

Tradable green certificates: The dynamics of coupled electricity markets

Klaus Vogstad, Ingrid Slungård Kristensen and Ove Wolfgang¹

Norwegian University of Science and Technology (NTNU)

1. Sintef Energy Research

SEFAS Sem Sælandsvei 11/N-7465 Trondheim

phone +47 73597644 fax +47 73597250

klausv@stud.ntnu.no

1 Abstract

Liberalisation of markets previously under regulatory control require new instruments for environmental policy making, because subsidies and regulatory intervention does not conform to trans-national, liberalised markets. This is the case for newly regulated electricity markets. An arrangement of Tradable Green Certificates (TGC) as a market-based subsidy for renewable energy has been proposed in several countries and already implemented in a few. However, introduction of TGCs have been postponed and delayed mainly due to the uncertainties involved for suppliers of renewables. Several studies have been undertaken using economic static comparative analysis and partial equilibrium models. However, few of these analyses address the dynamic price formation process or the mechanisms that are important in the design of a well-working stable market. To analyse the stability of a TGC market, we construct a system dynamic model of the TGC market coupled with the Nordic electricity market (Nord Pool). A set of trading strategies for the participants under various marked designs is examined. These trading strategies were deduced from laboratory experiments.

The results showed that the proposed TGC market designs are likely to become unstable. These instabilities arose endogenously from the trading strategies. Some crucial design parameters such as banking and borrowing can reduce these instabilities. In particular, the proposed banking arrangement intended to avoid price fluctuations caused by the yearly stochastic variation of renewables. As a side effect, banking opts for some trading strategies that cause even more harmful price fluctuations followed by price crashes. These undesirable instabilities can be reduced by allowing borrowing and limit banking. The conclusions from previous theoretical studies on the TGC market is examined and compared with our findings. This case study shows how system dynamics can be combined with experimental economics to address issues that cannot be dealt with within the framework of partial equilibrium models and standard economic theory.

2 Introduction

Liberalisation of European markets requires new tools and instruments for environmental policy making. Utilities and public services (i.e. electricity, waste management, telecommunications) previously under regulatory control are now subject to deregulation. Under these conditions, traditional national environmental policy instruments do not necessarily work as intended (Morthorst, 2000). As an example, the main goal of developing wind power in Denmark was to reduce national CO₂-emissions, but under the operations of the liberalised Nordic electricity market, these CO₂-reductions take place in Finland and Germany rather than Denmark (Vogstad et al, 2000). National subsidy schemes also distort

competition in transnational markets. This points to the need of environmental policy instruments that are compatible with open markets.

Tradable green certificates (TGC) have been proposed in Denmark, Sweden and within EU to achieve their goal of adding 340 TWh renewables within 2010. However, introduction of TGCs to replace the renewable subsidy scheme has been delayed several times in Denmark. A mandatory TGC market will start from May 1st, 2003, in Sweden. A TGC market has been in operation in the Netherlands since 2001, but differs from the proposed arrangements of the Nordic countries and EU by not being mandatory on the demand side. Langniss and Wiser (2003) discusses the experiences of renewable energy portfolio standards¹ (RPS), where the Texas RPS has given promising results in developing renewables. In the case of Texas, however, wind power received favourable subsidies in addition to the TGC's so that the system has not really been put to test yet.

Favourable feed-in schemes for wind power in Denmark, Germany and Spain have indeed been successful in developing the industry from being an alternative energy source to becoming a competitive energy technology. One disadvantage about this feed-in scheme is the large amount of costs it inflicts on the authorities as the renewable generation grows. As a result direct obligations on the consumers were proposed, coordinated by a TGC market.

3 The principle of tradable green certificates

The main purpose of tradable green certificates is to *increase the share of renewable generation* at minimum costs.

TGC's are financial assets issued to producers of certified green electricity and can be regarded as a market-based environmental subsidy. An issuing Body (IB) issues green certificates at the moment a producer registers the production of actual green electricity. They are later withdrawn from circulation at when customers account for their obligations by presenting the certificates to the registration authority, or if the certificates period of validity expire. Between issuing and withdrawing, the certificates are accounted and can be traded. The certificates function as an accounting system to measure the amount of electricity produced from renewable energy sources.

Figure 1 shows in principle how a TGC market will work within the Scandinavian electricity market (Nord Pool). In the Nord Pool market, electricity and its derivatives are traded in double-auction markets. The spot market is used for hourly *production scheduling*.

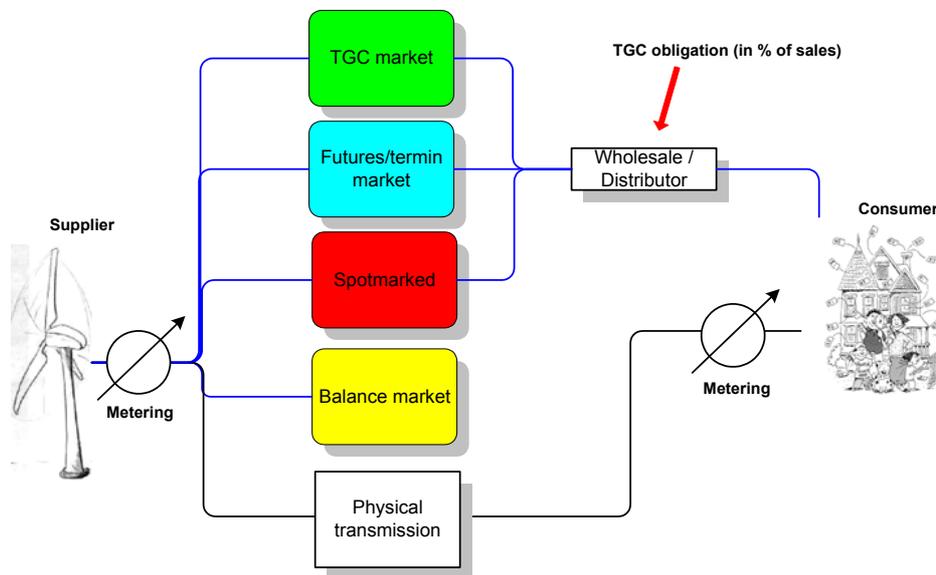
The Balance market coordinates *short-term regulation*². Futures contracts are used for electricity trading up to 3 years ahead, and are hence used for *long-term planning and investment planning*. A TGC market values the environmental benefit of renewables as a service. The authorities define a mandatory share of demand for renewable generation and the TGC market then finds the price needed to reach this target.

It should be noted that all these markets work independently of the physical transmission

1. Renewable Portfolio Standards is another term for Tradable green certificates

2. The balance market provide capacity for available for regulation within a period of 15 minutes.

Figure 1 The principle of a TGC market. TGC's are financial assets that can be traded independent of electricity generation. The value of a certificate reflects the cost of providing the additional amount of new renewables needed to fulfil the obligation.



and that all necessary metering for accounting is made at the supplier and consumer.

4 Implications of TGC markets

One of the main lessons from standard economic theory is that instrument must be directed directly towards its purpose in order to be efficient. Hence, a TGC system will typically be a cost-efficient way to increase the *share of renewable electricity* in consumption because the market will find the price needed to reach the predefined target, and the cost of renewables are directly paid by the consumers. Similarly a TGC system is not an efficient instrument of reducing CO₂-emission. Efficient CO₂-reduction can be obtained by a CO₂-quota market. However, both reducing CO₂-emissions and increasing the share of renewables are present environmental policies, which justifies the use of both in environmental policy making. Jensen & Skytte (2003) provides an analysis on the simultaneous attainment of CO₂ and renewables targets.

Subsidy schemes require authorities both to set renewable targets, and to find the sufficient level of subsidies that will ensure targets to be met. In a TGC market system, the authorities can focus on the renewable target, leaving the price setting to the market.

A large market is preferred to obtain the real benefits of a TGC market. Firstly, resources are unevenly distributed across countries. The EU-project Renewable Burden sharing (ReBUS,) identified a total 15% cost reduction potential of achieving the EU targets of additional 340 TWh new renewables within 2010. Some of the countries could however reduce their costs by 40%.

Secondly, a larger number of participants will reduce the possibilities for market power. However, opinions differ among EU countries with respect to which type of technologies

that can be defined in the TGC portfolio. Large-scale hydropower and waste incineration remains an issue as to whether these sources should be included in the TGC market. Allowing large-scale hydropower, is in conflict with the intention of TGC's. Hydropower, undoubtedly renewable, *is* a competitive source of generation, and most of its potential has already been utilised. The technology is mature, and projects that do not conflict with environmental interests are limited. Allowing hydropower in a TGC system would do little more than generate additional income to hydropower utilities until TGC prices drop to zero.

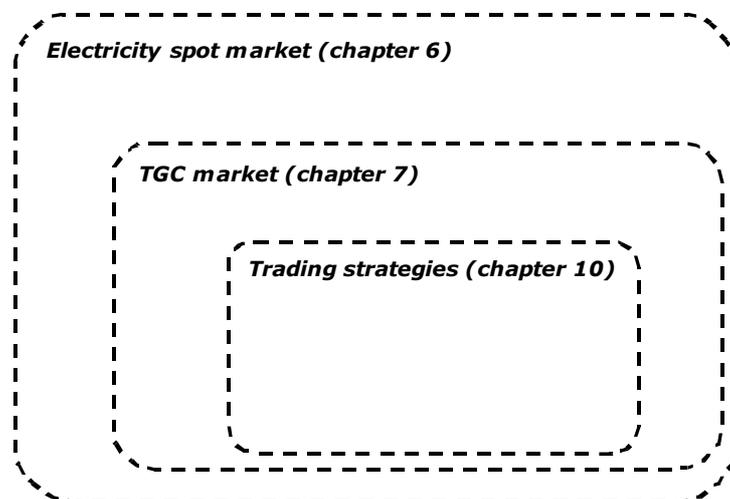
Waste incineration, can in some cases be considered as renewable, in some cases not - for instance when plastic is incinerated. In many cases, waste incineration is profitable due to high deposition costs. Such controversies must be sorted out to take advantage of the possible benefits of a TGC market.

A real disadvantage of TGC markets is that the less competitive sources such as PV and wave energy will not be able to compete against cheaper alternatives of wind energy and bio. Such technologies will still be in need of subsidies.

5 A system dynamics analysis of the TGC market

The implications of a TGC market have been the subject of studies in several reports, mainly in the form of comparative static analysis or using partial equilibrium models e.g.

Figure 2 Model hierarchy. In this approach, we model develop submodels of the electricity spot market, the TGC market and TGC Trading strategies before the models are fully interconnected.



the Swedish white paper on TGC's (SOU 77:2001), the EU-project REBUS and a series of studies at Risø and under the Nordic research project Nordleden¹ (Risø, 2002). To our knowledge, TGC markets have been simulated in the Markal energy model, plus Econs power market model and the Balmorle energy model (Hindsberger, 2003). These models are all partial equilibrium models and can be used to simulate the development of different sources of renewables the TGC price, and their substitutes. They do not however, address

1. For reports on from the Nordleden project on TGC's, see <http://www.nordleden.nu>

the consequence of time lags involved in construction of new capacity, or possibilities for strategic behaviour of purchase and sales of TGC's. To which extent these characteristics are important for the price and for the design of a TGC market is the subject of this study.

Figure 2 shows our stepwise approach of constructing a system dynamics model of the electricity spot market including a TGC arrangement. The purpose is twofold. First, to study the price formation in the TGC market under various designs. Second, to analyse its interactions with the electricity market.

In chapter 6 we develop a simplified model of the Nordic electricity market where renewable generation is traded in the spot market, with the present feed-in scheme for subsidising renewables.

In chapter 7, we develop the TGC market that replaces the feed-in scheme from 2003 on. There are uncertainties and different opinions concerning stability of the proposed TGC market designs (Schaeffer & Sonnemans, 2003; STEM 2002; Krohn 2001).

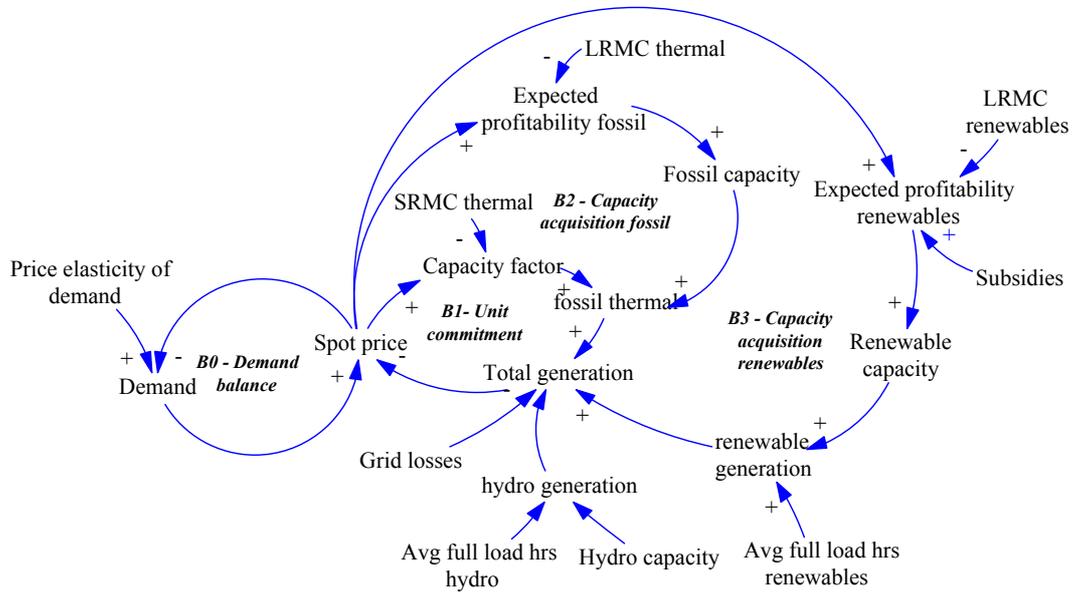
In chapter 10, we elaborate the TGC market model further by representing trading strategies of buyers and sellers, enabling us to address the issue of price stability under various market designs. Using the system dynamics approach, we explore some common trading strategies to study the impact on price dynamics under the proposed TGC designs. The trading strategies were deduced from a laboratory experiment with a group of players. Based on these simulations and experiments, we identify some crucial design parameters for a well-working TGC market. Finally, we connect the TGC market model with the Electricity spot market model to study the interaction of those.

6 The spot market for electricity

We start our analysis by establishing a stock & flow model of the supply and demand side of the Nordic Power Exchange (Nord Pool). The time horizon was set to 20 years, as renewable targets are part of long-term energy and environmental planning. Capacity utilisation is in turn determined by the spot prices, and a numerical time resolution of 3 days is sufficient to adjust spot prices according to the changes in demand and supply¹. We start with a description of the power market with a feed-in tariff subsidy scheme for renewables to be used as a reference for simulations with a TGCs market. *Figure 3* shows the causal loop diagram (CLD) of the spot market. For simplicity, we only distinguish between thermal generation, hydropower and renewables. Hydropower is indeed renewable, but for the purpose of certificates, existing large-scale hydro is not included for reasons mentioned in chapter 4. On the supply side, two balancing loops are involved in the price formation. The loop *B1* adjusts generation of electricity by the short-run marginal cost curve of existing capacity (see *Figure 6* for details on the supply curve of thermal generation). If spot prices sustain at a higher level than the long-run marginal costs of generation (LRMC), new capacity will be added. The capacity acquisition loop *B2* and *B3* is similar for both thermal and renewable generation, except that subsidies and tax policies affect their profitability. We assume hydropower capacity to be fixed in this simplified

1. To represent market spot prices as a goal-seeking process require small time constants in comparison to the other time delays in the system, i.e. time delays for capacity acquisition and lifetime of installed capacity. An alternative way is to find market equilibrium prices using a search algorithm within each time step.

Figure 3 Spot market dynamics CLD.



model.

6.1 Market dynamics

The Nord Pool electricity market is a double-auction market that clears every hour. Approximately 30% of all electricity is traded through the spot market, the remaining share is traded through bilateral contracts or long-term contracts. The time constant for the spot market is set to 1 week - enough to give a good estimate of how the capacity factor (capacity utilisation) changes over a year. The market dynamics formulation is given in equation set (1) where spot price is a level that adjusts in proportion to the fractional demand/supply balance.

(1) Market dynamics

$$1.1 \quad \text{Spot price}_t = \text{Spot price}_0 + \int \text{chg in price}_t \cdot dt \quad [NOK/MWh]$$

$$1.2 \quad \text{chg in price}_t = \text{Spot price} \cdot (\text{demand-generation tot}) / \text{demand} \cdot 1 / \text{Market adjustment time} \quad [NOK/MWh/da]$$

$$1.3 \quad \text{Market adjustment time} = 7 \quad [da]$$

$$1.4 \quad \text{Spot price}_0 = 200 \quad [NOK/MWh]$$

The Nord Pool futures market represents the joint expectations of market participants, where contracts for electricity can be traded up to 3 years ahead. This market is used as an indicator when investment decisions for new capacity are being made (see section 3.4). The expected future spot prices are modelled as an adaptive trend extrapolation (1.5) of prior average spot market prices (1.6), where the smoothing time horizon is 3 years, and

Figure 4 Spot market dynamics stock & flow diagram

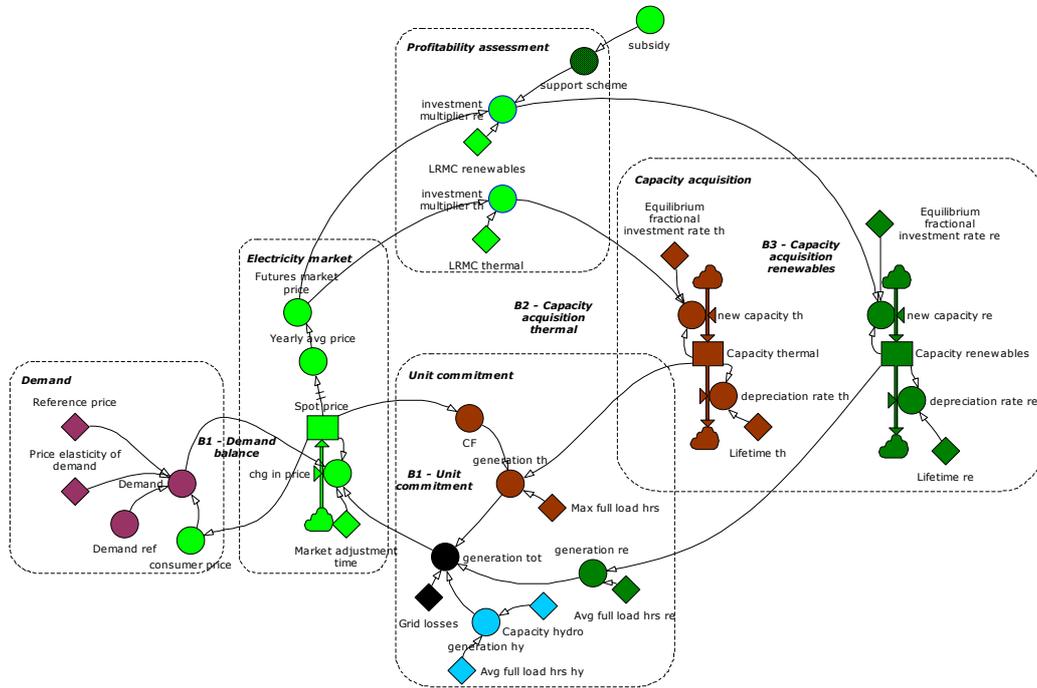
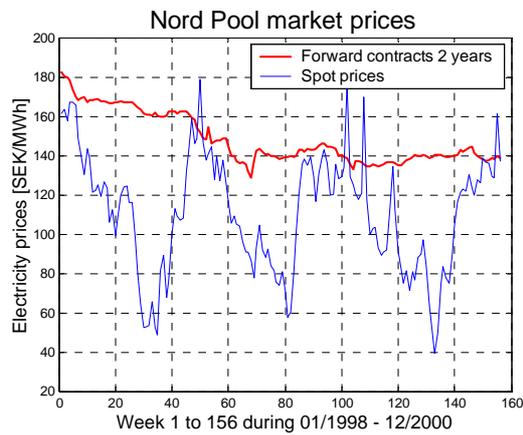


Figure 5 Nord Pool spot market prices and Forward contract prices (2 years ahead) from 01/98 to 12/2000. Source: Nord Pool



the forward time horizon is 2 years.

$$1.5 \text{ Futures market price} = \text{FORECAST}(\text{Yearly avg price}, 3, 2) \quad [NOK/MWh]$$

$$1.6 \text{ Yearly avg price} = \text{SLIDINGAVERAGE}(\text{Spot price}, 1) \quad [NOK/MWh]$$

6.2 Demand side

The demand side is kept simple in our model, as the main focus is on the supply side. De-

mand is modelled using a Cobb-Douglas function in *equation set (2)* with a price elasticity of demand equal to -0.3 on a yearly basis, although the reported estimates vary from -0.2 to -0.8 (NOU 1998, 99; Econ 1999, 11; Groenheit & Larsen 2001, 46). Simulating over 20 years, demand and price elasticity's will change significantly, but in this model we will only address consumer prices influence the demand, and keep the reference demand constant over the simulation period. All reference values refer to data from the year 2000.

(2) Demand side

$$2.1 \text{ demand} = \text{Demand ref} \cdot (\text{Spot price}/\text{Reference price})^{\text{Price elasticity of demand}} \quad [\text{TWh/yr}]$$

$$2.2 \text{ Demand ref}^1 = 420 \quad [\text{TWh/yr}]$$

$$2.3 \text{ Reference price} = 200 \quad [\text{NOK/MWh}]$$

$$2.4 \text{ Price elasticity of demand} = -0.3 \quad [1]$$

6.3 Unit commitment

Electricity is *not* a commodity, and cannot be traded as such. Electricity is a *service* and share many common features of service sectors. In service sectors, such as the airline industry, services must be produced in a timely manner. In the same way as airlines cannot store flights, electricity as a service cannot be stored.

For this reason, the generation capacity of electricity must be flexible to meet consumption at all times. The units are scheduled after increasing marginal operational costs, as can be seen from *Figure 6*. Normalising the below graph with total installed capacity yields the *capacity factor*, CF varying between 0 and 1, which is the maximum capacity utilisation.

The stock & flow equations for the unit commitment are presented in equation set (3)

(3) Unit commitment

$$3.1 \text{ generation } th = CF \cdot \text{Max full load hrs} \quad [\text{TWh/yr}]$$

$$3.2 \text{ CF} = \text{GRAPH}(\text{Spot price}_p, 0, 50, \{0, 0.014, 0.11, 0.58, 0.82, 0.914, 0.94, 0.98, 1, 1 // \text{Min: } 0; \text{Max: } 1 // \}) \quad [1]$$

$$3.3 \text{ Max full load hrs} = 8000 \quad [\text{hr/yr}]$$

The marginal operational costs of hydropower are negligible, and hydropower units with reservoirs use some different strategies² in production planning. For simplicity, hydropower is represented with constant capacity utilisation. Renewable generation however,

-
1. Reference demand differs from observed demand in 2000. We deliberately chose a demand that assured the model initially be in long-term equilibrium, to ease our analysis.
 2. Hydropower units are usually scheduled using the water value method, which represents the 'marginal costs' of hydropower. The water value is the marginal change of expected future cumulative profits from releasing water from reservoirs for generation. This problem can be solved as a stochastic dynamic optimisation. A simplified system dynamic representation of the water value method is implemented in the Kraftsim model (Vogstad et al. 2002)

has an element of stochasticity.

$$3.4 \text{ generation hydro} = \text{Hydro} \cdot \text{Avg full load hrs hydro} \quad [\text{TWh/yr}]$$

$$3.5 \text{ Avg full load hrs hydro} = 4800 \quad [\text{hr/yr}]$$

$$3.6 \text{ Capacity hydro} = 41600 \quad [\text{MW}]$$

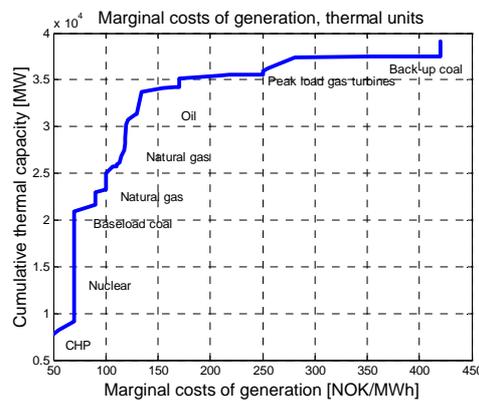
$$3.7 \text{ generation re} = \text{Renewable capacity} \cdot \text{Avg full load hrs renewables} \cdot (\text{Stochastic generation share} \cdot \text{Stochastic variation} + (1 - \text{Stochastic generation share})) \quad (1) \quad [\text{TWh/yr}]$$

$$3.8 \text{ Avg full load hrs renewables} = 3350 \quad [\text{hr/yr}]$$

$$3.9 \text{ Stochastic generation share} = 0.6 \quad [1]$$

C.1 Stochastic variation of wind was generated from wind energy series collected for Norway. See Tande & Vogstad (2000) for further details

Figure 6 Capacity factor based on marginal production costs of thermal units



Here average full load hours represent the average of hydropower units, and for renewables they represent the weighted average of present bio energy and wind power. Total generation is the sum of generation from each technology minus grid losses:

$$3.10 \text{ generation tot} = (\text{generation th} + \text{generation hydro} + \text{generation re}) \cdot (1 - \text{Grid losses}) \quad [\text{TWh/yr}]$$

$$3.11 \text{ Grid losses} = 0.1 \quad [1]$$

An important difference between renewables and thermal generation is the inability to control generation according to prices. Some bio/waste incineration units or small-scale hydropower (defined as new renewable) with reservoirs do operate after marginal costs, but it is a good approximation to regard short-term renewable generation as inelastic. In other words, renewable technologies lack the *Unit commitment loop B1*. The level of renewable generation is therefore determined by the long-term *capacity acquisition loop B3*, in combination with the stochastic properties of wind and water, which is not included in the simplified model. As we will see later in 7, this has important implications for the

TGC market.

6.4 Profitability assessment and capacity acquisition

In the short term, electricity generation is adjusted by the processes described by the *Unit commitment* feedback loop (chapter 6.3), in response to short-term demand variations. In the long term, expectations of future prices govern the investment of new capacity. If the expectations of future spot market prices are significantly higher than the long-run marginal costs (LRMC) of new generation capacity, the utility sector will invest in new capacity. Holding the futures market price (1.5) up against LRMC for thermal generation (4.2) in equation (4.1) indicates the *effect of profitability on investment rate* shown in *Figure 7* *Effect of profitability on investment rate*

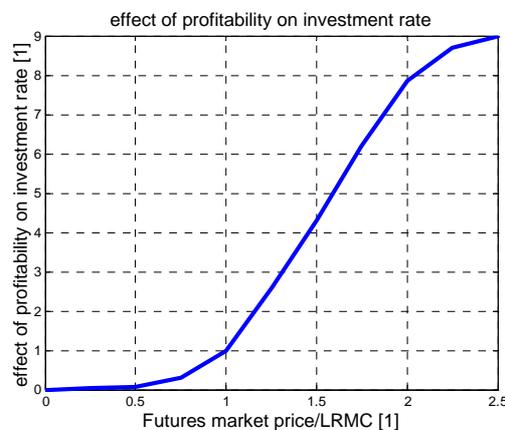


Figure 7. When futures market price equals LRMC, the effect of profitability on investment rate returns 1, at which the investment rate is in dynamic equilibrium with the depreciation rate (see section 3.4). When the futures market price significantly exceeds LRMC, the investment rate increases, up to a certain limit that corresponds to a maximum 45% growth rate. Growth within the power industry is limited by the availability of service and material from other industrial sectors. The shape of the curve in *Figure 7* can be recognised as a cumulative probability density function that represents the aggregate of a large number of possible profitable projects, which would differ in costs. The long-run marginal costs can be represented by a more disaggregated *net present value calculation* including profitability requirements, capacity factor, investment costs and operational costs, which is implemented in the Kraftsim model (see Botterud et al. 2002; Vogstad et al. 2002).

(4) Profitability assessment

4.1 *effect of profitability on investment rate* $th = \text{GRAPH}(\text{Futures market price/LRMC thermal}, 0, 0.25, \{0, 0.03, 0.06, 0.3, 1, 2.6, 4.3, 6.2, 7.86, 8.7, 9\} // \text{Min:0;Max:10//})$ [1]

4.2 $\text{LRMC thermal} = 200$ [NOK/MWh]

The same structure of profitability assessment applies to renewables except that subsidies

are included:

4.3 *effect of profitability on investment rate* $re = GRAPH((Futures\ market\ price + Support\ scheme)/LRMC\ renewables, 0, 0.25, \{0, 0.03, 0.06, 0.3, 1, 2.6, 4.3, 6.2, 7.86, 8.7, 9\})$
[1]

4.4 *Support scheme* = 188 [NOK/MWh]

4.5 *LRMC renewables* = 300 [NOK/MWh]

It should be pointed out that the Nord Pool power market is not in long-term equilibrium. A long-term (economic) equilibrium exists when the spot price equals the long-run marginal costs of new generation. For our case, the market is in long-term equilibrium when the futures market price equals the long run marginal costs of the generation technologies, that is

Futures market price = LRMC thermal = LRMC renewables + subsidies (i)

If this is not the case, the installed capacity of thermal and/or renewables and thereby long-term prices will change. To simplify our study, we assume the electricity market to be initially in equilibrium at a spot price of 200 NOK/MWh (which is the current observed futures price in the Nord Pool market) and by letting LRMC thermal equal 200 NOK/MWh while LRMC renewables is set to 300 NOK/MWh, requiring 100 NOK/MWh in subsidies to maintain present installed capacity.

The futures market price is now approaching long run marginal costs of new generation, while recent years have shown average market prices of around 157 NOK/MWh, which is far below LRMC for new generation. Noteworthy, the futures price history from 1998-2000 (*Figure 5*) showed a declining trend. Expectations of lower prices during the first years of deregulation can be attributed to the expectations of increased competition, efficiency that more than compensates for reduction of overcapacity. Most partial equilibrium models with endogenous investments assume markets to be in long-term equilibrium, although this is rarely the case in real world.

Much of the considerable variation, which distorts the price signals, is subject to the large variations of hydro inflow from year to year. Hydropower generation can vary as much as +/-40% in a system where hydropower accounts for 61% of electricity generation during normal years of hydro inflow. This problem is not encountered here in our simplified model, as we use normal years of hydrological conditions, omitting the stochasticity of hydropower. The lifetime of thermal units is set to 30 years and renewables to 20 years. Thus the equilibrium fractional investment rate sufficient to match this rate is 3.33 %/year and 5 %/yr respectively. Initial thermal capacity of 37360 MW and renewable capacity of

5685¹ correspond to the year 2000 situation for the Nord Pool market.

(5) Capacity acquisition

$$5.1 \text{ Capacity thermal}_t = \text{Capacity thermal}_0 + \int (\text{new capacity } th_t - \text{depreciation rate } th_t) \cdot dt \quad [MW]$$

$$5.2 \text{ new capacity } th_t = \text{Equilibrium fractional investment rate } th \cdot \text{effect of profitability on investment rate } th \cdot \text{Capacity thermal} \quad [MW/yr]$$

$$5.3 \text{ depreciation rate } th_t = \text{Capacity thermal} / \text{Lifetime } th \quad [MW/yr]$$

$$5.4 \text{ Equilibrium fractional investment rate } th = 3.33 \quad [%/yr]$$

$$5.5 \text{ Lifetime } th = 30 \quad [yr]$$

$$5.6 \text{ Capacity thermal}_0 = 37360 \quad [MW]$$

$$5.7 \text{ Capacity renewables}_t = \text{Capacity renewables}_0 + \int (\text{new capacity } re_t - \text{depreciation rate } re_t) \cdot dt \quad [MW]$$

$$5.8 \text{ new capacity } re_t = \text{Equilibrium fractional investment rate } re \cdot \text{effect of profitability on investment rate } re \cdot \text{Capacity renewables} \quad [MW/yr]$$

$$5.9 \text{ depreciation rate } re_t = \text{Capacity } re / \text{Lifetime } re \quad [MW/yr]$$

$$5.10 \text{ Equilibrium fractional investment rate } re = 5 \quad [%/yr]$$

$$5.11 \text{ Lifetime } re = 20 \quad [yr]$$

$$5.12 \text{ Capacity renewables}_0 = 5685 \quad [MW]$$

6.5 Simulation run with subsidy scheme

There has been a significant growth in renewables throughout the last years. On average, the growth in renewables has been around 10% from 1999 to 2003 for the Nord Pool area. We set the subsidy level to 188 NOK/MWh, which is the level of subsidies needed that can maintain this growth rate. Two simulation runs are presented in *Figure 8*. Thin lines show a simulation run with constant demand. The bold lines show the response of 10% step increase in demand from 2003. In *Figure 8a*), the effect of subsidies is shown on consumer price², which coincide with spot price in this case. Demand grows slightly in response to price reductions. Renewable generation increase its share of capacity and to a lesser extent generation while thermal generation must reduce both installed capacity and

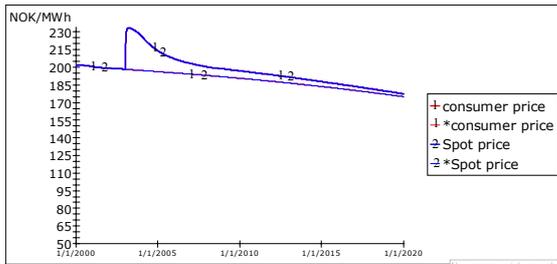
1. Renewable capacity is calculated as the sum of wind power and biomass installed in 2001, with a corresponding average full load hour utilisation.

2. The increased taxes on customers from governmental spending on feed-in tariffs is not included here.

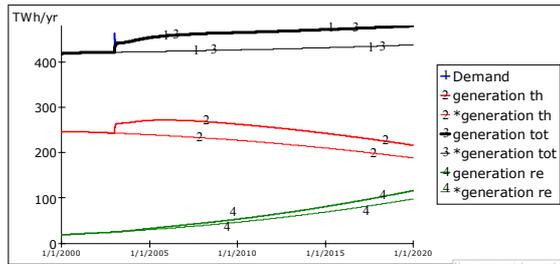
capacity utilisation (*Figure 8b-d*)). The second simulation run (bold lines) underlines

Figure 8 Two electricity spot market simulation runs with 188 NOK/MWh subsidies for renewables. **Run 1 (thin curves):** constant demand. **Run 2 (bold curves):** 10% step increase of demand in 2003.

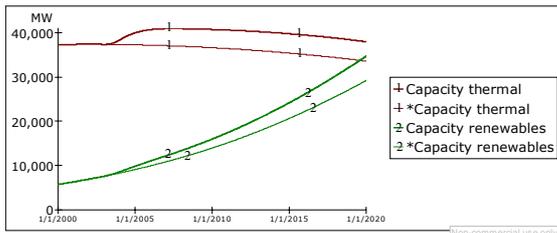
a) In both runs, Spot price and consumer price coincide (no taxes). Price decreases from increased supply of renewables. Run 2: Price responds rapidly from demand increase.



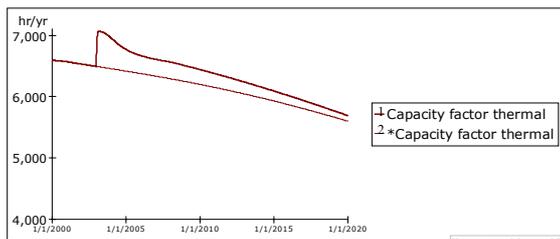
b) In both runs, demand increases (coincide with total generation) from price reductions. Run 2: Thermal generation responds rapidly by increasing capacity factor



c) Capacity development - renewables grow by 10% per year at the expense of thermal capacity in the long run. Run 2: Thermal capacity is more sensitive to electricity prices than renewables with subsidies.



d) In the long term, capacity utilisation is reduced from increased share of renewables. Run 2: In the short term, thermal generation can respond quickly to price changes, but capacity adjustments of thermal generation will in the long term deteriorate from increased renewable generation.



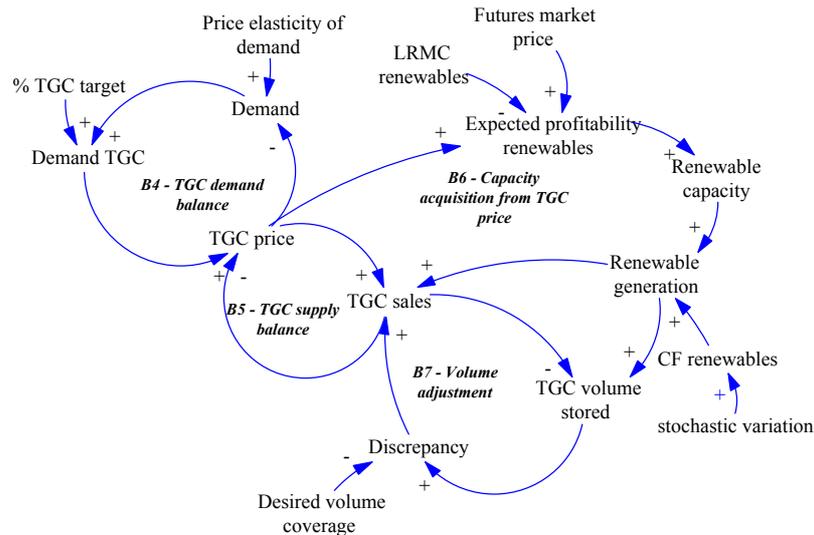
a major difference between renewables and thermal generation. Thermal generation has larger operational costs (i.e. fuel costs), and generation is scheduled according to their increasing marginal operational costs. Capacity utilisation is therefore governed by the spot price shown as the *B1 unit commitment* loop in *Figure 3*. In contrast, renewable generation depends on the intermittent source of wind and water, whereas biomass in most cases generates electricity as a by-product of heat and is therefore not sensitive to electricity prices. Renewable generation can only be adjusted by capacity acquisition (loop *B3* in *Figure 3*) which involves significant time delays. With respect to demand/supply balance and price stability in the electricity market, stochastic generation from renewables does not yet represent insurmountable problems for the operation of the electricity market¹. But how would prices in a TGC market form, knowing where supply/demand balance must be met on an annual basis, but where adjustments in supply involve long time delays in capacity acquisition? This will be our concern in the following chapter.

1. In the Jutland area of the Nord Pool market, stochastic wind power now comprise more than 40% of total generation, which can still be absorbed by the power system, but not without countermeasures.

7 The tradable green certificate market

A TGC certificate is a financial asset that can be traded independently of the physical generation of electricity. The physical supply of electricity is traded in the electricity spot market so that a renewable supplier receives the spot price *plus* the TGC price per MWh generation.

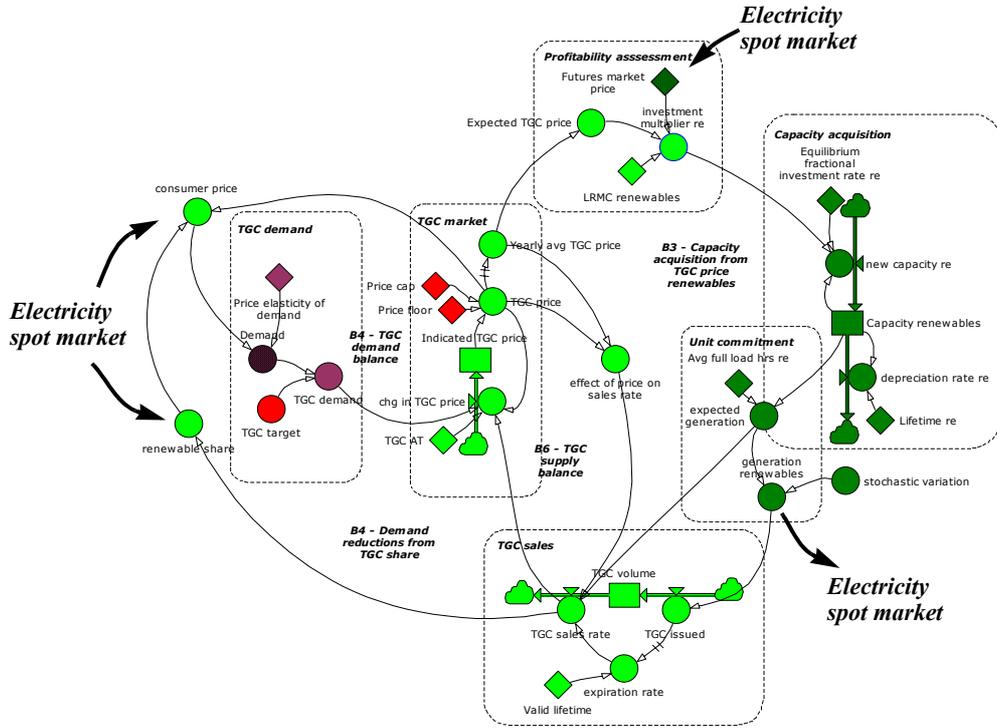
Figure 9 CLD of TGC market mechanism



The main idea is to stimulate capacity acquisition of renewables through the TGC price (loop B6, Figure 9) in order to fulfil the renewable share targets. This mechanism replaces the subsidies (compare with Figure 3) in the sense that authorities can set a renewables target, from which the TGC market will find the sufficient certificate price necessary to reach the target. The difference between the spot market mechanism and the TGC market mechanism, is the lack of short-term regulation by the unit commitment loop B1. As we will see, this makes the price formation in the TGC market sluggish, because the only way to adjust the supply goes through the capacity acquisition loop B6 (Figure 9). The exogenous stochastic variation of, primarily wind will also increase the price fluctuations significantly, and this is the main motivation for allowing banking of certificates. The compliance period of the Swedish TGC market is 1 year. If TGC obligations are not met during this period, consumers are charged by a penalty fee that exceeds the TGC price. Figure 10 shows the stock and flow diagram of the TGC market, where the linkage to the electricity market is indicated. The TGC market sector is similar in structure to the spot price - except that a maximum and a minimum price is introduced in eq. (6.1), and the TGC market does not need to clear as frequent as the electricity market. A major difference between conventional sources and renewables is the ability of controlling generation. Wind turbines and small scale hydropower are not operated by marginal production costs, but by wind and rainfall, whereas bio and waste generate electricity as a by-product and are rarely scheduled by electricity prices, but by heat demand.

The purpose of the TGC market is however give long-term price signals for development of new capacity, where market-clearing obligations should be met annually. In the ab-

Figure 10 TGC market SFD. Interactions with “Electricity spot market “indicated on the figure. In the following simulations, spot market price is constant, so that the futures market price is constant. TGC consumption is therefore only influenced by changes in TGC price at this stage. TGC price does however influence consumer price and thereby demand.



sence of a short-run price adjustment process, long-term price formation could turn out to be problematic.

(6) TGC market

- 6.1 $TGC\ price = MIN(Max\ price, MAX(Indicated\ TGC\ price, Min\ price))$ [NOK/MWh]
- 6.2 $Max\ price = 350$ [NOK/MWh]
- 6.3 $Min\ price = 0$ [NOK/MWh]
- 6.4 $Indicated\ TGC\ price_t = Indicated\ TGC\ price_0 + \int\ chg\ in\ TGC\ price_i\ dt$ [NOK/MWh]
- 6.5 $chg\ in\ TGC\ price_t = Indicated\ TGC\ price \cdot (TGC\ demand - TGC\ sales\ rate) / TGC\ AT$ [NOK/MWh/da]
- 6.6 $TGC\ AT = 2$ [wk]
- 6.7 $TGC\ price_0 = 178$ [NOK/MWh]
- 6.8 $Yearly\ avg\ TGC\ price = SLIDINGAVERAGE(TGC\ price, 1)$ [NOK/MWh]

The TGC target must be set for some time horizon ahead, preferably a rolling time horizon. The (almost) linear curve in Figure 11c) shows the demand for TGC certificates resulting from a linearly increasing TGC target measured as the percentage TGCs of total

generation. For our model, we start with the present share of 6 % renewable generation (2003), to reach 24 % in 2020.

(7) TGC demand

$$7.1 \quad TGC \text{ demand} = TGC \text{ target} \cdot \text{demand} \quad [TWh/yr]$$

$$7.2 \quad TGC \text{ target} = GRAPH(TIME, Starttime, 17, \{6, 24\}) \quad [\%]$$

The profitability assessment is the same as defined in equation set 4.1-4.3, except that TGC prices replace the feed-in tariff in the subsidy scheme so that equation 4.4 changes to:

$$4.4 \quad \text{Support scheme} = TGC \text{ price} \quad [NOK/MWh]$$

Due to the problems of intermittency of wind and small-scale hydro, some kind of storage possibility is desirable to ensure a smooth price formation. The Swedish TGC system allow unlimited lifetime of certificates. Another issue is the borrowing of certificates from year to year. We include the possibility of banking in equation set (8). Certificates are issued upon registered generation (8.1). A simple rule of selling TGC's is introduced in eq (8.6). Sale of certificates depends on the expected generation, and the price of TGC's in the market using a Cobb-Douglas function. With this formulation, we assume traders to change their sales rate by 0.8 per cent for each per cent TGC price change relative to the reference value. The reference value of TGC price is formulated as an adaptive smoothing of approximately TGC prices during the last three years. Alternatively, in case of rational traders - the price elasticity of supply would be very high, and a reference price that would achieve market equilibrium.

(8) TGC trading

$$8.1 \quad TGC \text{ volume}_t = TGC \text{ volume}_0 + \int (TGC \text{ issued}_t - TGC \text{ sales rate}_t) \cdot dt \quad [TWh]$$

$$8.2 \quad TGC \text{ volume}_0 = 25 \quad [TWh]$$

$$8.3 \quad TGC \text{ issued}_t = \text{generation re} \quad [TWh/yr]$$

$$8.4 \quad TGC \text{ sales rate}_t = MAX(\text{expected generation} \cdot \text{effect of TGC price on sales rate}, \text{expiration rate}) \quad [TWh/yr]$$

$$8.5 \quad \text{Min sales time} = 1 \quad [wk]$$

$$8.6 \quad \text{effect of TGC price on sales rate} = \text{generation re} \cdot (TGC \text{ price} / \text{Yearly avg TGC price})^{\text{Price elasticity of TGC supply}} \quad [TWh/yr]$$

$$8.7 \quad \text{Price elasticity of TGC sales} = 0.8 \quad [1]$$

$$8.8 \quad \text{expiration rate} = DELAYMTR(TGC \text{ issued}, \text{Valid lifetime}, 3) \quad [TWh/yr]$$

$$8.9 \quad \text{Valid lifetime} = 1e13 \quad [yr]$$

7.1 TGC market simulation results

The below simulations show the dynamics of the TGC market defined in the equation sets (1)-(8). As can be seen in *Figure 11a*), The TGC prices oscillates. This is mainly due to the time delay in the expectation formation. We did not explicitly model the time delays involved in the capacity acquisition¹. However, these time delays are implicitly modelled

in the “effect of profitability on investment rate” function (see *Figure 7*).b).

*Figure 11 TGC market dynamics introduced in 2003. Constant wind and constant electricity spot price. Reference curves are market with * and corresponds to the development of renewable generation and capacity with a fixed feed-in tariff of 178 NOK/MWh.*

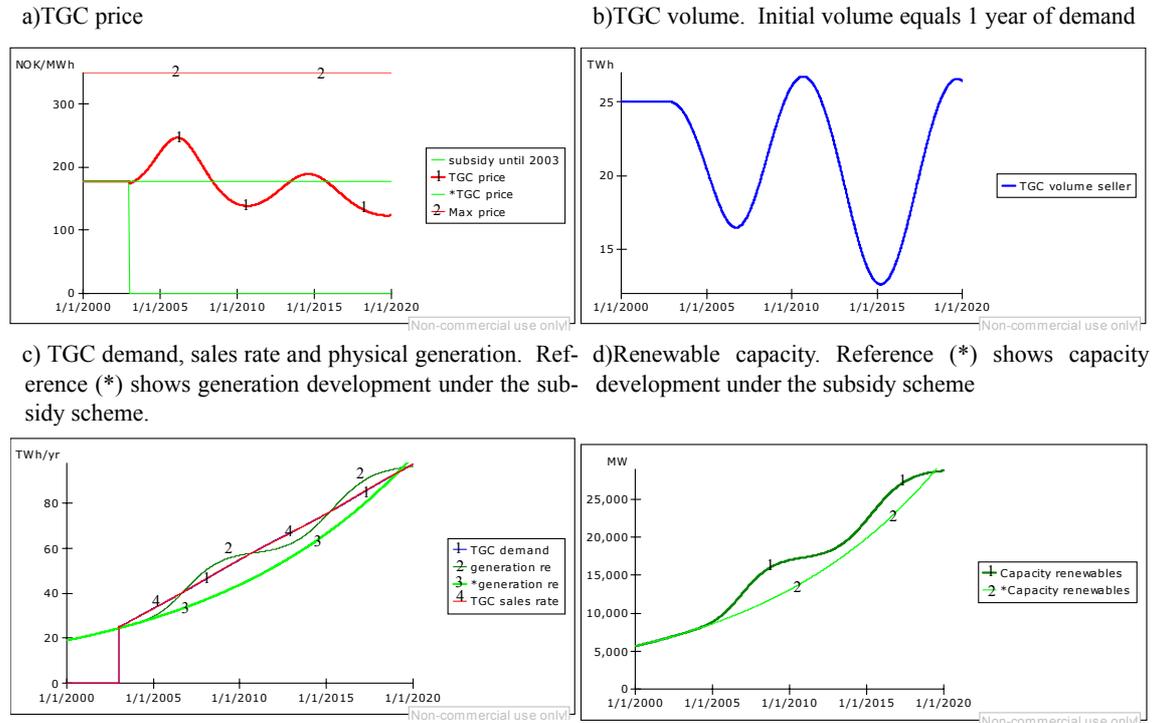


Figure 11a) show long-term fluctuation of TGC prices. This behaviour is attributed to the time delays involved in forming expectations about prices and the time delays for new capacity. The declining price trend is explained by the price rise from increasing obligations to purchase TGC's, which makes consumer prices higher. In *Figure 11c)* we can observe how the physical generation of renewables deviate from the TGC target in the (almost) linear curve starting from 2003. Sales rate and TGC demand matches perfectly, because deviations when storing and forwarding certificates are possible as in *Figure 11b)*. The development of renewables under a subsidy scheme is also shown for comparison as a reference case. With one-year average clearing time of the market, the TGC sales rate also deviates from the TGC demand. A smaller TGC Adjustment time (6.6) results in smaller deviations of TGC demand and TGC supply, but TGC prices fluctuations will increase, both in amplitude and frequency. Similarly, other delays along the capacity acquisition loop will influence the prices and TGC demand/supply balance, such as the expectations of future prices and the time delays of capacity acquisition. The supply and demand obligation at the beginning of the TGC period will be important. If there is a big gap between generation of renewables and TGC obligations, prices start rising (or down if there is overcapacity) because it will take at least two years before suf-

1. Time delays for building new renewable capacity amounts to 1.1 year for applications and at least half a year for construction.

ficient capacity can become available. This effect is more dramatic with restrictions on borrowing and banking. This indicates the importance of setting realistic targets for TGC's in the beginning, and to allow flexibility in terms of banking and borrowing. Constraints on prices are also important to protect consumers from having prices skyrocketing. It would also be important to secure or guarantee prices during the first years of the TGC market. This issue has also been a major concern in the discussion of the implementation of TGCs in Denmark and Sweden. Both countries have some subsidy scheme for various technologies. Current proposals are to establish TGC price caps and price floors that gradually will be phased out during the first years.

As a result of the price fluctuations, capacity develops in more or less pronounced boom and bust cycles (see *Figure 11d*).

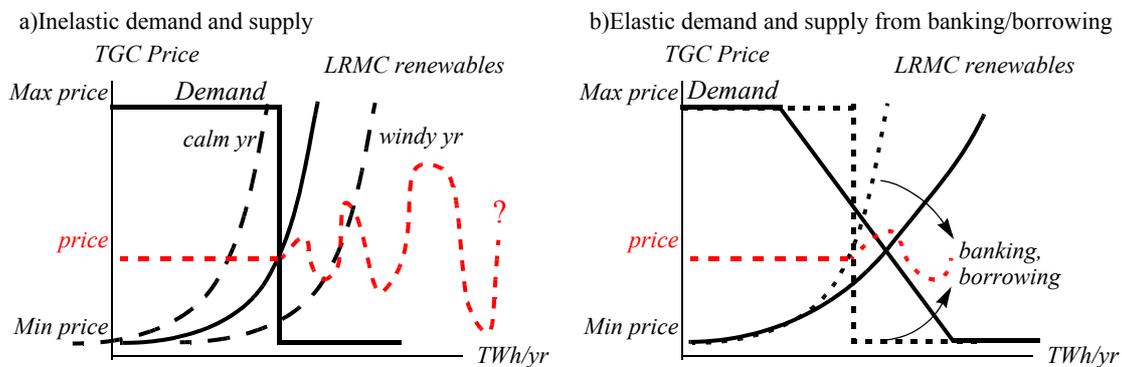
Figure 11b) shows the variations in TGC volume during the planning period. The main purpose of banking is to cope with the intermittency of renewable generation. Various options on banking and borrowing could alter the TGC sales strategy previously defined in equation set (8). Suppose unlimited banking is allowed, but no borrowing. If TGC suppliers decided to reduce their sales of TGC's prices would rise while there is few possibilities to increase the supply of TGC in the short run until sufficient capacity is added. To study the possibilities for market power and trading strategies under various market designs, we develop a more detailed description of buying and selling in the TGC market.

8 Market design

The intermittency of renewables has been the main concern in the discussion of price volatility of the TGC market.

Price volatility has been discussed qualitatively in Nielsen & Jeppesen (2003), Bye et al (2002) and in the Swedish white paper SOU 2001:77. The discussions take a traditional economic point of view, and the main concern in this discussion is the inelastic curves of supply and demand. As discussed in chapter 6.3, renewables do not operate after marginal costs, and the adjustments of the supply curve comes from investments in new capacity, involving time delays of permits and construction. Price will therefore fluctuate with the variability of generation from year to year for the consumers to meet their yearly obligations. Several options are considered to reduce the price volatility of TGC's:

Figure 12 Price volatility in the TGC market



- Include different technologies with operational costs.

By including biomass that operates after marginal costs, the problem of price volatility can be reduced. However, the potential for such technologies are questioned. Biomass and waste incineration are usually CHP¹ plants generating electricity as a by-product of their heat generation. Furthermore, income from electricity generation would come from both the spot market and the TGC market, so the likelihood that such units would be sensitive to TGC prices are questionable.

- Maximum and minimum prices

Price caps and price floors secure the consumer/producers against high/low prices (see Figure 12a). This arrangement is especially important in the introduction phase to reduce risk for investors.

- Banking and borrowing

To improve the stability of supply, certificates can have a valid lifetime longer than the yearly compliance period of consumers. This mechanism is referred to as banking, where producers and consumers can choose in periods of low prices (i.e. windy years) to store certificates for later years. Banking is assumed to have a price smoothing effect, and in the proposed Swedish TGC market, certificates have unlimited lifetime. According to the above-mentioned studies, the price elasticity of the supply and demand curves increase as

1. Combined heat and power generation units.

illustrated in *Figure 12b*). Similarly, allowing participants to fulfil their obligations in the future (similar to futures contracts), would also increase the elasticity's of demand and supply. The disadvantage of borrowing is that some regulation must secure that these future obligations are met, for instance by imposing penalties. Several arrangements of borrowing mechanisms are possible, but the principle remains the same, that is to increase flexibility of supply by allowing trading with future TGC production.

9 Laboratory experiments of TGC trading

The European Renewable Electricity Certificate Trading Project (RECeRT) took on the experimental approach to study the influence of price caps, banking and borrowing on price volatility in a TGC market. The first experimental economics study, reported in Schaeffer & Sonnemans (2000) - showed that unlimited banking in combination with high price caps could induce price crashes and increased volatility rather than the opposite. Price caps and borrowing and banking all had an influence on the price volatility. The best results were obtained when only borrowing was allowed. A larger internet based experimental study involving over 140 participants was also conducted under the same project, and the resulting price history is shown in *Figure 14b*). Unfortunately, the market turned out to be short most of the simulation period, and the TGC prices naturally settled one the maximum price, which makes this experiment inconclusive with respect to price volatility. Another initiative, the RECS project has been trading TGC's at an internet-based exchange for several years, but they did not report on price formation.

Figure 13 Laboratory experiments on TGC trading at NTNU

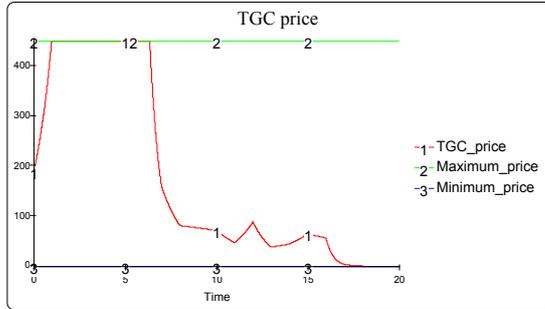


At NTNU, we set up a network simulation game and invited (wind) power engineers and energy policy administrators for a laboratory experiment on TGC trading. The model used is the same as the TGC market model shown in *Figure 10*, except that 5 buyers and 5 sellers interactively controlled the purchase and sales rate for each year through a user interface with relevant information on price, TGC's issued, volume etc. (see *Figure 13*).

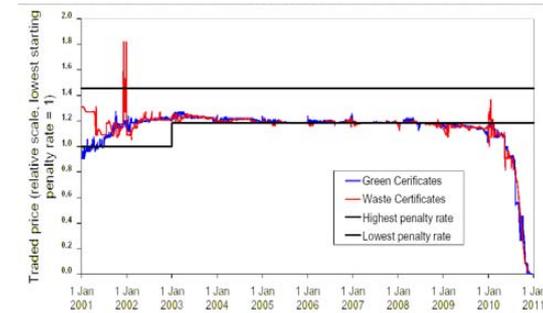
The model made investment decisions endogenously.

Figure 14 Laboratory experiment results of TGC markets

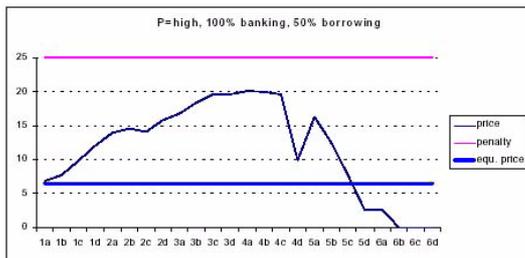
a) Price crash from the NTNU experiment. Low sales rate in the first years lead to persistent high prices and over investment in new capacity, which caused the price crash in the subsequent years.



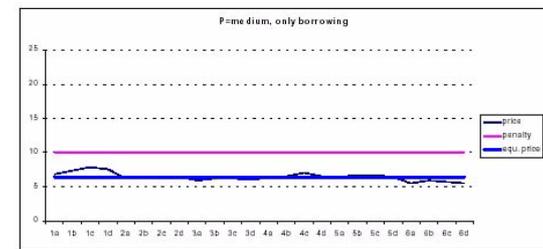
b) Price formation in the ReCERT internet experiment involving 140 participants. Prices stabilised on maximum price as the market was short throughout the whole simulation period. With respect to price stability, this experiment was therefore inconclusive (Source: ReCERT, 2001)



c) Price crash in a computer laboratory experiment. 100% banking and 50% borrowing allowed. Equilibrium price indicated by lower horizontal line. Upper horizontal line indicates maximum price (penalty). (Source: ReCERT, Schaeffer & Sonnemans, 2000)



d) Same experiment as in d) but with a lower maximum price and only borrowing. This market design lead to a price formation close to equilibrium.

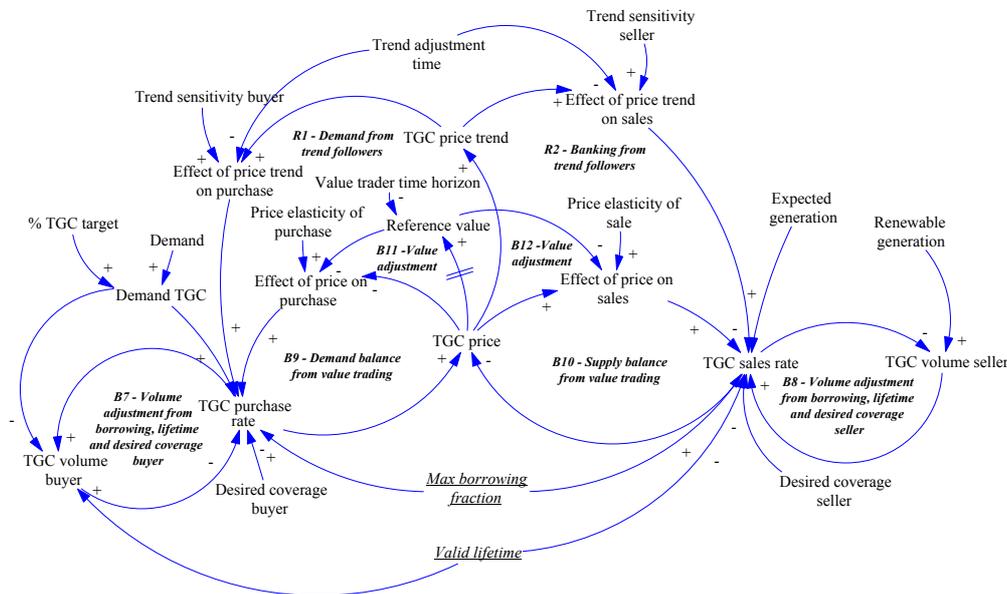


10 Modelling trading in a TGC market

Trading is constrained by the valid lifetime of a certificate (banking) and the possibilities of borrowing. In addition price caps represent constraints on the TGC price and buyers need to meet their TGC obligations defined as a percentage of electricity sold to the consumer. Trading with TGC certificates can be viewed as a problem of profit maximisation for the seller and a cost minimisation of the buyer. The optimisation problem is, however not simple, depending on the market design. If the TGC's are valid for one year, we should expect all certificates to be sold that year, and the price will then depend upon the conditions of wind and rainfall. If on the other hand, certificates have unlimited lifetime - it is possible to hold back certificates over longer periods of time, which opts for various trading strategies. The price of certificates in the long run should converge to the long-run marginal costs of new renewables, but since developing new capacity takes time and TGC obligations must be met every year, it is possible to hold back certificates to stimulate price increases and prices can persist far from equilibrium price. If borrowing is possible, holding back certificates would lead to more borrowing if prices exceed the expected long run marginal costs of new generation and thus reduce market power from suppliers.

Figure 15 shows the CLD of buying and selling in the TGC market. The market consist

Figure 15



of buyers and sellers, each constrained by possibilities of borrowing and banking. These regulations constrain their TGC volumes represented by Loop B7 and B8. Their respective sales and purchase strategy is represented by a combination of two loops: We hypothesize Value trading (B9, B10) and trend following (R1, R2) to be the trading strategy of buyers and sellers in the TGC market. Taking the seller as an example, value trading means that you have a reference value to which you compare the market price. If the market price is higher than your evaluation of the value of the certificate, you will sell more,

otherwise you will sell less. On the contrary, trend trading is a reinforcing process. The steeper the trend, the less you will sell because you can probably get a higher value for the certificate later on, which will reinforce the trend further.

The stock and flow diagram is shown in *Figure 16*. Equation set (9) defines the sellers TGC volume management. Issuing of certificates equals the generation from renewables, whereas the sales rate of TGC's take the expected generation from renewables as a reference (eq. 9.4), adjusted by the effect of price, the effect of trend and the constraints imposed on borrowing, banking and volume control due to risk aversion. If certificates expire, they will be sold immediately according to eq. 9.4 and 9.10. When borrowing limits are exceeded (eq. 9.5- 9.9), the sales rate is adjusted to keep within limits. The maximal borrowing fraction is defined as a fixed percentage of the expected generation (eq 9.8).

(9) TGC trading seller

$$9.1 \quad TGC \text{ volume seller}_t = TGC \text{ volume seller}_0 + \int (TGC \text{ issued}_t - TGC \text{ sales rate}_t) \cdot dt \quad [TWh]$$

$$9.2 \quad TGC \text{ volume}_0 = 12.5 \quad [TWh]$$

$$9.3 \quad TGC \text{ issued}_t = \text{generation re} \quad [TWh/yr]$$

$$9.4 \quad TGC \text{ sales rate}_t = MAX(\text{expected generation} \cdot \text{effect of TGC price on sales rate} \cdot \text{effect of TGC trend on sales rate} \cdot \text{adj for borrowing seller} + TGC \text{ vol adj seller, expiration rate}) \quad [TWh/yr]$$

$$9.5 \quad \text{adj for borrowing seller} = MAX(\text{borrowing margin}/\text{Borrowing AT}, 0) \quad [TWh/yr]$$

$$9.6 \quad \text{Borrowing AT} = 1 \quad [mo]$$

$$9.7 \quad \text{borrowing margin} = (\text{max borrowing seller} - TGC \text{ volume seller}) \quad [TWh/yr]$$

$$9.8 \quad \text{max borrowing seller} = \text{Fraction max borrowing} \cdot \text{expected generation} \quad [TWh/yr]$$

$$9.9 \quad \text{Fraction max borrowing} = -0.5 \quad [TWh/(TWh/yr)]$$

$$9.10 \quad \text{expiration rate} = DELAYMTR(TGC \text{ issued}, \text{Valid lifetime}, 3) \quad [TWh/yr]$$

The same structure applies to buyers of TGC's defined in equation set (10). The buyer must control his TGC volume through purchases, whereas the demand obligations control the consumption rate of TGC's. We assumed that the buyer adopted the same strategy as

taken into consideration, and they have enough time and resources to do so in order to make optimal decisions on buying and selling. Any price fluctuations are exogenously caused by new information of fundamentals (i.e. breakthrough's in technology or excess generation of TGC from last month) The rational expectations paradigm can be a sufficient approximation in many cases, but this assumption does not always hold.

A more realistic assumption is the paradigm of bounded rationality, where traders are restricted in terms of resources, time and cognitive capacity to make optimal decisions on buying and selling. Their decisions are based on a limited, selective set of information available to them. System dynamics and cognitive science provide us with theory to model boundedly rational agents by capturing their decision rules. Heuristic rules for trading could be inferred from analysing data from the laboratory experiments on TGC markets. Unfortunately, the quality of the conducted experiment at NTNU was not sufficient in order to use it for estimating decision rules, and there were too few experiments. Still, some observations and experience can be used to hypothesize their decision rules.

Price dynamics of common trading strategies in asset markets has been studied in emerging fields of economics (see for instance Farmer & Joshi, 2000 and Gaunersdorfer, 2000). Their studies show that simple and commonly used trading strategies based on adaptive belief endogenously generate price fluctuations and statistical behaviour of prices as those observed in real world markets. This indicates that representation of simple decision rules can capture characteristic behaviour of markets that in turn can be utilised for analysis and design. In the following, we will describe two trading strategies, namely *value trading* and *trend following*.

10.1 Value traders

Value traders make subjective evaluation of the “fundamental” value of the asset and believe the market sooner or later will adjust to this value. They attempt to make profits by selling if they think the market is overpriced and buying if they believe the market is underpriced. These traders are called “fundamentalists” in the sense that they make an assessment of the value of a TGC asset from the “fundamentals” of the market. In a TGC market, fundamentals are information about new project developments, permits, contracts, cost of new technologies etc. The “fundamentals” of renewables are fairly reliable in comparison to stock markets. However, such analyses would require time and resources. The most influential source of information is perhaps recent prices and thus we can represent the fundamental value denoted as *Perceived TGC value* as an adaptive expectation of recent prices in eq 11.2., where the *Value trader adjustment time* is the average smoothing time, which should be of the same magnitude as the time delays involved in construction of new capacity, because only new capacity can adjust price in the long run. The price elasticity of TGC supply indicates how many per cent a seller would change his sales in response to price changes. The effect of TGC price on sales rate function is a multiplier

used in the sales and purchase policies.

(11) Value trading

11.1 *effect of TGC price on sales rate* = (TGC price/Reference price)^{Price elasticity of TGC supply} [TWh/yr]

11.2 *Reference TGC price* = DELAYINF(TGC price, Value trader AT) [NOK/MWh]

11.3 *Value trader time horizon* = 3 [yr]

11.4 *Price elasticity of TGC sales* = 1.5 [1]

The same structure applies to buyers of TGC's as well, except for a change in parameters. We assume the same parameters as for sellers, except for the price elasticity of demand

Price elasticity of TGC demand = -1.5 [1]

(For the full set of equations for value traders, see appendix)

10.2 Trend followers

Trend followers have shorter time horizon than those of value traders. They believe that prices will fluctuate but that the market has some inertia that can be exploited. A seller would then hold his position of TGC's if the trend is positive, and sell when the trend is negative. Conversely, a buyer would hold his position when prices are falling, and buy when prices are rising:

(12) Trend followers

12.1 *effect of price trend on sales* = (1+TGC price trend)^{Trend elasticity} [1]

12.2 *Price trend* = TREND(TGC price, Trend AT) [1/yr]

12.3 *Trend adjustment time* = 1 [yr]

12.4 *Trend elasticity* = 2 [1]

The trend is observed over some time interval. It is not likely that short-term price fluctuations would occur in the TGC market, as demand obligations must be met once a year, but the trend horizon must be less than the expected average time to add new capacity. The trend adjustment time is therefore set to 1 year in eq (12.3).

The NTNU experiment strongly suggested that the trend strategy to be dominating, perhaps because this is the simplest strategy and only requires information on previous prices. We hypothesize that traders would both look to the value and to the trend when trading in a TGC market. If the price is high and the trend is positive, the seller would probably sell less than if the trend is pointing downwards. Similarly, if the price is low and the trend is pointing up, the seller would be more inclined to wait than if the trend is going down. This trading strategy is represented through eqs 9.4 and 10.4:

TGC sales rate_t = f(*expected generation re·effect of TGC price on sales rate·effect of TGC trend on sales rate, ... other factors ...*)

In asset markets, trend trading and value trading is separated by their difference in time horizon. In a TGC market, however, the slow dynamics of new capacity makes these

strategies relevant on the same time scale.

10.3 Managing risk by controlling the TGC volume

Using the trend and value strategies, TGC volumes could grow very large, which represent large risks if the market should crash. Neither the buyer nor the seller should keep large volumes of TGC's over a long period. This risk aversion can be taken into account by adjusting the TGC volume, with an adjustment time of up to 3 years as in equation set (13)-(14). The buyer would like to have some coverage of TGC's

(13) Volume adjustment seller

$$13.1 \text{ TGC vol adj seller} = (\text{SLIDINGAVERAGE}(\text{TGC vol seller}, 1) - \text{desired volume seller}) / \text{Volume adj time seller} \quad [\text{TWh/yr}]$$

$$13.2 \text{ desired volume seller} = \text{expected generation} \cdot \text{Desired coverage time} \quad [\text{TWh}]$$

$$13.3 \text{ Desired coverage time seller} = 6 \quad [\text{mo}]$$

$$13.4 \text{ Volume adj time seller} = 3 \quad [\text{yr}]$$

(14) Volume adjustment buyer

$$14.1 \text{ TGC vol adj buyer} = (\text{SLIDINGAVERAGE}(\text{TGC vol buyer}, 1) - \text{desired volume buyer}) / \text{Volume adj time buyer} \quad [\text{TWh/yr}]$$

$$14.2 \text{ desired volume buyer} = \text{TGC demand} \cdot \text{Desired coverage time buyer} \quad [\text{TWh}]$$

$$14.3 \text{ Desired coverage time buyer} = 6 \quad [\text{mo}]$$

$$14.4 \text{ Volume adj time buyer} = 3 \quad [\text{yr}]$$

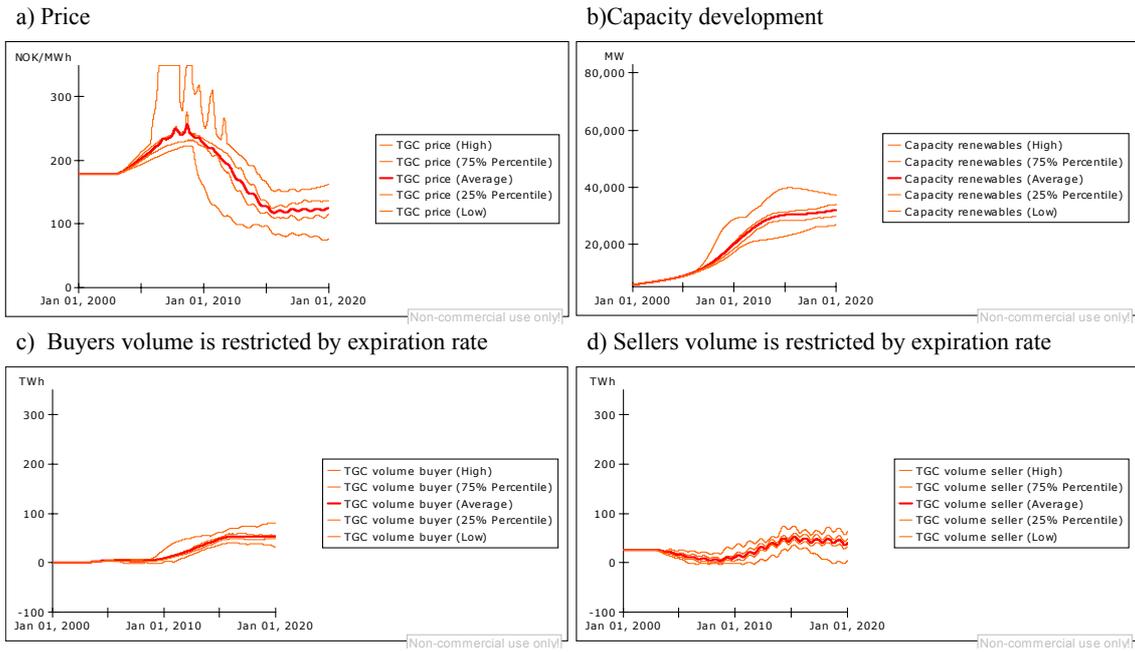
11 Simulation results

Consider the simplest case without borrowing and 1 year certificate valid lifetime. We assume a price elasticity's of -1 and 1 respectively for the TGC price elasticity of buyer and seller. No trend following strategy is applied. *Figure 17* shows a Monte Carlo simulation based on these assumptions, where wind energy accounts for the stochasticity from the renewables (see *Figure 17e*) Prices increase during the first years, peaks and decline well below the equilibrium price of 178 NOK/MWh. In the calmest years, prices hit the price cap of 350 NOK/MWh. The average price development however, can be compared with that of the TGC market model in chapter 7 (see *Figure 11*). This market design does not allow for banking and borrowing, as can be seen by buyers' TGC volume and sellers TGC volume in *Figure 17c-d*)

When we allow for banking, *Figure 18* shows almost the same behaviour during the first years, since there is shortage of renewable capacity in proportion to the TGC target. After 2010, buyer's and seller's start banking. No trend strategy is used in this simulation. It appears that banking does not reduce price volatility during the first years, due to the initial capacity deficit during the first years. When there is a surplus of TGC's, banking tend to smooth prices to some extent (compare end periods of *Figure 17a* *Figure 18a*).

In the next simulations, we include the trend strategy. Traders now consider both the

Figure 17 TGC 1 year valid lifetime, no borrowing. No trend followers



e) Normalised wind energy used to represent stochastic generation. Wind energy series adapted from Tande et. al & Vogstad 1999)

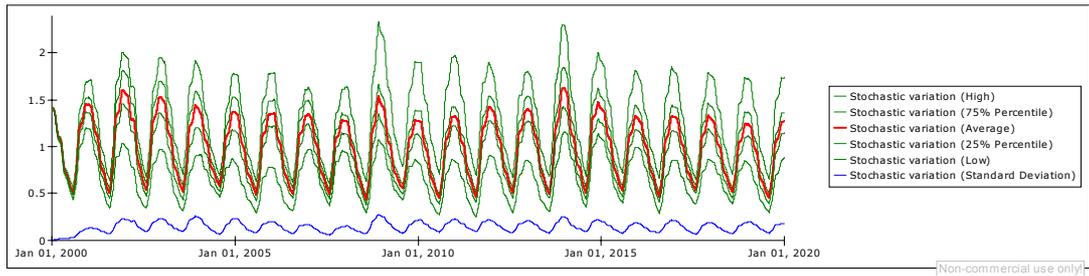


Figure 18 Infinite banking, no borrowing. No trend followers

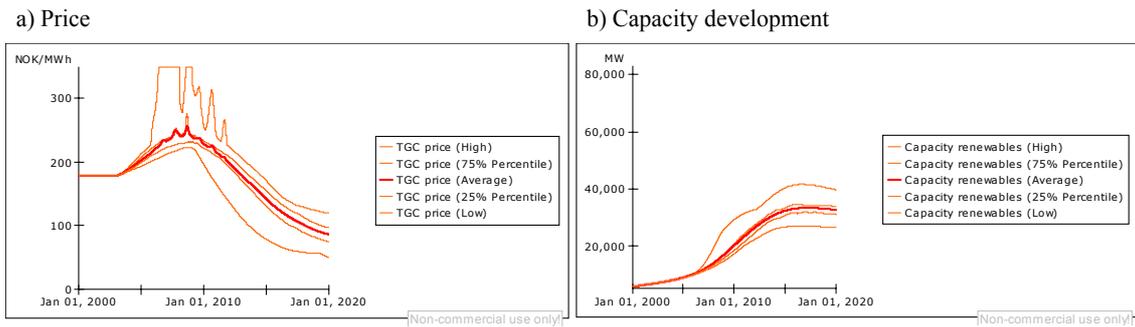
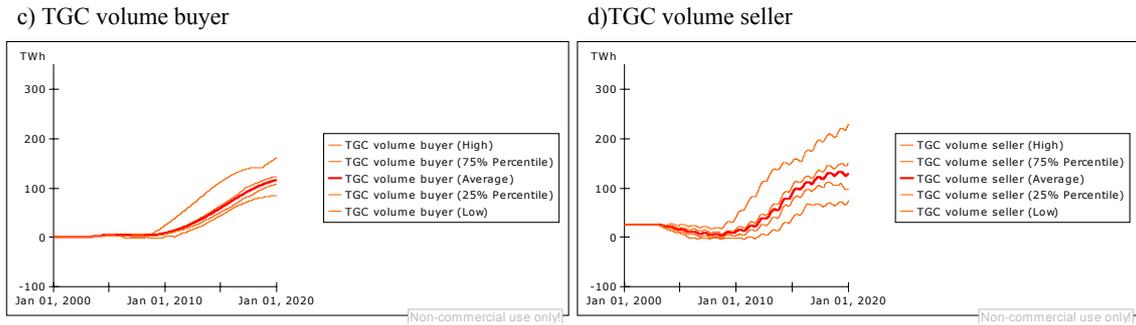
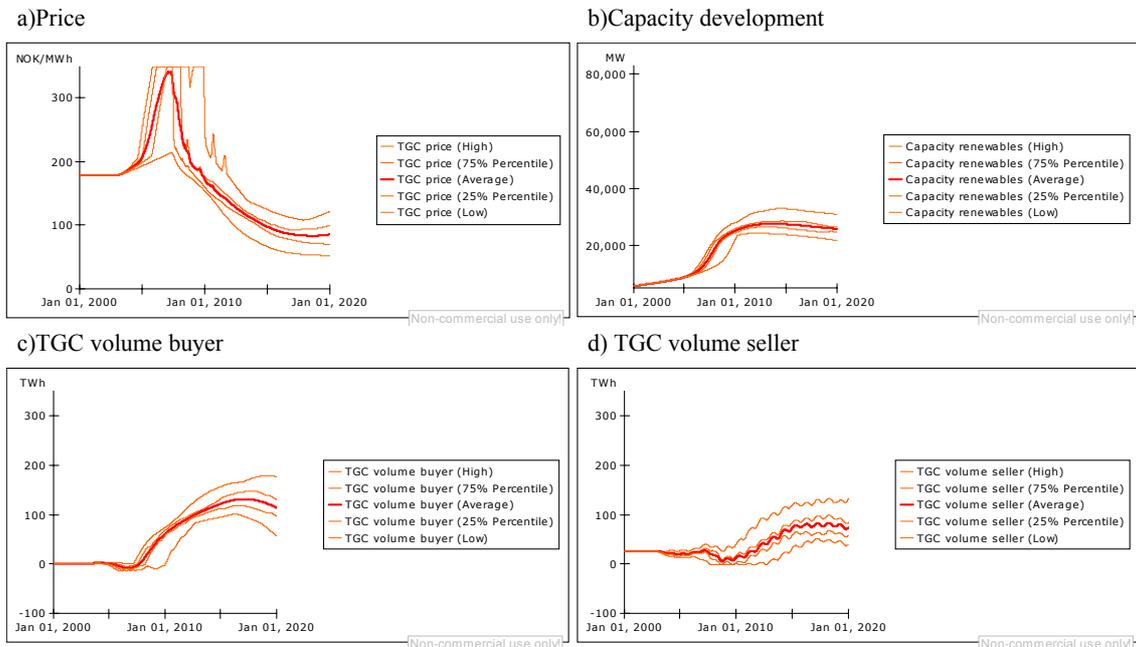


Figure 18 Infinite banking, no borrowing. No trend followers



price and the trend of the TGC when buying and selling. The price elasticity of trend is set to 2. Thus, 1 % price increase will increase the sales rate by 1 %, and 1% increase in trend will reduce the sales rate by 2 %. Similarly the buyer will increase his purchase rate when the price is dropping, but if the trend is negative, he will delay his purchase to wait for even lower prices. If we compare Figure 19d with Figure 18d, we can observe that the seller is slightly more restrictive in selling, which results in a deficit on the buyer side (compare Figure 19c with Figure 18c) - enough to drive up prices in Figure 19a, where the average price nearly hits the price cap. The conditions of capacity deficit in the start of the TGC period triggers the trend following strategy. In the case of initial overcapacity (or TGC targets less ambitious), a downward price trend would not have caused a similar problematic price drop, because the buyers are anyhow obliged to purchase certificates. Just after the price peaks, buyers begin to accumulate certificates due to the negative trend.

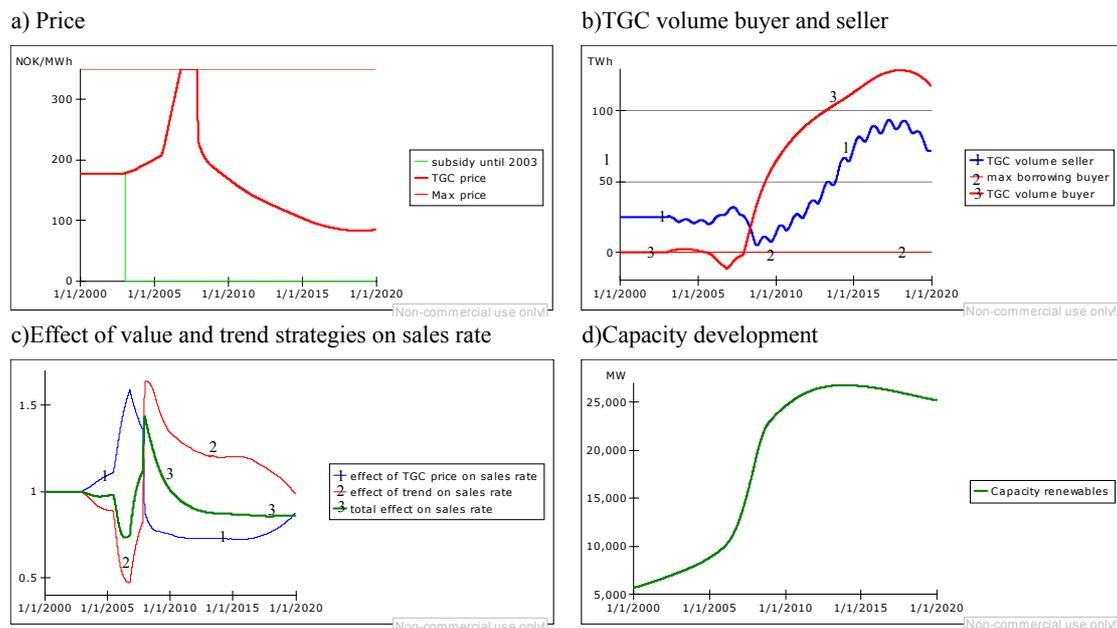
Figure 19 Infinite banking, no borrowing with trend strategy



To explore these strategies further, Figure 20 shows a typical simulation run with the same market design presented in the Monte Carlo simulation. In Figure 20b, sellers start

with an initial TGC volume of 25 TWh TGC's, and they do not increase sales rate even though the prices are rising. In 2006, buyers cannot fulfill their obligations, and their volume is negative, while the sellers in fact choose to bank TGC's. The price hits the price cap, and the sellers reduce their TGC volume towards 2010, but by this time, a significant amount of capacity has been developed, and prices fall below the initial equilibrium price of 178 NOK/MWh. *Figure 20c* show the relative effect of the trading strategies on sales rate. In this simulation run, the TGC trend effect dominates the sales strategy, while the value trading strategy serves to moderate the trend strategy.

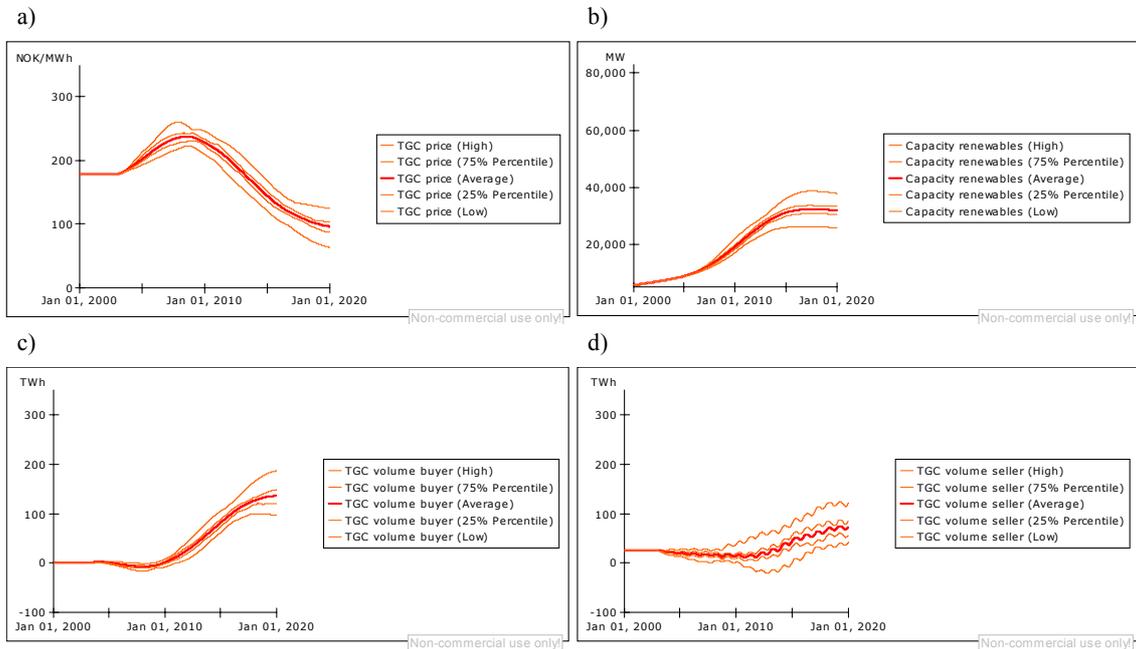
Figure 20 Typical simulation run, infinite banking, no borrowing with trend strategy.



Now let's consider allowing 50% borrowing of certificates, that is - buyers and sellers can borrow up to 50% of their respective yearly obligation and present TGC yearly generation. The results in *Figure 21* shows that prices show less volatility in response to sto-

chastic variation from in renewable generation.

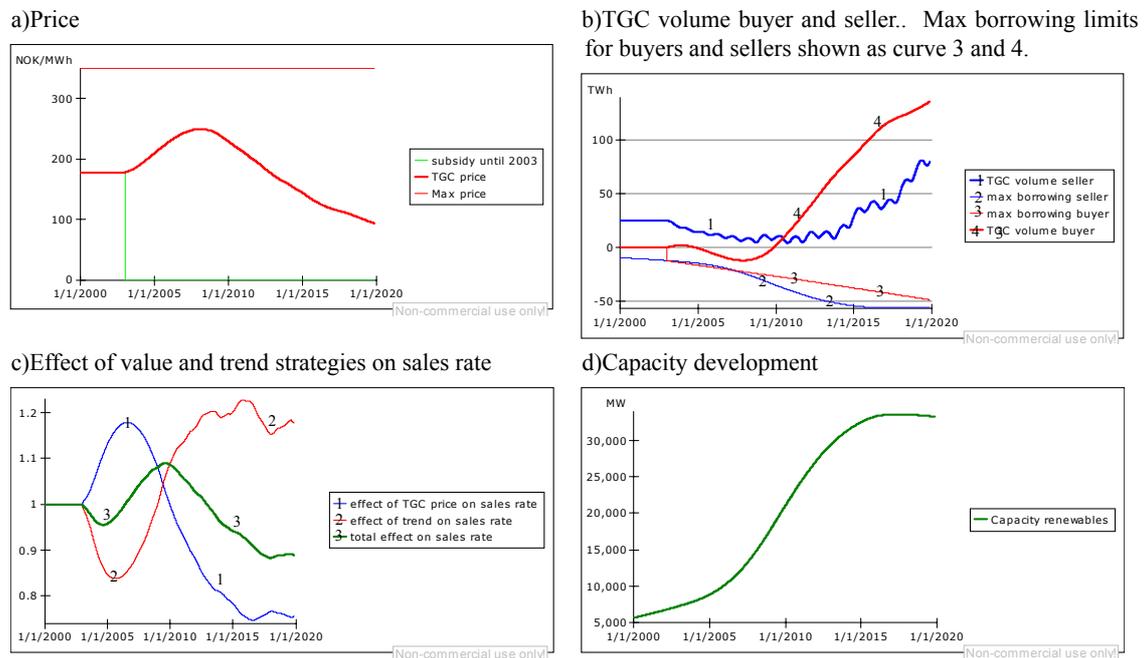
Figure 21 Banking, 50% borrowing trend



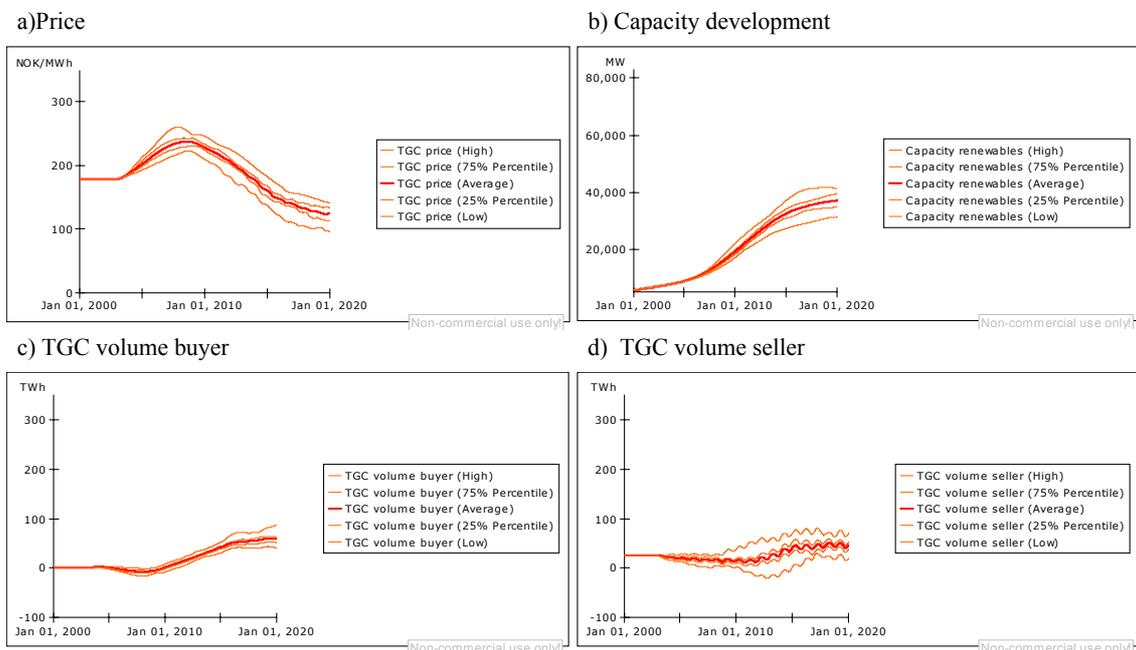
The trend strategy in a market with up to 50% borrowing does not have the same impact as when only banking is allowed. In *Figure 22b*, buyers now borrow certificates as prices rise. Comparing with *Figure 22c*, the seller tries to reduce his sales rate during the first years, but this strategy does not have a sufficient impact on the price any more. And after

some years, the value trading strategy becomes the dominant one.

Figure 22 Typical simulation run, infinite banking, 50% borrowing with trend strategy.



If we remove the possibilities for banking (Figure 23), the results show are similar, except Figure 23 No banking. 50% borrowing with trend strategy



that less TGC's are stored at the buyer in the end of the TGC period. Price variations from year to year do not seem to be significant compared with the simulation runs including borrowing.

The results of these simulations suggest that allowing banking to reduce price volatility

from the stochastic variation of renewables could in fact *increase* price volatility that arise from the strategic behaviour that becomes available. This effect does not appear if we assume traders only to use the value trading strategy described in 10.1. If, however, the traders also apply some trend following strategies as described in 10.2, price crashes will likely to occur. Laboratory experiments strongly supports the hypothesis that traders to some extent do apply trend strategies.

The problem can be avoided by allowing borrowing, with or without borrowing. Banking seems to shift market power in favor of sellers, whereas borrowing adjust this assymetry between buyers and sellers. These findings support the conclusions found in Schaeffer & Sonnemans (2000).

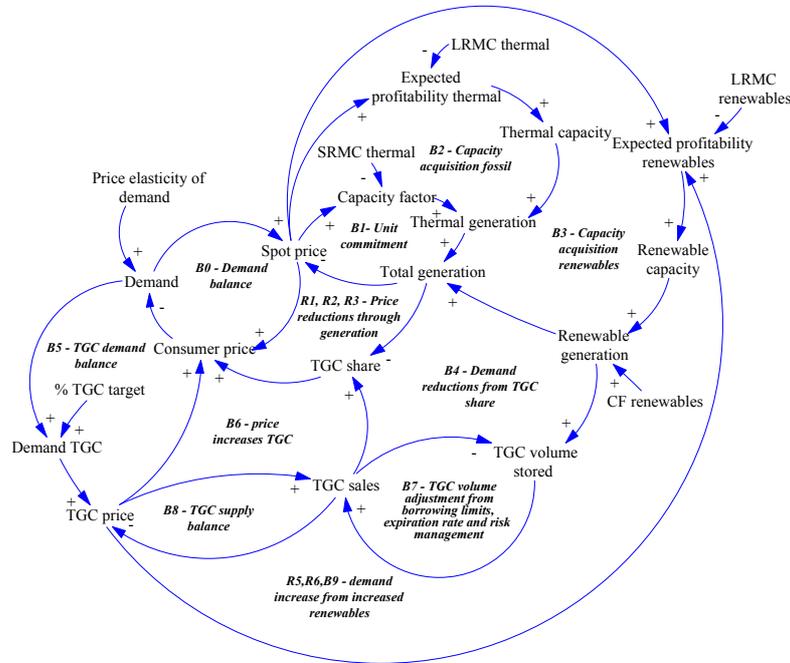
12 Interactions of the Spot market and the TGC market

A TGC system with mandatory demand has two partial effects on the electricity market. First, it produces extra revenue for producers of renewable electricity. This will increase supply of electricity and reduce electricity demand from other sources. Secondly, there will be a partial increase in the consumer price for electricity for given wholesale electricity prices since the consumer also has to buy certificates. With some price elastic demand, the wholesale prices for electricity are reduced. Hence, both the partial effects of the TGC system tend to reduce the income for traditional power producers. The effect on the consumer prices is, however, ambiguous: electricity prices net of certificates goes down, but the additional costs of certificates increase the consumer price. The total impact of TGC's on consumer prices thus depend on price elasticity's of demand, price elasticity of both electricity supply and TGC supply, and the price on certificates. Jensen & Skytte (2001) and Bye et.al (2002) reports that for some smaller share of TGC obligations, consumer prices can actually be *reduced*.

In contrast to subsidies, TGC prices will influence consumers directly through the consumer price of electricity, which is now both the payments from electricity generation and the TGC market. The consumer price now consist of the electricity spot price, plus the fraction of renewables that must be purchased (15.2-15.3). We can thus expect a reduced demand due to price elasticity of demand (see loop B4 - TGC demand balance in Figure 24). A reduced demand will also reduce spot prices (loop B0 - Demand balance, Figure 24). This means reduced generation from thermal units, because thermal generation is sensitive to spot prices (loop B1 - Unit commitment). In the long term, capacity acquisition will also be influenced by sustained lower spot prices through loop B2 - Capacity acquisition thermal and loop B3 - Capacity acquisition renewables. However, investment in renewables are stimulated by B7 - capacity acquisition from TGC price, which more than compensates for the reduced spot price. Finally, a more subtle interaction is discovered through loop R1 in Figure 24. Investments in renewables, increase total generation, which reduce the spot price. However, a reduction in spot price stimulates demand, which also means an increase in the TGC demand leading to a higher TGC price and therefore increased profitability of renewables and investment in new capacity, which increase generation and so forth. The importance of this reinforcing loop is not yet examined. A detailed feedback dominance loop analysis could reveal the relative importance of these previously mentioned loops, using the proposed method of David Ford (Ford, 1999). The TGC market and the electricity market interacts through the consumer price. The subsidy

scheme is now replaced by the TGC price (see eq 4.4)

Figure 24 Causal loop diagram showing the loops between the interacting spot market and the TGC market.



(15) Demand side including a TGC obligation (replaces equation set 4)

$$15.1 \text{ demand} = \text{Demand ref} \cdot (\text{consumer price} / \text{Reference price})^{\text{Price elasticity of demand}} \quad [\text{TWh/yr}]$$

$$15.2 \text{ consumer price} = \text{spot price} + \text{renewables share} \cdot \text{TGC price} \quad [\text{NOK/MWh}]$$

$$15.3 \text{ renewables share} = \text{generation re} / \text{generation tot} \quad [1]$$

$$15.4 \text{ Demand ref} = 420 \quad [\text{TWh/yr}]$$

$$15.5 \text{ Reference price} = 200 \quad [\text{NOK/MWh}]$$

$$15.6 \text{ Price elasticity of demand} = -0.3 \quad [1]$$

In the profitability assessment of renewables, the support scheme of 178 NOK/MWh in subsidies (4.4) is now replaced by the TGC price:

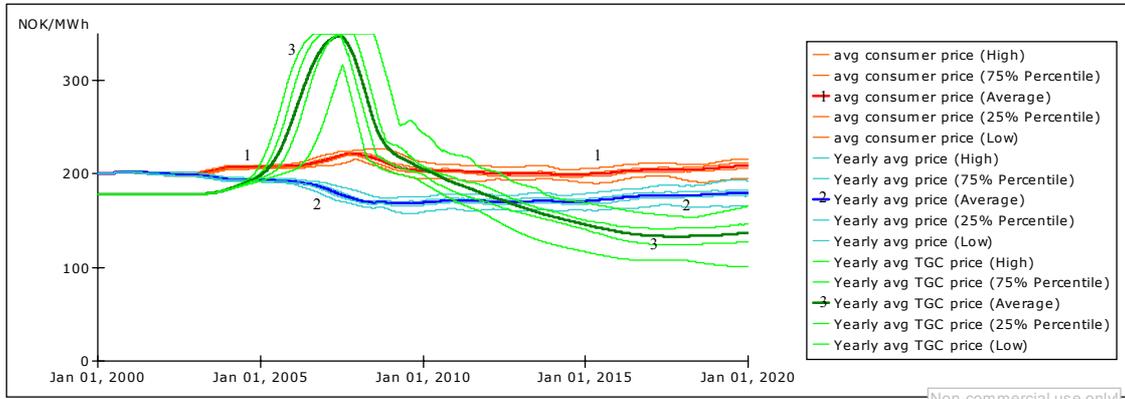
$$4.4 \text{ Support scheme} = \text{TGC price} \quad [\text{NOK/MWh}]$$

12.1 Simulation results, coupled markets

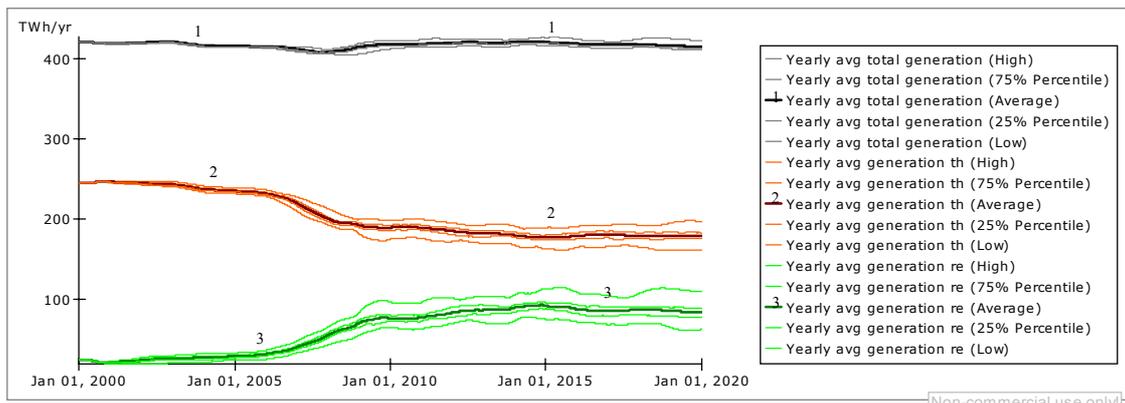
Integrating the TGC market with the electricity spot market developed in chapter 6 yields the results presented in the figures below. In Figure 25 there is no borrowing while TGC certificates have unlimited lifetime. In Figure 26, 50% borrowing is allowed and certifi-

cates have unlimited lifetime. In both simulations, the trend strategy is used in addition
Figure 25 Banking, no borrowing and trend strategy included. Price and generation shown as yearly averages

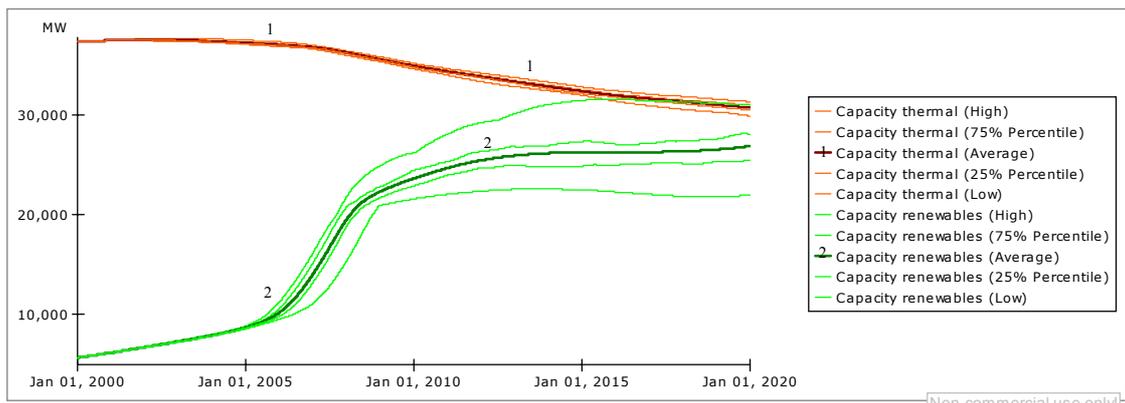
a) Consumer price, electricity spot price and TGC price



b) Total generation/demand, thermal generation and renewable generation development. (Demand coincide with generation)



c) Capacity development



to the value trading strategy.

From the preceding discussion and in chapter 4, the results are as expected. When introducing TGCs in 2003, consumer prices increase (*Figure 25a*), and spot prices are lowered.

Figure 25b) shows how demand and generation under a TGC market with unlimited banking. Surprisingly, the consumption remains fairly unaffected by the increasing costs

from TGC obligations, because electricity spot prices are suppressed by renewable generation. The relationship between the combined income of TGC markets and electricity markets will oppose each other in cases of wet/windy years or dry/calm years. These balancing mechanisms also shown in the loop diagram in *Figure 24* tend to stabilise variations in revenues of renewable suppliers. During windy years, the generation of wind will be high, but electricity market prices decrease, as will the TGC price¹. During calm years, the number of TGCs issued decreases while prices on TGC's rise, and electricity prices rises as well.

Developers of renewable technology may experience periods of growth and stagnation in the market for renewables, which is not desirable. A properly designed TGC market can reduce the possibilities of price crashes that arise endogenously from the trading strategies examined. Allowing borrowing (*Figure 26*) reduces the market power of suppliers in situations of capacity deficit. A higher and smoother development of renewables can be attained by allowing borrowing of TGC's.

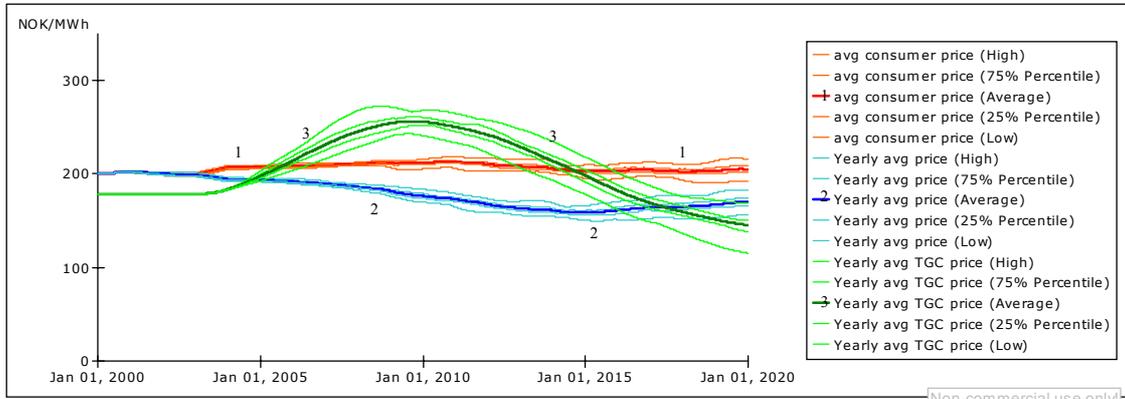
These simulations are based on realistic marginal operational costs, long-run marginal costs and price elasticity's. Consumer prices did not reduce as a consequence of the TGC market (see Jensen & Skytte (2002) and Bye et al. (2002) for a discussion). However, con-

1. Of course, some renewable suppliers will chose to store their certificates awaiting higher prices on TGCs

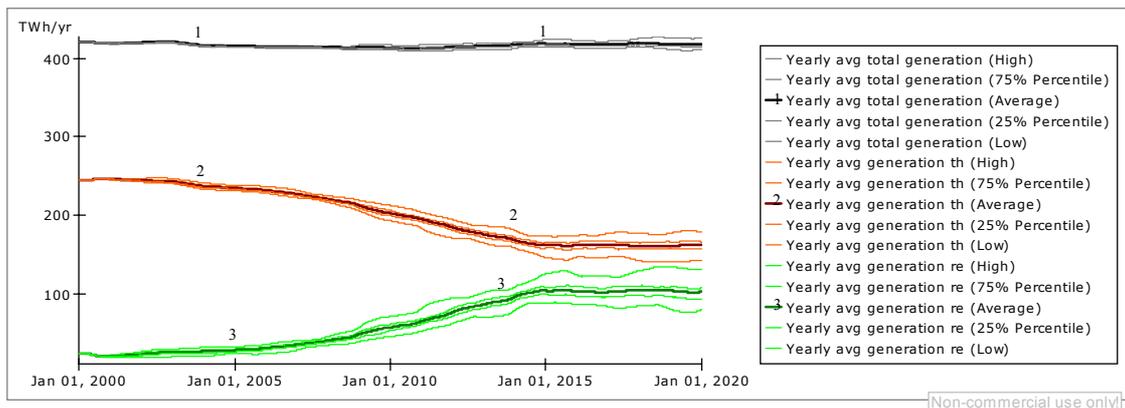
sumer prices did not increase significantly either, but remain fairly unchanged

Figure 26 Banking, 50% borrowing and with trend strategy . Price and generation shown as yearly averages

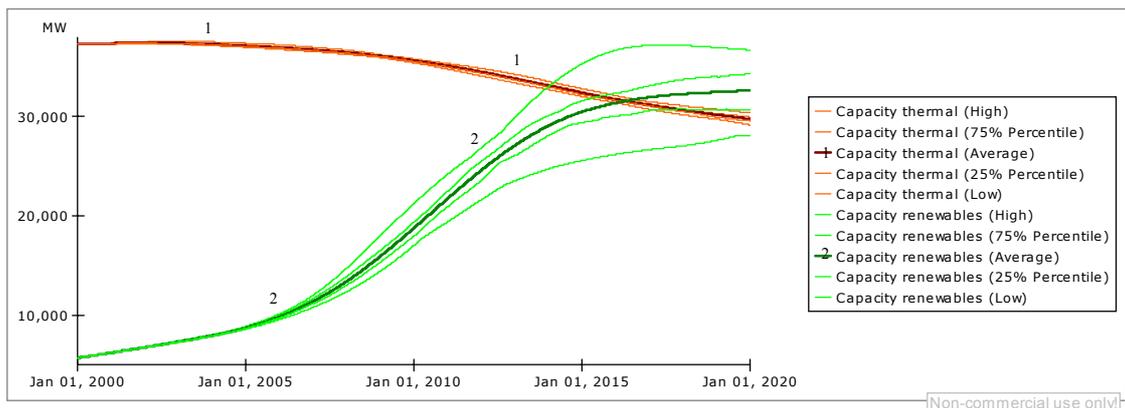
a) Consumer price, electricity spot price and TGC price



b) Total generation/demand, thermal generation and renewable generation development (Demand coincide with total generation)



c) Capacity development



d) Capacity factor thermal units

We should however note that present electricity market prices fluctuate significantly due to daily load variations, seasonal variations in demand, and the stochastic properties of hydropower generation in the Nord Pool. These considerations can be taken into account by implementing the TGC market model in the more detailed Kraftsim model (see chapter

13 below)

13 Simulations of TGCs in the Kraftsim model

A more detailed system dynamic model of the Nordic electricity market has previously been developed (Vogstad et al, 2002; Botterud et al. 2002). This model includes some additional long-term feedback loops of , technology progress and resource availability. Capacity acquisition includes a more detailed description of the application process and the construction process, plus the vintage structure of capacity. The profitability assessment includes a more detailed net present value calculation with feedbacks from technology progress for the investment costs and feedback from expected capacity utilisation concerning the operational costs and the expected profitability from sales of electricity. Furthermore, the model distinguishes between coal, nuclear, gas, gas peak load and gas with CO₂ sequestration; hydropower, wind power and bio energy plus imports/exports exchange. The supply side is still kept simple with an underlying growth of demand (1.6% per year) and a price elasticity of demand with an adaptive reference price. Seasonal variations in hydropower, wind energy and demand is included, and a simplified water value method for hydropower scheduling is represented endogenously in the model.

By implementing the TGC market model in the previously developed Kraftsim model, it is possible to assess the impact on various energy technologies and to which extent TGC markets can be used as an instrument to transit from a fossil fuelled towards a renewable power supply.

14 Summary of conclusions

In chapter 7 we developed a system dynamics model of the TGC market that pointed out the possible problem of price formation from the lack of short-term regulation of supply. Adjustments on the supply side of the TGC market can only be made in the long term by investing in new capacity, which makes the dynamics of the market sluggish.

The main concern of price stability in previous studies have been the yearly variations of renewables, which may cause large price variations from year to year. To circumvent this problem, a TGC market with banking (i.e. unlimited lifetime of certificates) has been the preferred solution. However, such an arrangement opens for strategic behavior that can induce much larger long-term price variations. If traders use price trends in their strategies, the reinforcing effect causes prices to crash when sellers withhold their TGC's over several years before new capacity comes on line. Allowing borrowing of certificates will reduce the impact of this strategy, as buyers can postpone their obligations, and developers can sell TGC's that will be produced in future years.

Partial equilibrium models and standard economics presently used to analyse TGC markets do not address these potential problems concerning price stability and trading strategies. A combination of system dynamic analysis and experimental economics can analyse the impact of various such trading strategies in order to avoid costly mistakes.

In chapter 13, we simulated the TGC market fully integrated with the electricity spot market. The balancing feedback loops between these markets seem to reduce the variations in investments of renewables that was observed in TGC market model. Consumer prices

were not significantly altered after the introduction of the TGC market.

15 Bibliography

- A. Gaunersdorfer 2001. Adaptive Beliefs and the Volatility of Asset Prices. *Central European Journal of Operations Research* 9, 5-30
- Botterud, A., M. Korpås, K. Vogstad and I. Wangensteen. 2002. *A Dynamic Simulation model for Long-term Analysis of the Power Market*. Proceedings, Power Systems Computation Conference, 25th-28th June, Sevilla, Spain.
- Bye, T., O.J Olsen and K. Skytte 2002. Grønne sertifikater - design og funksjon. Report no. 11/2002, Statistics Norway. (in Norwegian)
- Econ 1999. Dokumentasjon av ECON's kraftmarkedsmodell. Econ note 4/99, Econ centre of economic analysis.
- Farmer, J. D. and S. Joshi 2000. Price Dynamics of Common Trading Strategies. Santa Fe Institute Working Paper 00-12-069, to appear in the *Journal of Economic Behavior and Organization*.
- Ford, D.N, 1999. *A behavioural approach to feedback loop dominance analysis*. *System Dynamics Review* 15:3-36
- Forrester, J.W. 1961: *Industrial Dynamics*. MIT Press. Cambridge MA
- Groenheit, P.E., H.V. Larsen 2001. Balmorel - Data and Calibration. Balmorel Project Report March 2001. Available [online] <http://www.balmorel.com>.
- Hindsberger, M., M.H Nybroe, H.F. Ravn and R. Schmidt 2003. Co-existence of Electricity, TEP, and TGC Markets in the Baltic Sea Region. *Energy Policy*, Vol 31(1).
- Jensen, S.G, K. Skytte 2003. Simultaneous attainment of energy goals by use of green certificates and emission permits. *Energy Policy* Vol 31(1)
- Jensen, S.G, K. Skytte, 2002. Interactions between the power and green certificate market. *Energy Policy* Vol 30(5).
- Krohn, S (2001). An Industry View of a Proposed Danish Green Certificate Market. The Devil is in the Detail. Copenhagen Workshop on Tradables, 10-11 September 2001. Available [online]: <http://www.windpower.org/articles/busiview.htm>
- Langniss, O. and R. Wiser 2003. The renewables portfolio standard in Texas: an early assessment. *Energy Policy* 31 p527-535.
- Morthorst, P.E., 2000: "The development of a green certificate market" *Energy Policy* vol 28, pp 1085-1094, 2000.
- Nielsen, L., and T. Jeppesen 2003. Tradable Green Certificates in selected European countries- overview and assessment. *Energy Policy* 31(1).
- NOU 1998. Energi og kraftbalansen frem mot 2020. Whitepaper, Norwegian Ministry of Petroleum and Energy. (Norwegian)
- REBUS 2001. Renewable energy burden sharing: Effects of burden sharing and certificate trade on the renewable electricity market in Europe. EU Report, May 2001.

- RECeRT 2001. The European Renewable Certificate Trading Project Final Technical Report. Available [online] <http://recert.energyprojects.net/>
- Risø 2002. Green Certificates and Emission Trading. Risø report no. Risø-I-1936(EN)
- Schaeffer G.J & J. Sonnemans 2000. The influence of banking and borrowing under different penalty regimes in tradable green certificate markets - results from an experimental economics laboratory experiment. *Energy and Environment* Vol 11(4).
- SOU 2001: "Handel med elcertifikat - ett nytt sätt att främja el från förnybara energikällor" Svenska offentliga utredning. SOU 77:2001 (In Swedish)
- STEM 2002. Yttrande över Elcertifikatutredningens betänkande, "Handel med elcertifikat", SOU 2001:77 Statens energimyndigheter, yttrande. pp5-7 (In Swedish). Available [online] <http://www.stem.se>
- Sterman, J.D., 2000: "Business Dynamics: Systems Thinking and Modeling for a Complex World", McGraw-Hill. Book website: www.mhhe.com/sterman
- Vogstad, K., A. Botterud, K.M Maribu and S.G. Jensen. 2002. *The transition from a fossil fuelled towards a renewable power supply in a deregulated electricity market*. Proceedings, System Dynamics Conference, 28th-1st Aug, Palermo, Italy.
- Vogstad, K., H. Holttinen, A. Botterud and J.O. Tande 2000. System benefits of coordinating wind power and hydro power in a deregulated market. Proceedings "Wind Power for the 21st Century, 23-25 Sept. 2000, Kassel Germany.

16 Note

The TGC market Powersim Studio .sip file is available from <https://bscw.ntnu.no/pub/bscw.cgi/d229462/TGCmarket.sip>

The Kraftsim model Powersim Studio .sip is available from <https://bscw.ntnu.no/pub/bscw.cgi/d229462/Kraftsim11.sip>