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Bottom up modelling of an integrated power market

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1. Introduction

The present paper presents some reflections on bottom up modelling of an integrated power market. The scope of the modelling is the Baltic Sea area, where in a number of recent studies – in particular the Baltic 21 Energy and Baltic Ring studies - it has been expressed that a model for the analysis of CHP covering all the countries around the Baltic Sea is desirable. Such model should be a long-term model capable of providing assistance for policy analyses.

The work is carried out as a part of the EFP99 – Baltic Model project (from now on named Balmorel)[1], where the objective is to develop a model, including the relevant data set to be used as analysis tool in the region. This project is carried out in co-operation between research institutions around the Baltic Sea.

The Balmorel model is at the present state a demand driven model, though it is the ultimate goal to produce a partial equilibrium model. The model time scope is from 1995 to 2030. The model optimises the production of electricity and CHP heat and simulates investment decisions concerning building of new capacity of different technologies, if it a year becomes economically profitable or necessary for reasons of capacity.

In the present paper we describe the modelling, and present preliminary examples of analysis carried out using the model.

The paper is organised as follows. First we give some general observations on the bottom up modelling tradition and the pro's and con's of this, relative to the objectives of the project. Then in Section 3 we give an overview of the model, more or less describing the present state of development. In Section 4 we illustrate in the form of a case study the effects of varying the basic time step. Finally, Section 5 presents some general conclusions and some perspectives for the further work with the model.

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2. Some considerations on model details

The design of a model involves the determination of how much detail it should contain. The obvious temptation in any model work is to include too much detail, from the belief that omission of detail implies less accuracy, and therefore a ‘not so good’ model. This is based on a simplistic view on a model, cf. the end of this section.

In this section we briefly list some of the issues in the determination of the appropriate detail, in particular in relation to the Balmorel model.

Time structure

For a model that shall reflect the longer term development it will be quite natural to present results for annual values, say, over the period 1995 - 2030. However, this does not mean that the model in its internal mechanisms does not take into account, that the individual year is constituted of months, weeks, days, etc. that are not identical. To the contrary, some models of relevance for the electricity sector operate on basic time scales that are hours, minutes, seconds, or even fractions of seconds.

In particular, we focus on the time steps used in the model. This issue is motivated as follows. Some models use one year as the basic time step, however, in order to be able to analyse the effects of seasonal and daily variations in demand, wind power production etc., the Balmorel model can use smaller time steps than a year. This may be important for numerous reasons, for instance to get a better view on the actual transmission during a year. Consider Figure 1 where monthly values of transmission are shown. The 1998 net value of transmission is close to zero; however, as seen a transmission capacity of at least 700 MW is necessary in order to accommodate the actually observed transmission without bottleneck effects. Using a basic time unit shorter than one month might further increase the minimum transmission capacity required.

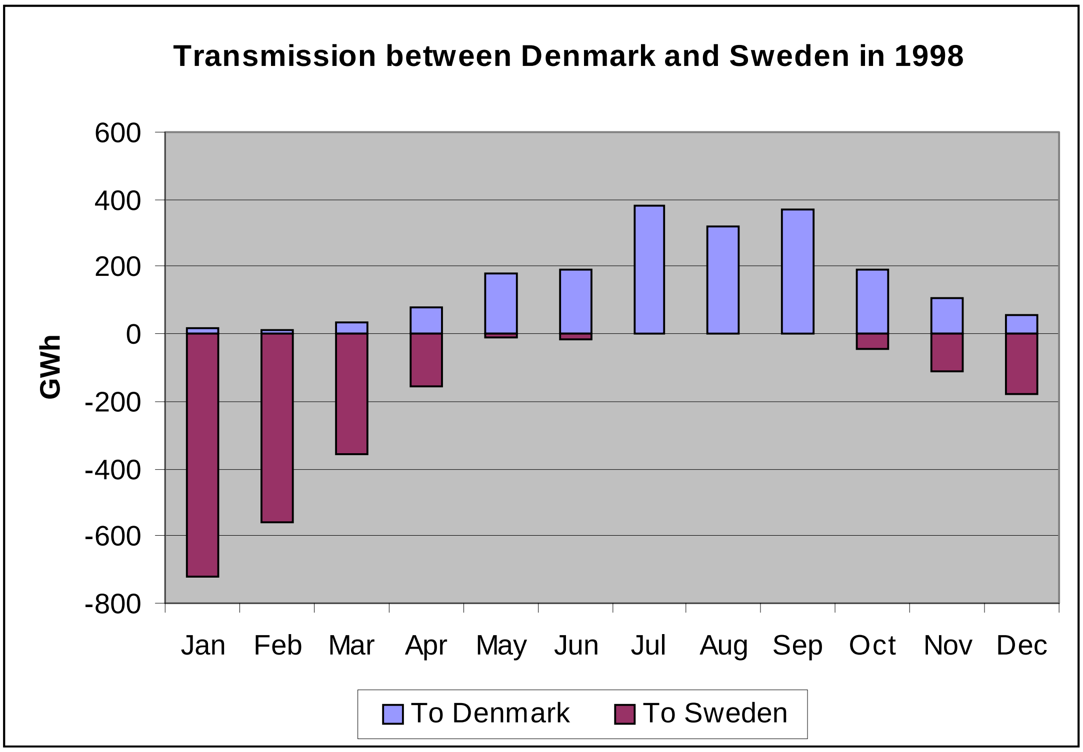

Figure 1 – Transmission between Denmark and Sweden (from Nordel Annual Report 1998)

The dissolution of the time axis within the year must be adapted to the purpose of the modelling. Speaking of longer term models, as those in focus here, there are a number of reasons why the year should be divided into subperiod, e.g.:

- Differentiation between units: base load, peak load, etc.
- Differentiation between fuels (partly in consequence of the difference between unit)
- Better reflection of the interdependencies between heat and power in CHP modelling
- Reflect applications of storages on scales less than one year (hydro, heat)
- Reflect natural production patterns of unregulated technologies (wind, solar)

Apart from the question of how many subperiods to have within the year is the question of how the subperiods are linked. If there are no linkages, then the load duration curve technique seems adequate. Otherwise, e.g. in case of energy storages or annual emission quota, more elaborate details are necessary, implying considerations on chronological models, feedback structures, delays etc.

In Section 4 we shall by example illustrate the importance of the subdivision of the year.

Geographical structure

The geographical area for the model is initially given as the Baltic Sea area. Hence, the model has as a natural subdivision the countries in the regions, i.e., ten countries. The subdivision into countries is necessary since many questions of interest in relation to the present hot policy issues are related to the national level – national regulations, emissions policies, etc. Moreover, many of the input data are national in their character – relative to historically given supply systems, ways of organising the energy sector, cost levels, taxation, and other aspects.

However, a finer subdivision may be appropriate for some purposes. Thus, seen from the electricity supply system it may be inappropriate to consider a country as a homogeneous area. In particular this holds true, if a country is geographically or electrically separated, as is the case with Russia/Kaliningrad region and Western/Eastern Denmark, respectively.

Also, the heat supply system may motivate a subdivision, viz., in the case where there are large district heating areas, such that a dispatch of the heat supply between the production units is of relevance.

The appropriate balance will have to be determined in accordance with the objectives of the study, the availability of data and the model solution capabilities, among other things, such that no clear preference is possible.

Deterministic versus stochastic models

Most models for long time analysis are deterministic in their construction. To the extent that the future is uncertain, various scenarios may be simulated, but for each scenario the model will typically be deterministic.

However, there are a number of reasons why the stochastics should be more systematically considered in modelling. Thus, in the Baltic Sea region, the hydropower is of significant importance for the power sector. However, the variations between the years of the hydropower potential are considerable. These variations explain part of the structural characteristics, e.g.:

- Variations of annual net exchange of power between e.g. Norway and Denmark
- Existence of certain technologies (e.g., peak and reserve units, electric boilers)
- Price differences between years

Data acquisition

Allowing more detail in the model structure implies the need for more data. Some issues here are:

- What is possible?
- Should there be consensus on the data?
- Confidentiality?
- Maintenance?

The Bottom Up/Top Down perspectives

One of the present tendencies in the approaches towards modelling in relation to the energy sector is that the traditional distinctions, cf. Table 1, between bottom up and top down models become less clear. A number of models that integrate these two perspectives have now appeared and demonstrated that the approaches are not absolute alternatives.

	(Early) Bottom Up	**(Early) Top Down**
Endogenisation of behaviour	Low	High
Details on non-energy sectors	Low	High
Details on energy end-uses	High	Low
Details on energy supply technologies	High	Low
Orientation towards prediction	Low	High

Table 1 - Traditional distinctions between Bottom Up and Top Down Approaches in relation to the energy sector

The Balmorel model in its present stage is a bottom up model, emphasising production technologies, optimal distribution between production units to satisfy given demands, etc. It is quite obvious that it will be possible to add a considerable amount of detail to such model, precisely because the modelling, according to the conventional philosophy of the bottom up approach indicated in Table 1, emphasises e.g. production technologies, where an abundance of detailed information of physical and technical nature is available.

The question is how to match the levels of detail of the bottom up aspects to those of the top down aspects. One element of this is the attainment of a balanced model, i.e. an evaluation issue, another is whether it is at all possible to integrate the two perspectives, irrespective of the level of details on the bottom up side. A specific example in relation to the time structure will be indicated in Section 5.

Summarising

With more details in the model is seems obvious that more questions can be meaningfully answered by the model. However, we do not believe that more details necessarily gives a more ‘correct’ model (whatever this might mean), and we do not believe that it gives necessarily a ‘better’ model either (again, whatever this might mean). And definitely there are a number of drawbacks associated with a detailed model. Thus, it is

- More difficult to establish
- More difficult to verify
- More difficult to manipulate (simulate, solve)
- More difficult to maintain
- More difficult to modify
- More difficult to understand
- More difficult to interpret
- More difficult to communicate

Presently, we do not know where the balance for the Balmorel model lies. In Section 4 we illustrate one element of this, viz., with respect to the division of the year into subperiods.

3. Balmorel Model overview

The model built until now is, according to the above classification, a bottom-up model with most emphasis on the modelling of the production technologies, on electricity and heat balance equations between demand and production (for electricity also for transmission) and on dynamics in relation to capacity investment and depreciation. The model is a linear optimisation model.

Modelling tool

The model is built using the GAMS modelling language.

Variables

The model is solved for each year in the period 1995-2030 and the optimal values for the decision variables listed below are found:

- Production of electricity in each sub-period of each technology type in each country
- Production of heat in each sub-period of each technology type in each country
- New production capacity built of each technology type in each country
- Transmission between all pairs of countries in each sub-period
- New transmission capacity built between each pair of countries

As a consequence of the values of the variables found, other relevant characteristics may be identified, e.g.,

- CO2 emission per country
- Demand for investments per country
- Consumption of various fuels per country

Also several of the dual variables connected to the restrictions are of great interest, e.g.:

- The marginal production cost of electricity (from the electricity balance constraint)
- The marginal production cost of heat (from the heat balance constraint)
- The shadowprice of CO_2 emission (from the emission level constraint)

Objective function

The objective function used for the optimisation is cost minimisation for the whole region each year. That is, for each year the model determines the minimal cost of production and new investments given some constraints, which might concern the current production capacity, national or regional emission limits, etc. The production costs include fuel costs, operation and maintenance costs, as well as taxes on production and emission. The types of constraints in the model can be seen in Figure 2, which gives an overview of the model with emphasis on the constraints.

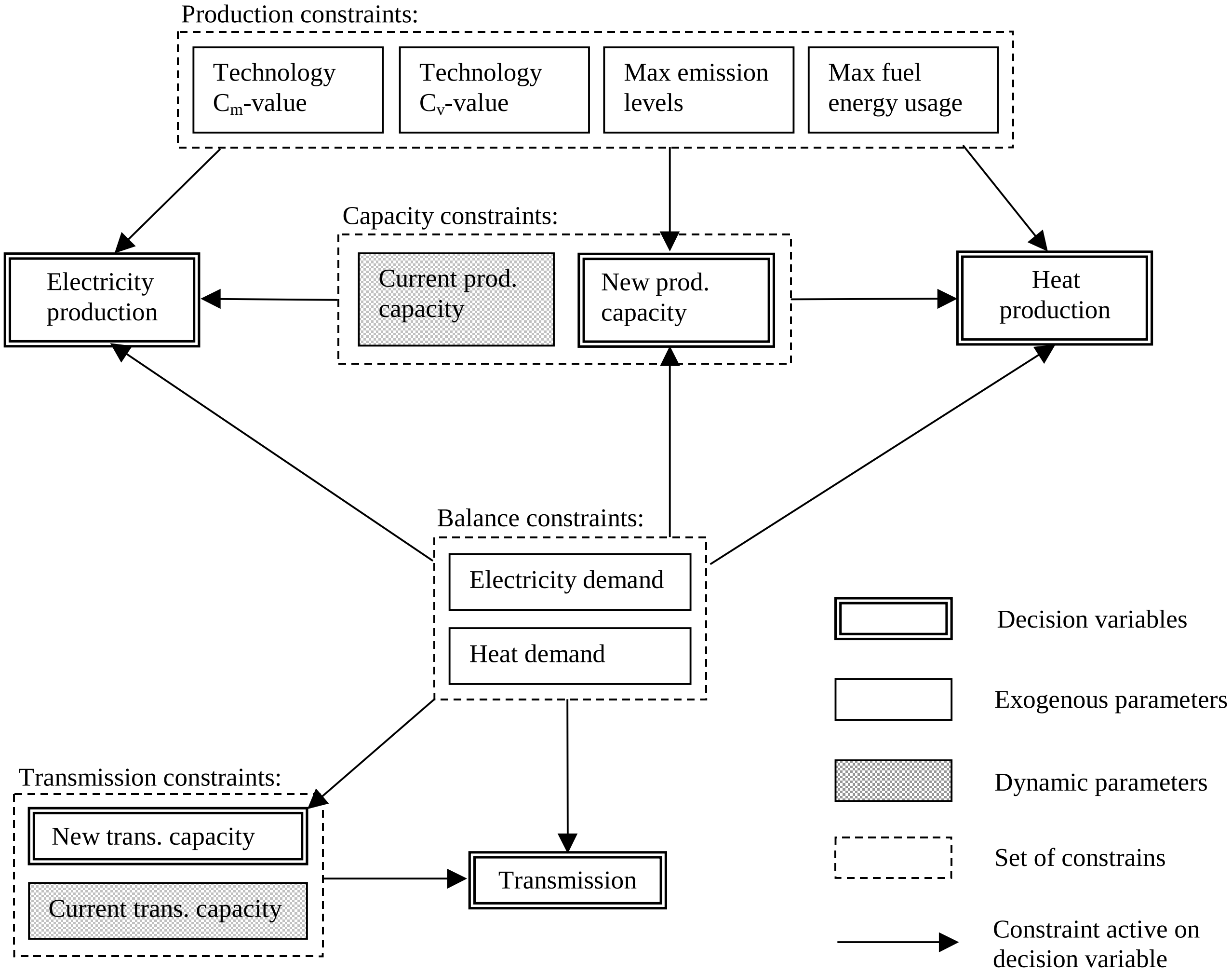

Figure 2 – An overview of the model

Dynamics

The dynamic parameters are in Figure 2 represented by the grey boxes. They are exogenously given for the start year. For the following years they are found as:

Production capacity: $p\_cap_{t+1} = p\_cap_t + new\_cap_t - decommis_t$

Transmission capacity: $t\_cap_{t+1} = t\_cap_t + new\_cap_t$

While the transmission capacity is given for each pair of countries, the production capacity is given for each technology type in each country. Decommissioning of the production capacity of each of the technologies in the start year is exogenously given (e.g., as a constant rate of decommissioning such that the last part of the initial capacity is phased out in a given year, e.g. year 2020).

Decisions on investment in new capacities (production and transmission) are taken on the basis of the information available during the 'present' year of simulation. Thus, the investment cost for a capacity of, say 1 MW, is represented by the annuity of this cost, assuming a particular life time and interest rate (e.g. 20 years and 5% p.a.). This cost is considered during the simulated year, together with the cost of operation of the new capacity, and the size of the investment is then determined as that one which minimises total costs this year.

The quantities of new capacities are selected from a continuous range. Hence, the modelling disregards that production plants have some typical 'minimal', 'maximal' or 'relevant' magnitudes. This is done for reasons of efficiency in the model solution phase, and is consistent with the considerations below on representation of technologies.

Technologies

The model works with national capacities of each of the implemented technologies. I.e. the model includes no information about single plants but looks at all similar plants as if it were one big unit (a consequence of the above described assumption of continuity of the decision variables for capacity sizes). Otherwise the model would no longer be a convex model – but a much harder to solve (and analyse) mixed integer problem.

In the model the technologies are divided into five different technology types as listed below:

- Pure electricity (includes thermal condensing, hydro, wind, photo-voltaic)
- Back pressure (CHP – fixed electricity/heat ratio)
- Extraction (CHP – variable electricity/heat ratio)
- Pure heat (boilers, solar heat, geothermal)
- Heat pumps (electric heat production, i.e. electric boilers or heat pumps)

Several production technologies of each type are defined; they differ with respect to efficiencies, what fuel they use, or otherwise. Each of the technologies is described by:

- Production areas (i.e. C_m and C_v – values for CHP plants)
- Fuel type used
- Efficiencies
- Emission of NO_x
- Emission reduction (de-sulphuring, de-NO_x)
- Investment costs
- Operations and maintenance costs

CO_2 emission are derived from the amount and type of fuel used. SO_2 emissions are, unlike that of calculated from the amount of each fueltype used on each particula type of unit. NO_x is calculated form the amout of fuel used at each particular type of unit.

Data

The current data set is based on the one from the Baltic 21 Energy study (originally from 1995 but it is being updated to 1997 data presently). A few extensions to this data set have been made – mainly concerning the transmission system.

4. Case analyses

In this paper we will present some analyses made using the Balmorel model focusing on the effects on overall cost, investments and fuel use, of changing the scale of the basic time unit. In particular, going from yearly values to subperiods within a year.

We emphasise that since the model is presently in an early verification phase, the results presented here may be taken only for their methodological implications, in particular concerning the directions of change of the indicators presented. Hence, nothing can be inferred from the absolute magnitude of those indicators – simply because the model is not presently fit for providing such magnitudes.

In the scenarios we have in general used the same assumptions as in the *Baltic 21 – Energy* report, e.g.:

- Simulation period is 1995 to 2030
- Initial production capacities in countries
- Growth in consumption and fuel prices
- Water inflow to hydro reservoirs.
- Decommissioning of initial production capacities using a linear function. The last parts are decommissioned in 2020
- Nuclear power is phased out in the period

The initial transmission capacities between countries and the cost of building new capacity are not included in the *Baltic 21 – Energy* report and have been assessed from data from UCPTE and Nordel.

Five different scenarios used in this paper, one using yearly values the others having split the year into 2-8 subperiods. The profiles for electricity and heat demand for these scenarios are covered in appendix A. No taxation of any kind was used in the calculations.

Total costs

The total system costs, which include all production costs and investment costs in the whole period, are shown in Figure 3.

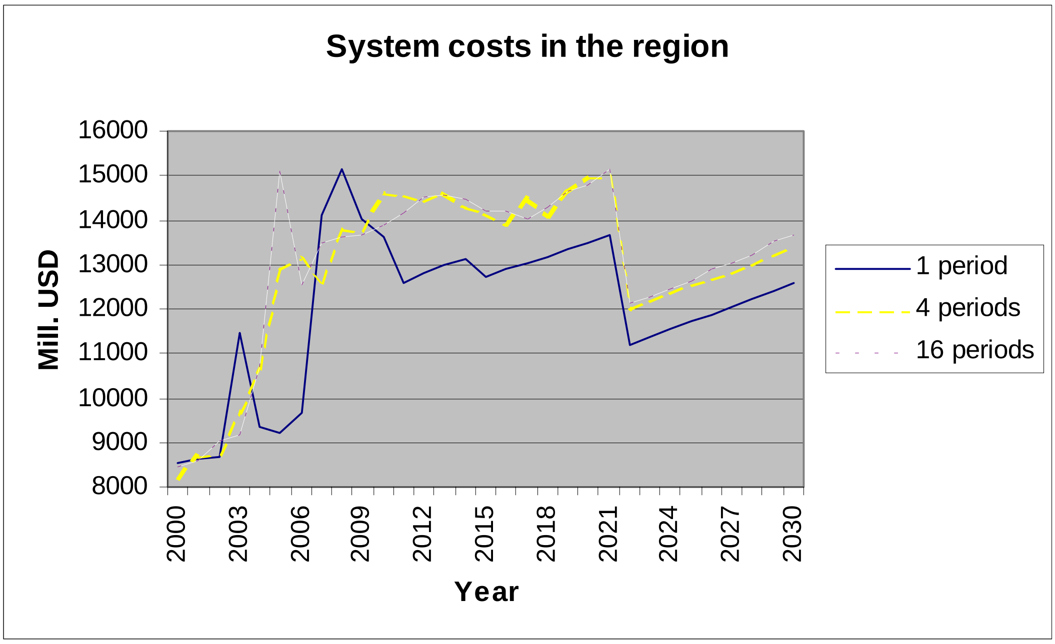

Figure 3 – System cost for each year in the period for different scenarios

We can see an increased cost due to the additional new capacity, which in this model is needed from 2003-2005 due to the decommissioning of older unit. It ends up in 2030 with almost a 10% difference in the yearly system costs between using 1 and 16 periods, while the difference the first years is much smaller. If we sum the costs of the whole period we get the numbers in Table 2.

Scenario	**1 period**	**2 periods**	**4 periods**	**8 periods**	**16 periods**
System cost (in mill US$)	373263	395661	399789	401162	402906
Index (1 period = 100)	100.00	106.00	107.11	107.47	107.94

Table 2 – the total system costs in the 1995-2030 period

We see that by using 1 period the total costs would be underestimated with about 8% compared to what is needed for handling variations in the demand. To this comes other contributions due to the need of absolute peak load capacity and reserve capacity requirements, which has not been included in this analysis.

Investments

As seen in Table 3 the trend is that more technologies are introduced as the number of subperiods is increased. Also the need for installed capacity is considerably higher for more than one period. The additional capacity introduced is for 4 or more periods almost 50% higher, a huge number, which though, as it can be seen in Table 3, does not affect the total system costs with more than 7-8%.

Production tech.	**Type**	**Fuel**	**1 period**	**2 periods**	**4 periods**	**8 periods**	**16 periods**
CC-Co-B15	Cond	Gas	0	0	0	150.64	1302.15
ST-Cond1-C	Cond	Coal	8681.06	120.28	94.77	0	0
ST-Co-C-B15	Cond	Coal	0	900.73	1028.18	101.06	307.96
ST-CHP1-C	CHP	Coal	21321.96	27739.09	29640.61	30168.48	30374.91
ST-CHP1-B	CHP	Biomass	360.03	0	0	0	0
ST-CHP1-P	CHP	Peat	7960	7148	6932.86	6883.38	6446.99
CC-CHP-B15	CHP	Gas	0	217.47	12074.44	10109.14	9446.79
ST-CHP-C-B15	CHP	Coal	0	2324.39	141.35	1611.7	423.53
De-CHP-W-B95	CHP	Waste	666.35	516.35	308.17	716.35	616.35
GM-CHP-B15	CHP	Gas	27153.22	26819.88	22780.14	22550.99	23505.54
HO-C-New	HO	Coal	9736.72	36566.18	36771.81	38109.55	37021.88
HO-B-New	HO	Biomass	7445.12	19498.4	21791.75	20811.69	20709.33
HO-W-New	HO	Waste	9280.77	8015.44	5477.41	4376.88	5684.69
HO-W-Old	HO	Waste	2152.88	3568.22	6314.42	7006.78	5798.96
HO-P-Old	HO	Peat	0	812	1027.14	1076.62	1513.01
HYDRO	Hydro	Water	4832	4862	4862	4862	4862
New production capacity			99590.11	139108.43	149245.05	148535.26	148014.09
Index (1period = 100)			100.00	139.68	149.86	149.15	148.62

Table 3 – Investments (MW) in new production capacities by technologies, 1995-2030

We see that the more periods the more need for investments in CHP and HOB (heat-only boilers), the latter being used as “cheap” peak load units for the heat demand while CHP is chosen for its flexibility. The usefulness of condensing plants though is less in scenarios with many subperiods. Note that the requirements for new capacity are higher for 4 periods than for 16.

If we look at the need for new transmission capacity, the picture is the same. In Table 4 we see the same underestimation of up to 33% of the needed capacity.

	1 period	**4 periods**	**16 periods**
New transmission capacity	9717.8	14643.5	14075.7
Index (1 period = 100)	100.00	150.69	144.84

Table 4 – Investments (MW) in new transmission capacities, 1995-2030

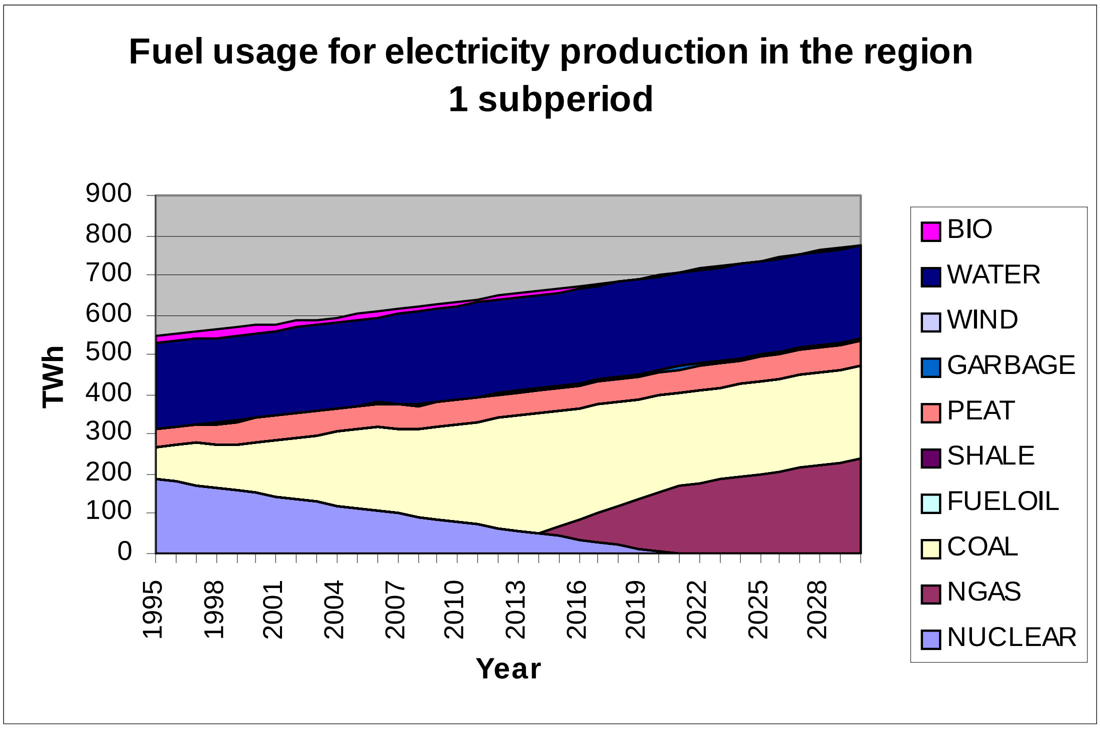

Figure 4 - Fuels used for electricity production – 1 period

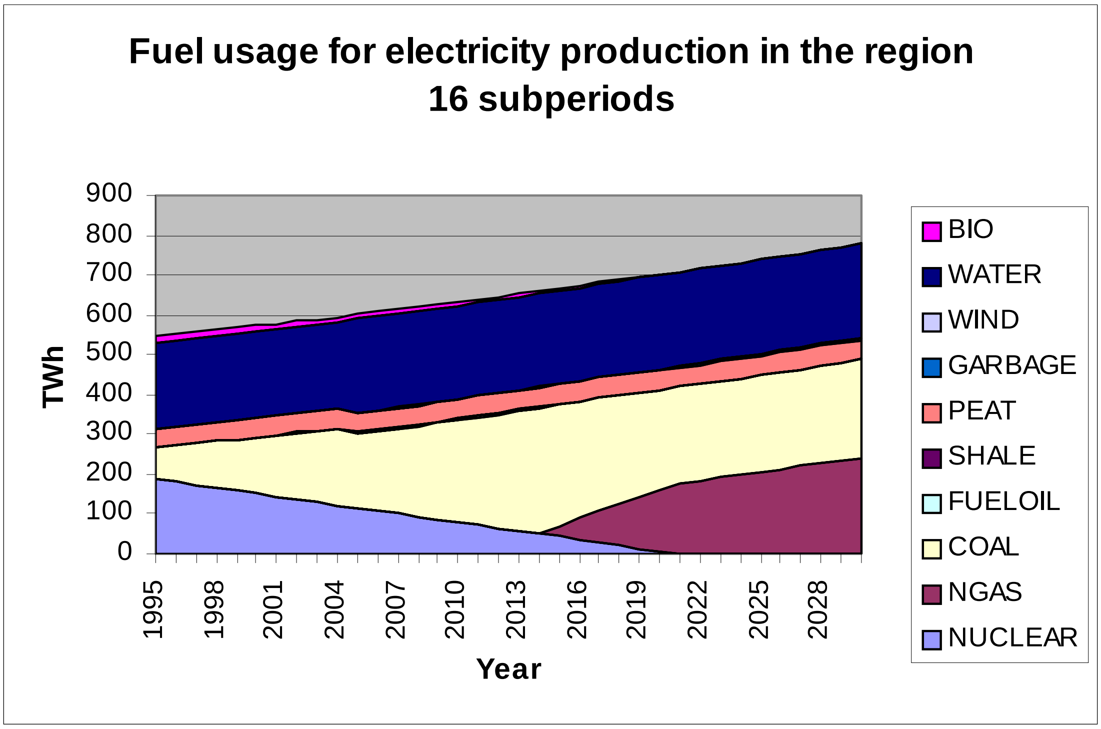

Figure 5 - Fuels used for electricity production – 16 periods

Fuels

We see from figures 4 and 5 that no big changes in the choice of fuel are made though a few more fuels (shale and fuel oil) are used for the 16 subperiods scenario. This shows that the diversity of fuels used in the solution (i.e. the number of non-zeroes) tends to be bigger when more periods are modelled. This corresponds to what was observed in relation to the investments in the production technologies.

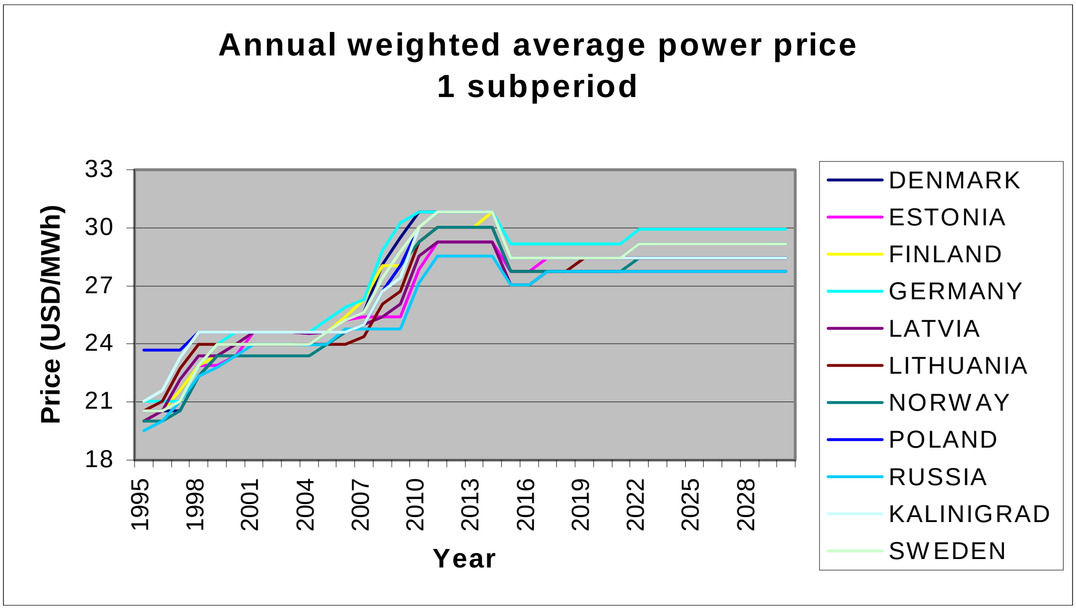

Figure 6 – The development in the electricity price for 1 period

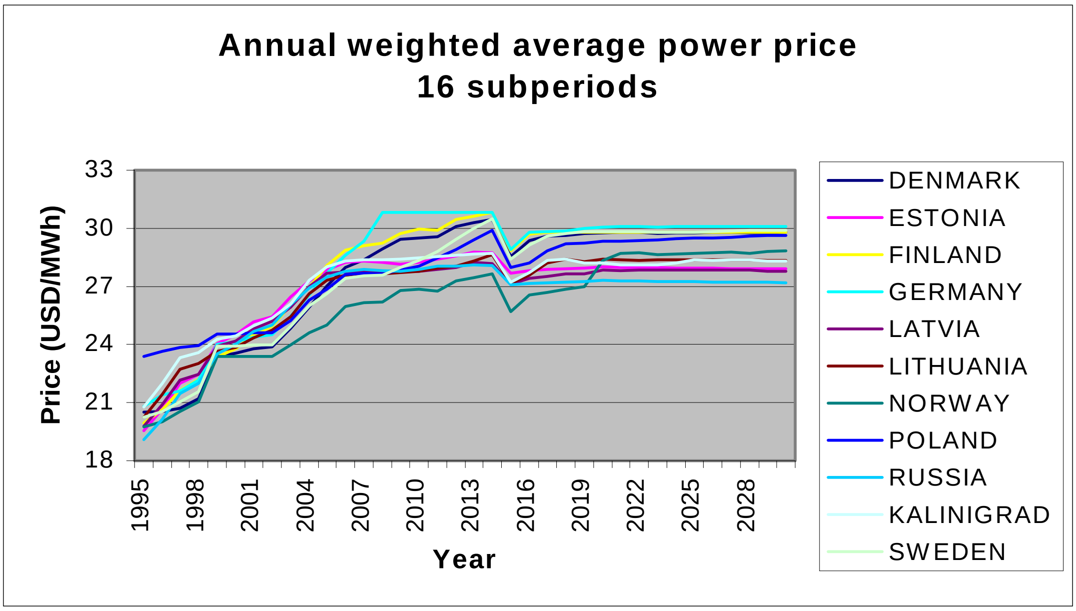

Figure 7 – The development in the electricity price for 16 periods

Electricity prices

From figures 6 and 7 it is observed that electricity prices are more differentiated between the countries in the 16 periods simulation, and display a more diversified development pattern. The dependence of the magnitude of the prices on the number of subperiods is not very large, a conclusion which is in line with what has previously been observed, cf. Table 2.

5. Conclusions

We have presented some reflections and illustrations in relation to bottom up modelling of an integrated power market around the Baltic Sea. The illustrations have been centred on the issue of the time scale – in particular, the number of subperiods - used for modelling the activities within the year.

Since the model is still in an early verification phase, it is not possible to interpret meaningfully the absolute magnitudes in the tables and figures presented in Section 4. However, direction of changes, as the number of subperiods is changed, are believed to have validity.

The following observations have been made:

- The costs in the model increases with increasing number of subperiods.
- The diversification of production technologies applied increases with increasing number of subperiods.
- To the extent that there is an association between technologies and fuels, the diversification of fuels applied increases with increasing number of subperiods.

For further studies we advance the hypothesis that the above observations are not only specific for the present model but that they have more general validity.

The observations also pose a number of interesting questions of relevance for further modelling activities, and in particular also for the bottom up – top down distinctions.

1. What is, all other things being equal, the relevant number of subperiods? The present case study of Section 4 indicates that the effects of application of smaller subperiods are decreasing (which is consistent with intuition) – therefore a suitable balance should be attempted. Can there be given general advice on this, or how and to what extent does this depend on circumstances modelling (e.g., solution effort, bottom up data requirements)?
2. What is the relevant number of subperiods - from the perspective of balancing this against other bottom up elements. An ideal could be that the details in the various sections of a model should be chosen to give a balanced totality. It seems not to be generally known what other model elements need refinement as the subperiods are made smaller. For example, hydropower, with the associated storages, has the tendency to level marginal production

costs. How much detail is necessary on modelling of hydropower, if this tendency should be adequately reflected for a specific number of subperiods?

3. What is the relevant number of subperiods - from the perspective of balancing this against top down elements in an integrated top down - bottom up model? Typically, a bottom up - top down linkage is the elasticity of electricity demand, and the number of elasticities should intuitively match the number of subperiods. If such subperiod elasticities are meaningful, then to which extent are they available (or how can they be made so)? Is it necessary or desirable to have the same subperiod division in the top down submodel as in the bottom up submodel?

As previously mentioned, the present version of the Balmorel model is a demand driven, bottom up version. The aim of the project is the development of a partial equilibrium model for the Baltic Sea region, and in the further work towards this, the above issues will be addressed, among others. The model and documentation of the project work is available at http://www.balmorel.dk

Appendix A

Profiles for electricity and heat demand

The model is solved for five different scenarios. One is using yearly values, another is splitting the year into two different seasons, and the third has each of the two seasons is split into 2, 4, and 8 subperiods respectively. The three latter are described in the sections below with the actual profiles shown in tables. Note that the values in the tables are relative so that e.g. for 4 subperiods the daytime heat demand during the summer season will be four times less than the daytime demand during winter. Hence, the absolute values for heat and electricity demand cannot be derived from the tables.

Though different profiles can be given for each country, all profiles are at the time being using the same, which were aggregated from Danish load profiles.

4 subperiods (2 seasons – 4 hour types)

The two seasons, summer and winter, are representing 6 months each, while it is assumed that each day of the seasons has 15 day-hours and 9 night-hours. The yearly demand is then split out to each of the four subperiods using the weights indicated above (by the relative lengths of the seasons, and by the relative lengths of the day and night periods) as well as the load profiles shown in tables 2 and 3.

	Day	Night
Summer	56	42
Winter	88	66

Table 1 – Profile for the electricity demand of each country

	Day	Night
Summer	7	6
Winter	28	24

Table 2 – Profile for the heat demand of each country

8 subperiods (2 seasons – 4 hour types)

Here each of the two seasons (of 6 months each) is split into 4 subperiods representing 6 hour intervals (i.e. they are also weighted equal). The profiles for heat and electricity demand can be seen in the tables below.

	0-6	6-12	12-18	18-24
Summer	27	41	44	36
Winter	32	50	57	46

Table 3 – Profile for the electricity demand of each country

	0-6	6-12	12-18	18-24
Summer	7	8	7	7
Winter	31	36	35	32

Table 4 – Profile for the heat demand of each country

16 subperiods (2 seasons – 8 hour types)

Here the two seasons are split into 8 subperiods representing 3 hour intervals.

	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
Summer	28	25	35	45	46	42.5	39	33.5
Winter	33.5	32	44	57	56	57.5	53.5	42.5

Table 5 – Profile for the electricity demand of each country

	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
Summer	7.2	7.5	8	7.5	7.5	7.5	7.5	7.7
Winter	30.5	32.5	37	37.5	36	35	33	31

Table 6 – Profile for the heat demand of each country