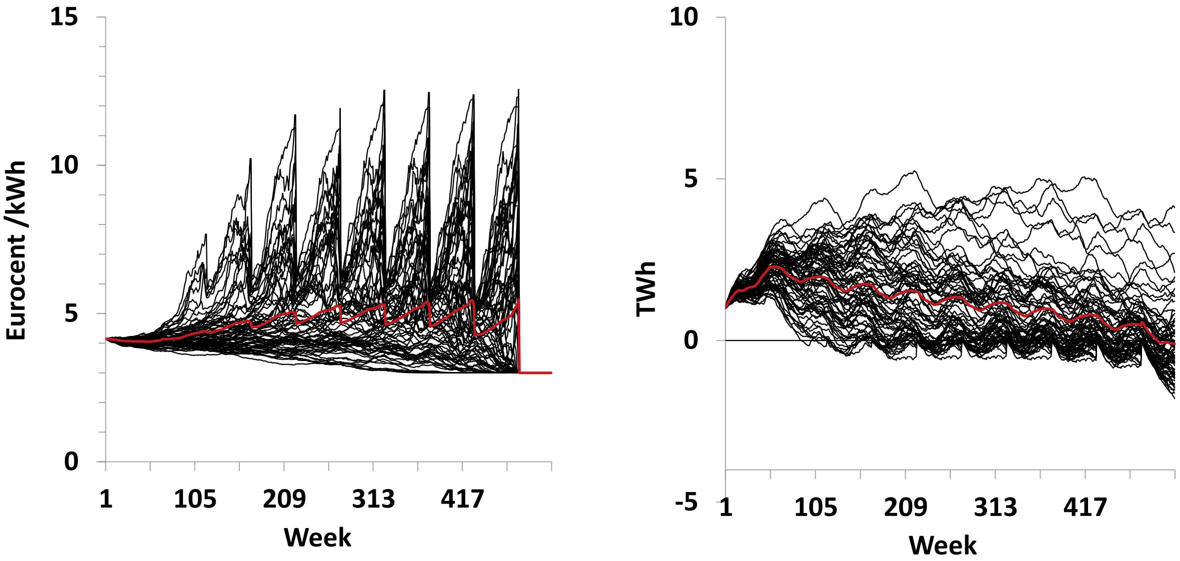
(a) 1.000


15
10
5
0
Eurocent /kWh
1
105
209
313
417
Week
10
5
0
-5
TWh
1
105
209
313
417
Week

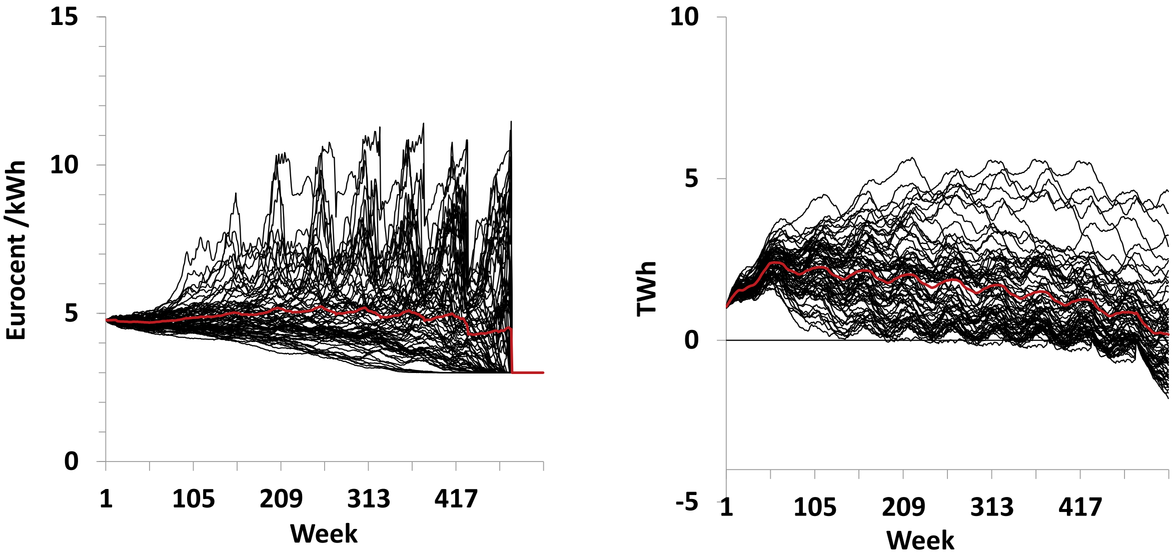
(b) 1.020


15
10
5
0
Eurocent /kWh
1
105
209
313
417
Week
10
5
0
-5
TWh
1
105
209
313
417
Week

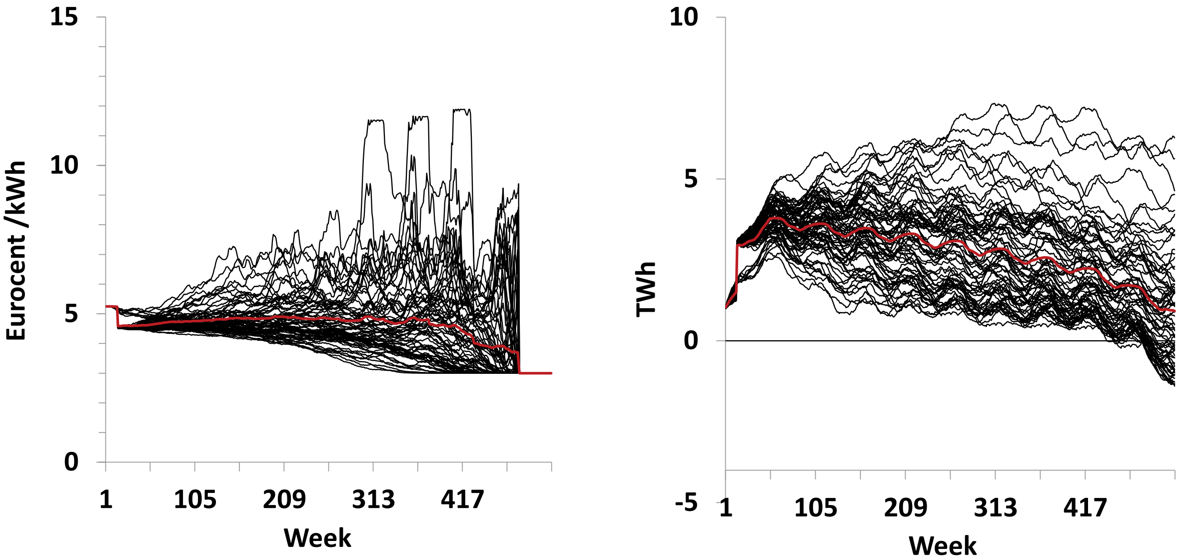
(c) 1.040


15
10
5
0
Eurocent /kWh
1
105
209
313
417
Week
10
5
0
-5
TWh
1
105
209
313
417
Week

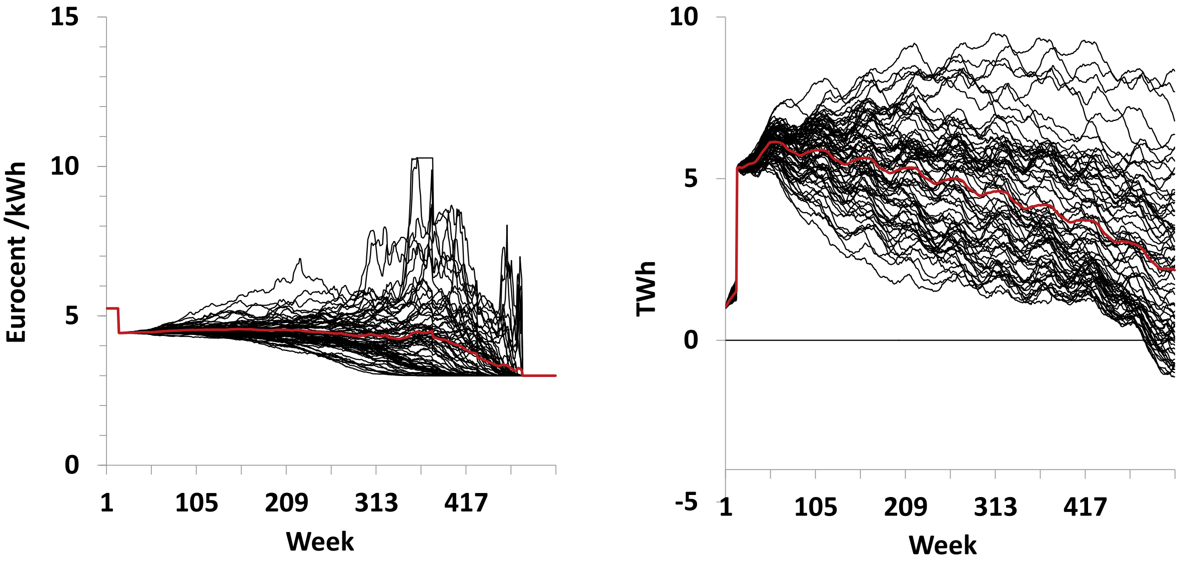
(d) 1.050


15
10
5
0
Eurocent /kWh
1
105
209
313
417
Week
10
5
0
-5
TWh
1
105
209
313
417
Week

(e) 1.060


15
10
5
0
Eurocent /kWh
1
105
209
313
417
Week
10
5
0
-5
TWh
1
105
209
313
417
Week

(f) 1.070



(g) 1.080

Figure 3.2 El-certificate prices (left panel) and el-certificate balance (right panel) for all 520 weeks, 75 scenario and average (red curve), for 8 calibrations. .

<u>Case a: 1.000</u>
In this case the feed-back factor is set to 1.000. Here we can see that simulated prices are increasing towards the settlement week (week 14 of each year) on average and for a large share of the scenarios, and dropping thereafter. Also, a considerable penalty is taken in many scenarios. This is a typical situation where the feed-back factor is too low. Too little demand is seen during the strategy-calculation. Therefore, the certificate values in the strategy become too low. During simulation, certificate prices are low after a settlement. However, as the settlement gets close, the model see that there is a large probability for deficit, and prices start to rise. In a market with rational players, this price increase would have increased much before. The calculated value of certificates is too low. By increasing the feed-back factor, the demand for certificates are increased during strategy-calculation and this will increase initial prices after a settlement.

<u>Case b: 1.020</u>
The increase from 1.000 to 1.020 did not change much. However, there is a bit longer duration of the period with high prices before the settlement. Still, average prices are increasing through the certificate-year, before dropping after the settlement. The feed-back factor must be increased further.

<u>Case c: 1.040</u>
With this calibration factor prices are in general higher, and the within-year increase in average prices is relatively less. However, there is still a systematic trend that average prices rise towards the settlement-week and drop thereafter. There is also an upward year-to-year trend which is not consistent with the possibility of saving certificates for the use in later years. The feed-back factor must be increased further.

<u>Case d: 1.050</u>
The within-year profile for average prices, as well as the year-to-year price increase, has been damped compared to Case c. However, the feed-back factor must further up to eliminate those trends.

Case e: 1.060
In this case the average price is almost constant within and between different years. However, it is not totally a straight line because the average price is not a variable in the model. The model is simulated for each stochastic scenario, and thereafter the average price is calculated.

Case f: 1.070
For this case the average price is even flatter than in the previous case. However, there is a drop in the average price from the first settlement to the week after. As seen from the storage development figure, a penalty is taken in the first settlement for most scenarios. The penalty taken, or at least the amount of penalty taken, is too large since the price drop below the penalty price after the settlement. This is an indication that a too high demand is specified in the strategy calculation, giving a too high value during the settlement. The feed-back factor should be reduced.

Case g: 1.080
This case is similar to the previous case, except that the penalty taken is even higher. As a consequence, the price after the first settlement drops even lower. The value of certificates is set too high during the first settlement because the feed-back factor is set too high.

Unbalance in calibration and specification
Even though the certificate market needs to be calibrated, one should be aware that the calibration can only help to provide the correct result for the specified problem. Major unbalances, deficit taken or other unbalanced results can be a result of the specified input for the certificate market. This cannot be solved by the calibration of the model.

4 Suggested further development

More testing on large datasets, and update to 9.6

The most important further development to make the functionality accessible for EMPS model users is to

- Do additional testing on large datasets, and with much functionality, which may reveal additional needs for adjustments.
- Update implementation from the current 9.2 / 9.3 to the most updated version (9.6 by 27. October 2014) so users operational data-sets can be applied without special modifications.

Expected certificate price in future years

As described in Chapter 2, during simulations the expected value for the first future penalty taken is estimated in every week and scenario. Basically, the expected value is calculated by estimating expected prices in different future weeks, and expected probability for deficit at different settlements seen from the time of forecasting. However, simulated prices will probably be relatively high in those scenarios that actually lead into deficit. It is therefore likely that estimated prices as seen from the forecasting week will give too low values for likely prices in futures that lead to deficit and a penalty taken. One approach to adjust for this could be to only consider those scenarios that lead to deficit when expected future prices are estimated. Then the expected future prices would be conditional on deficit, which should be correct when calculating expected penalty. However, this issue should be studied further. An adjustment of the calculation method for the expected future penalty rate will influence simulated prices and price-volatility.

Settlement for calendar year

In the model, the balance is developing week by week on basis of consumption and renewable power generation till the settlement week. However, in the certificate market the settlement at 1. April is for the previous calendar year 1/1 – 31/12, and not for the previous certificate year 1/4 - 31/3. On the supply-side, some of the production (e.g in January and February) will be available at the first settlement, but not production close to the settlement-week. Those specific details about the settled amount and availability on certificates can be important for forecasting if the number of certificates available at the first settlement is scarce.

Calculation of penalty rate

The model calculates the penalty rate on basis of calendar year. However, the penalty rate is in practice calculated on basis of turnover in the certificate year 1/4 - 31/3.

A Appendix. Additional information about implementation.

A.1 Introduction

The methodology for the implementation of the el certificates in EMPS is described in Chapter 2.

The main point in the methodology is to create a new "green" area which contains all the production and consumption of green certificates as well as a reservoir to store these certificates. To integrate these green certificates the previous structure of EMPS is used as good as possible. For that the exogenous price methodology is used, calculating certificate values for a set of different expected penalty prices.

An overview of the additional implementations within EMPS is given in the figure below

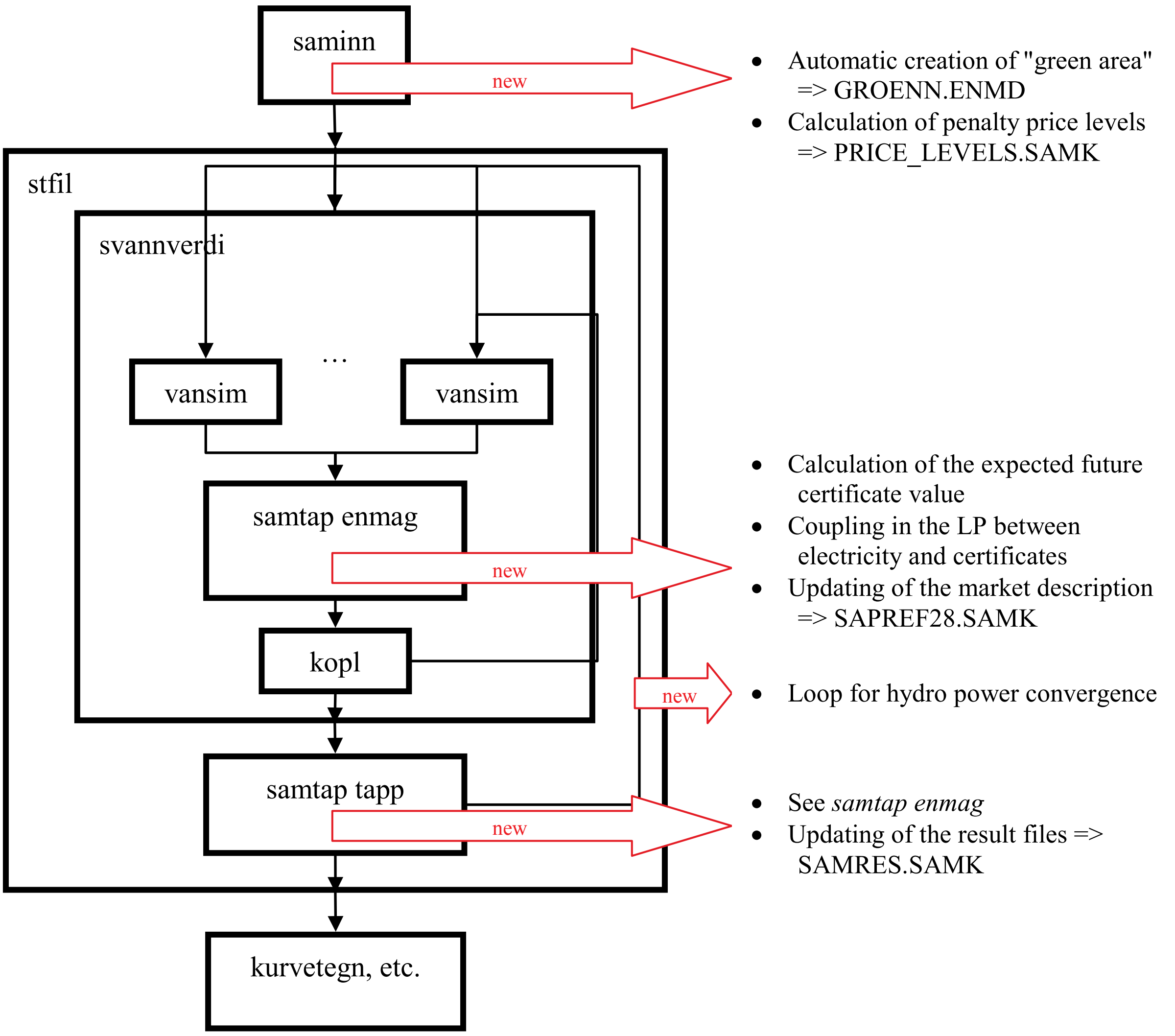


Figure A.1. Schematic of the additional implementations

Within the implementation a new library is created (Elserifikat.lib), containing several modules. Furthermore the main changes are done in saminn and samtap. A specification of changes is reported in the following.

A.2 Input file

The one and only input file to the green certificates methodology is grsert.csv, which contains a number of parameters as well as the electricity production and electricity consumption with el certificates, including their required share. The input file is described in the user manual for green certificates modelled within EMPS.

A.3 Saminn

The main focus in extending saminn is to create a new "green" area, which contains the production, storage and consumption of certificates.

To that an additional area is created and put into the data structure. Within this area production and consumption assets as well as an aggregated reservoir are defined. The certificate reservoir is defined according to automatic calculated (or specified) parameters. The requirements here are that the upper/lower limits of the reservoir are never reach during the simulation. Moreover, as reservoirs defined in EMPS do not allow negative levels, a virtual (zero level) offset is implemented.

The thermal production and consumption assets for certificates are copied from their according electricity part, adapted by the required share (quota). The same accounts for energy series for RES, such as wind and solar power production. However, certificates for hydro power production on module basis are handled by the unregulated inflow in the green area, which is updated iteratively.

Furthermore, in order to allow the storage of certificates, a dummy (regulated) inflow as well as an equal dummy consumption is defined.

Finally, a separate group is created for the "green" area, so that there is no exchange with / impact on the other areas.

The "green" area is saved as .ENMD file, which can be opened in enmdat.

A.4 Stfil

Running stfil should include also running tappefordeling.

Then the only addition in stfil is the convergence check for certificates from hydro power. This means, it is check if the certificates for the individual hydropower modules is in accordance with the actual hydro power production of the modules. This is necessary as there is iteration for the certificates from hydro power, meaning that certificates for hydro power are issued based on the actual hydro power production in the last iteration (run of tappefordeling).

A.5 Svannverdi

In svannverdi, there is only a change in the screen printout, hiding the actual use of the exogenous price methodology.

A.6 Samtap

Significant changes are done in within samtap. These include three different issues, firstly the state variable for the expected future certificate value is calculated, based on which the certificate value table is determined. Secondly the LP within the simulation is adapted to incorporate the green certificates. Thirdly the "green" area is updated within the water-value calculation iterations after the simulation, right before kopl is run.

A.6.1 The additional state of the expected future certificate value

In order to account for the settlement methodology for the green certificates (the penalty price depends on the certificate prices last year), an additional state, the expected future certificate value has to be introduced.

However, this expected future value depends on the probability for the shortage of certificates and hence on the actual certificate reservoir level. To estimate the shortage probability, the certificate reservoir trajectories of the previous iteration are used, stored in the file ELSERTOVERSKUDD.SAMK.

Furthermore, the expected future value is influence by the price within the simulated week. Thus, there is an additional iteration, first assuming a certificate price in the week. Next the simulation is run and the certificate price is calculated. Then the difference between the assumed and the calculated price is checked. If the difference is above a threshold, the new assumed price is the last calculated price and the simulation is rerun. If the price is converged, the next week is simulated.

A.6.2 Adapting the LP

In the LPs, defined for each week the coupling between electricity and certificate production is directly included. Therefore, the marginal production costs of all units in the green area are set to zero and a set of additional constraints is added in the LP. These constraints define the direct connection between producing energy and receiving certificates respectively consuming electricity and requiring certificates.

A.6.3 Updating the "green" area

After the water values are calculated and simulation is run, before running kopl, the green are is updated. This means, bidding prices (marginal costs) for production and consumption is calculated new based on the simulated electricity prices for the according plants. Thereby the file SAPREF28.SAMK is rewritten.

A.7 Kurvetegn / result programs

In order for the results programs to work properly, result files are updated. These files are SAMRES.SAMK as well as the binary files located with SekvRes\. The updating includes a shifting of trinns, adjustments of the regulated and unregulated inflow as well as an adjustment of the certificate reservoir to the given zero level.

A.8 Calculating the expected future penalty price

Within the water value calculation (vansim), certificate value tables for several penalty price scenarios are calculated, accounting for the expected penalty price as an additional state variable (besides the storage level of the certificate storage).

In order to determine the correct certificate value table in a given week, the expected penalty price has to be taken into account. This penalty price depends on certificate prices so far and the probability of certificate shortage in the next (and second next) settlement. As it is not only the expected penalty price in the next settlement, but also the expected penalty prices in the next, the second next and the third next settlement, which might define the long-term value of certificates, a reference price is calculated. The reference price gives the certificate value table which is used.

The calculation of the reference price is given in the following. Fig. shows an example of probabilities for the certificate shortage. Thereby, ***a*** is the probability of certificate shortage in the next settlement, while ***c*** is the probability for the second next settlement. For each simulation scenario in a given week, the storage level is determined, giving values a_u and c_u, where the index ***u*** identifies the week number. Furthermore, the expected penalties prices for the next, the second next and the third next settlement are determined. Thereby historic certificate prices are recorded, while the certificate prices in the future weeks are assumed to be equal to the price in week ***u***:

$$p_x = p_u \; for \; x > u$$

The expected penalty price for the next settlement:

$$p_u^{pen} = 1.5 \times \frac{\sum_{52}^{x=1} p_x}{52}$$

The expected penalty price for the second next settlement:

$$p_{u+52}^{pen} = 1.5 \times \frac{\sum_{104}^{x=53} p_x}{52}$$

The expected penalty price for the third next settlement:

$$p_{u+104}^{pen} = 1.5 \times \frac{\sum_{156}^{x=105} p_x}{52}$$

These calculations are valid for weeks between number 15 and 118 (assuming the settlements to be in week 14). For other weeks the indexes have to be adapted to the according years.

Then the reference price is calculated as:

$$p_u^{ref} = a \times p_u^{pen} + (1-a) \times \left(c \times p_{u+52}^{pen} + (1-c) \times p_{u+104}^{pen}\right)$$

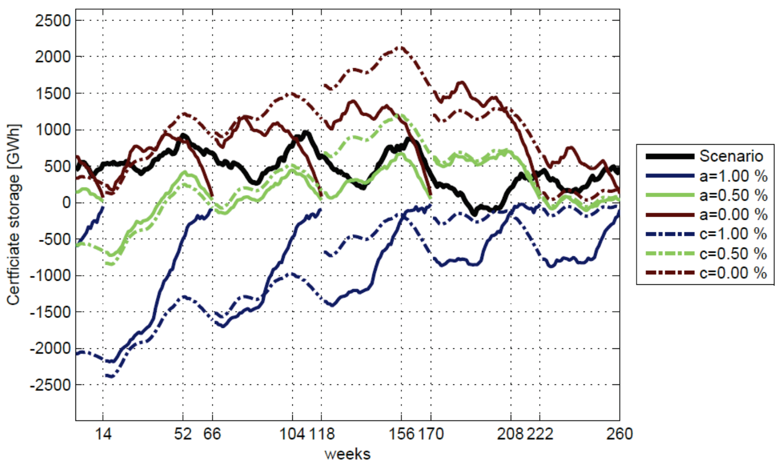


Figure A.2. Percentiles for the probability of certificate shortage based on certificate storage trajectories

The percentiles for the probability of certificate shortage shown in Figure A.2 is based on the trajectories of the certificate storage development. For storage development for each single year in each single scenario is adjusted to zero storage level in the settlement week. Then percentiles for these trajectories are calculated, shown in the figure above. The trajectories used for the second and third next settlement (defining value ***c***) are a continuation of the trajectories for the first and second settlement (defining value ***a***).

The reference price is then used to take out the water value curve for week ***u***. Figure A.3 shows an example for the certificate price, the expected penalty price (in the next settlement) as well as the reference price. It can be seen, that the reference price is higher than the expected penalty price in some cases. There, it is implemented in the model the resulting certificate values are capped at the expected penalty price.

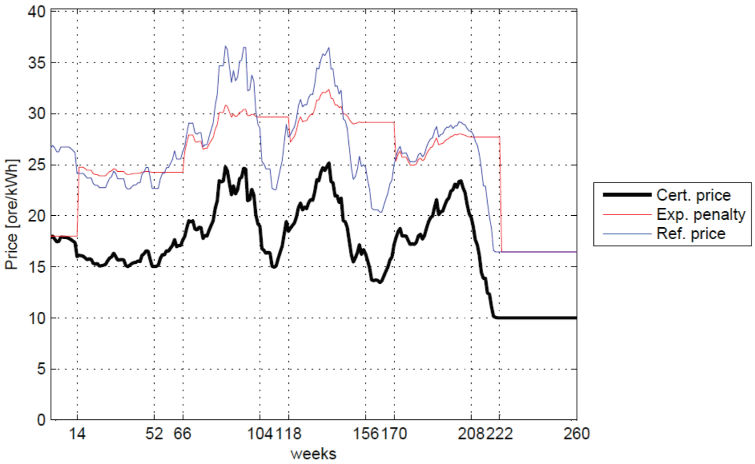


Figure A.3 Development of the certificate price, the expected penalty price (in the next settlement) and the reference price for one scenario in the simulation

In order to choose the correct certificate value table, an expected certificate valued is necessary

The reference price is calculated according to the following formula:

$$p_u^{ref} = a_0 \times p_{u+0\times 52}^{pen} + (1 - a_0) \times \left(a_1 \times p_{u+1\times 52}^{pen} + (1 - a_1) \times \left(a_2 \times p_{u+2\times 52}^{pen} + (1 - a_2) \times (\dots)\right)\right)$$

The factors a_k are given by the probability of going into deficit in the according settlement week.

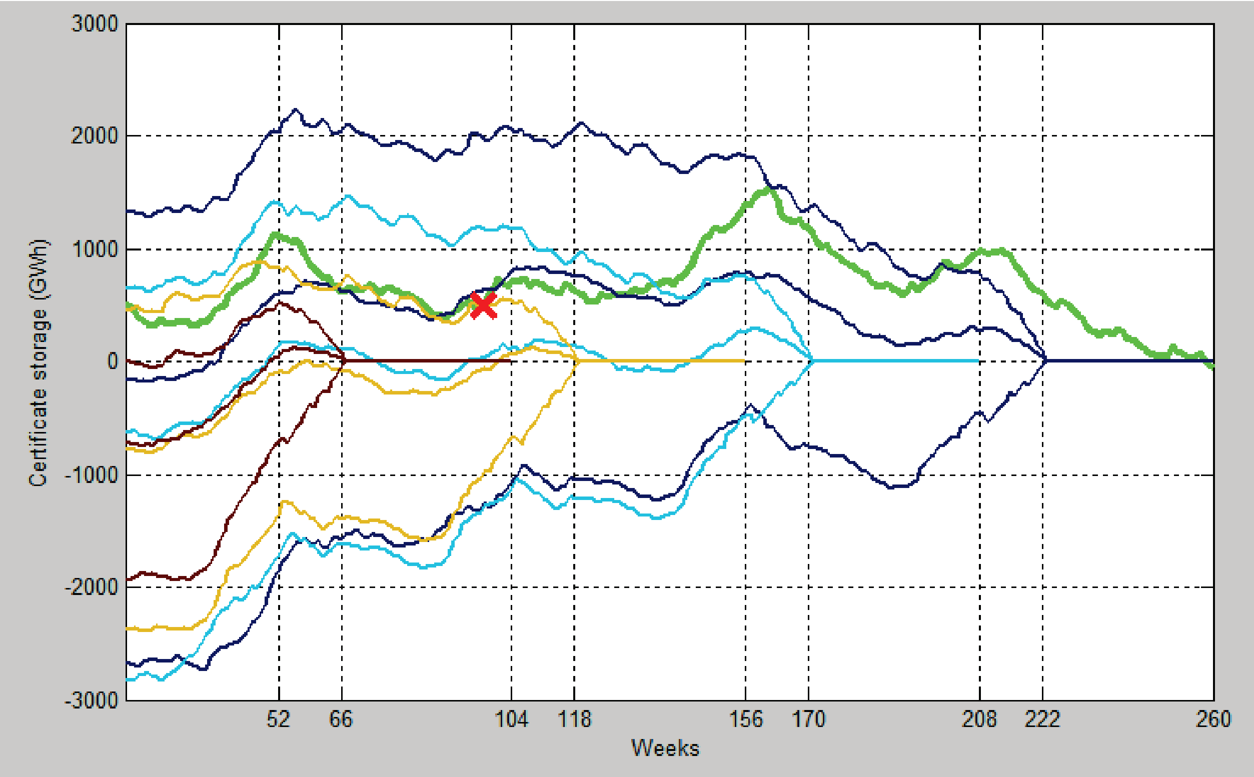


Figure A.4 Probabilities for going into deficit

Figure A.4 shows the probabilities for going into deficit with certificates for the various settlements:

- The dark blue curves refer to the settlement in week 222
- The light blue curves refer to the settlement in week 170
- The yellow curve refers to the settlement in week 118
- The brown curve refers to the settlement in week 66

The green curve shows the certificate storage development for one scenario. The red cross marks the certificate storage in week 98. As this week is past week 66 only the upper three probability curves (yellow, light blue and dark blue) are taken into account.

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