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HEAT ACCUMULATORS IN CHP NETWORKS

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Abstract—In a Combined Heat and Power (CHP) network, it is sometimes optimal to install a device for storing heat from one period of time to another. Several possibilities exist. If the electricity demand is high, while at the same time the district heating load is too small to take care of the heat from the CHP plant, it could be optimal to store heat from peak periods and discharge the storage under off-peak. It might also be optimal to store heat during off-peak and use it under the district heating peak load. The storage is then used for decreasing either the district heating demand or for decreasing the electricity load used for space heating. The paper shows how a mixed integer program is developed for use in the optimization process. As a case study, the CHP system of Malmö, Sweden, is used. Further, a sensitivity analysis is elaborated in order to show how the optimal solution will vary due to changes in certain input data.

Heat accumulators Heat storage Optimization District heating Combined Heat and Power Electricity production Linear programming Time-of-use tariffs

INTRODUCTION

In a CHP plant, both electricity and heat are produced by burning fuels in a boiler. Steam from the boiler is used in the turbine in order to run the generator. The difference in steam pressure between the inlet and the outlet of the turbine should be as high as possible when the electricity output is to be maximized. The outlet pressure depends on the condenser where returning water from the district heating grid is used for cooling. The district heating net is, thus, used as a sink for the heat from the electricity plant. If the district heating load is too small, the possibilities to produce electricity will decline. A heat accumulator might, thus, be profitable to install where surplus heat could be stored during the electricity peak load. When the demand gets lower, there may be room for this surplus heat in the district heating system. It is, however, only profitable to use the accumulator under certain circumstances, depending on e.g., electricity and fuel prices for various periods of time or on the distribution between the electricity and district heating loads. In Sweden, it is common to use electricity for space heating, at least in smaller buildings. One means to reduce the electricity load may subsequently be to use a heat storage in, or close to the building, where the accumulator is charged during off-peak conditions and discharged under electricity peak periods. Such a storage may also be useful for storing heat from the district heating plant base load and using it during peak conditions. For exemplifying the situation, we have used the CHP plant and other conditions in Malmö, sited in the south of Sweden. The same example has been used in a number of other papers, see e.g. Refs [1], [2], or [3], and thus, only a brief description is made here for convenience. The electricity load is monitored during 1988 and is shown in Table 1.

In Fig. 1, the load is shown graphically. The load has been split up for each month due to the electricity tariff, where high price conditions are valid during working days 06–22 and low prices during the rest of the time (see Table 2). There are also other tariff elements, such as a cost due to the electricity demand (270 SEK/kW).One USD is about 6 SEK.

The district heating load is shown in Table 3 and graphically in Fig. 2. This load is not monitored for the same time elements as found in the electricity tariff, but is calculated with the assumption that a gigantic building is coupled to the district heating net [1]. The overall heat use is, however, consistent with the monitored load for 1988.

Table 1. Electricity load in Malmö

Month	High (GWh)	Low (GWh)	Month	High (GWh)	Low (GWh)
January	117.9	103.5	July	68.1	56.7
February	122.1	94.9	August	96.7	70.9
March	131.0	98.5	September	107.2	81.0
April	105.7	94.1	October	111.5	99.5
May	87.9	69.6	November	129.9	98.4
June	88.6	65.1	December	135.6	111.2

As can be found from Table 3 and Fig. 2, the load in MW is the same for the high and low price time elements because of the electricity tariff. However, the amount of heat, in GWh, in each element will vary according to the number of hours in each segment.

The heat in the district heating system could be produced in a number of ways. In Table 5, the equipment, its size and the prices for the fuels are shown.

LINEAR AND MIXED PROGRAMMING

In recent years, there has been an increased interest in optimization of real world problems, by use of the so-called linear programming technique. A thorough examination of this technique is made in Ref. [4], and in this paper, only a very short description is made. The scope is to minimize, or maximize, a function called the objective function. In our case, this function will show the total Life-Cycle Cost (LCC) and is to be minimized. There are also a number of constraints in the problem all of which must be satisfied at the same time.

These constraints are designed for ascertaining that e.g., the need for heat or electricity is satisfied for each of the time elements under consideration. One drawback with linear programming is that the mathematical problem must be linear in its entirety. By the use of binary integers, i.e. variables that can only have the values 0 or 1, nonlinear problems can be piecewise linearized. The major advantage by linear programming is that, as long as the problem is totally linear, i.e. no binary integers, it can be mathematically proved that an optimal solution has been found, if it exists. This paper does not deal with how to solve such problems but instead how to transfer a real world energy system into a mathematical problem, which in turn, can be optimized by the use of the linear programming technique. We have frequently used two commercial computer programs, LAMPS [5] and ZOOM [6], for the solving process. These programs must have an input data file which must be written in the so-called MPS format. The number of variables and constraints in a problem of our type will often become very large, and several thousands of lines must sometimes be written for each optimization. This could be a very tedious procedure, but by the use of a small FORTRAN program, this process could be made automatically. We have used large computers, DEC-2065 and

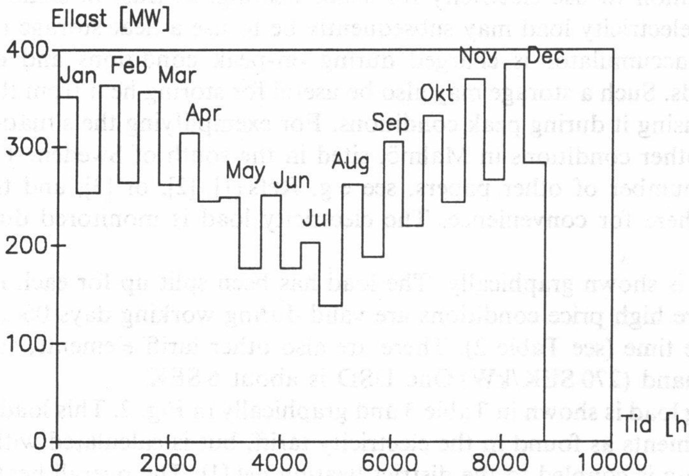

Fig. 1. Electricity load in Malmö [1].

Table 2. Electricity tariff, Sydkraft 1990

Month	Energy price (SEK/kWh) High price	Energy price (SEK/kWh) Low price
November–March	0.235	0.142
April, September, October	0.126	0.0997
May–August	0.068	0.057

NORD 570, for the solving process, but nowadays, smaller computers can be used. By the use of so-called DOS extenders, even IBM AT:s might be appropriate if enough RAM memory is implemented.

CASE STUDY

As mentioned above, the basic facts, the thermal and electric load etc., have been dealt with in other papers [1–3]. In those papers, the optimal solution for the system without any heat accumulators has been shown. The solution has been obtained by use of 12 time elements for the district heating load, one for each month, while 24 elements, two for each month, are necessary when heat has to be stored from high price to low price conditions, or vice versa. The original model must subsequently be slightly modified, and the new 12 elements be included. In the referenced papers, the model has been shown for one month only, i.e. January, so here February is chosen instead. The model for this month is shown in its entirety, but the facts described elsewhere are only covered in short. We have chosen to use the electricity and thermal power, in MW, as variables to find optimal values for, and the first part of the objective function showing the cost for electricity production in the CHP plant may be expressed as [2]:

$$\{\mathrm{EDH2} \cdot 336 \cdot 85/0.85 + \mathrm{EDL2} \cdot 360 \cdot 85/0.85 + \mathrm{HEH2} \cdot 336 \cdot [85/0.85) + 29] + \mathrm{HEL2} \cdot 360 \cdot [(85/0.85) + 29]\} \cdot 18.26 \cdot 10^{-6} \qquad (1)$$

where

EDH2 = the electricity power production, $\mathrm{MW_e}$, in February (high price element),
336 = the number of hours in the February high price element (see Table 4),
85 = the natural gas price in SEK/MWh fuel (see Table 5),
0.85 = the efficiency of the natural gas boiler (see Table 5),
EDL2 = the electricity power production, $\mathrm{MW_e}$, in February (low cost element),
360 = the number of hours in the February low cost element (see Table 4),
HEH2 = the heat from condenser during high price conditions in MW (February),
29 = the natural gas taxation for district heat production in SEK/MWh,

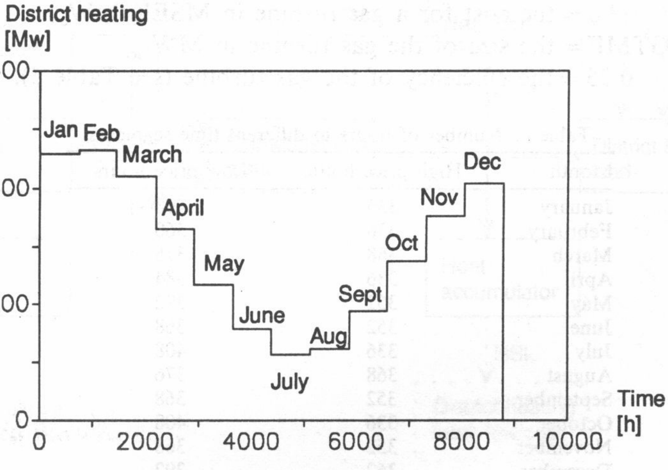

Fig. 2. District heating load in Malmö.

Table 3. District heating load in Malmö

Month	High (GWh)	Low (GWh)	Month	High (GWh)	Low (GWh)
January	153.8	186.7	July	38.0	46.2
February	156.0	167.1	August	45.2	46.2
March	154.8	158.2	September	65.6	68.6
April	111.7	127.7	October	92.3	112.1
May	82.3	91.7	November	124.5	130.2
June	55.4	57.9	December	144.0	160.3

HEL2 = the heat from condenser during high price conditions in MW (February),
18.26 = the present worth factor for annual costs, rate 5%, project life 50 yr,
10^{-6} = used for making the objective function show MSEK.

The need for electricity, including the need for a sewage water heat pump, see Fig. 3, may be covered by use of the CHP plant, a gas turbine which might be optimal to install, or by purchase from the Sydkraft power company. This will give us the first constraints in the model:

$$(\mathrm{EDH2}+\mathrm{GTH2}+\mathrm{REH2}-\mathrm{EHPH2})\cdot 336 \quad >=122.1\cdot 10^{3} \tag{2}$$

$$(\mathrm{EDL2}+\mathrm{GTL2}+\mathrm{REL2}-\mathrm{EHPL2})\cdot 360 \quad >=94.9\cdot 10^{3} \tag{3}$$

where

GTH2 = the electricity power from the gas turbine in $\mathrm{MW_e}$ (high cost, February),
REH2 = the electricity power purchase from Sydkraft in $\mathrm{MW_e}$ (high cost, February),
EHPH2 = the electricity need in $\mathrm{MW_e}$, from the sewage water heat pump (high cost),
122.1 = the electricity high cost need in February, GWh (see Table 1).
GTL2 = the electricity power from the gas turbine in $\mathrm{MW_e}$ (low cost, February),
REL2 = the electricity power purchase in $\mathrm{MW_e}$ (low cost, February),
EHPL2 = the electricity need in $\mathrm{MW_e}$ for the sewage water heat pump (low cost),
94.9 = the electricity low cost need in GWh, February (see Table 1).

The purchase of electricity from Sydkraft costs money, and subsequently, this cost (see Table 2) must be added to the objective function (1):

$$(\mathrm{REH2}\cdot 336\cdot 235+\mathrm{REL2}\cdot 360\cdot 142)\cdot 18.26\cdot 10^{-6}. \tag{1a}$$

The gas turbine, operated by natural gas, is a non-existent device and must be purchased, if optimal. The following expression is assumed to reflect the cost for acquisition, installation and operation, and must be added to the objective function (1):

$$3.0\cdot \mathrm{GTMF}+(85.0\cdot 18.26\cdot 10^{-6}\cdot(\mathrm{GTH2}\cdot 336+\mathrm{GTL2}\cdot 360)/0.25) \tag{1b}$$

where

3.0 = the cost for a gas turbine in $\mathrm{MSEK/MW_e}$,
GTMF = the size of the gas turbine in $\mathrm{MW_{fuel}}$,
0.25 = the efficiency of the gas turbine (see Table 5).

Table 4. Number of hours in different time segments

Month	High price hours	Low price hours
January	336	408
February	336	360
March	368	376
April	336	384
May	352	392
June	352	368
July	336	408
August	368	376
September	352	368
October	336	408
November	352	368
December	352	392

Table 5. Equipment in the district heating plant, etc.

Equipment type	Fuel price (SEK/MWh)	Efficiency (SEK/MWh)	Taxation (SEK/MWh)	Heat price (SEK/MWh)	Size (MW)
Garbage	54	1.0	—	54	65
Industrial waste	100	1.0	—	100	30
Coal	42	0.8	55	107.5	125
Heat pump	198	3.0	50	See Table 2	40
Natural gas	85	0.85	29	129	120
Oil	57	0.8	89	160.3	240
Gas turbine	85	0.25	—	340	New
CHP plant	85	0.85	—	100	120

GTMF above must show the maximum value of the gas turbine in $\mathrm{MW_e}$ for any time segment which is accomplished by the following constraints,:

$$(\mathrm{GTH2}/0.25) - \mathrm{GTMF} < = 0.0 \tag{4}$$

$$(\mathrm{GTL2}/0.25) - \mathrm{GTMF} < = 0.0. \tag{5}$$

The same technique is used for finding the maximum electricity power demand in $\mathrm{MW_e}$ but here only the high price element during 5 months is of interest (November–March) because of the tariff design [2]:

$$\mathrm{EDH2} + \mathrm{PMAX} + \mathrm{GTH2} - \mathrm{EHPH2} > = 419.2 \tag{6}$$

where

PMAX = the maximum electricity demand in any of the 5 months in $\mathrm{MW_e}$,
419.2 = the maximum demand monitored in February.

The demand charge, 270 SEK/kW, must also be added to the objective function (1):

$$\mathrm{PMAX} \cdot 270 \cdot 10^{-3} \cdot 18.26. \tag{1c}$$

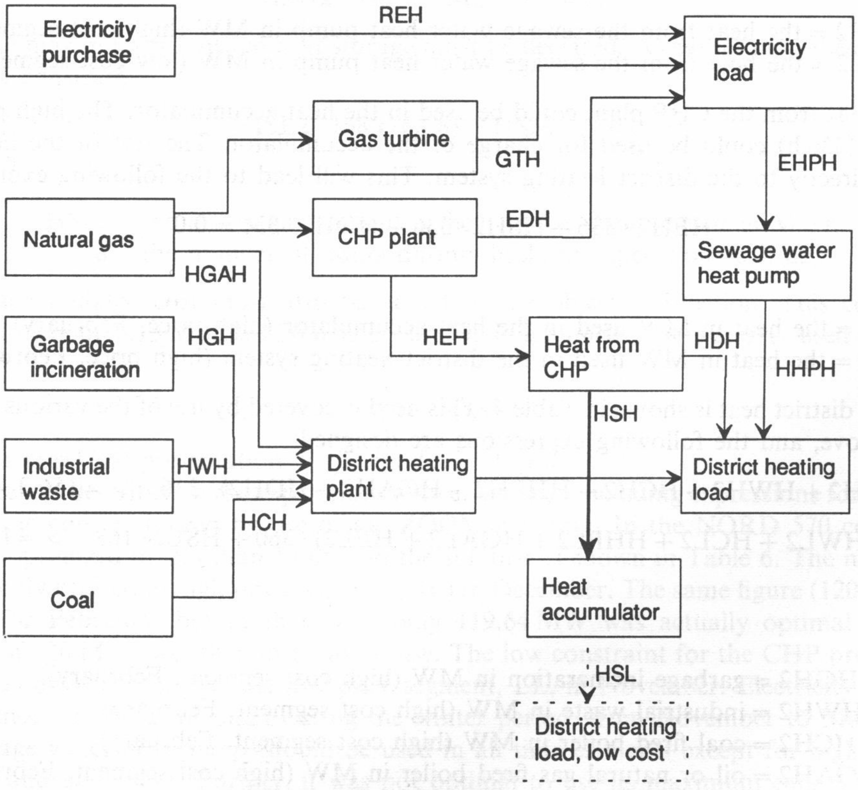

Fig. 3. Graphical presentation of the model.

The existing CHP plant has a maximum capacity of 120 $\mathrm{MW_e}$, and further, it must be turned off if the electricity demand is lower than 48 $\mathrm{MW_e}$. The model must contain this information, and this is accomplished by use of binary variables:

$$\mathrm{EDH2} - \mathrm{INTH2} \cdot 120 \quad < = 0.0 \tag{7}$$

$$\mathrm{EDL2} - \mathrm{INTL2} \cdot 120 \quad < = 0.0 \tag{8}$$

$$\mathrm{EDH2} - \mathrm{INTH2} \cdot 48 \quad > = 0.0 \tag{9}$$

$$\mathrm{EDL2} - \mathrm{INTL2} \cdot 48 \quad > = 0.0 \tag{10}$$

where

INTH2 = binary variable, 0 or 1, for high price conditions in February,
INTH2 = binary variable, 0 or 1, for low price conditions in February.

The district heat production is covered by use of waste heat from the CHP plant and from some industries, or by burning fuels in the district heating plant. The fuel could be garbage in the incineration plant, coal, oil or natural gas. The plant can also use heat from a heat pump system in the sewage water facility (see Table 5). Further, it possibly will be optimal to use the heat accumulator. Firstly, the amount of heat from the CHP plant must be considered. It is assumed that three parts of heat must be produced for each unit of electricity [2]:

$$3.0 \cdot \mathrm{EDH2} - \mathrm{HEH2} = 0.0 \tag{11}$$

$$3.0 \cdot \mathrm{EDL2} - \mathrm{HEL2} = 0.0. \tag{12}$$

In the same way, there must be expressions showing the influence of the sewage water heat pump:

$$3.0 \cdot \mathrm{EHPH} - \mathrm{HHPH2} = 0.0 \tag{13}$$

$$3.0 \cdot \mathrm{EHPL2} - \mathrm{HHPL2} = 0.0 \tag{14}$$

where

HHPH2 = the heat from the sewage water heat pump in MW (high cost segment)
HHPL2 = the heat from the sewage water heat pump in MW (low cost segment).

Part of the heat from the CHP plant could be used in the heat accumulator. The high price hours in February (336 h) could be used for charge of the accumulator. The rest of the heat will be distributed directly to the district heating system. This will lead to the following expression:

$$\mathrm{HEH2} \cdot 336 - \mathrm{HSH2} \cdot 336 - \mathrm{HDH2} \cdot 336 = 0.0 \tag{15}$$

where

HSH2 = the heat in MW used in the heat accumulator (high price, February)
HDH2 = the heat in MW used in the district heating system (high price, February).

The need for district heat is shown in Table 4. This need is covered by use of the various equipment discussed above, and the following expressions are designed:

$$(\mathrm{HGH2} + \mathrm{HWH2} + \mathrm{HCH2} + \mathrm{HHPH2} + \mathrm{HGAH2} + \mathrm{HDH2}) \cdot 336 \quad > = 156.0 \cdot 10^3 \tag{16}$$

$$(\mathrm{HGL2} + \mathrm{HWL2} + \mathrm{HCL2} + \mathrm{HHPL2} + \mathrm{HGAL2} + \mathrm{HEL2}) \cdot 360 + \mathrm{HSL2} \cdot 168 \quad > = 167.1 \cdot 10^3 \tag{17}$$

where

HGH2 = garbage incineration in MW (high cost segment, February)
HWH2 = industrial waste in MW (high cost segment, February)
HCH2 = coal fired boiler in MW (high cost segment, February)
HGAH2 = oil or natural gas fired boiler in MW (high cost segment, February)
HGL2 = garbage incineration in MW (low cost segment, February)

HWL2 = industrial waste in MW (low cost segment, February)
HCL2 = coal fired boiler in MW (low cost segment, February)
HGAL2 = oil or natural gas fired boiler in MW (low cost segment, February)
HSL2 = heat storage in MW (low cost segment, February)
168 = the number of hours for storage discharge in February.

The number of discharge hours is much lower than the charging hours for the storage. This is so because it is assumed that the discharge must be fulfilled during the low cost hours under one working day or from 2200 to 0600, equalling 8 h. The cost for the district heat production must also be added to the objective function:

$$\{(\mathrm{HGH2}\cdot 336+\mathrm{HGL2}\cdot 360)\cdot 54.0+(\mathrm{HWH2}\cdot 336+\mathrm{HWL2}\cdot 360)\cdot 100.0 \\ +(\mathrm{HCH2}\cdot 336+\mathrm{HCL2}\cdot 360)\cdot 107.5 \\ +(\mathrm{HGAH2}\cdot 336+\mathrm{HGAL2}\cdot 360)\cdot[(85/0.85)+29]\}\cdot 18.26\cdot 10^{-6} \tag{1d}$$

where

54.0 = The heat price, in SEK/MWh, from the garbage incinerator
100.0 = The heat price, in SEK/MWh, from industrial waste
107.5 = The heat price, in SEK/MWh, from the coal fired boiler (see Table 5).

In Table 5, there is also information about the maximum power in MW from the different equipments which will yield the following expressions:

$$\mathrm{HGH2}<=65,\quad \mathrm{HGL2}<=65,\quad \mathrm{HWH2}<=30,\quad \mathrm{HWL2}<=30,\quad \mathrm{HCH2}<=125, \\ \mathrm{HCL2}<=125,\quad \mathrm{HHPH2}<=40,\quad \mathrm{HHPL2}<=40,\quad \mathrm{HGAH}<=120,\quad \mathrm{HGAL2}<=126. \tag{18}$$

The heat storage is, in this first case, charged during high price conditions and discharged other times. It is necessary to include an expression showing that the heat transferred in and out of the accumulator is equal from high to low cost periods:

$$\mathrm{HSH2}\cdot 336-\mathrm{HSL2}\cdot 168=0.0. \tag{19}$$

Further, the maximum size of the heat storage must be declared. As earlier described, this is done by use of a constraint:

$$\mathrm{HSL2}\cdot 168/(168/8)-\mathrm{HSM}<=0.0 \tag{20}$$

where

HSM = the maximum amount of heat in the accumulator in MWh
8 = the number of hours during discharge operation each day.

The heat accumulator cost must also be added to the objective function. This cost has been estimated to about 0.15 MSEK/MWh heat, and it is assumed that water is used as a storing medium:

$$0.15\cdot\mathrm{HSM}. \tag{1e}$$

In Fig. 3, a graphical presentation of the model is shown.

The model, as described in the expressions above, and also including expressions for all the other 11 months, is now optimized by use of the ZOOM program. In the NORD 570 computer, the problem is optimized in less than 1 min and the solution is shown in Table 6. The maximum use of CHP is only utilized in high price segment (HL) in December. The same figure (120 MW) is also presented for February, but in that case, only 119.64 MW was actually optimal to use. The constraint of 120 MW, was therefore, not in use. The low constraint for the CHP production, i.e. 48 MW, was only in effect for the low price segment, LL, in November. Electricity was optimal to be produced in the CHP plant during the winter period, from November to March.

The sewage water heat pump should be used in all time elements except for high load during November and December. Further, it was not optimal to use its maximum capacity in the high load segment in January.

Table 6. Optimal use of electricity and heat in MW in Malmö, Sweden

	Electricity				District Heating											
	CHP		Purchase		CHP		Garbage		Heat pump		Waste		Coal		Natural gas	
Month	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL
January	119	66	243	201	358	198	65	65	35	40	—	40	—	125	—	—
February	120	68	257	209	359	204	65	65	40	40	—	30	—	125	—	—
March	105	53	264	222	316	160	65	65	40	40	—	30	—	125	—	—
April	—	—	328	258	—	—	65	65	40	40	30	30	125	125	72	72
May	—	—	263	191	—	—	65	65	40	40	30	30	99	99	—	—
June	—	—	265	190	—	—	65	65	40	40	30	30	22	22	—	—
July	—	—	216	153	—	—	65	65	40	40	8	8	—	—	—	—
August	—	—	276	201	—	—	65	65	40	40	18	18	—	—	—	—
September	—	—	318	233	—	—	65	65	40	40	30	30	51	51	—	—
October	—	—	345	257	—	—	65	65	40	40	30	30	125	125	15	15
November	98	48	271	233	295	144	59	65	—	40	—	30	—	75	—	—
December	120	50	265	247	360	149	49	65	—	40	—	30	—	125	—	—

The district heating equipment is used in all the time segments, even if the maximum capacity for the garbage incineration plant was not utilized for the high load segments in November and December. This fact is very important, because it shows the very low marginal cost for heat when the CHP plant is used. The heat price for garbage is only 0.054 SEK/kWh, but even this low price could not compete with the heat price from the CHP plant. In Ref. [7], there is a thorough examination of optimal prices for heat and electricity. Heat from the sewage water heat pump is also utilized to a very low cost, but for some time segments it is optimal to turn it off. The waste heat should mostly be used during the summer season, even if there are elements during low price conditions where it is profitable during the winter as well. The coal fired boiler is used with its maximum capacity during spring and autumn and for some low price elements during the winter. Natural gas should only be used in April and October.

Note that no heat storage was found to be optimal, and further, the gas turbine was excluded from the solution. Table 6 makes it also possible to examine if the solution is accurate due to the expressions shown above. In February, there is to be produced 119.64 MW_e, equalling 40,199 MWh in the CHP plant. The purchase from the market is 257.08 MW_e, equalling 86,378 MWh or added to the produced electricity 126,577 MWh. The electricity use for the heat pump is 13.33 MW_e, or 4478 MWh, which means that 122,099 MWh are used for the original electricity load, see expression (2). The district heating load, for the low price element in February, is covered by 204.17 MW from the CHP plant, 65 MW from garbage incineration, 40 MW sewage water heat pump, 30 MW waste heat and 125 MW from the coal fired boiler. In total, this becomes 464.17 MW or 167,101 MWh, which value is found in expression (17). We have also designed a computer program for calculating the cost split up for different equipment (see Table 7). The major part of the cost comes from the purchase and CHP production of electricity, while the district heating system is operated by use of very cheap fuels, such as garbage. The average mean value heat cost for the district heating plant is only about 0.08 SEK/kWh.

If the total annual cost above is multiplied by the present value factor, the LCC becomes about 11.5 GSEK. As found above, no heating storage was optimal to use. This is so because of the installation cost for the heat accumulator, i.e. 150 SEK/kWh. If the heating storage was an existing device, no such cost would emerge. Setting the installation cost to zero, an accumulator of 2744 MWh would be optimal. The total LCC will then be reduced to 11.45 GSEK. In Table 8, the use of the heat storage is shown.

The heat accumulator is used during 6 months, November–April. It is interesting to see that the storage is optimal to use even under those months when the CHP plant, without the storage, is used at its maximum capacity, or close to it (see Table 6). In January, the CHP plant should use 119 MW_e when the storage does not operate, and 120 MW_e when it is optimal to use a storage. This extra MW cannot explain why the storage will be a part of the optimal solution. Instead, it is the result of saving electricity and heat during the low cost segments of the electricity tariff. The situation is clarified in Table 9.

Table 7. The total annual cost for operation of different equipment

Source	Energy production in GWh Electricity	 Heat	Annual cost in MSEK
CHP plant	304.3	148.3	148.3
Garbage inc.		563.0	30.4
Heat pump		321.3	12.4
Waste heat		185.9	18.6
Coal		529.0	56.9
Natural gas		63.1	8.1
Purchase el.	2041.3		266.5
Demand fee el.			90.5
Sum			631.7

Table 8. Optimal use of heat accumulator in GWh

Month	Heat stored	Month	Heat stored
January	21.8	July	—
February	52.4	August	—
March	63.1	September	—
April	27.8	October	—
May	—	November	49.9
June	—	December	60.4

Note that the energy cost for the sewage water heat pump is included in the money spent for producing and purchase of electricity. From Table 9, it is obvious that it is cheaper to use the heat accumulator, if it is free. The savings in February are very small, and the same is valid for the other 6 months. Therefore, it is also clear that the accumulator will fall out from the optimal solution even for a low acquisition and installation cost. It is also interesting to see that the major differences between the costs emerge in the low cost segments, even if the storage was intended for an increased electricity production in the CHP plant during the high cost segments. The reason for this is mostly due to the fact that the heat sink in the district heating grid was not a constraint but instead the maximum capacity of the CHP plant. However, we have shown that, because of the cost for installation of the heat accumulator, it is not plausible that such a device will ever be optimal. The decrease in the total LCC is only about 50 MSEK, i.e. 2.7 MSEK/yr, and the storage will cost 0.15 MSEK/MWh storage volume. The storage could, thus, only be of the size 18.5 MWh while the profit above was calculated for a storage of 2744 MWh.

There is also a possibility that a storage could be profitable to use for storing heat from the low to the high cost segment. In order to find out if this could be the case, the model must be changed in some aspects. Expression (15) must be changed to:

$$\mathrm{HEL2} \cdot 360 - \mathrm{HSL2} \cdot 168 - \mathrm{HDL2} \cdot 360 = 0.0 \tag{15a}$$

and the expressions (16) and (17) will change to:

$$(\mathrm{HGH2} + \mathrm{HWH2} + \mathrm{HCH2} + \mathrm{HHPH2} + \mathrm{HGAH2} + \mathrm{HEH2} + \mathrm{HSH2}) \cdot 336 >= 156.0 \cdot 10^3 \tag{16a}$$

$$(\mathrm{HGL2} + \mathrm{HWL2} + \mathrm{HCL2} + \mathrm{HHPL2} + \mathrm{HGAL2} + \mathrm{HDL2}) \cdot 360 >= 167.1 \cdot 10^3. \tag{17a}$$

Table 9. Optimal solution and annual costs with and without a heat accumulator (February)

Equipment	Without accumulator Size (MW)	 Energy cost (MSEK)	With accumulator Size (MW)	 Energy cost (MSEK)
$\mathrm{CHP_{el.}}$ HC	119.6	4.018	120.0	4.032
$\mathrm{CHP_{el.}}$ LC	68.0	2.448	48.0	1.728
Purchase HC	257.1	20.301	256.7	20.269
Purchase LC	209.0	10.684	229.0	11.706
$\mathrm{CHP_{heat}}$ HC	359.3	15.573	360.0	15.603
$\mathrm{CHP_{heat}}$ LC	204.2	9.482	144.0	6.688
Garbage HC	65.0	1.179	65.0	1.179
Garbage LC	65.0	1.264	65.0	1.264
Heat pump HC	40.0	—	40.0	—
Heat pump LC	40.0	—	40.0	—
Waste heat HC	—	—	30.0	1.008
Waste heat LC	30.0	1.080	30.0	1.080
Coal HC	—	—	125.0	4.515
Coal LC	125.0	4.838	39.4	1.525
Sum		70.867		70.597

This new model results in the same optimal solution as before, no heating storage is to be installed in the system. If the cost for the heat accumulator is reduced to zero, the result differs from the first model, and now, no accumulator is optimal even if it is free of charge. This is so because there is no shortage in the heat sink during the low cost segments. If it would be profitable to produce more electricity and heat in the CHP plant, this is possible even without the heat storage.

The third case to examine is to find out if a heat accumulator could be profitable for saving electricity in the electricity grid. In Sweden, where many buildings are electrically heated, at least smaller ones, it might be possible to produce hot water during the low cost period, while using it during the high cost period. The model must once again be changed in order to include also this type of a storage. First, an expression similar to (19) must be added:

$$\mathrm{HS2H2} \cdot 336 - \mathrm{HS2L2} \cdot 168 = 0 \tag{21}$$

where

HS2HS = the thermal size in MW of heating storage type 2 (high cost)
HS2L2 = the thermal size in MW of heating storage type 2 (low cost.)

Further, the left-hand sides of expressions (2) and (3) must be added with:

$$\mathrm{HS2H2} \cdot 336 \tag{2a}$$

$$-\mathrm{HS2LS} \cdot 168. \tag{3a}$$

It is also necessary to change the $>=$ to a $=$ sign, because there is no cost for the operation of the storage. If the $>=$ sign still is present, it is cheaper to choose a slightly larger storage, but this will also mean that the expressions (2a) and (3a) will become greater than the actual need for electricity which is impossible in real life. The maximum size of the storage must also be modelled, and as in expression (20):

$$\mathrm{HS2LS} \cdot 168/(168/8) - \mathrm{HS2M} < = 0.0 \tag{22}$$

where

HS2M = the maximum size of the type 2 storage in MWh.

The cost for the storage is assumed to be the same for the two types, and thus, the objective function must include:

$$+0.15 \cdot \mathrm{HS2M}. \tag{1f}$$

The optimal solution to this new mathematical model is that a large heat accumulator (4273 MWh) should be chosen. For February, the variables will have the values shown in Table 10, and they show that there should be a major increase in electricity purchase during the low cost segment, i.e. 458.28 instead of 209.01 MW. This amount of energy is used during the high cost period instead. However, it is not possible to utilize an accumulator for storing all this heat. Only a part of the electricity load is used for space heating, even in Sweden, but the important thing to notice is that there is a significant difference in the profitability for the different types of accumulators. Small accumulators in, or close to, the buildings might be very interesting items to consider as building retrofits for getting a lower LCC for the proprietor. This is so even if the cost for smaller accumulators will increase compared to the big storing devices examined here.

The last case discussed here deals with a heat storage used for storing district heat from low cost segments to high cost segments or vice versa. The cheapest heat utilized in the district heating grid emerges when the CHP plant operates (see Table 6). The storage must, thus, be used for storing heat from the electricity high cost to the low cost elements. However, the cheapest heat is the waste from the CHP plant, and this case is examined above with the result that a storage was to be used only if the cost was very low. No storage was optimal if the cost was in the vicinity of 0.15 MSEK/MWh. A mix of CHP heat and heat from other more expensive fuels must, therefore, be even less advantageous, no storage will be chosen. It might be different if there were a significant difference between the high cost and low cost use of district heat, but in this case study, this has not been the situation. A heat storage will also have an increased profitability if it is loaded and

Table 10. Optimal use of heat accumulator for February

Variable name	Value (MW)	Variable	Value (MW)
EDH2	109.65	EDL2	67.98
HEH2	329.28	HEL2	204.16
REH2	—	REL2	458.28
EHPH2	13.33	EHPL2	13.33
GTH2	—	GTL2	—
GTMF	—	PMAX	92.21
HHPH2	40.0	HHPL2	40.0
HS2H2	267.07	HS2L2	534.14
HGH2	65.0	HGL2	65.0
HWH2	30.0	HWL2	30.0
HCH2	—	HCL2	125.0
HGAH2	—	HGAL2	—

discharged at a higher rate. In order to study this, the time segments must be split up in shorter intervals which also means that the electric and thermal loads, as well as the cost for producing and purchase of electricity and heat, must be split up in the same time elements.

CONCLUSIONS

We have shown that heating storage devices might be of interest in Combined Heat and Power (CHP) networks. The storage should primarily be used for that part of the electricity load which is used for space heating, common in Sweden. Using the cheaper night hours, due to the electricity tariff, for heating domestic hot water and water used in the radiators shows the highest profitability. A storage used for accumulating the heat from an increased use of the CHP plant seems to be of no interest at least in Malmö, where a very big district heating grid is available as a heat sink. If the storage cost is very low, or if it is already installed, there is an optimal use for it. Storing heat from the district heating plant seems to be of no interest at all. This is so because of the low cost for heat from the plant. Most of it comes from waste and very cheap fuels, and further, there is no difference in thermal load between the high and low cost segments in the cases that have been examined.

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