HOT WATER HEAT ACCUMULATORS IN SINGLE-FAMILY HOUSES

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Abstract

In Sweden, as in many other countries, there is a significant difference in electricity demand between day and night. In order to encourage the end use consumer to use less electricity during peak situations, time-of-use tariffs gets more common. The price differs from about 0.8 to 0.35 SEK/kWh, taxation included. (1ECU equals about 7 SEK.) If some of the electricity under the high price period, which falls between 0600 to 2200 during November to March, could be transferred to the low price hours, the electricity bill could be reduced. In Sweden it is common to use electricity for space and hot water heating at least in single-family houses. By use of a hot water accumulator the need for heat could be produced during the cheap hours and the storage could be discharged when the high price hours occur. This paper describes the electricity use for hot water and space heating in a single-family house sited in Linköping, Sweden, where extensive monitoring have been utilized during 1987. Some 30 values for temperatures and electricity demands have been measured each hour, or sometimes even for shorter time intervals. These monitored data have been the base for examining if a water accumulator could be of interest for the proprietor of the building, i.e. if the cost for the accumulator is less than the money saved by the reduced electricity cost.

INTRODUCTION

In Sweden the electricity is produced mainly by use of hydro and nuclear power stations. The marginal cost for producing one more unit of electricity is thus very low, often lower than 0.1 SEK/kWh. However, during peak conditions these power stations cannot produce as much electricity as is needed and condense power stations fired with oil or coal, and sometimes even gas turbines, must be used as well. This means that the marginal cost during peak load will increase substantially. See reference [1] for more details about marginal cost pricing of electricity and heat. In order to reflect this marginal cost to the end use consumer, time-of-use rates get more common. The idea is that this will make the consumer aware of the real price for producing electricity and at the same time encourage to save electricity when there is a need for it. Many small buildings in Sweden are today heated by use of electricity. If the proprietor of the building could reduce the demand during peak hours there would be a significant societal benefit. Less power stations would be needed and a cheaper electricity grid could be used. There are many possibilities in order to achieve such a behavior, e.g. more thoroughly insulated buildings, using heat pumps for heating, utilizing free heat from appliances etc. One other means is to store heat in the building, for example increasing the indoor temperature during the late hours of the night. The electrical radiators will thus not be in use for some morning hours. When ordinary tariffs are used, i.e. not time-of-use, the opposite behavior is common, i.e. the owner of the house decreases the indoor temperature during the night, which make all radiators turn on at the same time in the morning when heat is requested. This will therefore aggravate the peak load problem. If the building is provided with hot water radiators another solution might be of interest, viz. using a hot water accumulator where water is heated mainly during low price hours. The storage is then discharged during the electricity peak. However, it might not be possible, or profitable, to use a storage large enough to totally avoid the high price hours. In this paper we will examine the situation in more detail.

THE EXAMINED BUILDING AND THE HEATING SYSTEM

The building examined is sited in Linköping, Sweden, about 200 km south of Stockholm. It is thoroughly insulated with a total transmission coefficient of approximately 60 W/K. Further, heat is recovered from the exhaust air system by use of a heat exchanger. There are only two ordinary radiators in the building and heat is instead distributed by use of the ventilation air. The radiators have a total demand of 450 W while the electrical heater in the ventilation system has a demand of 4000 W. Further, there is an electrical preheater, of 1200 W, in order to prevent ice problems in the heat exchanger, and a domestic hot water heater of 3000 W. The total apartment area of the building is 126 m^2. The heating system is shown schematically in Figure 1.

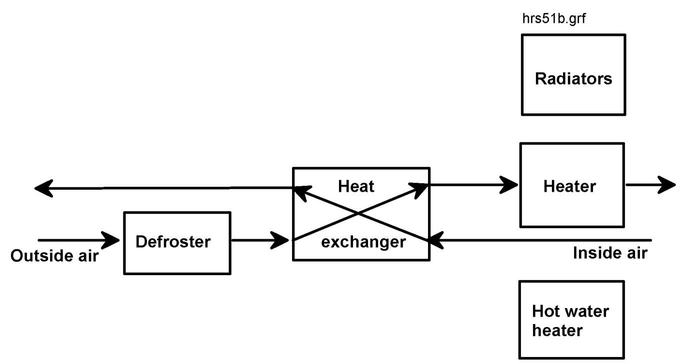

Figure 1: Schematic view of the heating system

Cold outside air is first passing the preheater, or defroster. If the temperature is very low, below -7 °C, the device will warm the air in order to prevent condensation and ice problems in the heat exchanger. The air after this passes through the heat exchanger where the warm air from the building will heat the cold air stream. If the desired indoor temperature, 20 °C, cannot be provided the heater in the ventilation system turns on. The two radiators are located in the bath and shower rooms because most people want a higher temperature there. In order to enlighten the situation the first hours of the monitoring period will be described.

The first hour registered, i.e. 1987-01-01 1500, showed that the outdoor temperature was - 10.2 °C. This temperature was measured on a special spot outside the building. Very close to the defroster the temperature was 9.6 °C which is almost the same as the monitored outside temperature and the difference can be neglected. The air stream passes the defroster and the temperature increased to -4.0 °C. The device was thus working during the hour of concern. The defroster has a demand of 1200 W but it has not been turned on for the whole hour. This is shown by a pulse meter which has registered 6 pulses. The monitoring system scanned the probe 12 times during each hour, i.e. each five minutes, which implies that the defroster was working at least these 6 moments. Assuming that the device was working during the whole five minute interval shows that the electricity used adds up to 600 Wh.

After this, the air passes the heat exchanger and the temperature monitored was + 24.7 °C. The increase was thus 28.9 °C. Measurements of the temperatures for the air led out of the building showed however, that a much smaller temperature interval was observed, 20.0 °C. If the air flow from the inside of the building to the outside is equal to the flow in the opposite direction such values cannot occur. The energy passed from the heating air must be equal or less than the energy passed to the heated air stream. A plausible reason for this discrepancy is the fact that the measuring probe was located very close to a circulating air stream internal to the house. This circulating air is thus assumed to have affected the temperatures measured after the heat exchanger.

The air passes a fan and is then led into the electrical heating device. The measurements show that there was use for extra heat and the air stream was heated to 57.0 °C. An electricity meter was specially connected to this device and 1.667 kWh was registered during the hour of concern. The hot water heater used 1 kWh while the meter for the electric radiators monitored only 0.02 kWh.

USING AN ACCUMULATOR

If a hot water accumulator is to be used it should be able to store some heat during the low price hours of the night, and discharge the heat during the high price hours. It is therefore necessary to examine how much heat it is possible to store in say one m^3 of water. The water cannot be too hot because it will boil at 100 °C and therefore 90 °C seems to be an upper limit. On the other hand, the water cannot be too cold because it must be able to provide heat to the air of approximately 50 °C. The span in temperature is therefore about 40 degrees. The heat capacity for water varies with the temperature, but 4.19 kJ/kg$\times$K seems to be a fair approximation, see reference [2]. The density of water varies as well with the temperature but 970 kg/m^3 is likewise an approximate value. This will imply that water will contain about 4064 kJ/m$^3\times$K or 1.128 kWh/m$^3\times$K.

Using the temperature span above shows that one m^3 will store about 45 kWh.

THERMAL DEMAND

It is also important to examine how the thermal demand varies due to time, see Figure 2 where the demand is shown for the heat exchanger and the defroster during January 1987.

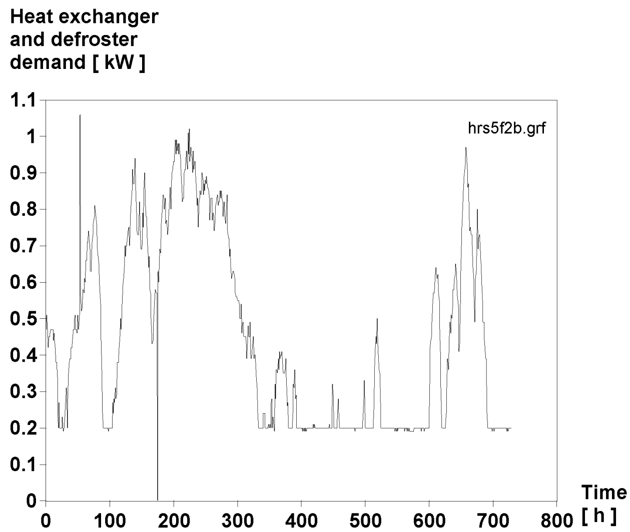

Figure 2: Heat exchanger and defroster demand, January 1987

It is shown that the minimum demand is about 200 W, except for one value where some error occurred. This minimum level shows the demand for the fans installed in the heat exchanger. The highest demand, about 1.1 kW shows an hour where the defroster has been turned on for almost the whole interval. The electricity used for the fans cannot be avoided by use of hot water so the demand for the fans must be excluded from the values shown in Figure 2. Note that hour no. 0 is the value registered between 1500 and 1600, 1987-01-01. The total energy use for the device was 326 kWh and if the fans are excluded the use in the defroster was about 180 kWh.

The electrical heater demand for the same period of time is shown in Figure 3.

From the figure it is obvious that it is a higher degree of variation in the demand compared to the defroster. It is also obvious that the heater was in use almost during all hours in the month. The maximum demand is about 4.3 kW which is more than the manufacturer specified. The total energy use in the heater is 1 372 kWh.

It is also interesting to examine the outdoor temperatures during the month. Figure 4 depicts the situation and it is obvious that the temperatures are very low if they are compared to the 30-year average value for December which is

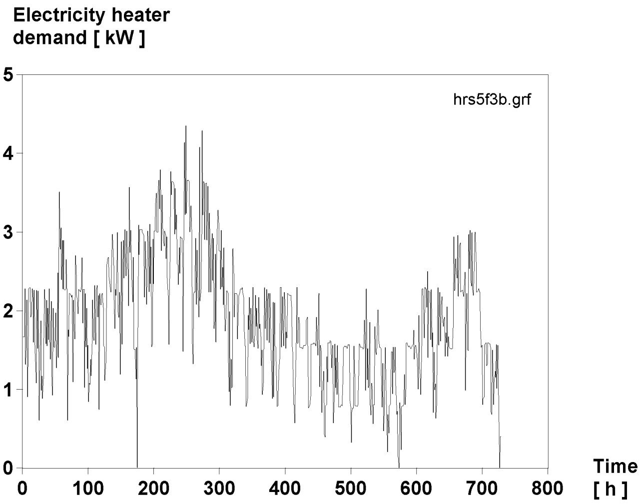

Figure 3: Electricity heater demand in January 1987

± 0.0 °C. The lowest temperature observed is - 24.1 °C in January 10 at 0700 A.M.

The domestic hot water heater is also suitable for utilizing heat from the hot water accumulator. The demand in January is shown in Figure 5.

The resolution for the demand is here 1 kWh which yields a somewhat strange graph. It is however, obvious that the maximum demand is 2 kW but this has only occurred once during the month. Most times the demand is 1 or 0 kW. The heater has a power of 3.0 kW but this maximum was never used during January 1987. For this month 300 kWh was used.

STORING AND DISCHARGING HEAT

In order to find out if a hot water accumulator is profitable the electricity use must be studied in closer detail. Assume we start the process with an accumulator of one m^3, and therefore with 45 kWh stored. The electricity rate in Linköping does not include a time-of use tariff. Instead a tariff used in Gothenburg has been tested her. The rate has high price hours, i.e. 0.796 SEK/kWh, from 0600 to 2200 during working days under November to March. All the other days, and hours, have the price 0.34 SEK/kWh. The charging process in the accumulator therefore starts at 2200 while it ends at 0600 when the discharge begins. During the first day, i.e. 1987-01-02 the use of heat is shown in Table 1.

Table 1 shows the use of electricity from 6 A.M. when the storage starts to discharge its contents of heat. The storage contained 45 kWh and, as is shown in the column for the cumulative electricity use, the storage still is not totally discharged at 2200 when the time has come for charging again. Still there is 7.24 kWh present and for this particular day the heat storage was too large.

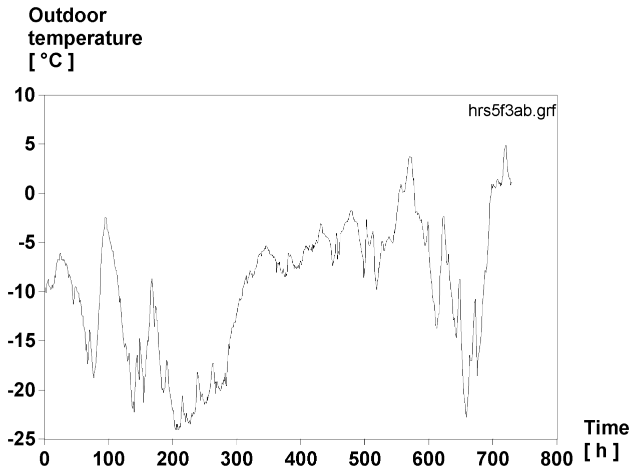

Figure 4: Outdoor temperature in Linköping, Sweden, January 1987

Other days, however, the storage will be totally discharged. Important is also the fact that the storage must be charged during the 8 cheap hours for working days but has a much longer period of time to charge under the weekends. The thermal power of the charging device is therefore of interest. We have developed a program which reads the data file of the thermal demand in the house and calculates the electricity cost for different sizes of storage and thermal power. One month, i.e. January 1987 is examined and the result is shown in Table 2.

Without any storage at all the electricity cost is 1 028 SEK. For a very small thermal power the storage cannot be charged properly during working days. The minimum electricity cost for the 2.5 kW storage is found for the largest examined storage of 120 kWh.

The device is only fully stored on Monday mornings at 0600 and the storage is discharged during the rest of the week. Each working day that follows will discharge the storage and it will contain less heat even if charging occurs, see Table 3. The storage therefore works on a more ore less weekly, instead of a daily basis which was intended.

If a more powerful charging device is chosen, see Table 2 for 5 kW, the cost for electricity is the same for very small accumulators. This is so because there is enough time to charge the small storage even with low power. When the accumulator size is increased, i.e. larger than 30 kW, the cost for electricity will be lower if 5 kW is used for charging instead of 2.5 kW. It is also important to note that the electricity cost has a minimum at a certain point. When the thermal size is 90, or 100 kWh, the cost is 674 SEK while the cost for 120 kWh will increase to 681 SEK. The difference is very small but the principal is important. Still the storage cannot be fully charged for all working days, this happens 11 times during the considered month, and for the situation examined it is also now operating more or less on a weekly basis. When the thermal size of the charging device is increased to 7.5 kW the optimal size of the storage will

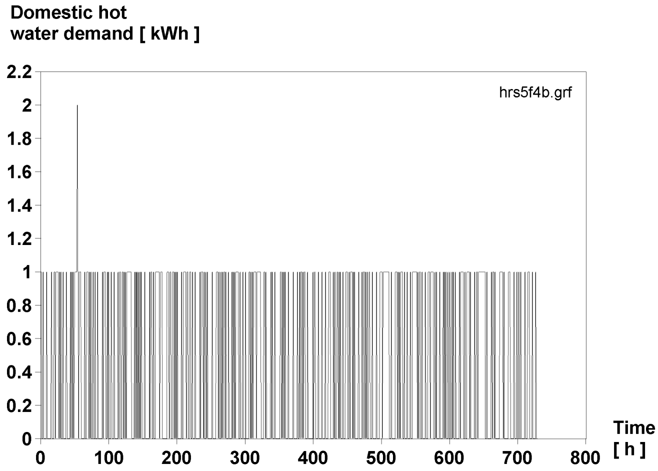

Figure 5: Domestic hot water demand, January 1987

become about 60 kWh, yielding a cost of 671 SEK. Now the charging power is so large that the storage is fully charged every night. Important to note however, is that the weekly discharging process still is in some effect, or at least heat is stored from one day to the other. This is emphasized in Table 4.

A further increase of the thermal charging power is of no use, see Table 2, power 10 kW, which yield the same electricity costs as were found for 7.5 kW. This is natural because the storage is fully charged each night for the 7.5 kW device. The storage will of course be charged faster if more power is installed, but this is of no use because the same amount of cheap kWh are used. In Figure 6 the situation in the storage is shown for each hour during the examined month.

The process starts by charging the storage. The charging power is enough to fill the accumulator completely with heat, i.e. 60 kWh after 8 hours. Then the discharging takes place but the use for heat is not enough for emptying the storage, some 22 kWh remains when charging starts again. Now the weekend starts and the storage is once more filled completely but no discharging occurs until Monday morning at 0600.

The storage is not totally discharged before the second Friday and heat is stored from one day to the other. However, it is shown that the accumulator is charged completely each day, while it is only discharged totally three times during the month.

ECONOMIC ANALYSIS

Up to now only the electricity cost was considered. Above it is shown that this cost could be reduced from 1 028 to 671, i.e. by 357 SEK. If it is assumed that the same amount could be saved for all the months, November to March, when there is a time-of-use rate, 1 758 SEK would be saved each year. Further, assuming that a heat storage has a life-cycle of 20 years and the real discount rate is

Hour no.	Defroster	El. heater	Hot water	Radiators	Tot. demand	Cum. demand
1	0.38	2.17	1	0.03	3.58	3.58
2	0.38	1.6	0	0	1.98	5.56
3	0.34	2.26	0	0.02	2.62	8.18
4	0.23	1.56	0	0	1.79	9.97
5	0.2	1.35	1	0	2.55	12.52
6	0.27	1.08	1	0.03	2.38	14.9
7	0.2	2.26	0	0	2.46	17.36
8	0.2	1.52	1	0	2.72	20.08
9	0.2	2.25	1	0.02	3.47	23.55
10	0.2	1.48	1	0.03	2.71	26.26
11	0.23	0.6	1	0.03	1.86	28.12
12	0.2	1.56	0	0.03	1.79	29.91
13	0.19	1.87	1	0.03	3.09	33
14	0.2	0.98	0	0	1.18	34.18
15	0.23	1.17	1	0	2.4	36.58
16	0.27	0.88	0	0.03	1.18	37.76

Table 1: Electricity demand for heating from 0600 to 2200 1987-01-02

5 %, the net present value of these savings would become approximately 22 000 SEK, see reference [3] for more details about the net present value method. In reference [4] the cost for a water heat storage is assumed to be of the magnitude of 7 000 SEK/m^3 or 150 SEK/kWh. A 60 kWh heat storage should therefore cost about 9 000 SEK. There is also a cost for installing the accumulator but it seems that it is possible to implement water heat accumulators with profitability. In the specific house electricity is used for both space and hot water heating. The electricity heater must therefore be changed to a device heated by hot water instead if an accumulator is to be used. The hot water heater already works as an accumulator, where no regulation due to time is utilized, but the volume is too small for proper operation as a time dependent charging device. If the accumulator could be installed when the house is built the profitability of the storage will be still higher.

CONCLUSIONS

When time-of-use rates gets more common there will be an increasing interest in avoiding electricity use during the expensive hours in the tariff. One means for doing so is to implement a water heat accumulator in the building. The accumulator is charged during the low cost hours, in Sweden between 2200 to 0600, and it is discharged under the rest of the day. It is shown that it is profitable to install a storage with a capacity of about 60 kWh, i.e. 1.3 m^3 of water with a temperature span of about 40 K. Further, it is shown that the charging power is essential for proper operation of the accumulator. If the power is too low the storage cannot be fully charged during the cheap hours in the tariff. If it is too large no extra benefits occur. The storage will be charged faster but the same amount of kWh is used in spite of extra charging power. In Sweden, there is a low cost segment in the tariff during weekends. This could be of benefit because then the storage could be totally charged because of the long

Thermal size, kWh	Thermal power for charging, kW			
	2.5	5.0	7.5	10.0
10	979	979	979	979
20	887	887	887	887
30	864	795	795	795
40	845	723	723	723
50	827	705	688	688
60	817	692	671	671
70	799	687	672	672
80	779	684	675	676
90	767	674	679	679
100	757	674	682	682
110	743	678	686	686
120	725	681	689	689

Table 2: Electricity cost in SEK for some different sizes of heat accumulators, January 1987

Day no. & type	Stored heat	Day no. & type	Stored heat	Day no. & type	Stored heat
1 Fri	0.0	11 Mon	59.8	21 Thu	54.2
2 Sat	60.0	12 Tue	17.6	22 Fri	41.4
3 Sun	120.0	13 Wen	0.0	23 Sat	101.4
4 Mon	82.1	14 Thu	0.0	24 Sun	120.0
5 Tue	56.1	15 Fri	0.0	25 Mon	86.0
6 Wen	20.5	16 Sat	60.0	26 Tue	65.6
7 Thu	0.0	17 Sun	120.0	27 Wen	35.8
8 Fri	0.0	18 Mon	86.9	28 Thu	2.6
9 Sat	60.0	19 Tue	74.5	29 Fri	0.0
10 Sun	120.0	20 Wen	66.3		

Table 3: Contained heat at 2200 in a 120 kWh storage, charging power 2.5 kW

interval of cheap hours even if a very low power is implemented for charging. The storage must then be used more or less on a weekly basis which means that the contents is discharged during a longer period of time. In spite of the charging between 2200 to 0600 the storage will contain less heat for each working day at 2200. It is also shown that the benefits from the lower electricity cost will adds up to a present value of about 22 000 SEK which probably is enough for changing the installations in the house. If the devices are installed when the house is constructed the profitability will increase substantially.

References

[1] Gustafsson Stig-Inge, Karlsson Björn G. Production or Conservation in CHP Networks? *Heat Recovery Systems & CHP*, 10(2):151–159, 1990.

[2] Holman J. P. *Heat Transfer*. McGraw-Hill International Book Co., Singapore, 1989. First printing. ISBN 0-07-100487-4.

Day no. & type	Stored heat	Day no. & type	Stored heat	Day no. & type	Stored heat
1 Fri	22.2	11 Mon	0.0	21 Thu	27.9
2 Sat	60.0	12 Tue	0.0	22 Fri	27.2
3 Sun	60.0	13 Wen	13.0	23 Sat	60.0
4 Mon	22.1	14 Thu	21.5	24 Sun	60.0
5 Tue	14.0	15 Fri	22.4	25 Mon	26.0
6 Wen	4.5	16 Sat	60.0	26 Tue	19.6
7 Thu	8.2	17 Sun	60.0	27 Wen	10.2
8 Fri	0.0	18 Mon	26.9	28 Thu	6.8
9 Sat	60.0	19 Tue	27.6	29 Fri	18.9
10 Sun	60.0	20 Wen	31.8		

Table 4: Contained heat at 2200 in a 60 kWh storage, charging power 7.5 kW

[3] Gustafsson Stig-Inge and Karlsson Björn G. Life-Cycle Cost Minimization Considering Retrofits in Multi-Family Residences. *Energy and Buildings*, 14(1):9–17, 1989.

[4] Gustafsson Stig-Inge. Optimization of Building Retrofits in a Combined Heat and Power Network. *Energy - The International Journal*, 17(2):161–171, 1992.

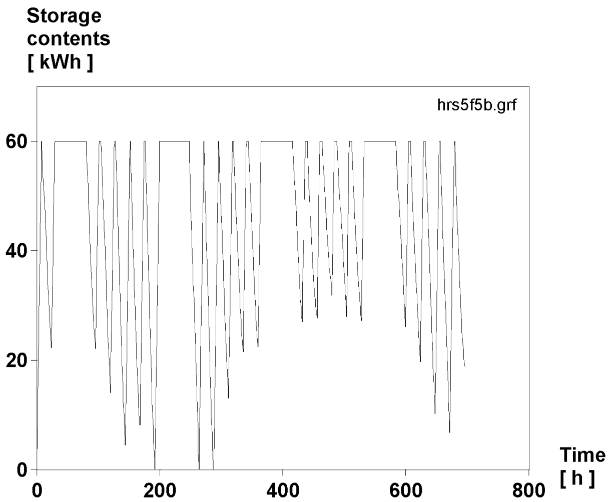

Figure 6: Storage contents in an accumulator of 60 kWh, charging power 7.5 kW, January 1987.