KTH VETENSKAP OCH KONST

KTH Electrical Engineering

Exam in EG2050 System Planning, 14 January 2015, 14:00–19:00, V01

Allowed aids

In this exam you are allowed to use the following aids:

- Calculator without information relevant to the course.
- One **handwritten**, **single-sided** A4-page with **your own** notes (original, not a copy), which should be handed in together with the answer sheet.

PART I (MANDATORY)

Write all answers on the answer sheet provided. Motivations and calculations do not have to be presented.

Part I can yield 40 points in total. The examinee is guaranteed to pass if the score is at least 33 points. If the result in part I is at least 31 points, then there will be a possibility to complement for passing the exam with the grade E.

Problem 1 (4 p)

Answer the following theoretical questions by choosing *one* alternative, which you find correct.

a) (2 p) In a modern, restructured ("deregulated") electricity market, the system operator is responsible for the short-term balance between generation and consumption. This means that I) The system operator has to ensure that the frequency is kept within given limits, II) If the system operator does not ensure that the system in every moment is supplied as much power as is consumed, then the system operator will have to pay a penalty fee to the balance responsible players, III) If the system operator does not ensure that the system in every trading period (for example an hour) is supplied as much energy as is consumed, then the system operator will have to pay a penalty fee to the balance responsible players.

1. None of the statements is true.
2. Only I is true.
3. Only II is true.
4. Only III is true.
5. I and II are true but not III.

b) (1 p) Consider a balance responsible player which during one hour has generated 1 500 MWh, sold 1 200 MWh to the power exchange, sold 320 MWh to consumers with take-and-pay contracts and purchased 50 MWh regulation power from the system operator. What obligation does this player have in the post trading for this hour?

1. The player must buy balance power from the system operator.
2. The player must sell balance power to the system operator.
3. None—it is voluntary for balance responsible players to participate in the post trading.

c) (1 p) What is a firm power contract?

1. The customer must in advance notify the supplier about how much the customer will consume during each trading period.
2. The customer buys the same amount of energy in each trading period as long as the contract is valid.
3. During the time the contract is valid, the customer is allowed to consume as much energy they want in each trading period, provided that the maximal power is not exceeded.

Problem 2 (6 p)

Assume that the electricity market in Land has perfect competition, all players have perfect information, and there are neither transmission nor capacity limitations. However, the hydro reservoirs of Land has a limited storage capacity. The variable operation cost in the hydro power is negligible. On 1 January the reservoirs holds in total 24 TWh and according to the long-term forecast for the electricity market (which as already mentioned is assumed to be faultless), the reservoirs should hold 26 TWh on 31 December. The inflow and other data for the electricity market in Land are given in table 1 below. The variable costs are assumed to be linear in the given interval; the production is zero if the price is on the lower price level and the production is maximal at the higher price level.

Table 1 Data for the electricity market in Land.

Power source	Production capability [TWh]		Variable cost [¤/MWh]
	1 January to 30 June	1 July to 31 December	
Nuclear	30	30	100–120
Biofuels	10	10	150–350
Fossil fuels	10	10	250–450
Inflow to the hydro reservoirs [TWh]	46	14	
Electricity consumption [TWh]	73	67	

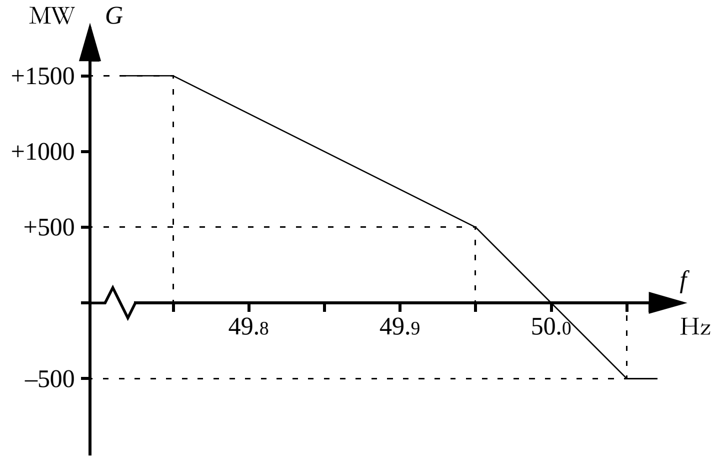
a) (2 p) What would the price be in the electricity market of Land if there is no reservoir limitation?

b) (2 p) How much would the reservoirs hold at midnight between 30 June and 1 July if there is no reservoir limitation?

c) (2 p) Assume that the reservoirs in Land cannot store more than 30 TWh. Which electricity price will there be between 1 January and 30 June and between 1 July and 31 December respectively?

Problem 3 (6 p)

Consider a power system where the primary control is divided in a normal operation reserve and a disturbance reserve. The normal operation reserve is designed to manage normal variations in for example load and wind power generation. The disturbance reserve is designed to manage outages in larger power plants. The figure below shows how the generation in the primary control is changing (in relation to the base generation) as a function of the frequency.

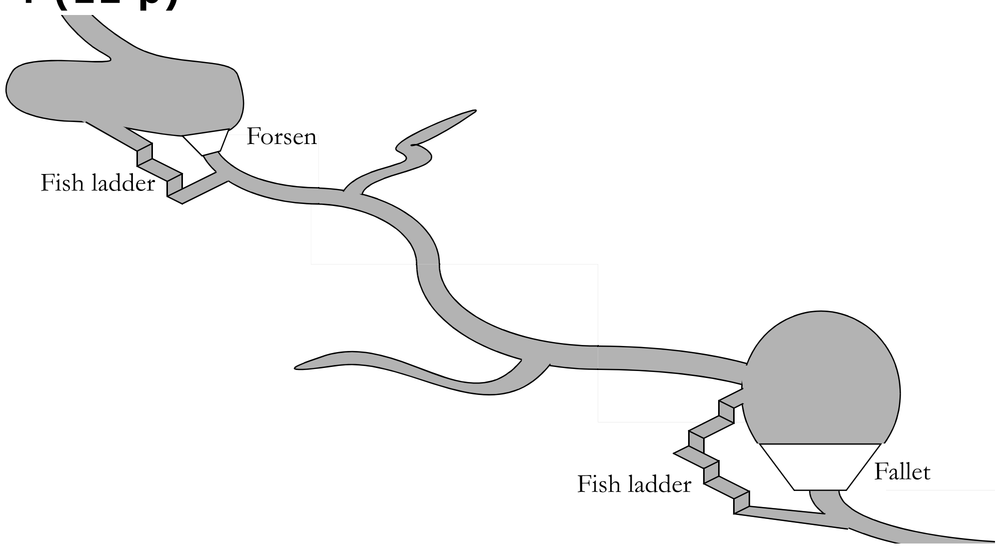


a) (2 p) In which frequency range is the normal operation reserve available and what is the gain of the normal operation reserve?

b) (2 p) In which frequency range is the disturbance reserve available and what is the gain of the disturbance reserve?

c) (2 p) At 14:06 there is balance between production and consumption in the system and the frequency is 49.97 Hz. At this time a lightning strike in a substation causes 750 MW of generation to be lost. The concerned power plants were not part of the primary control. What will the frequency be when the primary control has restored the balance between generation and consumption?

Problem 4 (12 p)

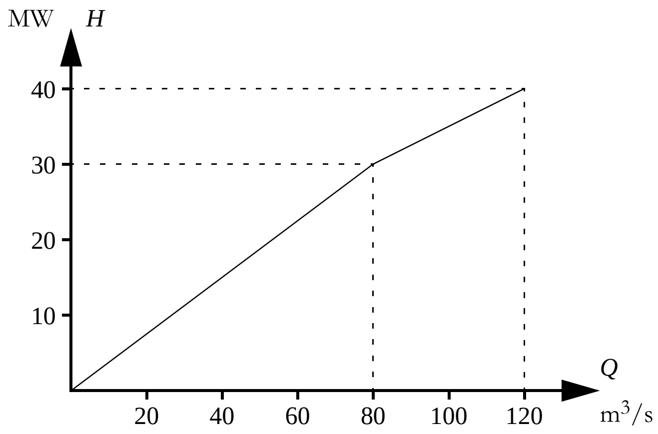


AB Vattenkraft owns two hydro power plants located as in the figure above. The following symbols have been introduced in a short-term planning problem for these hydro power plants:

Indices for the power plants: Forsen 1, Fallet 2, Strömmen 3.

γ_i = expected future production equivalent for water stored in reservoir i, i = 1, 2,
λ_t = expected electricity price at ElKräng hour t, t = 1, …, 24,
λ_{25} = expected electricity price at ElKräng after the end of the planning period,
$\overline{M}_i$ = maximal contents of reservoir i, i = 1, 2,
$M_{i,0}$ = contents of reservoir i at the beginning of the planning period, i = 1, 2,
$M_{i,t}$ = contents of reservoir i at the end of hour t, i = 1, 2, t = 1, …, 24,
$\mu_{i,j}$ = marginal production equivalent in power plant i, segment j, i = 1, 2, j = 1, 2,
$Q_{i,j,t}$ = discharge in power plant i, segment j, during hour t, i = 1, 2, j = 1, 2, t = 1, …, 24,
$\overline{Q}_{i,j}$ = maximal discharge in power plant i, segment j, i = 1, 2, j = 1, 2,
$S_{i,t}$ = spillage from reservoir i during hour t, i = 1, 2, t = 1, …, 24,
$\overline{S}_i$ = maximal spillage from reservoir i, i = 1, 2,
$V_{i,t}$ = local inflow to reservoir i during hour t, i = 1, 2, t = 1, …, 24.

a) (2 p) The figure below shows a piecewise linear model of the electricity generation as a function of the discharge in Forsen. Calculate the marginal production equivalents and maximal discharge of each segment.



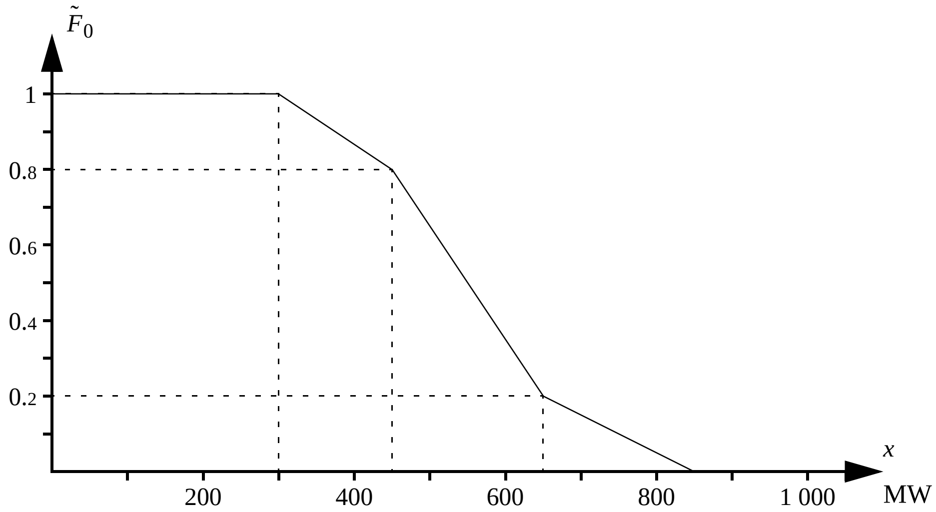
b) (3 p) Which of the symbols above represent optimisation variables and parameters respectively?

c) (5 p) Formulate the objective function if the purpose of the planning is to maximise the income of generated hydro power plus the value of stored water. Use the symbols defined above.

d) (2 p) The reservoir of Fallet holds 4 320 000 m^3 water at 14:00 and the total inflow (i.e., both local inflow as well as discharge and spillage from the power plant upstream) between a 14:00 and 15:00 amounts to 720 000 m^3. Assume that AB Vattenkraft will discharge 25 HE at Fallet and has to spill 1 m^3/s through the fish ladder at Fallet. How large is the contents of the reservoir at 15:00? The answer should be given in HE.

Problem 5 (12 p)

The national grid in Nchi is supplied by hydro power plants with a combined installed capacity of 750 MW and a 50 MW thermal power plant. The figure below shows the duration curve of the total load in Nchi.



a) (2 p) The hydro power plants are assumed to have 100% availability. What is the availability of the thermal power plant if the *LOLP* in Nchi is 5.75%?

b) (2 p) Calculate $EENS_1$!

c) (2 p) Calculate $EENS_2$!
Hint: Remember that $\int(a(x) + b(x))dx = \int a(x)dx + \int b(x)dx$.

d) (2 p) Generate a value of the load using the inverse transform method and the random number 0.35 from a $U(0, 1)$-distribution.

e) (3 p) Assume that the power system in Nchi is simulated using control variates. The simplified model corresponds to the model used in probabilistic production cost simulation, while the detailed model is a multi-area model which takes into account losses and limitations in the transmission system. 10 000 scenarios are generated in the Monte Carlo simulation. The result is power deficit for both the multi-area model and the simplified model in 547 of these scenarios. The result is power deficit only in the multi-area model in 48 scenarios. Which estimate of *LOLP* is obtained from this simulation?

f) (1 p) Assume that stratified sampling is used instead of control variates for the simulation of Nchi. Results for each stratum are given in table 2. Which estimate of *LOLP* is obtained for this simulation?

Table 2 Strata in the simulation of Nchi.

Stratum, h	1	2	3	4	5	6
Stratum weight, ω_h	0.85	0.0075	0.015	0.0425	0.0425	0.0425
Estimated risk of power deficit, m_{LOLOh}	0	0.20	1	0	0.10	1

PART II (FOR HIGHER GRADES)

All introduced symbols must be defined. Solutions should include sufficient detail that the argument and calculations can be easily followed.

The answer to each problem must begin on a new sheet, but answers to different parts of the same problem (a, b, c, etc.) can be written on the same sheet. The fields *Namn* (Name), *Blad nr* (Sheet number) and *Uppgift nr* (Problem number) must be filled out on every sheet.

Part II gives a total of 60 points, but this part will only be marked if the candidate has obtained at least 33 points in part I. Then the results of parts I and II and the bonus points will be added together to determine the examination grade (A, B, C, D, E).

Problem 6 (10 p)

Electricity prices in Land are based on long-term forecasts considering the next 12 months. In these long-term forecasts, the maximal generation in different time periods are estimated, as shown in table 3. At the end of April, the hydro reservoirs have the normal contents for this time of the year, and the players in the electricity market expect that the next year will be a normal year. However, during the annual maintenance shutdown of the nuclear power plants in Land, numerous safety issues are detected and must be taken care of; hence, from August the players expect lower nuclear generation until the end of the year. Then, the autumn turns out to be unusually wet and windy, which means that the hydro reservoirs are unusually filled and that the wind power generates more than expected.

Besides the above described incomplete information (which is the same for all players) it can be assumed that there is perfect competition and that there are neither capacity, transmission nor reservoir limitations in the electricity market in Land. The variable operation costs are shown in table 3 and 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. The load in Land is not price sensitive and can be assumed to be 150 TWh for the next year regardless of when the forecast is made.

Table 3 Forecasts for electricity generation in Land during the next twelve months.

Power source	Production capability during the next twelve months [TWh]			Variable costs [¤/MWh]
	May	August	October	
Wind power	6	6	7	5
Hydro power	65	65	75	5
Nuclear power	70	62	65	80–120
Fossil fuels	20	20	20	300–500

a) (6 p) Compute how the electricity price in Land is varying during the period May to November.

b) (4 p) Strålinge Kraftverksgrupp AB owns two nuclear power plants with a total installed capacity of 1 200 MW. The reactors in Strålinge were thoroughly revised already last year and are not affected by the safety issues mentioned above. According to the planning of the company, Strålinge 2 should be shut down from 1 July to 31 August. Would it be profitable for the company to deliberately delay the maintenance works in Strålinge 2 during one week in September? Such a delay would mean that the generation capacity of the company for August and September would decrease from 1.1 TWh to 1.0 TWh. The variable cost in Strålinge 2 can be assumed to 100 ¤/MWh and it can be assumed that all players in the electricity market would receive information about the additional reduction in generation capacity in their August forecast (that the reduction is intentional would however be a well kept company secret).

Problem 7 (10 p)

The power system in Rike is divided in two parts. There is a lot of hydro power in the northern part of the system, but most of the load is located in the southern part. There are several parallel AC transmission lines between the two areas. The maximal flow from north to south is 7 000 MW—if this limit is exceeded, the power system becomes unstable and there is a risk that there will be extensive blackouts in the entire or parts of the power system. Therefore, in order to avoid this, the maximal flow is set to 6 000 MW at nominal frequency. The unused transmission capacity is reserved for frequency control.

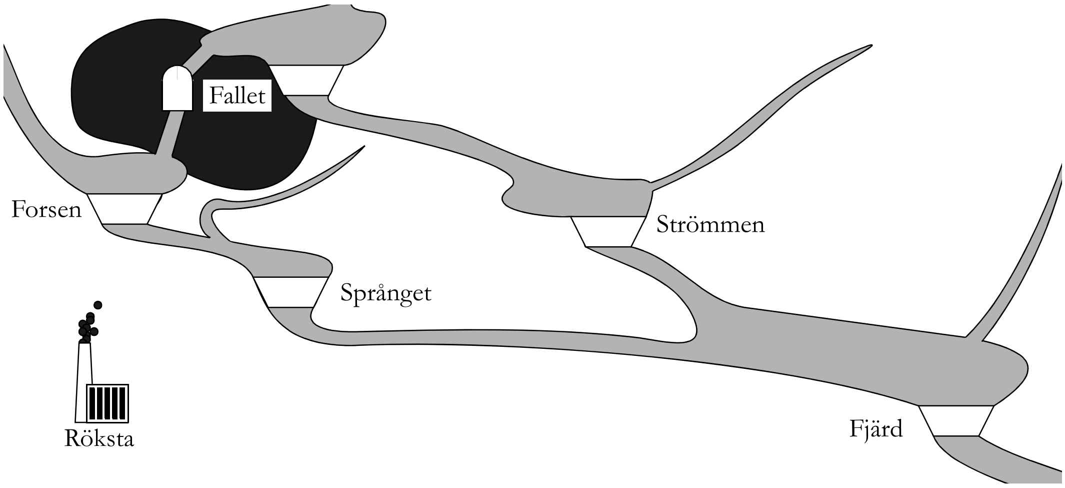
Riksnät is the system operator in Rike and has the responsibility for the frequency control. The primary control that Riksnät is purchasing is divided in two parts: the normal operation reserve and the disturbance reserve. The normal operation reserve should be available in the frequency interval 49.9 to 50.1 Hz and has a total gain of 3 000 MW/Hz, where 2 000 MW/Hz is located in power plants in the northern part of Rike. The disturbance reserve should be available in the frequency interval 49.5 to 49.9 Hz and must be large enough to make the system capable of managing an outage in the largest power plant during normal operation (i.e., when the frequency varies between 49.9 and 50.1 Hz) without overloading the interconnections between the northern and the southern part of the country.

a) (5 p) The largest power plant in Rike is a nuclear power plant, located in the southern part of Rike, with the installed capacity 1 400 MW. How large gain must the disturbance reserve have in order to guarantee that a failure in this power plant during normal operation does not cause the frequency to drop below 49.5 Hz?

b) (5 p) How much of the disturbance reserve must be located in the southern part of Rike?

Hint: Keep in mind that a part of the transmission capability from north to south may be used be the normal operation reserve!

Problem 8 (20 p)



Energibolaget AB owns five hydro power plants located as in the figure above. Data for the hydro power plants are given in table 4. Notice that Fallet is an underground power plant and that water that is discharged through the turbine is flowing to Forsen, whereas spillage ends up in Strömmen. Stored water is assumed to be used for electricity generation at the best marginal production equivalent in each power plant and future electricity generation is valued 365 SEK/MWh. The water delay time between the power plants can be neglected.

Besides hydro power, Energibolaget AB also owns the thermal power plant Röksta, which has two separate blocks. Data for Röksta is given in table 5.

Energibolaget AB is planning to sell their electricity generation at the local power exchange, ElKräng. It is assumed that the company can sell as much as they want to the prices listed in table 6.

a) (15 p) Formulate the planning problem of Energibolaget AB as a MILP problem. Use the notation in table 7 for the parameters (it is however permitted to add further symbols if you consider it necessary).

NOTICE! The following is required to get full score for this problem:

- The symbols for the optimisation variables must be clearly defined.
- The optimisation problem should be formulated so that it is easy to determine what the objective function is, which constraints there are and which limits there are.
- The possible values for all indices should be clearly stated for each equation.

b) (5 p) The hydro reservoirs of Energibolaget AB are quite large. Storing a lot of water in the reservoirs can have an impact on future electricity prices, as more hydro power will be available. The company still assumes that stored water will be used for electricity generation at the best marginal production equivalent, and if the total stored energy is less than or equal to 9 000 MWh then they expect this future generation will be sold for 365 SEK/MWh. However, any additional MWh above 9 000 MWh will only generate a future income of 320 SEK/MWh.

In order to include the relation between stored energy and future price, it is possible to introduce a variable for the total stored energy. This variable is then divided in two segments (one for energy that will be sold at the higher price and one for energy that will be sold at the lower price). The problem must also include constraints that state the relation between reservoir contents and stored energy. How must the planning problem from question a be reformulated? Do not forget to define all new variables and parameters that you introduce!

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

Power plant	Start contents of reservoir [HE]	Maximal contents of reservoir [HE]	Marginal production equivalents [MWh/HE]		Maximal discharge [HE]		Local inflow [HE]
			Segment 1	Segment 2	Segment 1	Segment 2	
Fallet	4 000	8 000	0.50	0.45	100	20	80
Strömmen	3 000	5 000	0.25	0.20	60	10	15
Forsen	3 500	6 000	0.34	0.30	150	20	140
Språnget	1 400	3 000	0.40	0.36	175	25	10
Fjärd	12 000	16 000	0.32	0.28	200	50	25

Table 5 Data for the thermal power plant Röksta.

	Block I	Block II
Installed capacity [MW]	120	96
Minimal generation when committed [MW]	40	30
Generation cost [SEK/MWh]	300	325
Start-up cost [SEK/start]	36 000	31 000

Table 6 Expected prices at ElKräng.

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 at ElKräng [SEK/MWh]	290	290	285	285	290	300	310	330	390	380	325	320
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 at ElKräng [SEK/MWh]	315	315	315	320	330	325	315	310	305	300	300	290

Table 7 Notation for the planning problem of Energibolaget AB.

Symbol	Explanation	Value
β_{Gg}	Variable operation cost in power plant *g*	See table 5
C_g^+	Start-up cost in power plant *g*	See table 5
$\overline{G}_g$	Installed capacity in power plant *g*	See table 5
$\underline{G}_g$	Minimal generation when power plant *g* is committed	See table 5
λ_t	Expected electricity price at ElKräng hour *t*	See table 6
λ_{25}	Expected electricity price at ElKräng after the end of the planning period	365
$\overline{M}_i$	Maximal contents of reservoir *i*	See table 4
$M_{i,0}$	Contents of reservoir *i* at the beginning of the planning period	See table 4
$\mu_{i,j}$	Marginal production equivalent in power plant *i*, segment *j*	See table 4
$\overline{Q}_{i,j}$	Maximal discharge in power plant *i*, segment *j*	See table 4
V_i	Local inflow to reservoir *i*	See table 4

Problem 9 (20 p)

The Ström family has recently moved to a house with electrical heating. Due to strained private economics, they are slightly worried about the electricity bills for the coming winter. Therefore, the family wants to calculate the estimated electricity cost for the period December to February.

The family has a take-and-pay contract with AB Elleverantören, where they pay a fixed price of 81 öre/kWh. In addition to that they have to pay the variable grid fee (19 öre/kWh) and energy tax (28 öre/kWh), as well as 25% VAT on the total amount (i.e., the electricity price plus variable grid fee plus energy tax). Besides this, the family have installed a small wind power plant—which earlier served the family's holiday house—on their garden. The maximal generation in the wind power plant is 2 kW and the generated electricity can be used to reduce the need for buying electricity from AB Elleverantören via the grid. If the wind power plant generates more than what is consumed in the house, the excess will be injected to the grid, but the family will not be paid for this surplus.

a) (10 p) The figures on the next page show the duration curves of the consumption, $\tilde{F}_D(x)$, and the wind power generation $\tilde{F}_W(x)$, for the period December to February. The probability that the load exceeds 7 kW depend on the average temperature during the period according to

$$\pi = \begin{cases} 0.1 - 0.01T & T \geq -2, \\ 0.12 - 0.02(T + 2) & T \leq -2, \end{cases}$$

where

π = probability that the load exceeds 7 kW = $\tilde{F}_D(7)$,
T = average temperature December to February [°C].

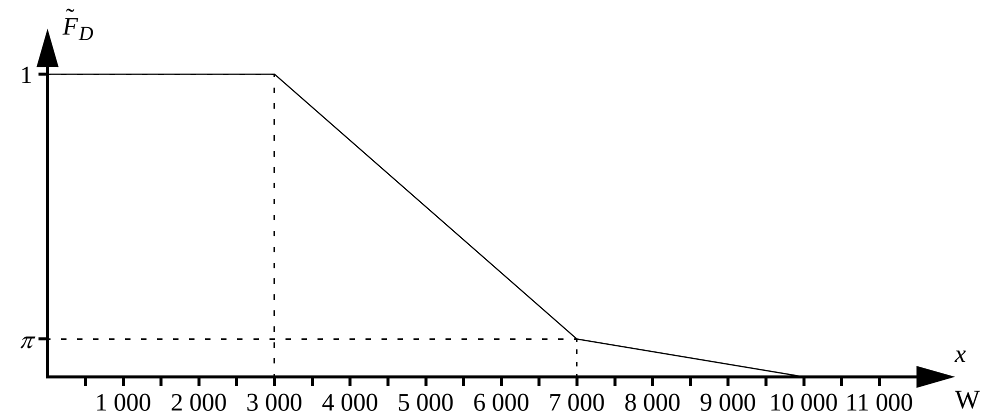
Determine the expected electricity bill of the family for the three months as a function of the average temperature.

b) (10 p) Assume that the average temperature is normally distributed with the mean 0°C and the standard deviation 1°C. Estimate the expected electricity bill of the family for the three months.

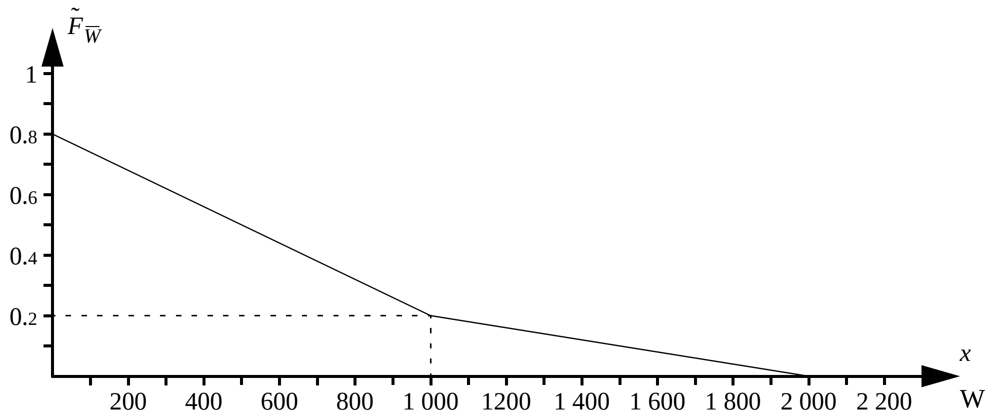
NOTICE! To get full score for this problem it is necessary to use some kind of variance reduction technique!

Table 8 Random numbers from an $N(0, 1)$-distribution.

0.5	–2.3	0.3	–0.4	3.6
1.8	0.9	–1.3	0.3	2.8



$\tilde{F}_D$
1
π
x
1 000 2 000 3 000 4 000 5 000 6 000 7 000 8 000 9 000 10 000 11 000
W



$\tilde{F}_{\overline{W}}$
1
0.8
0.6
0.4
0.2
x
200 400 600 800 1 000 1200 1 400 1 600 1 800 2 000 2 200
W