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.

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 examplifying 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. [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.

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

Table 1: Electricity load in Malmö

In Figure 1 the load is shown graphically.

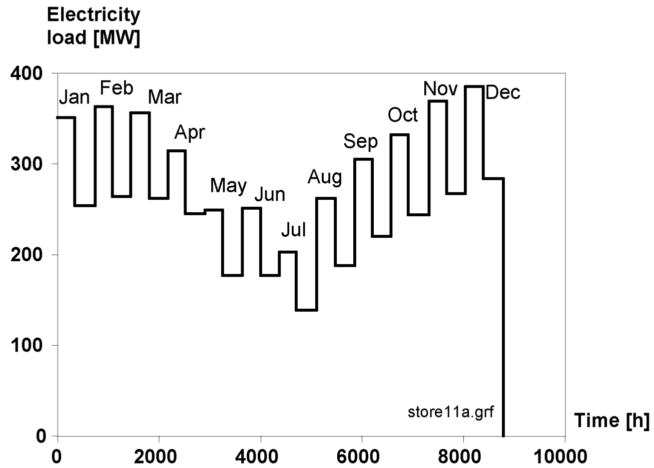

Figure 1: Electricity load in Malmö, see Ref. [1].

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 Figure 2.

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

Month	Energy price [SEK/kWh] High price	Low price
November - March	0.235	0.142
April, September, October	0.126	0.0997
May - August	0.068	0.057

Table 2: Electricity tariff, Sydkraft 1990

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

Table 3: District heating load in Malmö

As can be found from Table 3 and Figure 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 4 the equipment, its size and the prices for the fuels are shown.

Equipment Type	Fuel price (SEK/MWh)	Efficiency (SEK/MWh)	Taxation (SEK/MWh)	Heat price (SEK/MWh)	Size (MW)
Garbage	54	1.0	-	54	65
Ind. 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

Table 4: Equipment in the district heating plant etc.

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 [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

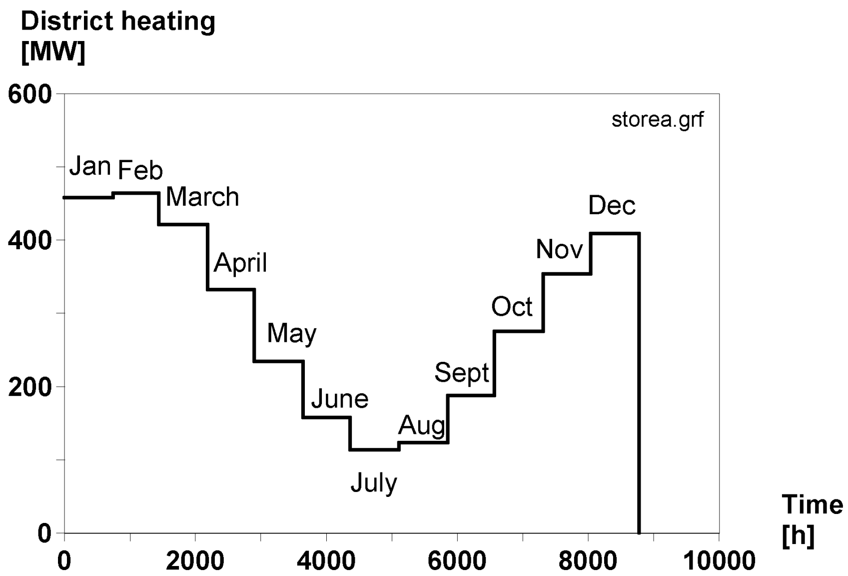

Figure 2: District heating load in Malmö

Cost, LCC, and is to be minimized. There are also a number of constraints in the problem which all of them 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 linearizied. 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 see Ref. [5] and ZOOM Ref. [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 thousends 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 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, see Refs. [1], [2] and [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 twelve 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 twelve 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 found 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 found in Ref. [2]:

$$(\frac{EDH_2 \times 336 \times 85}{0.85} + \frac{EDL_2 \times 360 \times 85}{0.85} +$$

$$+HEH_2 \times 336 \times [\frac{85}{0.85} + 29] + HEL_2 \times 360 \times [\frac{85}{0.85} + 29]) \times 18.26 \times 10^{-6} \quad (1)$$

where EDH_2 = The electricity power production, MWe, in February, high price element, 336 = The number of hours in the February high price element, see Table 5, 85 = The natural gas price in SEK/MWh fuel, see Table 4, 0.85 = The efficiency of the natural gas boiler, see Table 4, EDL_2 = The electricity power production, MWe, in February, low cost element, 360 = The number of hours in the February low cost element, see Table 5, HEH_2 = The heat from condenser during high price conditions in MW, February, 29 = The natural gas taxation for district heat production in SEK/MWh, HEL_2 = The heat from condenser during low price conditions in MW, February 18.26 = The present worth factor for annual costs, rate 5 %, project life 50 years, and 10^{-6} = Used for making the objective function show MSEK.

The need for electricity, including the need for a sewage water heat pump, see Figure 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:

$$(EDH_2 + GTH_2 + REH_2 - EHPH_2) \times 336 \geq 122.1 \times 10^3 \quad (2)$$

$$(EDL_2 + GTL_2 + REL_2 - EHPL2) \times 360 \geq 94.9 \times 10^3 \quad (3)$$

where GTH_2 = The electricity power from the gas turbine in MW_e, high cost, February, REH_2 = The electricity power purchase from Sydkraft in MW_e, high cost, February, $EHPH_2$ = The electricity need in MW_e, from the sewage water heat pump, high cost 122.1 = The electricity high cost need in February, GWh, see Table 1, GTL_2 = The electricity power from the gas turbine in MW_e, low cost, February, REL_2 = The electricity power purchase in MW_e, low cost, February, $EHPL_2$ = The electricity need in MW_e for the sewage water heat

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: Number of hours in the different time segments

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, i.e. number (1):

$$(REH_2 \times 336 \times 235 + REL_2 \times 360 \times 142) \times 18.26 \times 10^{-6} \tag{4}$$

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 (1):

$$3.0 \times GTMF + \frac{(85.0 \times 18.26 \times 10^{-6} \times (GTH_2 \times 336 + GTL_2 \times 360))}{0.25} \tag{5}$$

where 3.0 = the cost for a gas turbine in MSEK/MW$_e$, GTMF = the size of the gas turbine in MW fuel, 0.25 = the efficiency of the gas turbine, see Table 4.

GTMF above must show the maximum value of the gas turbine in MWe, for any time segment which is accomplished by the following constraints,:

$$\frac{GTH_2}{0.25} - GTMF \leq 0.0 \tag{6}$$

$$\frac{GTL_2}{0.25} - GTMF \leq 0.0 \tag{7}$$

The same technique is used for finding the maximum electricity power demand in MW$_e$ but here only the high price element during five months is of interest, November to March, because of the tariff design, see Ref. [2]:

$$EDH_2 + PMAX + GTH_2 - EHPH_2 \geq 419.2 \tag{8}$$

where $PMAX$ = the maximum electricity demand in any of the five months in 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):

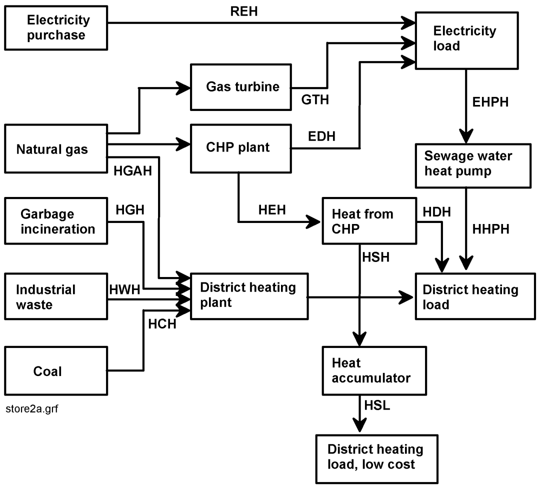

Figure 3: Graphical presentation of the model

$$PMAX \times 270 \times 10^{-3} \times 18.26 \tag{9}$$

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

$$EDH_2 - INTH_2 \times 120 \leq 0.0 \tag{10}$$

$$EDL_2 - INTL_2 \times 120 \leq 0.0 \tag{11}$$

$$EDH_2 - INTH_2 \times 48 \geq 0.0 \tag{12}$$

$$EDL_2 - INTL_2 \times 48 \geq 0.0 \tag{13}$$

where $INTH_2 =$ binary variable, 0 or 1, for high price conditions in February, $INTL_2 =$ 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 4. 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, see Ref. [2]:

$$3.0 \times EDH_2 - HEH_2 = 0.0 \tag{14}$$

$$3.0 \times EDL_2 - HEL_2 = 0.0 \tag{15}$$

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

$$3.0 \times EHPH_2 - HHPH_2 = 0.0 \tag{16}$$

$$3.0 \times EHPL_2 - HHPL_2 = 0.0 \tag{17}$$

where $HHPH_2$ = the heat from the sewage water heat pump in MW, high cost segment and $HHPL_2$ = 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 hours, 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:

$$HEH_2 \times 336 - HSH_2 \times 336 - HDH_2 \times 336 = 0.0 \tag{18}$$

where HSH_2 = the heat in MW used in the heat accumulator, high price, February and HDH_2 = the heat in MW used in the district heating system, high price, February.

The need for district heat is shown in Table 5. This need is covered by use of the various equipment discussed above and the following expressions are designed:

$$(HGH_2 + HWH_2 + HCH_2 + HHPH_2 + HGAH_2 + HDH_2) \times 336 \geq$$

$$156.0 \times 10^3 \tag{19}$$

$$(HGL_2 + HWL_2 + HCL_2 + HHPL_2 + HGAL_2 + HEL_2) + HSL_2 \times 168 \geq$$

$$167.1 \times 10^3 \tag{20}$$

where HGH_2 = garbage incineration in MW, high cost segment, February, HWH_2= industrial waste in MW, high cost segment, February, HCH_2 = coal fired boiler in MW, high cost segment, February, $HGAH_2$ = oil or natural gas fired boiler in MW, high cost segment, February, HGL_2 = garbage incineration in MW, low cost segment, February, HWL_2 = industrial waste in MW, low cost segment, February, HCL_2 = coal fired boiler in MW, low cost segment, February, $HGAL_2$ = oil or natural gas fired boiler in MW, low cost segment, February, HSL_2 = Heat storage in MW, low cost segment, February and 168 = The number of hours for storage discharge in February.

The number of discharge hours are much lower than the charging hours for the stoarge. 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 hours. The cost for the district heat production must also be added to the objective function:

$$((HGH_2 \times 336 + HGL_2 \times 360) \times 54.0 + (HWH_2 \times 336 + HWL_2 \times 360) \times 100.0+$$

$$+(HCH_2 \times 336 + HCL_2 \times 360) \times 107.5+$$

$$+(HGAH_2 \times 336 + HGAL_2 \times 360)) \times [\frac{85}{0.85} + 29] \times 18.26 \times 10^{-6} \qquad (21)$$

where 54.0 = The heat price, in SEK/MWh, from the garbage incinerator, 100.0 = The heat price, in SEK/MWh, from industrial waste and 107.5 = The heat price, in SEK/MWh, from the coal fired boiler, see Table 4.

In Table 4 there is also information about the maximum power in MW from the different equipment which will yield the following expressions:

$$HGH_2 \leq 65,\ HGL_2 \leq 65,\ HWH_2 \leq 30,\ HWL_2 \leq 30,$$

$$HCH_2 \leq 125\ HCL_2 \leq 125,$$

$$HHPH_2 \leq 40,\ HHPL_2 \leq 40,\ HGAH_2 \leq 120,\ HGAL_2 \leq 120 \qquad (22)$$

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:

$$HSH_2 \times 336 - HSL2 \times 168 = 0.0 \qquad (23)$$

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

$$\frac{HSL_2 \times 168}{\frac{168}{8}} - HSM \leq 0.0 \qquad (24)$$

where HSM = the maximum amount of heat in the accumulator in MWh and 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:

$$0.15 \times HSM \qquad (25)$$

In order to make the situation a bit clearer, a graphical presentation of the model was shown, see Figure 3. 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 one minute and the solution is shown in Table 6.

The maximum use of CHP is only utilized in the 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

Month	Electricity				District heating											
	CHP		Purchase		CHP		Garbage		Heat pump		Waste		Coal		Natural gas	
	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL	HL	LL
Jan	119	66	243	201	358	198	65	65	35	40	-	30	-	125	-	-
Feb	120	68	257	209	359	204	65	65	40	40	-	30	-	125	-	-
Mar	105	53	264	222	316	160	65	65	40	40	-	30	-	125	-	-
Apr	-	-	328	258	-	-	65	65	40	40	30	30	125	125	72	72
May	-	-	263	191	-	-	65	65	40	40	30	30	99	99	-	-
Jun	-	-	265	190	-	-	65	65	40	40	30	30	22	22	-	-
Jul	-	-	216	153	-	-	65	65	40	40	8	8	-	-	-	-
Aug	-	-	276	201	-	-	65	65	40	40	18	18	-	-	-	-
Sep	-	-	318	233	-	-	65	65	40	40	30	30	51	51	-	-
Oct	-	-	345	257	-	-	65	65	40	40	30	30	125	125	15	15
Nov	98	48	271	233	295	144	59	65	-	40	-	30	-	75	-	-
Dec	120	50	265	247	360	149	49	65	-	40	-	30	-	125	-	-

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

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.

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 MWe, equalling 40,199 MWh, in the CHP plant. The purchase from the market is 257.08 MWe equalling 86,378 MWh or totally 126,577 MWh. The electricity use for the heat pump is 13.33 MWe, or 4,478 MWh which means that 122,099 MWh are used for the original electricity load, see Expression (2). The district heating load is for the low price element in February covered by 204.17 MW from the CHP plant, 65 MW from garabage 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 (20). 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.

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 7: The total annual cost for operation of different equipment

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 2 744 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.

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

Table 8: Optimal use of heat accumulator in GWh

The heat accumulator is used during six months, November to 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 MWe 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 claryfied in Table 9.

Note that the energy cost for the sewage water heat pump is included in the money spent for producing and purchase of electricity. From the 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 six months.

	Without accumulator		With accumulator	
Equipment	Size [MW]	Energy cost [MSEK]	Size [MW]	Energy cost [MSEK]
CHPel. HC	119.6	4.018	120.0	4.032
CHPel. 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
CHPheat HC	359.3	15.573	360.0	15.603
CHPheat 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

Table 9: Optimal solution and annual costs with and without a heat accumulator, February

Therefore, it is also clear that the accumulator will fall out from the optimal solution even for a low acquisition and installation cost. Interesting is also 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/year, 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 2 744 MWh. There is also a possibility that a storage could be profitable to use for storing heat from the low cost 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 (18) must be changed to:

$$HEL_2 \times 360 - HSL_2 \times 168 - HDL_2 \times 360 = 0.0 \tag{26}$$

and the Expressions (19) and (20) will change to:

$$(HGH_2 + HWH_2 + HCH_2 + HHPH_2 + HGAH_2 + \\ + HEH_2 + HSH_2) \times 336 \geq 156.0 \times 10^3 \tag{27}$$

$$(HGL_2 + HWL_2 + HCL_2 + HHPL_2 + HGAL_2 + \\ + HDL_2) \times 360 \geq 167.1 \times 10^3 \tag{28}$$

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 posssible 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 Expression (23) must be added:

$$HS2H_2 \times 336 - HS2L_2 \times 168 = 0 \tag{29}$$

where $HS2H_2$ = The thermal size in MW of heating storage type 2, high cost and$HS2L_2$ = 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:

$$HS2H_2 \times 336 \tag{30}$$

$$-HS2L_2 \times 168 \tag{31}$$

It is also necessary to change the $>=$ sign 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 (30) and (31) 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 (24):

$$\frac{HS2L_2 \times 168}{\frac{168}{8}} - HS2M \leq 0.0 \tag{32}$$

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:

$$+0.15 \times HS2M \tag{33}$$

The optimal solution to this new mathematical model is that a large heat accumulator, 4 273 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 209.01MW.

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

Variable name	Value [MW]	Variable name	Value [MW]
EDH_2	109.65	EDL_2	67.98
HEH_2	329.28	HEL_2	204.16
REH_2	-	REL_2	458.28
$EHPH_2$	13.33	$EHPL_2$	13.33
GTH_2	-	GTL_2	-
$GTMF$	-	$PMAX$	92.21
$HHPH_2$	40.0	$HHPL_2$	40.0
$HS2H_2$	267.07	$HS2L_2$	534.14
HGH_2	65.0	HGL_2	65.0
HWH_2	30.0	HWL_2	30.0
HCH_2	-	HCL_2	125.0
$HGAH_2$	-	$HGAL_2$	-

Table 10: Optimal use of heat accumulator for February

heat utilized in the district heating grid emerge 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 was 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 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 show 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 cost and low cost segments in the case that have been examined.

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