Project assignment E

This project assignment is divided in four problems, which cover electricity pricing, frequency control, short-term planning and simulation of electricity markets. The total score of this project assignment is 44 and you need at least 40 points to pass. Points are obtained by preparing oral presentations of the solution to a question. The oral presentations are given at special seminars (see the course syllabus). To pass a presentation the student should show that he or she is able to discuss the solution with other students and the teaching assistant. This means that the student must be able to explain why he or she decided to solve the problem in a particular way and to explain all details in the solution, such as for example how input values have been chosen or why a particular formula has been used. The student should also be able to compare his or her solution to alternative solution methods suggested by the other participants and discuss which method that should be used.

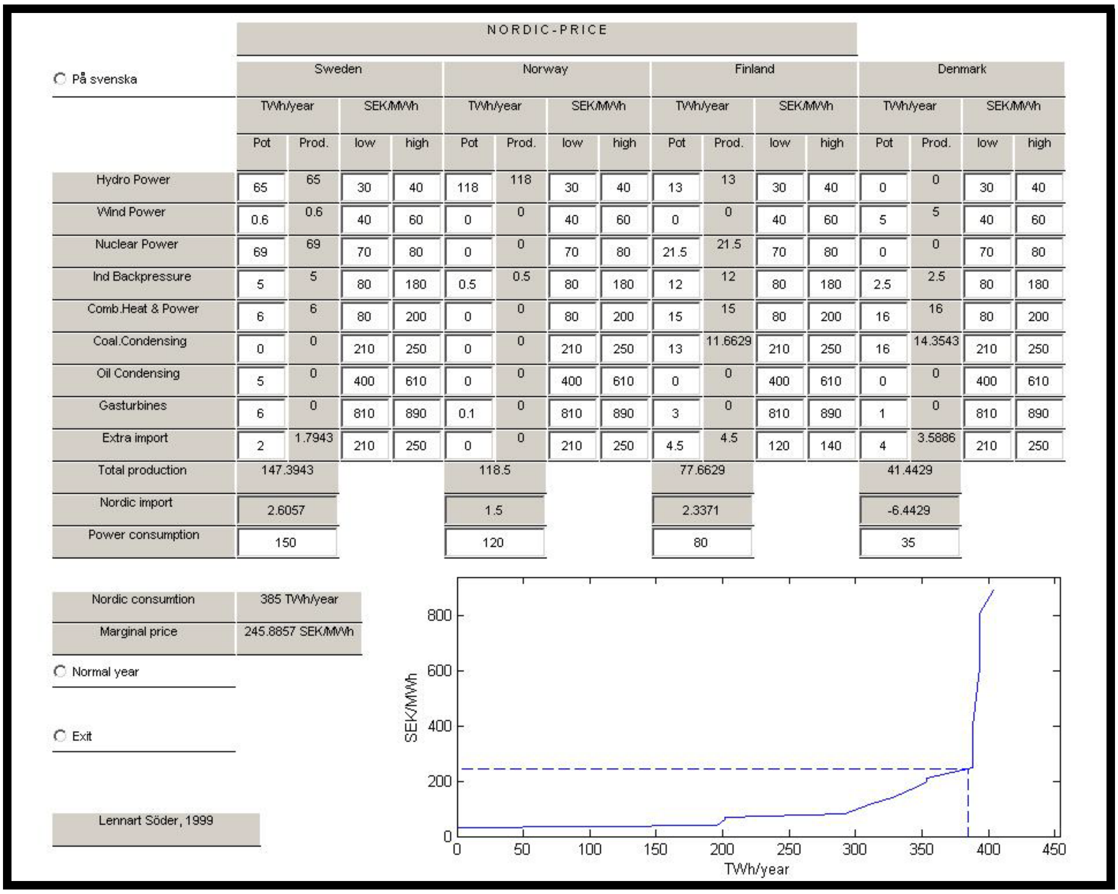
Problem 1 (8 p)

In this problem you will study electricity pricing in the Nordic power system. You will need the Matlab program *Nordicprice* to solve problems c–d. The program can be downloaded from the course web pages. Open Nordicprice.zip and save the files in some appropriate folder on your computer. Then go to that folder and double-click on Nordicprice.m. This will launch Matlab and automatically run *Nordicprice* in Figure 1, as shown in the picture below. You may change all values written in white fields. Type a new value and press ↵ and then a new marginal price of the Nordic system will be calculated.

Nordicprice is based on the simple price model presented in the compendium, section 3.2. This means that the model is based on the following assumptions:

- Perfect competition.
- Perfect information.
- No capacity limitations.
- No transmission limitations.
- No reservoir limitations.
- The load is not price sensitive.

The data used in the program have been compiled from official statistics concerning generation, consumption and import, as well as estimated variable costs for different power sources. It should be noted that these data are from the early 2000s and that the conditions on the Nordic electricity market today are slightly different, not least concerning the cost levels for fossil fuels.



NORDIC-PRICE	Sweden				Norway				Finland				Denmark			
	TWh/year		SEK/MWh		TWh/year		SEK/MWh		TWh/year		SEK/MWh		TWh/year		SEK/MWh	
	Pot	Prod.	low	high	Pot	Prod.	low	high	Pot	Prod.	low	high	Pot	Prod.	low	high
Hydro Power	65	65	30	40	118	118	30	40	13	13	30	40	0	0	30	40
Wind Power	0.6	0.6	40	60	0	0	40	60	0	0	40	60	5	5	40	60
Nuclear Power	69	69	70	80	0	0	70	80	21.5	21.5	70	80	0	0	70	80
Ind Backpressure	5	5	80	180	0.5	0.5	80	180	12	12	80	180	2.5	2.5	80	180
Comb.Heat & Power	6	6	80	200	0	0	80	200	15	15	80	200	16	16	80	200
Coal.Condensing	0	0	210	250	0	0	210	250	13	11.6629	210	250	16	14.3543	210	250
Oil Condensing	5	0	400	610	0	0	400	610	0	0	400	610	0	0	400	610
Gasturbines	6	0	810	890	0.1	0	810	890	3	0	810	890	1	0	810	890
Extra import	2	1.7943	210	250	0	0	210	250	4.5	4.5	120	140	4	3.5886	210	250
Total production	147.3943				118.5				77.6629				41.4429			
Nordic import	2.6057				1.5				2.3371				-6.4429			
Power consumption	150				120				80				35			

a) (2 p) Assume a very simplified model of Sweden and Denmark. In Sweden there is a potential of 60 TWh hydro generation (cost 30–40 SEK/MWh) and 50 TWh nuclear power (70–80 SEK/MWh). The consumption in Sweden is 100 TWh. In Denmark there is only 20 TWh of coal condensing (210–250 SEK/MWh) and the consumption is 20 TWh. Assume that there is perfect competition, that all players have perfect information, and that there are neither reservoir nor capacity limitations in the power plants. The variable operation costs are assumed to be linear within the intervals; the production is zero if the price is on the lower price level and the production is maximal at the higher price level. Which electricity price is obtained in the two countries and how much will be traded between Sweden and Denmark?

b) (2 p) Consider the same system as in problem a. Assume that a tax of 6 öre/kWh is added on nuclear power. How does this change the price and generation in different power sources? What will happen if the tax is 16 öre/kWh instead of 6 öre/kWh?

c) (2 p) Select data for a normal year in the Nordic power system. Which electricity price is obtained? Compare this price to the price during a wet year (78 TWh hydro power in Sweden 142 TWh in Norway and 14 TWh in Finland) and a dry year (51 TWh in Sweden, 104 TWh in Norway and 12 TWh in Finland) respectively. How much must the Nordic countries import during a dry year? Is an import of that size reasonable?

Hint: Compare the import and the transmission capability between the Nordic countries and their neighbours according to table 1 assuming that it is always possible to transmit maximal power on each connection, i.e., neglect the risk of failures in cables, risk of power deficit in the exporting country, etc..

Table 1 Connections between the Nordic countries and their neighbours.

Connection	Capacity [MW]
Sweden ↔ Germany	400
Sweden ↔ Poland	600
Denmark ↔ Germany	1 550
Finland ↔ Russia	1 560

d) (2 p) During 2001 the hydro power in Sweden produced 78 TWh and the Norwegian hydro power 121 TWh. Finland imported 7 TWh from Russia and the Danish wind power plants produced 4 TWh. The consumption in Norway was 125 TWh. Except for these deviations, 2001 corresponded to the normal year data in the software. Which electricity price do you get from the model? In reality the average price at the power exchange Nord Pool was about 21 öre/kWh. Explain the difference between the result of the model and the actual average price.

Problem 2 (8 p)

In this problem you will study the frequency control of a small power system. The system is divided in four areas. The load in each area and the current transmission flows are shown in figure 1. Each transmission line is equipped with a protection system which after a short time delay disconnects the line if the power flow exceeds the maximum capacity of the line, which is stated within parentheses at each line.

Table 2 provides details about the power plants in the system.

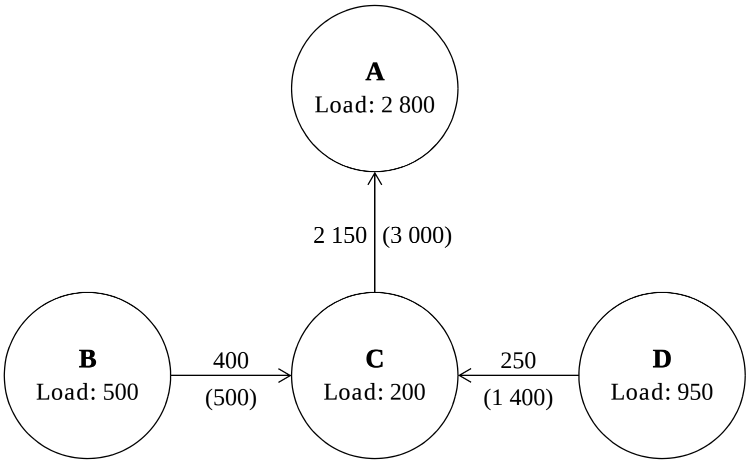


Figure 1 The power system in problem 2.

Table 2 Data for the power plants in problem 2.

Power plant	Area	Gain [MW/Hz]	Generation before the error [MW]	Maximal capacity [MW]
1	A	—	600	1 200
2	A	200	50	250
3	B	—	200	200
4	B	300	200	400
5	B	500	300	600
6	B	500	200	800
7	C	—	300	300
8	C	—	600	600
9	C	400	800	1 200
10	D	800	300	400
11	D	300	350	800
12	D	200	550	1 000

The power plants for which no gain is stated are not participating in primary control.

a) (2 p) At a certain occasion the power system is in balance and the frequency is exactly 50 Hz then a failure occurs in power plant 12, which means that 550 MW generation is lost. Due to the error, the voltage decreases in the area A. Some loads are voltage dependent and therefore the load in area D is reduced by 50 MW.

Disregard the generation and transmission limits of the system. What will the frequency be once the primary control has stabilised the frequency in the system again?

b) (3 p) Consider the same system as in problem a, but take the generation limitations of the power plants into account. (Continue to disregard the transmission limitations in the system.) Which generation is obtained in each power plant when the primary control has stabilised the frequency in the system again?

c) (3 p) Consider the same system as in problem a, but take generation as well as transmission limitations into account. Which generation is obtained in each power plant when the primary control has stabilised the frequency in the system again? Moreover, what is the frequency in each area?

Problem 3 (18 p)

In this problem you will plan the operation of AB Elbolaget for the next 24 hours. AB Elbolaget owns three hydro power plants and one thermal power plant. The company has a firm power contract with Industri AB and is also a trader at Nord Pool. The problem is thus to decide how much that should be purchased and sold at the power exchange, as well as to decide generation plans for the power plants.

Notice that all numbers used in this problem text is a mix of real and fictitious values (the thermal power plant is for example not always using the fuel specified here).

a) (3 p) The relative efficiency in the three hydro power plants can be found in table 3. Other data about the hydro power plants are given in table 4. Installed capacity is generated at maximal discharge in these power plants.

Determine models of the electricity generation in the three hydro power plants. The models should be piecewise linear and have two segments. The marginal production equivalents should be stated using four decimals. Do not forget to motivate your choice of breakpoint between the two segments!

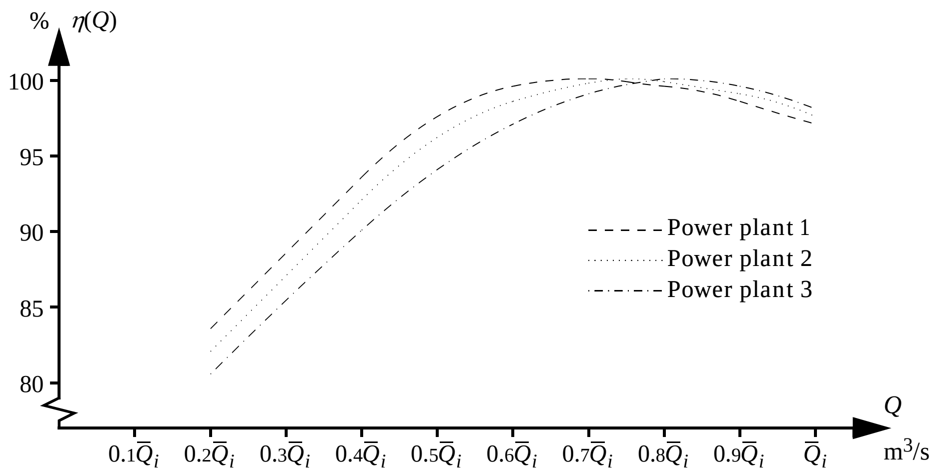


Figure 2 Relative efficiency in the three hydro power plants.

Table 3 Relative efficiency for some discharges.

Power plant	0	$0.2\overline{Q}_i$	$0.4\overline{Q}_i$	$0.6\overline{Q}_i$	$0.7\overline{Q}_i$	$0.75\overline{Q}_i$	$0.8\overline{Q}_i$	$0.9\overline{Q}_i$	$\overline{Q}_i$
1	0	83.5	93.5	99.5	100	99.8	99.5	98.5	97
2	0	82	92	98.5	99.7	100	99.8	99	97.5
3	0	80.5	90	97	99	99.6	100	99.5	98
where $\overline{Q}_i$ is the maximal discharge in power plant *i*.									

b) (4 p) Assume that AB Elbolaget only owns the three hydro power plants (i.e., disregards the thermal power plant). Formulate the planning problem of AB Elbolaget as an LP problem. The local inflow to the first power plant is assumed to be equal to the mean annual flow at the power plant. The local inflows to the other reservoirs are assumed to be equal to the difference in mean annual flow between the power plant in question and the power plant directly upstream. The reservoirs are filled to 50% in the beginning of the planning period. Future generation is assumed to be sold for 309 SEK/MWh and stored water is assumed to be used for electricity generation at average production equivalent, i.e, installed capacity in MW divided by maximal discharge in HE. The water delay time between the power plants can be neglected. The firm power contract with AB Industri comprises 95 MWh/h. Assume that AB Elbolaget can purchase and sell unlimited quantities at Nord Pool for the prices stated in table 5.

c) (2 p) Data for the thermal power plant are given in table 6. Which variable generation cost (SEK/MWh) is obtained with the specified fuel and efficiency?

d) (4 p) Assume that AB Elbolaget only owns the thermal power plant (i.e., disregards the hydro power plants). Formulate the planning problem of AB Elbolaget as a MILP problem. The start-up cost of the thermal power plant is assumed to be independent of the down time. There are no requirements on up and down times respectively. The power plant was not committed during the hour before the beginning of the planning period. The firm power contract with AB Industri comprises 95 MWh/h. Assume that AB Elbolaget can purchase and sell unlimited quantities at Nord Pool for the prices stated in table 5.

e) (3 p) Formulate the planning problem of AB Elbolaget considering both hydro power and the thermal power as a MILP problem.

f) (2 p) Make a list of the approximations you have used in your planning model.

Table 4 Data for the hydro power plants of AB Elbolaget.

	Power plant 1: Rengård	Power plant 2: Båtfors	Power plant 3: Finnfors
Year of completion	1970	1961	1935/1954/1979
Type of power station	Above ground	Above ground	Above ground
Head [m]	19	17	21
Mean annual flow [m^3/s]	137	145	150
Design flow [m^3/s]	220	280	300
Number and type of turbines	1 × Kaplan	2 × Kaplan	4 × Kaplan
Installed capacity [MW]	36	42	54
Average annual energy generation [GWh]	202	183	232
Active storage of reservoir [m^3]	5 000 000	5 000 000	1 000 000
Maximal discharge capacity of spillways [m^3/s]	1 000	940	880

* The three power plants are located in a line with the first power plant furthest upstream.

Table 5 Expected prices at Nord Pool.

Hour	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
Price [SEK/MWh]	296	296	291	291	294	299	302	316	327	317	312	310
Hour	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Price [SEK/MWh]	312	310	315	323	343	354	328	316	305	305	300	297

Table 6 Data for the thermal power plant Lövholmen.

Fuel	Bio fuel
Fuel price [SEK/ton]	485
Heat contents of the fuel [MWh/ton]	5.3
Efficiency [%]	31
Installed capacity [MW]	75
Minimal generation when committed [MW]	30
Start-up cost [SEK/start]	21 000

Problem 4 (10 p)

In this problem you will study a small electricity market. The small island republic Land consists of two main islands: Storön and Lillön. The two islands are connected by an HVDC transmission line. At present time the power supply in Land is based on a hydro power plant and an oil-fired condensing plant. The hydro power plant is a so-called run-of-the-river plant, i.e., there is no hydro reservoir. However, the natural water flow passing the hydro power plant is always sufficient to generate the installed capacity. Moreover, the southern coast of Lillön is quite windy; therefore, a large scale development of wind power is considered in this area.

It may be noted that Land is a completely fictitious system, which means that all numerical values (for example production and investment costs) should be taken with a pinch of salt. However, the methods that you will apply are general and can also be used for real systems.

a) (2 p) Assume that the total load duration curve of Land can be approximated according to

$$\tilde{F}_0(x) = \begin{cases} 1 & x < 450, \\ 0.95 & 450 \le x < 600, \\ 0.5 & 600 \le x < 750, \\ 0.05 & 750 \le x < 900, \\ 0 & 900 \le x. \end{cases}$$

Use probabilistic production cost simulation to compute *ETOC* and *LOLP* if the electricity supply of Land consists of existing hydro power and oil condensing. Data of the power plants are given in table 7.

Table 7 Data for the power plants in Land.

Power source	Area	Installed capacity [MW]	Availability		Operation cost [¤/MWh]	Investment cost [M¤/yr.]
			Available capacity [MW]	Probability [%]		
Hydro power	Lillön	600	600	100	Negligible	Existing power plant
Oil condensing	Storön	450	0 450	10 90	150	Existing power plant
Wind power	Lillön	300	0 150 300	25 40 35	Negligible	40

Table 8 Data for the HVDC link between Storön and Lillön.

Transmission capacity [MW]	900
Losses [%]	4
Availability [%]	100

b) (2 p) How many hours per year can the oil condensing power plant be expected to be operated?
Hint: Compare the *LOLP* of the system with and without the oil condensing.

c) (3 p) Consider the same system as in problem a, but assume that the wind farm on Lillön is also built. Use probabilistic production cost simulation to compute *ETOC* and *LOLP*.

d) (2 p) Is the wind farm investment profitable for the power companies? Is the investment profitable for the society, assuming that disconnected consumptions represents a social cost of 800 ¤/MWh?

e) (1 p) Make a list of the approximations you have used in your study of Land.