

# Simulation Model of the Hydro-Thermal Power System in Iceland

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## Introduction

Encouraged by the current trend in the European Union and the rest of the world Iceland is on the threshold of deregulating the energy sector. The Icelandic government has already prepared the transition from the current monopolistic system to a deregulated system. A bill has been put forward in the Althing (the Icelandic Parliament) but it has not yet been passed and further discussion and studies on the matter have been postponed and are awaiting the autumn session.

The basic idea of deregulation is that instead of following an operation and expansion plan produced by central agencies, private agents will decide on construction of generating units and compete on an open market for sale of power. This is supposed to create favorable economic signals from customers and the open market to guarantee more optimal operation and expansion than under the old system.

The small size of the Icelandic Power System and also the small population of only 270.000 has created worries if the deregulating models of the big national blocks could be implemented in this small island in the middle of the North Atlantic. There are no electrical connections to other countries and even though projects of submarine transmission cables have been studied, there are vanishing probabilities that the project will be realized in the near future.

All this is not proof that a free market can not exist in Iceland, but it is more likely here than elsewhere, that the only possibility for both stable and beneficial solution will be in the form of controlled oligopoly rather than unregulated competition.

The electricity sector has some characteristics that differ from other sectors and in a considerable more complicated manner. A few such examples are:

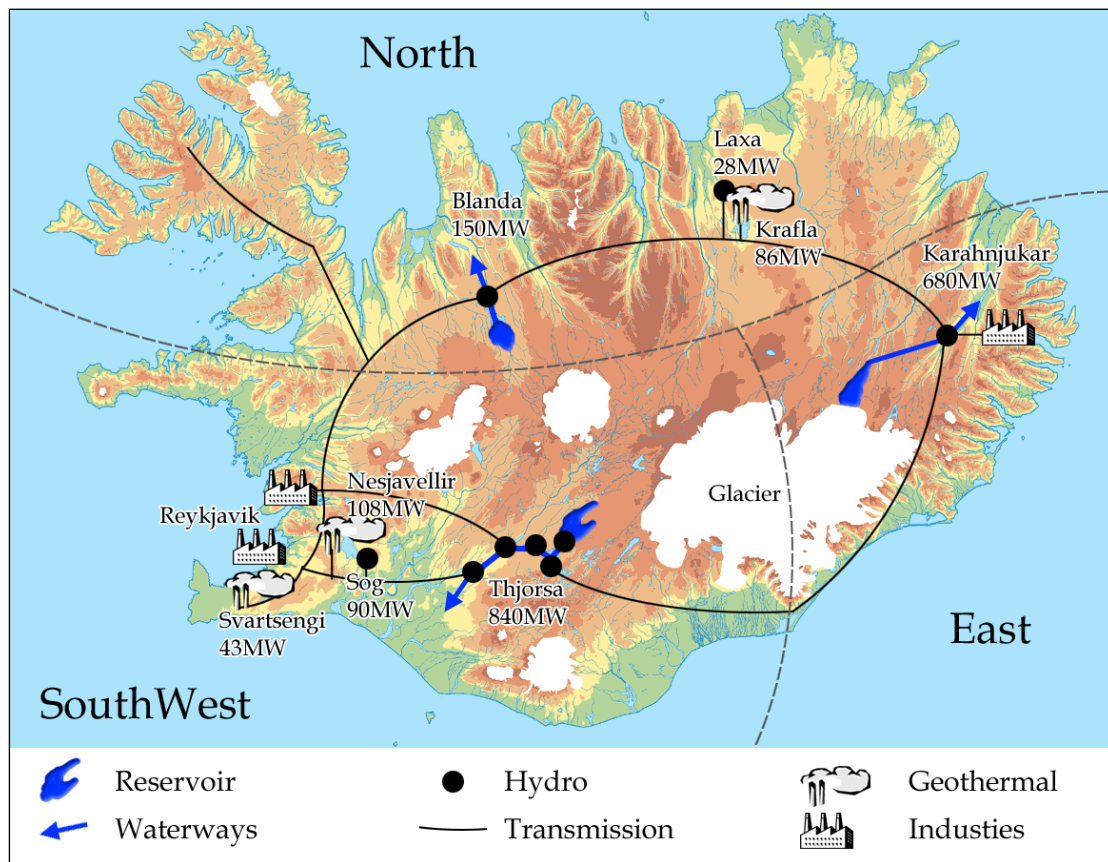
- Electricity from one producer to a customer can not be differentiated and electricity flows through the transmission networks only according to the laws of physics rather than commercial contractual agreements.
- Electricity can not be stored economically and there has to be continuous balance between demand and supply.
- The way to store power in a hydro-thermal power system is to store excess water in reservoir storage to be used in periods of low water supply.
- There are very high requirements to reliability and costs of power shortage accordingly high.

- There are increasing problems associated with building new hydro power plants because of environmental considerations. In Iceland the vegetation rich dips in the lava covered highlands are also the best places for new water reservoirs. It is by no means guaranteed that privately owned new hydro would receive a different attitude from the environmental movements, the political system or the general public than under the current system.

As a consequence this sector has to be carefully monitored at all times and radical changes in the business environment must be thoroughly prepared. Access to a good decision support system is of paramount importance. The central part of such a system is a simulation model to study the operational characteristics of the power system.

In this report a new simulation model of a hydro-thermal power system is presented. The model includes all features of former models that have been used in Iceland and also includes several new important features i.e. taking account of congestions in the transmission system. The model is considered well suited for studies on the Icelandic Power system in order to analyze consequences of necessary decisions when changing the order from monopoly to deregulation.

## The Icelandic Power System



The Electrical Power System used to demonstrate the model is shown in figure 1. The year is 2013 and the scenario includes the Karahjukar project and a new aluminium factory in East-Iceland, both fully operational.

The system is divided into 3 subsystems: South-West, North and East. Transmission capacity between subsystems is not sufficient for free interchange of power.

The main characteristics of this power system are shown in table 1.

Table 1 Main characteristics of the Icelandic power system 2013

Item	Unit	Total	S-West	North	East
Energy inflow to reservoirs	GWh/y	9,020	2,565	875	5,580
Energy in other inflow	GWh/y	6,475	5,285	1,030	160
Total inflow of energy	GWh/y	15,495	7,850	1,905	5,740
Energy demand	GWh/y	14,975	7,925	840	6,210
Energy balance	GWh/y	520	-75	1,065	-470
Reservoir storage capacity	GWh	4,395	1,395	285	2,715
Storage in % of demand	%	29%	18%	34%	44%
Hydro plants	MW	1,760	876	193	691
Geothermal plants	MW	237	151	86	0
Total Hydro and Geothermal	MW	1,997	1,027	279	691
Interruptible power, class A <sup>a)</sup>	MW	162	63	21	78
Interruptible power, class B	MW	49	49	0	0
Thermal reserve power	MW	104	47	41	16
Interruptible power, class C	MW	91	39	0	52

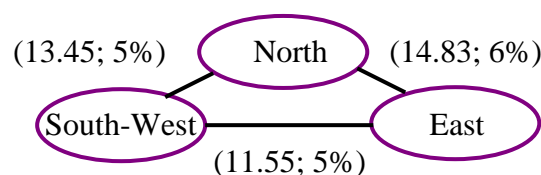
<sup>a)</sup> time dependent series

The three big reservoirs are glacier fed so inflow is highly correlated with yearly temperature distribution.

The limited storage capacity in the South-West is compensated by a substantial groundwater flow from the porous lava covered highlands throughout the winter.

The geothermal plants get steam from over 2000 meters deep boreholes and are unaffected by weather conditions. Thus synergy is created between those power resources by relatively diminishing the extent of shortage in extreme low water years while preserving the flexibility of the hydro.

The transmission system is modelled as a three-node network and 132 kV transmission lines between subsystems are defined by the figures in the parenthesis: (Capacity in GWh/week; Energy losses in %).



## Hydrothermal Scheduling

Hydrothermal Scheduling models aim at optimal use of hydro and geothermal resources, in relation to the characteristics of the generation capacity, uncertain future inflows, thermal generation, power demand and costs of transmission between subsystems.

The most important aspect of the Icelandic Power System is the utilization of water stored in reservoirs under the constraints of isolation from other systems and limited backup capacity in the form of fossil plants.

Traditional water value methods involve using a strategic part to create an optimal operations policy for the hydro-thermal power system in Iceland. There after simulations are performed for the purpose of mapping the characteristics of the system, creating probabilistic views into the future for the purpose of operation planning, expansion planning and optimization of hydro plants and their components.

The current method is based on the concept of a monopolistic system and only one overall water value is calculated for the whole country. Some important factors are obscured by this simplification, like:

- ✓ different hydrological conditions in different parts of the country
- ✓ geographical distribution of the power demand and production
- ✓ power exchanges
- ✓ effects of transmission losses and congestions.

The model presented here is meant to take all this into account , thus in effect creating coherent operation policies although independent for each part of the country. The model has features to make studies possible in an open market condition. Its main features are:

- The system can be divided into subsystems of any number and connected by power lines in any configuration.
- Transmission constraints and losses between subsystems can be defined.
- Water values are calculated for each subsystem taking into account local market, local production and energy transmission in and out of the subsystem.

Time unit in the model is one week and calculations are based on river flow series for the years 1950-2000, totaling 51 years.

## Solution methodology

The idea behind the model presented here is to solve the problem several times and reallocate load between subsystems subject to transmission congestions and losses between subsystems after each iteration, until sufficient convergence of solutions is obtained. This procedure is described in figure 2.

In the strategy evaluation part of the model, regional decision tables in the form of incremental water values are computed for each of the subsystems, using stochastic dynamic programming. The optimisation takes into account variable head for hydro plants connected to the main reservoirs in the subsystem.

In the simulation part, optimal operational decisions for the system as a whole are evaluated for a number of hydrological years, currently 51 years with time unit of one week.

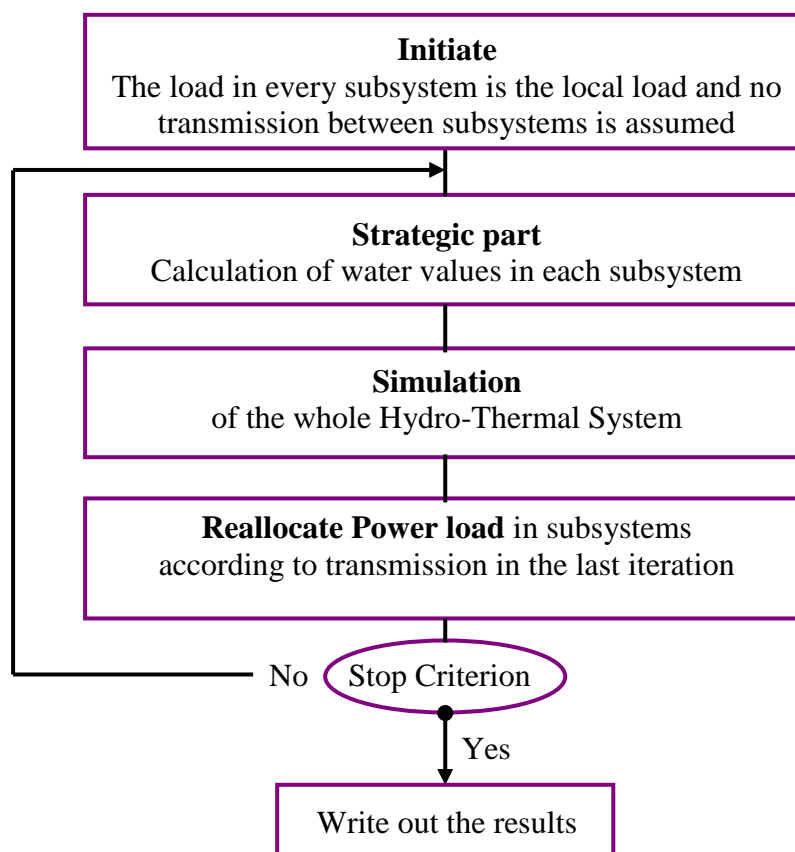


Figure 2 Solution methodology

Hydro and thermal production are determined for each time step using linear programming, based on the water values for each aggregate regional subsystem. Each Hydro module is described by generating capacity, reservoir capacity, relation of head to reservoir level, storable and non-storable inflow, destinations for overflow, bypass and plant discharge, maintenance outages and constraints on water flow etc.

The new model will after completion be used for studying the operation of the Power System and for expansion studies both for generation and transmission capacity alternatives.

Some of the categories of intended studies are as follows:

#### Market

- Spot price forecasting in deregulated markets
- Risk assessment in dry water years
- Price evaluation for financial contracts with large industries

#### Generating system

- Long-term operational scheduling of hydropower
- Reservoir operation
- Analysis of overflow losses
- Calculation of probability of power production in the hydro-, geothermal and thermal power plants in each subsystem
- Maintenance planning
- Expansion planning of generating capacity
- Probability distribution of operational costs within each area

#### Transmission System

- Utilization of transmission capacity between subsystems – duration curves.
- Expansion planning of transmission capacity between subsystems.

### **Calculation of Water Values**

With reservoirs it is possible to store excess water in the summertime when demand is minimal to be used in the wintertime when demand is high.

In the strategic part of the problem as described in figure 2 the value of water in reservoirs is calculated.

Water value is an evaluation of operational cost for the power system in the future that can be avoided by storing water in reservoirs for later use instead of using it immediately.

The decision process can be explained in a decision tree:

<u>Decision</u>	<u>Future Inflows</u>	<u>Operating Consequences</u>
Use water	Wet	OK
	Dry	Deficit
Store water in reservoirs	Wet	Spillage
	Dry	OK

Figure 3 Decision tree

For each subsystem and in each iteration the incremental water values are calculated as shown in figure 4.

The procedure is as follows:

1. All reservoirs in the subsystem are combined to form an equivalent reservoir and all hydro and geothermal plant are combined to form an equivalent power plant representing power production capabilities in the subsystem
2. Say we are calculating water value at point A in figure 4. The operation of the power subsystem is optimized for one week onward.
3. The marginal cost of operation is calculated as one of the following:
  - a. Zero at spillage.
  - b. Cost of not delivering interruptible power.
  - c. Cost of Thermal Power.
  - d. Penalty for Power shortage.
  - e. Water value at end of period.
4. The watervalue at point A is set as the average of the marginal cost for all water years.

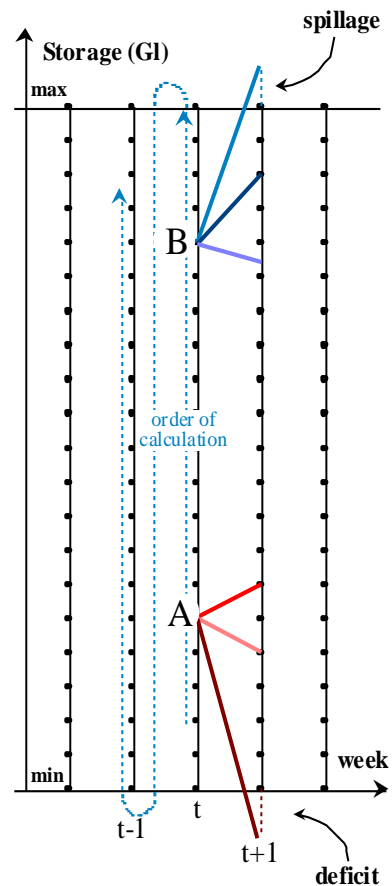


Figure 4 Calculation of water values

The calculation is performed from empty to full reservoirs content and moving backward in time as shown by the dotted line in figure 4.

The whole table is calculated in 6 iterations in only a split of a second on an ordinary desktop computer.

Typical water values are shown in figure 5.

## Formulation of the Hydrothermal Dispatch

### Objective Function

Given the water values for reservoirs in each subsystem the objective is to minimize the sum of immediate and future operating costs:

$$\min \sum c(j) g_t(j) + \sum \rho(k, v_{t+1}) \alpha_{t+1}(k) v_{t+1}(k) \quad (1)$$

$\sum c(j) g_t(j)$  the immediate cost is given by the thermal operating costs in stage  $t$

$\sum \rho(k, v_{t+1}) \alpha_{t+1}(k) v_{t+1}(k)$  the future cost is represented by:  
 $\rho(k, v_{t+1})$  production coefficient of reservoir  $k$  (GWh/GI);  
 can vary with reservoir content.  
 $\alpha_{t+1}(k)$  the water value function of reservoir content in  
 (Mkr/Gwh=kr/kWh)  
 $v_{t+1}(k)$  reservoir volume at the end of stage  $t$  (start of stage  $t+1$ )  
 in (GI).

The operating constraints are as follows:

### Load Supply

For each subsystem:

$$\sum \rho(i, v_{t+1}) u_t(i) + \sum g_t(j) - \sum (1+\tau) L^+ + \sum L^- = d_t \quad (2)$$

where:

$\sum \rho(i, v_{t+1}) u_t(i)$  Hydro production in the subsystem  
 $\sum g_t(j)$  Thermal production in the subsystem  
 $\sum (1+\tau) L^+$  Sum of all power exports from the subsystem incl losses  
 $\sum L^-$  Sum of all power imports to the subsystem

The transmission  $L$  in each power line between subsystems is represented by two components one in each direction:

$$L = L^+ + L^- \quad (3)$$

### Water balance.

The water balance equation relates storage and outflow. Reservoir storage at the end of stage  $t$  (beginning of stage  $t+1$ ) is equal to initial storage minus outflow volumes (turbined and spilled) plus inflow volumes (lateral inflow plus releases from upstream plants):



$$v_{t+1}(i) = v_t(i) - u_t(i) - s_t(i) + a_t(i) + \sum_{m \in U(i)} [u_t(m) + s_t(m)] \quad (4)$$

where:

$i$	index for hydro plants
$v_{t+1}(i)$	stored volume in plant $i$ at the end of stage $t$
$v_t(i)$	stored volume in plant $i$ at the beginning of stage $t$
$a_t(i)$	lateral stream flow arriving at plant $i$ in stage $t$
$u_t(i)$	turbined outflow during stage $t$
$s_t(i)$	spilled outflow volume in plant $i$ during stage $t$
$m \in U(i)$	set of plants immediately upstream of plant $i$

### Limits on Storage and Outflow

$$\begin{aligned} v_t(i) &\leq v(i) \\ u_t(i) &\leq u(i) \end{aligned} \quad (5)$$

where  $v(i)$  and  $u(i)$  are respectively the maximum storage and turbine capacities.

### Limits on Thermal Generation

$$g_t(j) \leq g(j) \quad (6)$$

The objective function with the operational constraints represent a standard linear programming optimisation problem that can be easily solved with software packages that are commercially available.

The signature in the formulation of the problem is taken from [1].

## **Case study**

A case study was performed based on a scenario of the Icelandic Power system in the year 2013 as shown in figure 1.

The overall demand in this case is actually very high compared to the power production capability of the system. As seen in table 1 there is an excessive production capability in the North but an insufficient production capability in the South-West and the East. The model balances this incompatibility by simulating transmission of power between the subsystems.

The simulation uses river flow series for the water years 1950-2000 (51 years) and the model is based on the methodology shown in figure 2. Time unit is one week.

It is worth observing that one simulation, which reallocates load 5 times to iterate to a stable solution according to figure 2, takes about 70 seconds on a small desktop IBM computer NetVista with a 733 Mhz Pentium 3 processor and 384 Mb RAM. This includes reading in data of river flow and demand, calculating water values 90 times, solving 13.260 linear optimisations (40 rows and 60 columns) and writing out extensive files than can be imported easily to EXCEL.

The program is written in C++ and uses a DLL linear programming package from Frontline Systems Inc in USA.

In the simulation, volume of the reservoir at the end of one water year was used as the volume in the beginning of the following water year.

The system was divided into three subsystems according to figure 1. Main characteristics of the power system used in the simulation are described in table 1.

Figure 5 shows the resulting water values of each subsystem after the 5 iterations.

Figure 6 shows the volume of the three reservoirs in the subsystems as a group of curves, one curve for each of the 51 water years used in the simulation model. The group of curves reflects visually the expected mean and variation and also the extreme values of reservoir content within the year.

Figure 7 shows the resulting shadow prices for energy market in each subsystem, also as a group of curves.

Figure 8 shows in more detail 10 years (1977-1986) of the 51 water years used in the simulation. As shown the drawdown of the reservoir in the East is 4-5 weeks later than in the South-West reflecting that spring arrives that much later. This explains one of the most important feature of the model i.e. how it takes account of different hydrological conditions in the subsystems and the operation is optimised according to that.

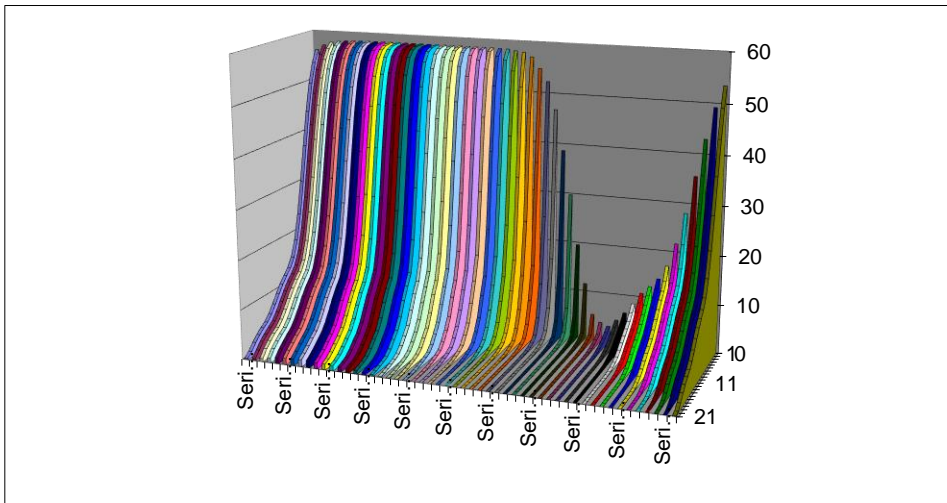
Figure 9 shows for the same years the evaluation of the market shadow prices. The heavier demand compared to production capability in the East results in higher shadow prices caused by bottlenecks in the transmission system. Most of the time the three subsystems have the same shadow price reflecting that during that time congestions in the transmission network do not limit exchange of power as needed for cost minimization.

Simulation results have shown that if transmission constraints are eliminated by doubling or tripling the transmission capabilities between the subsystems the shadow prices will be the same in all the subsystems. The resulting values are actually the trajectory of water values throughout the simulation, and those water values are actually the marginal cost of the system at every time.

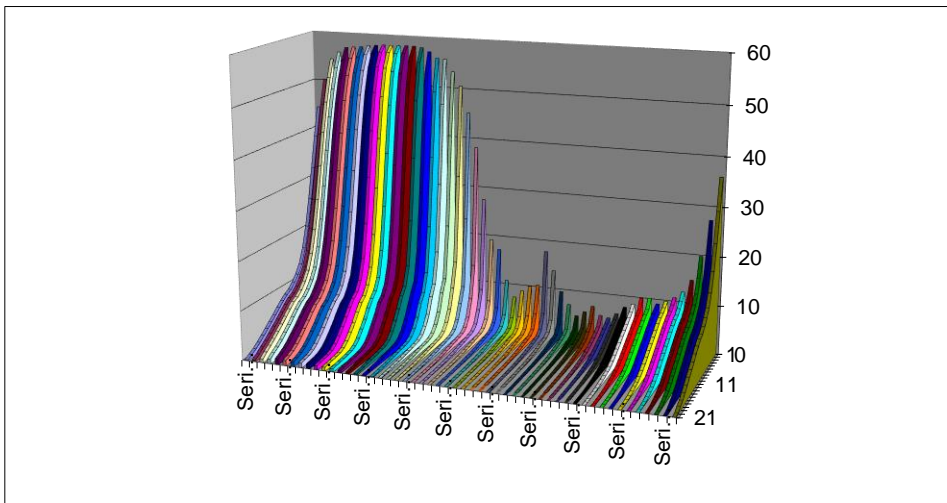
Figure 10 shows transmission in the high voltage power lines between subsystems as duration curves. This is very important piece of information regarding feasibility studies in expansion planning of the overall transmission network.

**Figure 5 Water values**

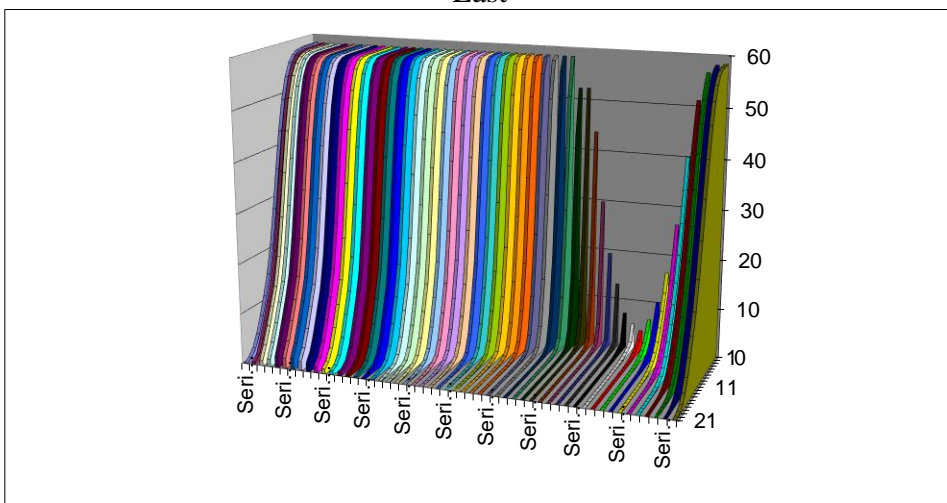
South-West



North

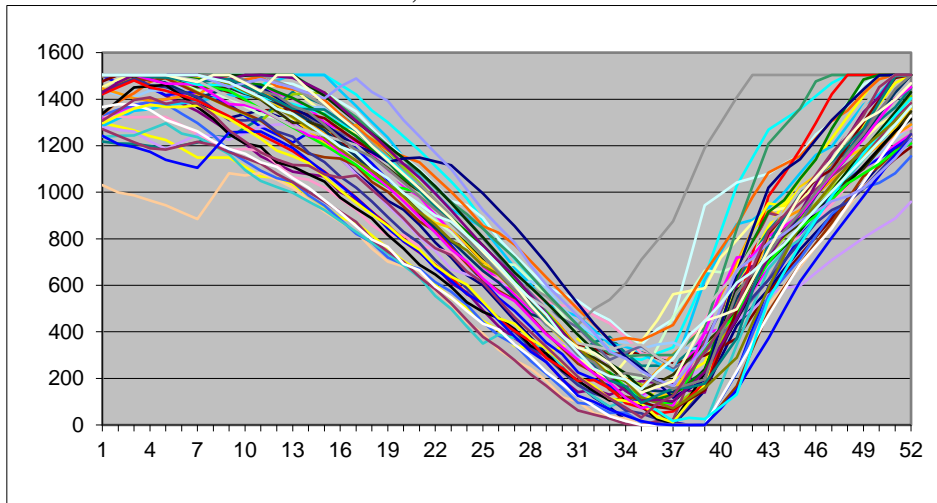


East

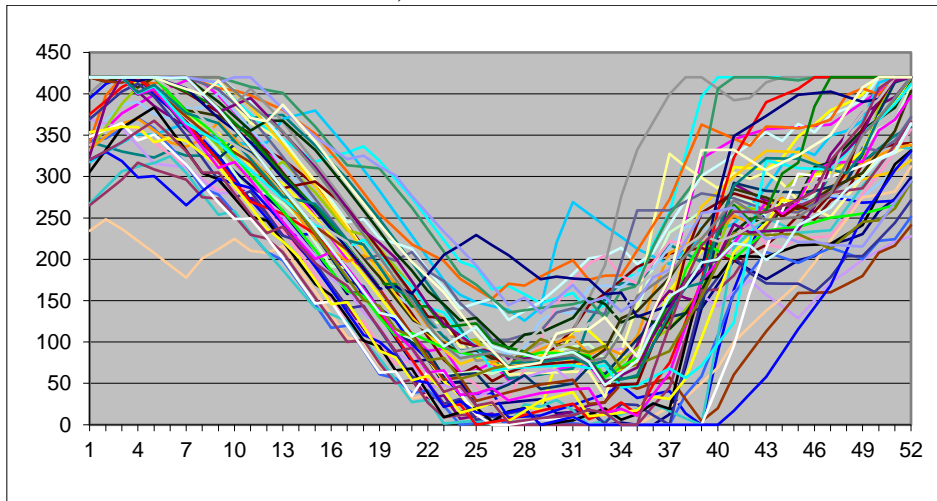


**Figure 6 Reservoir volume in GI**

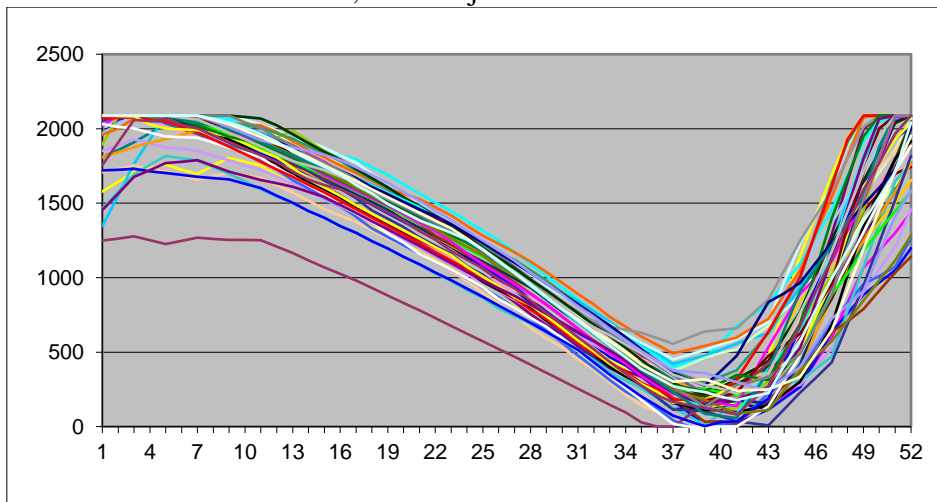
South-West, Thorisvatn reservoir



North, Blanda reservoir

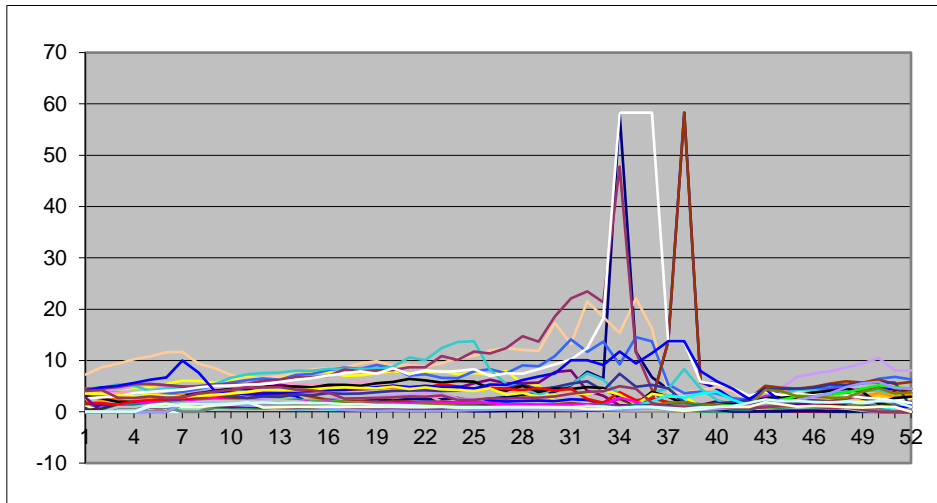


East, Karahnjukar reservoir

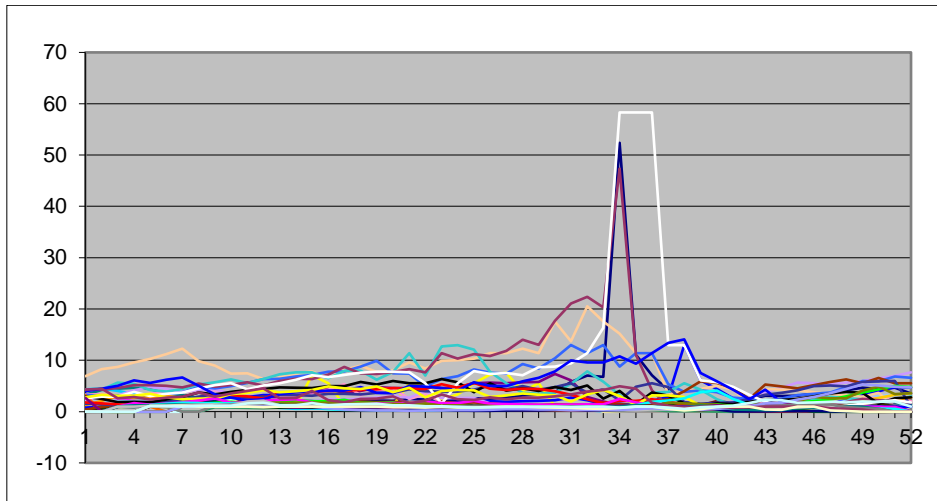


**Figure 7 Shadow prices in kr/kwh or Mkr/GWh**

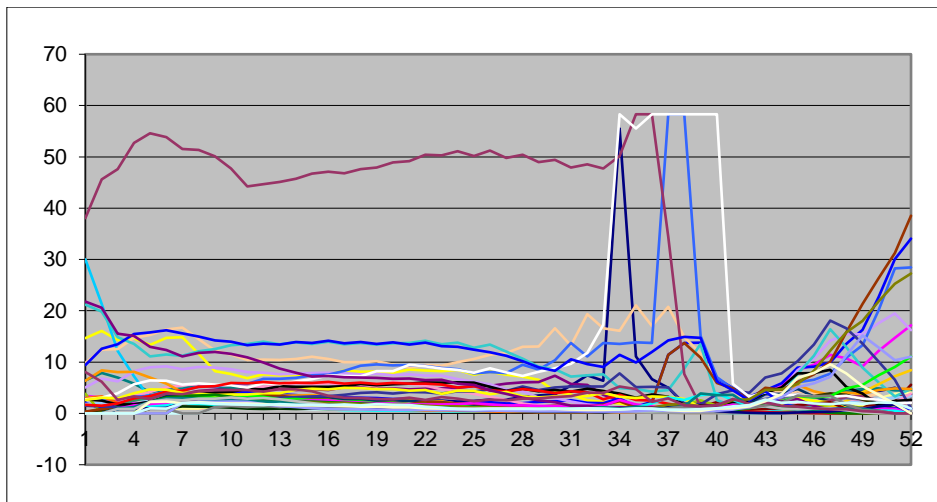
South-West



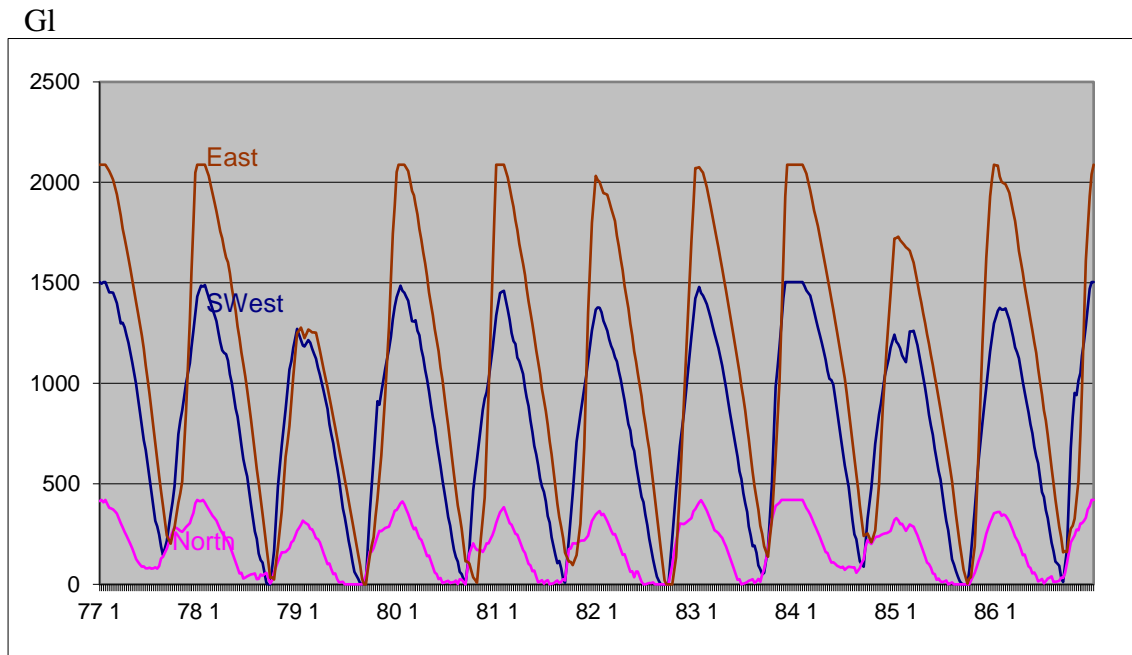
North



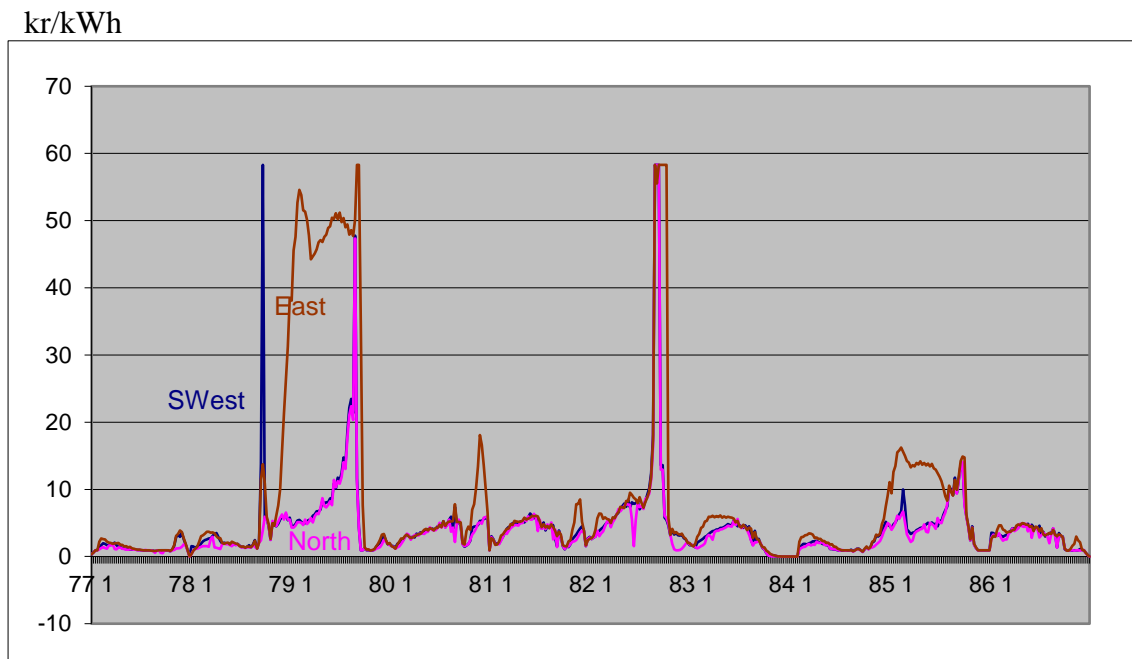
East



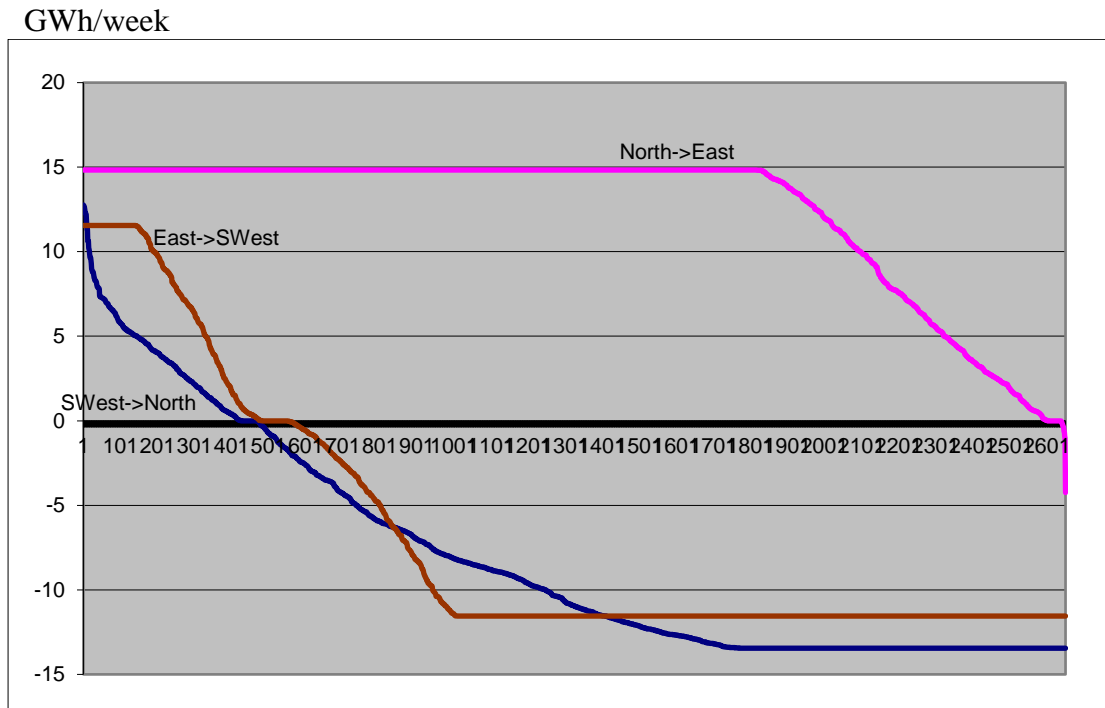
**Figure 8 Reservoir volume in GI for water years 1977-1986**



**Figure 9 Shadow market prices for water years 1977-1986**



**Figure 10 Transmission between subsystems. Duration curves.**



## Market power issues

In studying deregulation there always arises the question of what will be the result of proposed changes in law and regulation. Will the proposal lead to competition or oligopoly? If the latter, how can or should the market then be regulated?

In [2] it is assumed that energy production is divided between price makers with potential market power and price takers which do not have influence on the spot price but sell their power when spot price is higher than their variable operating cost.

The variable operating cost of the price makers is  $c(i)$ ,  $1, \dots, N$ .

In [2] the price takers are assumed to have quadratic production cost given by:

$$\delta(O) = O^2/2\alpha \quad (7)$$

where  $O$  is the production and  $\alpha$  a scalar parameter.

By differentiation we get the price taker production to be a linear function of the spot price  $p$ :

$$O(p) = \alpha p \quad (8)$$

The spot price can be related to the total price makers production Q:

$$p(Q) = (D-Q)/\alpha \quad (9)$$

where D is the total demand.

By using the Nash-Cournot equilibrium in [2] the total price makers energy production is given by:

$$Q = \frac{ND - \alpha \sum c(i)}{N+1} \quad (10)$$

Lets assume there are three main players (N = 3) on the Icelandic power market, one in each subsystem, and their variable cost of production c(i) is defined by the market shadow prices that have now been calculated by the simulation model.

One way to identify the price takers is to arrange all classes of interruptible power, thermal plants and penalty cost for shortage in increasing order by price and capacity and approximate it with a quadratic cost function . The result for whole of Iceland is a rough estimate of  $\alpha \cong 40$ .

Some values of  $\alpha$  around 40 where studied based on results from the simulation model. The price makers part of the total production is given by (10). The spot price was estimated by (9) and in table 3 it is shown as a percentage of the average market shadow price in a least cost solution of central dispatch. The table shows results for N = 3, N = 5 and N = 10 price makers.

**Table 3. Production and spot market price in Nash-Cournot equilibrium**

Number of price-makers	$\alpha$	price makers production as % of total demand	average spot price,as % of shadow price in least cost solution
3	10	68%	366%
3	20	61%	224%
3	30	53%	176%
3	40	46%	153%
3	50	39%	138%
5	10	79%	244%
5	20	74%	149%
5	30	69%	117%
5	40	64%	102%
5	50	59%	92%
10	10	88%	133%
10	20	86%	81%
10	30	83%	64%
10	40	81%	56%
10	50	78%	50%



We notice from table 3 that for  $N = 3$  and  $\alpha=40$  we get the average spot price as 1,53 times the average shadow price. At the same time the production level of the price makers is down to only 46% of the total demand which is inconceivable in the Icelandic market.

Table 3 shows that only three price makers competing in the market are too few to establish a real competition. The spot market tends to be all too high. The rule of thumb is that to create some kind of genuine competition there must be at least 5 equally sized price makers acting on the market which is more than the foreseeable number.

The National Power Company could eventually sell some of its power plants to investors or the aluminium industries could be allowed to become active players on the market by decreasing their production level in times of increasing demand and spot market price. Thereby enabling them to sell their buying rights to other agents in the market. Neither arrangement has yet been considered nor a plausible method to find the market value of each plant has been realized.

In Iceland long-term contracts with the heavy industries at a fixed price already make up a large proportion of energy transactions. If the heavy industries are allowed to sell parts of their power contracts on the market can this be regulated so that the resulting price distortions do not become intolerable to other players?

The Nash-Cournot competition model is based on the assumption that agents on the market will compete in quantities which is also the probable outcome after deregulation in Iceland. It can be argued that the large water reservoirs feeding downstream hydro plants play a significant role in that respect. The owners of the reservoirs have the possibility to regulate water use from the reservoirs in a different way than would be practiced by a central dispatch aiming at overall cost minimization. In that way situation of water shortage and therefore rise in energy prices could be easily manipulated by the reservoir owners. They also have the market power to offer very cheap energy on the market in times of water spillage to play the competition out of the market.

The only substantial owner of water reservoirs in Iceland today is the National Power Company, Landsvirkjun, and then they have the potential of becoming the sole price maker in the country. The question arises, what the terms are under which this can be allowed and still having some form of a competition on the power market.

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- [1] Mario Pereira, Nora Campodonico, Rafael Kelman: “Longterm Hydro Scheduling based on Stochastic Models” Power Systems Research Inc, PSRI Rio de Janeiro, Brazil.
- [2] Rafael Kelman, Luiz Augusto N. Barroso, Mario Veiga Pereira: “Market Power Assessment and Mitigation in Hydrothermal Systems”.
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