Electric Power Systems Lab
EG2050 SYSTEM PLANNING
Spring 2013

Home assignments

Instructions

There are in total 25 home assignments in the course divided into four parts, which cover electricity pricing, frequency control, short-term planning and simulation of electricity markets. The objective of the home assignment is that you should train to solve problems related to reality. The home assignments will also give you the opportunity to try using different kinds of software to solve larger problems.

Laboratory course

The home assignments that are part of the laboratory course can give in total 50 lab points. To pass the laboratory course, the student must have at least 45 lab points. To get lab points, the student should prepare an oral presentation of the solution to the assignment. The oral presentations are given at special seminars (see the course syllabus). To pass a presentation the following requirements must be fulfilled:
- **The presentation must be completed within the time limit.** The student is given three minutes per lab point.
- **The presentation must be performed independently.** This means that the student must be able to give the presentation without turning to fellow students or the course assistant to ask for help.
- **The presentation must be clear.** All details in the calculations do not have to be shown, but the presentation must provide sufficient details so that a fellow student who have not done the assignment should know what to do in order to solve the problem.
- **The solution must be reasonable.** The solution method that is presented must be appropriate for the problem. However, the student will not fail if some minor computation error has slipped into the presentation.
- **The student must be able to answer questions after the presentation.** The other participants and the course assistant should have the opportunity to ask questions about the solution after the presentation. During this questioning the student must be able 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.

Bonus problems

The voluntary home assignments are marked by ***** and can give bonus points for the exams in March 2013 and June 2013 respectively. These home assignments are presented in a written report. It is not possible for the one marking the home assignments to print out reports sent by e-

mail and it is therefore only possible to submit the assignments in the mailbox marked "*System planning*", which is found in the stairwell at Teknikringen 33, first floor. Home assignments that are submitted in any other way will not be marked.

To receive bonus points for a home assignment, the following requirements must be fulfilled:

- **The report must be submitted in time.** The deadlines for the home assignments are given in the course syllabus.
- **The report must be an individual work.** It is not allowed to copy neither parts nor the entire report of another student! If several submitted reports are much the same in essential parts then neither report will receive any bonus points.
- **The solution must be clear and correct.** All introduced symbols must be defined. Solutions should include sufficient detail that the argument and calculations can be easily followed. The score will be reduced if there are computation errors, insufficient motivations or incorrect conclusions.

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Home assignments part I
Electricity Pricing

In these assignments you will study electricity pricing in the Nordic power system. You will need the Matlab program *Nordicprice* to solve problems 3–8. The program is installed on the computers in the Student room, Teknikringen 33. Please notice that you need a special computer account to use these computers (see the course syllabus).

Click on the symbol My computer, then choose the network drive Public on Prosit (G) and the folder EG2050. Start the program by clicking on the file Nordicprice. The window shown below should now appear on your screen. 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.

NORDIC-PRICE

○ På svenska

	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			

Nordic consumtion   385 TWh/year

Marginal price   245.8857 SEK/MWh

○ Normal year

○ Exit

Lennart Söder, 1999

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.

Problem 1 (2 lab point)

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, i.e., 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?

Problem 2 (2 lab points)

a) Consider the same system as in problem 1. 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?

b) Consider the same system as in problem 1. Assume that a tax of 16 öre/kWh is added on nuclear power. How does this change the price and generation in different power sources?

Problem 3 (3 lab points)

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 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

Problem 4 (3 lab points)

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 5 (1 bonus point)

A fifth nuclear power plant is being built in Finland. The production capacity is about 8 TWh/year. A rough estimate of the investment cost of this power plant is between two and three billion SEK per year. How will this power plant affect the electricity price during a normal year? What is the expected profit of this nuclear power plant during a normal year?

*Problem 6 (0,6 bonus points)

Assume that the consumption increases by 2.5% compared to the normal year, but no new power plants are constructed (hence, disregard the expansion of nuclear power in problem 5). How much does the Nordic electricity price change? Is this price change reasonable?

*Problem 7 (1 bonus point)

How is the Nordic electricity price affected in a normal year if a cost for emissions of carbon dioxide is introduced? The cost is 10 öre/kWh for coal condensing and 8 öre/kWh for oil condensing. Moreover, how is the total profit of the Nordic producers affected?

*Problem 8 (0,4 bonus points)

How large tax can be added on nuclear generation without changing the electricity price during a normal year? What would the consequences be if such a tax really was introduced?

Home assignments part II
Frequency Control

In these problems 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 the figure below. 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.
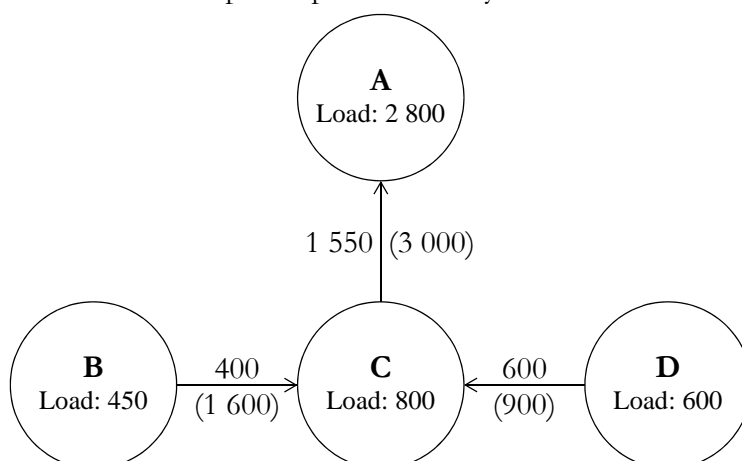
Problem 9 (5 lab points)

At a certain occasion the power system is in balance and the frequency is exactly 50 Hz then a failure occurs in power plant 1, which means that 1 100 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 A is reduced by 100 MW

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?

Problem 10 (5 lab points)

Consider the same system as in problem 9, but take the transmission limitation between the areas

Table 2 Data for the power plants in problem 9–10.

Power plant	Area	Gain [MW/Hz]	Generation before the error [MW]	Maximal capacity [MW]
1	A	—	1 100	1 100
2	A	200	150	200
3	B	—	0	200
4	B	—	300	400
5	B	500	350	850
6	B	500	200	800
7	C	—	300	300
8	C	—	600	600
9	C	600	450	1 100
10	D	250	300	500
11	D	300	350	800
12	D	400	550	1 000

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

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?

Home assignments part III
Short-term Planning

In these problems 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).

Problem 11 (3 lab points)

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!
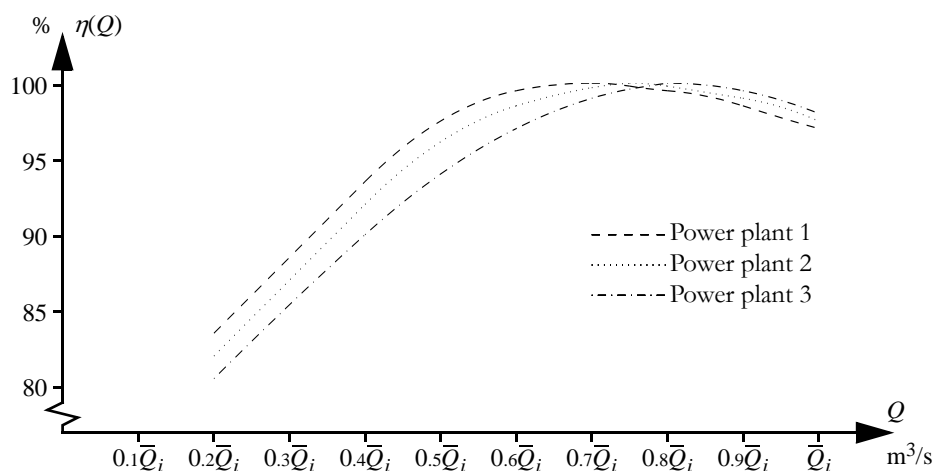

Figure 1   Relative efficiency in the three hydro power plants.

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*.									

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

	Power plant 1* Nämforsen	Power plant 2* Moforsen	Power plant 3* Forsmo
Year of completion	1946/1973	1968	1948/1957
Type of power station	Buried	Above ground	Underground
Head [m]	22	28	33
Mean annual flow [m^3/s]	325	326	327
Design flow [m^3/s]	630	600	600
Number and type of turbines	3 × Kaplan	3 × Kaplan	4 × Kaplan
Installed capacity [MW]	113	139	155
Average annual energy generation [GWh]	453	685	753
Active storage of reservoir [m^3]	2 000 000	2 000 000	5 000 000
Maximal discharge capacity of spillways [m^3/s]	2 820	2 700	2 950

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

Table 5 Data for the thermal power plant Skutskär.

Fuel	Bio fuel
Fuel price [SEK/ton]	526
Heat contents of the fuel [MWh/ton]	5.3
Efficiency [%]	33
Installed capacity [MW]	70
Minimal generation when committed [MW]	40
Start-up cost [SEK/start]	15 200

Table 6 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]	300	305	308	313	306	307	311	310	328	327	313	317
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]	313	323	316	333	320	298	298	318	308	298	297	298

Problem 12 (2 lab points)

Data for the thermal power plant are given in table 5. Which variable generation cost (SEK/MWh) is obtained with the specified fuel and efficiency?

Problem 13 (8 lab points)

Formulate the planning problem of AB Elbolaget as a MILP 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 320 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 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 200 MWh/h. Assume that AB Elbolaget can purchase and sell unlimited quantities at Nord Pool for the prices stated in table 6.

*Problem 14 (4 bonus points)

Use a computer to solve the planning problem from problem 13. How should AB Elbolaget operate their power plants and how much should they purchase and sell at Nord Pool? What is the value of the objective function?

You may choose any software you like to solve this problem, but we recommend that you use GAMS, which is installed on the computers in the student room at Teknikringen 33. A short description of GAMS programming is given in the course compendium, appendix B.

Hint: If you get the error message `**** Terminated due to a licensing error` in your list file, then GAMS has been unable to find a licence for the default solver of `mip` problems. Try to add this row before the `solve` statement to choose the correct solver:

```
option mip = bdmlp;
```

If this row does not solve the problem then there is an error to the GAMS license file. Please notify the course coordinator about which computer that is malfunctioning; meanwhile, try to run your program on some other computer.

NOTICE! The following is required to get full score for this problem:
- The operation plan should be displayed as a table, where it is stated for each hour how much the power plants are generating and the trading at Nord Pool (cf. the example in table 7).
- The value of the objective function should be rounded to an integer value.
- The program code should be included in the report as an appendix. (Notice that it is only the code that is required and that output files generated by the software—for example `.lst` files from GAMS—may not be included in the report!)

*Problem 15 (1 bonus point)

There is a shopping mall close to the hydro power plants of AB Elbolaget. In the winter, AB Plogbilen clears the parking lot of this mall from snow. The day before the planning period in problem 13, AB Plogbilen has collected 50 tonnes of snow, which must be transported away.

Table 7 Example of operation plan.

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
Generation in hydro power plant 1 [MWh]												
Generation in hydro power plant 2 [MWh]												
Generation in hydro power plant 3 [MWh]												
Generation in thermal power plant [MWh]												
Purchase from Nord Pool [MWh]												
Sales to Nord Pool [MWh]												
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
Generation in hydro power plant 1 [MWh]												
Generation in hydro power plant 2 [MWh]												
Generation in hydro power plant 3 [MWh]												
Generation in thermal power plant [MWh]												
Purchase from Nord Pool [MWh]												
Sales to Nord Pool [MWh]												

Assume that the snow melts immediately if it is dumped in a hydro reservoir. In which reservoir and during which hour would it be best for AB Elbolaget to receive the snow? How much would it be worth for AB Elbolaget to pay for the snow? Do not forget to motivate your answer!

Problem 16 (2 lab points)

Make a list of the approximations you have used in your planning model.

Home assignments part IV
Simulation of an Electricity Market

In this assignment 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.

Problem 17 (2 lab points)

Assume that the total load duration curve of Land can be approximated according to

$$\tilde{F}_0(x) = \begin{cases} 1 & x < 300, \\ 0.9 & 300 \le x < 400, \\ 0.5 & 400 \le x < 500, \\ 0.1 & 500 \le x < 600, \\ 0 & 600 \le x. \end{cases}$$

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 8.

Problem 18 (3 lab points)

Consider the same system as in problem 17, but assume that the wind farm on Lillön is also built. Use probabilistic production cost simulation to compute *ETOC* and *LOLP*.

Table 8 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	500	500	100	Negligible	Existing power plant
Oil condensing	Storön	300	0	10	150	Existing power plant
			300	90		
Wind power	Lillön	200	0	40	Negligible	25
			100	50		
			200	10		

Table 9 Data for the HVDC link between Storön and Lillön.

Transmission capacity [MW]	700
Losses [%]	3
Availability [%]	100

Table 10 Data for the load in Land.

Probability distributions for the load in MW* Storön Lillön	$N(400, 80)$ $N(50, 10)$
Social cost of disconnected load [¤/MWh]	500

*The loads in Storön and Lillön can be assumed to be independent.

Problem 19 (2 lab points)

Is the wind farm investment profitable for the power companies? Is the investment profitable for the society (i.e., include the social cost of disconnected load)?

*Problem 20 (1 bonus point)

The approximate load duration curve that you used in problem 17 and 18 is not very accurate. To obtain more precise results, the segment size of the load duration curve must be decreased (cf. the compendium page 101). You can download the Matlab function `ppc` from the course web pages. You can use this function to perform a probabilistic production cost simulation of the system. You supply data for the load and the power plants.[1] You can yourself set the segment size to be used when approximating the load duration curve. To get detailed instructions for calling the function in Matlab, type `help ppc` in the Matlab window. Notice that `ppc` uses a different approximative load duration curve compared to the one in problem 17 even if you use the same segment size as in problem 17.

Use `ppc` to simulate your system with at least five different segment sizes. How important is the segment size for the *ETOC* and the *LOLP*? Do the changes affect your conclusion about the profitability of investing in the wind farm?

Hint: You can also find the Matlab function `compareldc` on the course web pages. This function can be used to compare the exact load duration curve of a normally distributed load compared to a duration curve divided in segments.

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1. Set the availability parameter `Wavail` to `[1 0 0]` in order to remove the wind power.

Problem 21 (3 lab points)

Define an electricity market model which can be used to analyse scenarios for a Monte Carlo simulation of Land. The model should take into account the losses and transmission limits of the HVDC link. Data of the electricity market in Land are given in tables 8–10. State the scenario parameters, model constants and result variables of your model, and describe how the result variables are calculated.

Problem 22 (3 lab points)

Table 11 provides some scenarios for a Monte Carlo simulation of the electricity market in Land if the wind farm is built. No variance reduction techniques have been used in this simulation. Which estimates of *ETOC* and *LOLP* are obtained from these scenarios?

Table 11 Some scenarios for a Monte Carlo simulation of Land.

Scenario	Available generation capacity [MW]			Load [MW]	
	Hydro	Oil condensing	Wind power	Storön	Lillön
1	500	300	0	509	53
2	500	300	100	538	68
3	500	300	200	397	58
4	500	300	200	465	67
5	500	0	100	520	55
6	500	300	0	432	41
7	500	0	0	265	37
8	500	300	0	532	32
9	500	300	100	466	41
10	500	300	100	444	57

*Problem 23 (1 bonus point)

Assume that stratified sampling should be used for a simulation of the electricity market in Land *without* the wind farm. Use a strata tree to define appropriate strata. You should also calculate the stratum weights.

*Problem 24 (3 bonus points)

In this problem you are to perform a small Monte Carlo simulation of the electricity market in Land *without* the wind farm. You should use a combination of all the three variance reduction techniques described in the course. It is sufficient that you randomise one scenario (and its complementary scenarios) for each stratum. Compile your scenarios in a table, which shows the values of the scenario parameters as well as the result variables and control variates for each studied scenario (including the complementary scenarios), for example as shown in table 12. You should also describe how you have computed the expectation value per stratum, and what the final estimates of *ETOC* and *LOLP* are.

Hint: You can use Matlab to generate random numbers from a normal distribution. You can download the three functions described below from the course web pages. More detailed instruc-

Table 12 Example of compilation of analysed scenarios.

Stratum	Available generation capacity [MW]		Load [MW]			Result variables		Control variates	
	Hydro	Oil condensing	Total	Storön	Lillön	···		···	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

tions of how the files are used in Matlab can be obtained by typing `help` followed by the name of the function.

`norminterval`

When applying stratified sampling, it is necessary that the generated random numbers are within a specified range (otherwise they will not belong to the correct stratum). The function `norminterval` can generate random numbers from a particular interval of a general normal distribution. The inputs are the mean, μ, and standard deviation, σ, of the normal distribution, as well as the minimal and maximal values desired.

`Phi`

This is simply the distribution function of the standardised normal distribution, $\Phi(x)$. The function is used by `norminterval`, but may also be useful for calculating stratum weights.

`normvalue`

This function applies the approximate inverse transform method (see the compendium, appendix E) to transform random numbers of a $U(0, 1)$-distribution to random numbers from an $N(0, 1)$-distribution. The function is used by `norminterval`.

Problem 25 (2 lab points)

Compile a list of advantages and disadvantages of the two simulation methods (probabilistic production cost simulation and Monte Carlo). Which method do you find most appropriate to simulate the electricity market in Land?