BOTTOM UP MODELLING OF AN INTEGRATED POWER MARKET WITH HYDRO RESERVOIRS

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ABSTRACT

The paper presents methodological reflections on bottom up modelling of an integrated power market. The geographical scope of the modelling is the Baltic Sea Region (BSR), i.e., of considerable extension. This paper will discuss the structure of sub periods and profiles of electricity and heat demands, which is appropriate for such model. Special emphasis will be devoted to methods for modification of the dispatch of electricity supply among the sub periods in order to reflect the operation of the pumped storage in Lithuania.

INTRODUCTION

In line with the increased liberalisation of the energy markets and the similarly increased attention on environmental aspects a number of recent studies - in particular the Baltic 21 Energy and Baltic Ring studies – have demonstrated the need for a model for the analysis of the electricity and CHP (combined heat and power) sector, covering all the countries around the Baltic Sea. Such model should be capable of providing assistance for policy analyses in a long-term international perspective.

A modelling project with this scope is presently being carried out with support from the Danish Energy Research Programme in co-operation between research institutions around the Baltic Sea. The new model, named Balmorel, simulates the production of electricity and CHP heat and investment decisions concerning building of new capacities of different technologies. The main period of the model is one year, which can be divided into a number of sub periods that are composed of seasons and hours, e.g. 2 seasons and 4 hour types.

As in any modelling project, a key consideration concerns the level of detail in the model. In one perspective it is desirable to include as much detail as available in the belief that this will give maximum accuracy of the model. In another perspective it is necessary to keep modelling at a more aggregated level due to limitations in data acquisition, simulation or solution capabilities, and in order to keep the model and the results reasonably transparent. In any case there is the problem of having a degree of detail that is even over the different aspects of the model in order to get a balanced representation.

In this perspective the present paper discusses the structure of sub periods and profiles of electricity and heat demands which are appropriate for a long-term model describing the development of national energy systems with cross-border trade and pumped storages. Special emphasis will be devoted to methods for modification of the distribution of electricity supply among the sub periods in order to reflect the operation of the pumped storage in Lithuania.

ECONOMICS OF STORAGE OPERATION

Energy storage is important for several reasons. The demand of heat and electricity vary considerably between seasons, weekdays and hours of the day. Thus, in a system consisting of units with slow power output regulating capacities (e.g. nuclear power plants) or very different marginal costs the balancing of production and demand may become difficult and/or expensive. Hence, storing the electrical energy may be an option. But energy storage is also important due to the increased application of renewable energy sources, of which several types have a very fluctuating power output (viz., wind turbines and solar power). Current technologies for storing electrical energy include batteries, kinetic energy storage, compressed air storage and hydro pumped storage plants (see e.g. Jensen and Sørensen 1984). This paper deals with the latter type and specifically with the Kruonis Hydro Pumped Storage Power Plant in Lithuania and how the operation of this plant could be modelled.

For the purpose of introducing the fundamentals of economics of power storage operation consider the following simple numerical example. For a 48-hour period the demand in each hour is known and given as in Figure 1 (a sine curve is used). The traditional load duration curve, where demands are sorted according to size, is shown as the decreasing curve in Figure 1. For comparison the actual electricity demand curve for Lithuania in 1999 and the corresponding duration curve are shown in Figures 2 and 3.

The economics of the operation of the storage will depend on the electricity production system in combination with the demand characteristics. Assuming that the production system has a cost function such that the marginal cost depends linearly on the production level, the marginal cost of production will have a shape like the demand curve in Figure 1 where also the corresponding marginal price duration curve is shown.

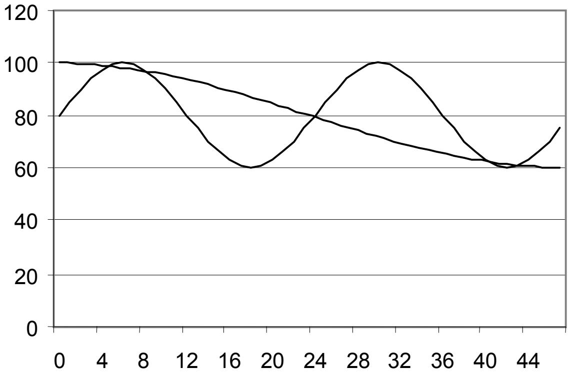

Figure 1: Sample demand curve and the corresponding duration curve (decreasing) in MWh/h.

It is easy to see that the optimal operation of a storage will imply that the storage is discharged during time periods when the marginal production costs (demand) are high, and charged during the periods when the marginal production costs (demand) are low.

Assume now that there is a storage with infinite capacity and no losses, neither due to the storage volume nor due to the charging or discharging of it. In this ideal case the use of the storage would imply a complete levelling over time of the production.

It is not difficult to realise that the following is the optimality condition for economic operation of the storage:

$$p_t^{in} = p_s^{out}, \forall t, \forall s \qquad (1)$$

where p_t^{in} is the marginal production cost in a time period t when the storage is charged, and p_s^{out} is the marginal production cost in a time period s when the storage is discharged. (It is here assumed for simplicity that the marginal costs constitute a continuum such that equality may actually be obtained.)

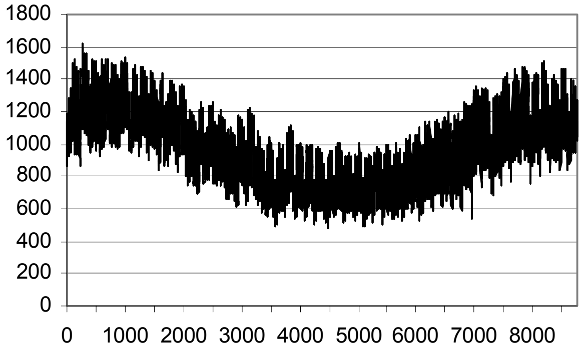

Figure 2: Lithuanian electricity demand curve for 1999 in MWh/h.

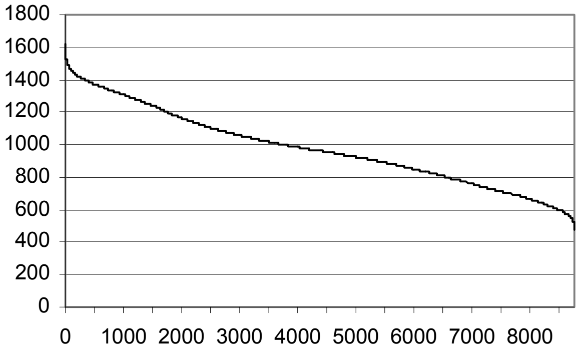

Figure 3: The duration curve corresponding to the curve in Figure 2 in MWh/h.

If there is a loss or a cost associated with the use of the storage then the application of the storage will be less extreme. In the case of a cost a, such that one unit of energy taken out of the storage must pay a cost of a, then the storage will only be used to level out marginal cost differences that are greater than a, such that the optimality condition in (1) is now modified to:

$$p_t^{in} = p_s^{out} - a, \forall t, \forall s \qquad (2)$$

Similarly, if there is a loss $b \in [0,1)$ such that energy taken out of the storage is only (1-b) times the energy put into the storage then the storage will only partially level out marginal cost differences and the optimality condition is now:

$$p_t^{in} = p_s^{out}(1-b), \forall t, \forall s \qquad (3)$$

Other storage losses or costs will not be considered within this context.

The consequences of a positive a are indicated on Figure 4 which shows the resulting cost duration curve relative to Figure 1 for a = 22. This is a typical illustration of the *peak shaving* of the marginal cost duration curve. The corresponding production pattern is shown in Figure 5 along with the storage contents assuming an initial and final storage contents of 50 MWh equivalents. A similar illustration could be made relative to a positive b.

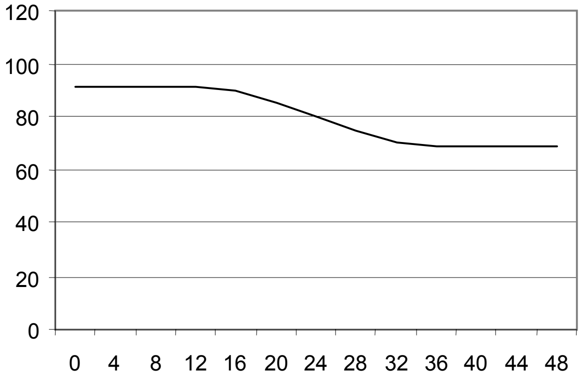

Figure 4: Marginal cost duration curve of a system with a pumped storage and a fixed cost (in USD/MWh).

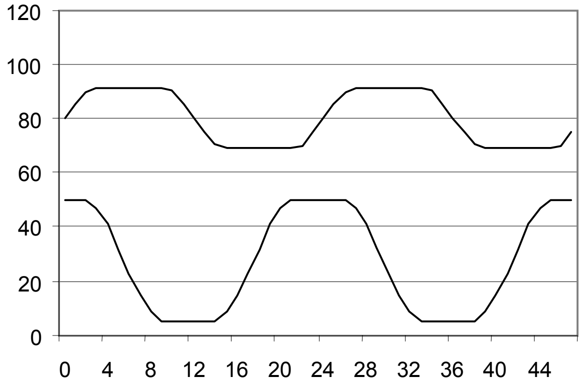

Figure 5: Production in MWh (upper graph) and pumped storage contents (lower graph) also in MWh, fixed cost case.

Finally consider a storage with a finite storage capacity $\bar{x}$. Further analysis would show that in this case it is not possible to use the load *duration curve* technique illustrated above, and in particular also the peak shaving principle is invalid. In order to analyse the optimal economic operation of the storage it is necessary to perform a *chronological* analysis because the sequence of the different loads are of importance, a fact which is not reflected in the duration curve techniques. When using a chronological approach, restrictions on pumping and generation capacities can easily be handled. In the sequel this will be illustrated by a case study in relation to the Balmorel model.

THE BALMOREL MODEL

The Balmorel model version 1.02 was used in the analyses. This version of the model has exogenously given demands for electricity and heat. It is a linear optimisation model written in the GAMS modelling language. The convex objective function used for the optimisation is cost minimisation for the whole Baltic Sea Region each year. It means that the model determines the minimal cost of production and new investments for each year given some constraints, which might concern the current production capacity, national or regional emission limits, etc. In this respect the model is a typical bottom up model. For a discussion of the top down and bottom up modelling approaches, see e.g. Wilson and Swisher (1993).

The optimisation period of the model is one year, which can be divided into a flexible number of sub periods (viz., seasons that are further subdivided into hours) making the model capable of handling seasonal and diurnal variations in the demand of electricity and heat. The model is described in detail in several documents, which are available at the homepage: www.balmorel.dk. The problem to be addressed is then how to represent the time structure in order to get a satisfactory basis for the analysis, which in this case is a pumped storage.

IMPLEMENTATION OF PUMPED STORAGE

The applied version of the Balmorel model does not represent energy storages directly, but has been modified to include such a unit, which in this case was the Kruonis hydro pumped storage plant situated in Lithuania (see data in Table 1).

Pumping capacity	4 x 220 MW
Generating capacity	4 x 200 MW
Cycle efficiency	0.72
Storage capacity	4300 MWh (to be 8700)
Inflow	No natural inflow
Outflow, loss	No
Annual fixed cost	31 Lt/kW ≈ 7.75 USD/kW
Variable O&M cost	0

Table 1: Data for the Kruonis Hydro Pumped Storage Plant used in the case study.

The geographical scope of the model was limited so that in most runs only Lithuania was included. The export from Lithuania was fixed to 250 MWh/h ≈ 2.2 TWh a year. Also a fixed production profile for the Ignalina nuclear power plant was used (approximating the actual production profile from 1999); thus, economic dispatch of this plant was excluded from the modelling. The model was solved for one year, thus excluding any investment possibility.

The cycle loss on the pumping operation was 28%, i.e. $b = 0.28$ in (3), and with no significant variable costs, $a = 0$ in (2). Restrictions on maximum energy level of the storage and the pumping and generating capacity were modelled.

To reflect the use of the storage for levelling out weekly and diurnal variations (as opposed to seasonal variations), a restriction was added so that the energy stored in the plant at the start of each season should be equal to that at the end of that season. The maximum error introduced by disregarding continuity in storage from one season to the next one equals the capacity of the storage times the number of seasons, which turns out to be small compared with the total use of the storage during the year.

Two types of modelling of the hydro energy balance in the pumped storage plant were used:

$$V_{t+1} = V_t + i_t - o_t, \forall t \qquad (4)$$

$$V_{lower} \le V_t \le V_{upper}, \forall t \qquad (5)$$

$$\sum_t i_t - o_t = 0 \qquad (6)$$

In (4)-(5), V_t is the energy contents of the storage at the beginning of period t, and V_{lower} and V_{upper} are the lower and upper limits of the storage, respectively. (In the model (4)-(5) initial and final conditions on the storage must be added, however, we will not discuss this here.) In (4) and (6), i_t is the energy put into the storage and o_t is the energy taken out of the storage during time period t. (6) is less accurate than (4)-(5) since it ignores storage limits. (6) is the basis for the duration techniques.

COMPUTATIONAL RESULTS

In the analyses several different time structures have been tried as listed in Table 2. The time structures were made from the hourly load profile of Lithuania in 1999. The 8760 time structure was this profile without any modifications while it in the 1095 time structure was divided into 8-hours steps (i.e. three each day) with the average load for that period. For the 4-168 and 4-24 scenarios, the year was split into four seasons each of three months' duration. For each season an average week and an average day was calculated. The average day profile for the summer and winter season was used for making the aggregated profiles 2-4 and 2-2 as indicated for the latter structure in Figure 6. Finally structure 1-1 with no subdivision of the year was tried.

Name	Description
8760	All 8760 hours of the year chronological
1095	The year divided into 8 hours step
4-168	4 seasons each of 168 time periods (representing an average 168 hour week)
4-24	4 seasons each of 24 time periods (representing an average 24 hours day)
2-4	2 seasons each of 4 time periods
2-2	2 seasons each of 2 time periods
1-1	No subdivision of the year

Table 2: The time structures used in the analyses.

The model was then solved both with the pumped storage plant included and excluded and with Lithuania as the only country. The results can be seen in Table 3.

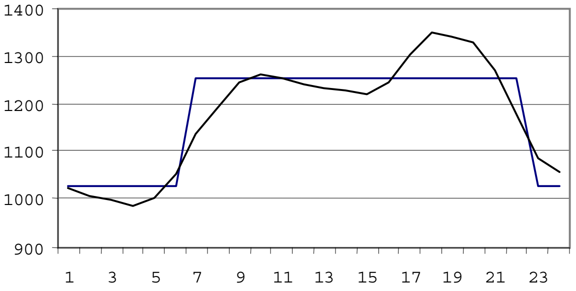

Figure 6: The demand profiles for a winter day in MWh/h for the 4-24 and the 2-2 time structures.

Time struct-ure	System costs, with storage (in MUSD)	System costs, without storage (in MUSD)	Generation from storage (in MWh)
8760	562.85	564.89	190878.11
1095	570.07	571.13	91572.48
4-168	551.83	553.23	168034.49
4-24	551.64	552.51	120595.02
2-4	546.75	546.88	63268.66
2-2	546.55	546.55	0.00
1-1	546.51	546.51	0.00

Table 3: Results for Lithuania.

For solving the model, CPLEX 6.5.2 was used on a Pentium III 500 MHz computer. Especially the 8760 hour scenario was large (the memory needed for generating the model was close to 200 MB), but nothing in the Balmorel model, GAMS nor CPLEX limited the level of detail. In Table 4 the computation time used for the different time structures can be seen. The time used by GAMS for generating the model is of the same order of magnitude as that used by CPLEX for solving the problem. It can be seen that the computation time is not very dependent on whether the storage is modelled or not. But it is observed that the model is somewhat smaller when the storage is excluded.

From Tables 3 and 4 it appears that the 1095 time structure is inferior to the others, since it both underestimates the use of the pumped storage and still takes longer time to solve than when using most other time structures.

From Table 3 it can be seen that the use of different time structures has little influence on the total system costs, viz., they are within the same 3 percent range. So when analysing the overall system the fineness of seasonal and diurnal variations does not need to be that high.

Time structure	Computation time, with storage (in secs.)	Computation time, without storage (in secs.)
8760	1004.75	841.95
1095	14.28	15.05
4-168	8.84	7.47
4-24	0.61	0.60
2-4	0.11	0.11
2-2	0.05	0.05
1-1	0.06	0.05

Table 4: Computation time used by CPLEX solving the model with, respectively without the storage.

However, the situation is different when the interest is on a particular detail in the model. Thus, costs for the 8760 hours case without storage are 564.89 MUSD (MUSD=10^6 US$), and thus the annual operational saving from the storage may be assessed to be approximately 2 MUSD based on the 8760 hours case. Since the storage is not used in the 2-2 and 1-1 cases these time structures implies vanishing savings. Note that the model may underestimate the use of the storage, since no start-up costs for the thermal power plants are included—neither are any restrictions on the regulating capabilities of these units.

Table 5 shows that when considering the energy storage, the level of fineness in the time structure need to be much higher in order to get reasonable results. This result is not surprising since the functioning of the storage precisely is linked to the variations over time.

Time structure	Difference in system costs (in MUSD)	% of the 8760 time structure value
8760	2.04	100
4-168	1.40	69
4-24	0.87	23
2-4	0.13	6
2-2	0.00	0
1-1	0.00	0

Table 5: Difference in system costs with and without storage for different time structures.

In Figure 7 the results from Table 3 and Table 5 have been combined graphically, such that the results from Table 5 are given by the left bars, and the similar percentage change of the system costs with storage (derived from Table 3) is given by the right bars.

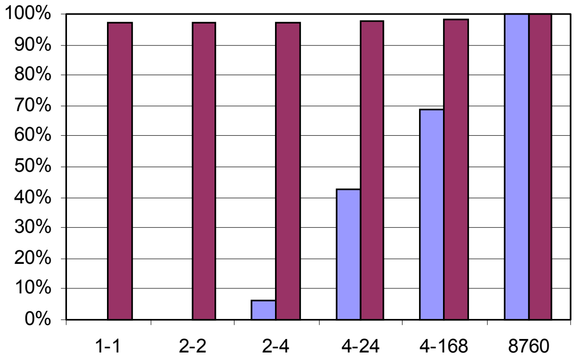

Figure 7: Precision of a total system analysis (right bar) and a specific technology analysis (left bar) for different time structures.

The Balmorel model can, among many things, be used for assessing the marginal production cost of electricity. In Figure 8 the marginal production costs for the 4-24 case are shown for Lithuania, both with and without the storage. It is seen that the storage is able to 'buy' electricity at night at a price 28 percent lower than the price to which it can sell the generated power during peak hours. It is seen that the storage capacity is not used fully, since the marginal cost difference in that case would have been higher in some hours. Figure 8 also indicates that a storage can take over production from typical peak units (usually condensing oil or gas fuelled power plants). This will influence fuel usage and thus also emissions (CO_2, SO_2, and others).

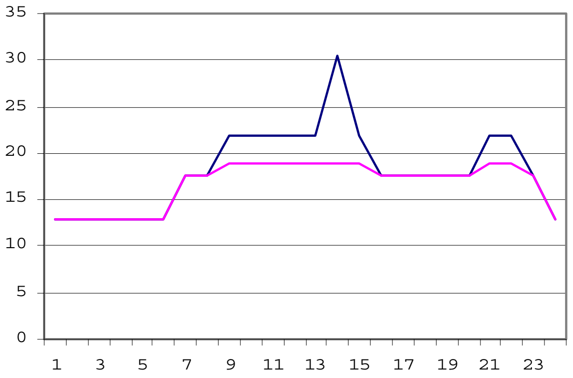

Figure 8: The Lithuanian marginal production cost in US$/MWh an average winter day with (lower graph) respective without (upper) storage.

It was tried to use the 4-168 time structure in the Balmorel model including Estonia, Latvia, and the Russian region Kaliningrad in addition to Lithuania. A result was an increase in computation time from 8.84 seconds to 140.01 seconds. In this scenario the storage was used for storing less than 1100 MWh electricity for the whole year. A reason for this is that Latvian hydropower, with a capacity of 1500 MW, can level out the market price to such a degree that the price difference only on few occasions was bigger than the pumped storage loss.

So if no bottlenecks occur in the transmission network, a pumped storage is not expected to be used much in such a power market with extensive hydro reservoirs.

In other systems this need not hold true. Thus, considering the Nordic power exchange, Nord Pool, fluctuations in prices of more than 28% may be observed, even though large hydro power capacities exist in this area. In Figure 9 the Nord Pool spot system price of electricity in EUR/MWh in week 22 of 2000 is shown. It can be seen that the price varies more than 28% during most days, which should make the Kruonis hydro pumped storage advantageous if integrated into this system.

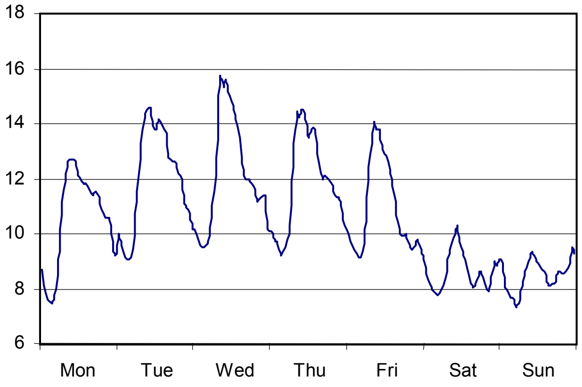

Figure 9: The Nord Pool spot system price in EUR/MWh in week 22, 2000. (Nord Pool)

Of all the scenarios the storage capacity of 4300 MWh equivalents were only used fully in the 8760 and the 4-168 scenarios. So for the more aggregated time structures no large error will be made by assuming infinite capacity (V_{upper} in (5)) of the pumped storage. This allows the use of the duration curve peak shaving technique for these time structures, i.e. modelling the hydro storage using (6) rather than (4)-(5). This hypothesis was confirmed in the sense that the total costs and the use of the storage were close between models (6) and (4)-(5). However, it was observed in all the cases compared, that the computation time was higher with (6) than with (4)-(5), and since the formulation (4)-(5) is the more theoretically satisfactory there seems to be no need to prefer (6) to (4)-(5).

CONCLUSIONS

The paper has analysed the modelling and functioning of a hydro pumped storage unit. As overture the functioning of a hydro pumped storage in the electrical system was considered with emphasis on the illustration of the peak shaving mechanism of the storage. In particular this was related to the duration curve technique, which is illustrative and intuitively appealing for simple analyses. However, the duration curve technique neglects the chronological nature of the storage problem and thus is an approximation.

It is clear from the presentation of the computation time that the fine time structure within the year has a significant influence on this. The temptation is clearly to use a coarse subdivision of the year (in particular when analysing a larger geographical area as illustrated), this must in any particular case be balanced against the accuracy of the results, as just discussed. – Two representations of the storage have been analysed, and it appears that the more theoretically satisfactory one is, luckily, the less computationally demanding.

As the goal of the work is the modelling of the CHP sector in a large geographical area, attention has been devoted to the trade off between accuracy of results and computation time. Here it may be concluded from Table 3 that the aggregation of time has little (viz., less than 3%) influence on the total costs of the Lithuanian system.

On the other hand, if the economy of the storage alone is considered, then the 8760 hours case implies a positive saving while the 2-2 and 1-1 cases imply no savings. Hence, apparently the time structure must be finer for the analysis of individual plants than for the analysis of costs for the whole system. Moreover, as Table 5 shows, it is necessary with a quite fine time structure in order to approach the 8760 hours accuracy. Also with respect to representing the functioning of the storage a fine time structure is necessary, cf. the last column of Table 3, although this is not as outspoken as for the costs.

The contrast between the conclusions for the total systems cost and for the cost relative to the individual technology is clearly exposed in Figure 7. The appropriate time structure therefore depends on the specific purpose of the study in question.

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