Volume 12, Number 4, July 1992 ISSN 0890-4332

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HEAT RECOVERY SYSTEMS & CHP

combined heat & power

Editor-in-Chief: **D.A. REAY**

PERGAMON PRESS
OXFORD · NEW YORK · SEOUL · TOKYO

Heat Recovery Systems & CHP Vol. 12, No. 4, pp. 303–310, 1992
Printed in Great Britain

0890-4332/92 $5.00 + .00
Pergamon Press Ltd

HOT WATER HEAT ACCUMULATORS IN SINGLE-FAMILY HOUSES

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(*Received* 21 *December* 1991)

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 have become 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 and 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 has 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 condensing 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 have become 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 him 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 social benefit. Less power stations would be needed and a cheaper electricity grid could be used. There are many possibilities in order to achieve such 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. 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 store is then discharged during the electricity peak. However, it might not be possible, or profitable, to use a store 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

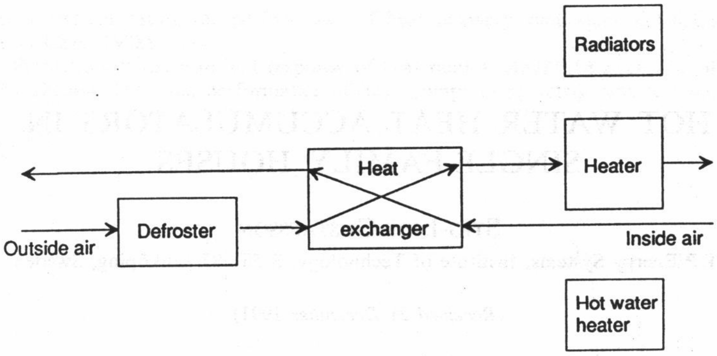

Fig. 1. Schematic view of the heating system.

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 Fig. 1. Cold outside air is first passed through 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. 1 January 1987 1500, showed that the outdoor temperature was -10.2°C. The 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 every hour, i.e. every five minutes, which implies that the defroster was working during 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 thereby necessary to examine how much heat it is possible to store in say 1 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,

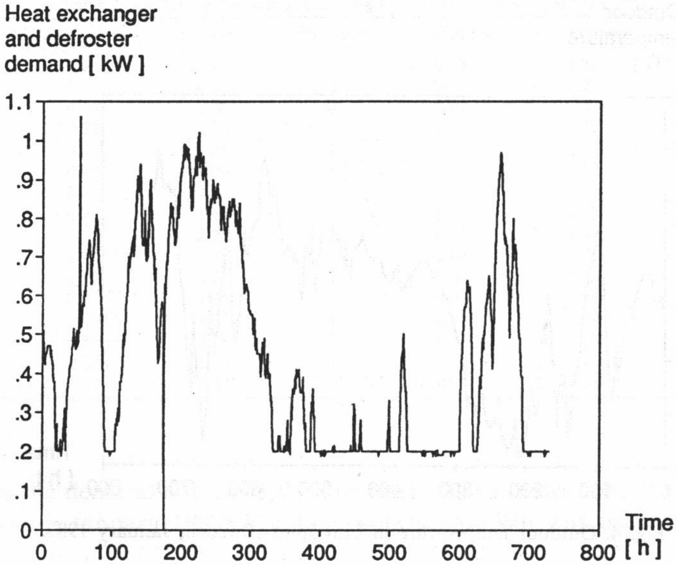

Fig. 2. Heat exchanger and defroster demand, January 1987.

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·K seems to be a fair approximation [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·K or 1.128 kWh/m^3·K. Using the temperature span above shows that 1 m^3 will store about 45 kWh.

THERMAL DEMAND

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

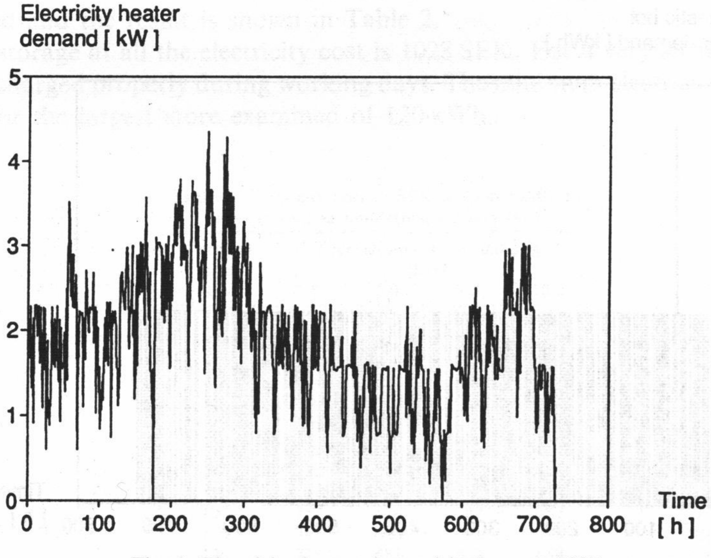

Fig. 3. Electricity heater demand in January 1987.

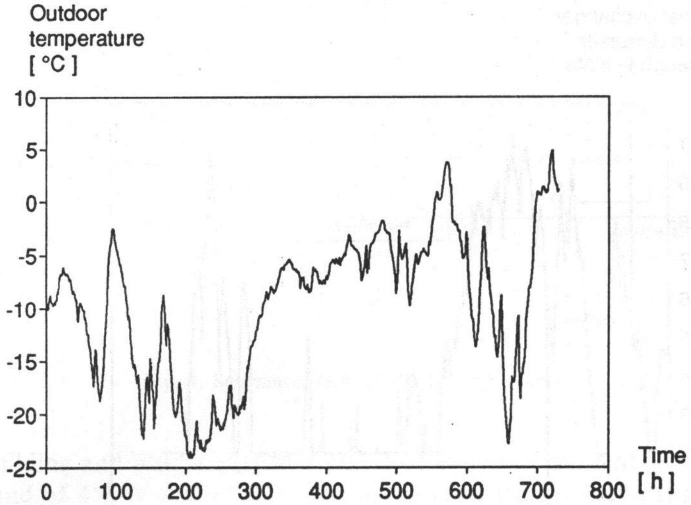

Fig. 4. Outdoor temperature in Linköping, Sweden, January 1987.

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 Fig. 2. Note that hour No. 0 is the value registered between 1500 and 1600, 1 January 1987. 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 Fig. 3. From the figure it is obvious that it exhibits a higher degree of variation in the demand compared to the defroster. It is also obvious that the heater was in use during almost all hours in the month. The maximum demand is about 4.3 kW which is more then the manufacturer specified. The total energy use in the heater is 1372 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 ± 0.0°C. The lowest temperature observed is −24.1°C on 10 January at 7 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 Fig. 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

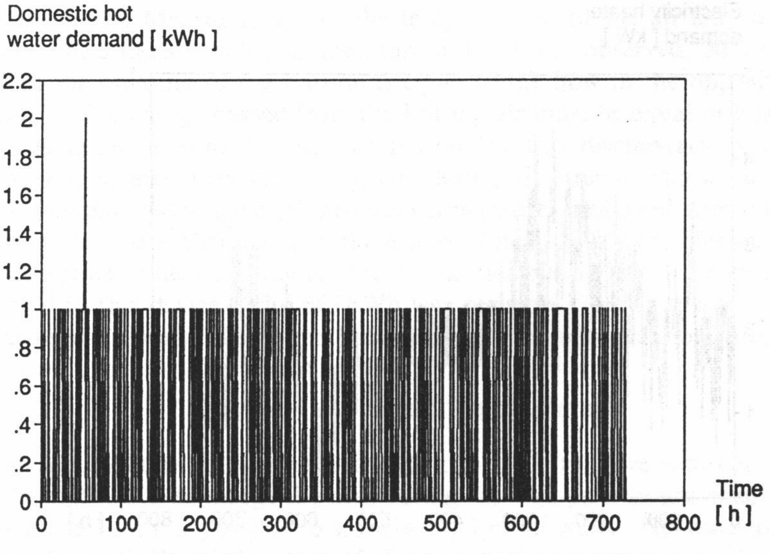

Fig. 5. Domestic hot water demand, January 1987.

Table 1. Electricity demand for heating from 0600 to 2200 2 January 1987

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

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 1 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 here. The rate has high price hours, i.e. 0.796 SEK/kWh, from 0600 to 2200 during working days from 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 store starts to discharge its contents of heat. The store contained 45 kWh and, as is shown in the column for the cumulative electricity use, the store still 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 store was too large.

Other days, however, the store will be totally discharged. Important also is the fact that the store must be charged during the 8 cheap hours for working days but has a much longer period of time to charge during 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 store 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 1028 SEK. For a very small thermal power the store cannot be charged properly during working days. The minimum electricity cost for the 2.5 kW store is found for the largest store examined of 120 kWh.

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

Thermal size [kW]	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 3. Contained heat at 2200 in a 120 kWh, charging power 2.5 kW

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 Wed	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 Wed	20.5	16 Sat	60.0	26 Tue	65.6
7 Thu	0.0	17 Sun	120.0	27 Wed	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 Wed	66.3		

Table 4. Contained heat at 2200 in a 60 kWh charging power 7.5 kW

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 Wed	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 Wed	4.5	16 Sat	60.0	26 Tue	19.6
7 Thu	8.2	17 Sun	60.0	27 Wed	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 Wed	31.8		

The device is only fully stored on Monday mornings at 0600 and the store is discharged during the rest of the week. Each working day that follows will discharge the store and it will contain less heat even if charging occurs, see Table 3. The store therefore works on a more or 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 store 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 store cannot be fully charged for all working days, this happens 11 times during the considered month, and for the situation examined it is now operating more or less on a weekly basis. When the thermal size of the charging device is increased

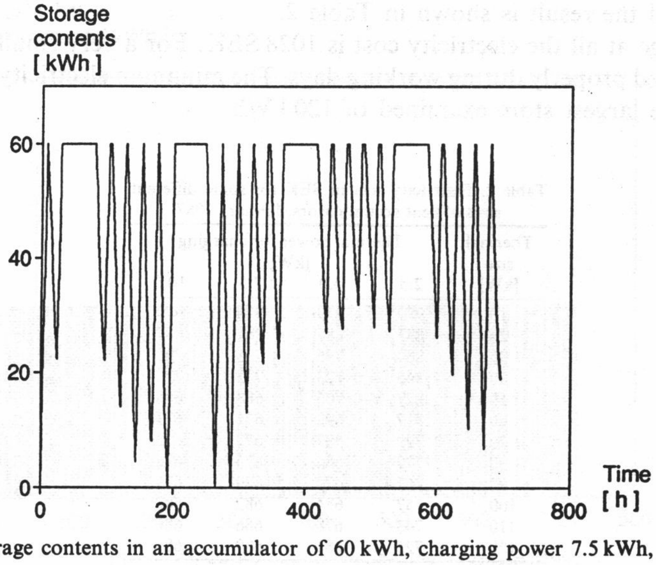

Fig. 6. Storage contents in an accumulator of 60 kWh, charging power 7.5 kWh, January 1987.

to 7.5 kW the optimal size of the store will become about 60 kWh, yielding a cost of 671 SEK. Now the charging power is so large that the store 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 yields the same electricity costs as were found for 7.5 kW. This is natural because the store is fully charged each night for the 7.5 kW device. The store will of course be charged faster if more power is installed, but this is of no use because the same amount of cheap kWh is used. In Fig. 6 the situation in the store is shown for each hour during the examined month. The process starts by charging the store. The charging power is enough to fill the accumulator completely with heat, i.e. 60 kWh after 8 h. Then the discharging takes place but the use for heat is not enough for emptying the store, some 22 kWh remains when charging starts again. Now the weekend starts and the store is once more filled completely but no discharging occurs until Monday morning at 0600.

The store 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 1028 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, 1758 SEK would be saved each year. Further, assuming that a heat store has a life-cycle of 20 years and the real discount rate is 5%, the net present value of these savings would become approximately 22,000 SEK, see [3] for more details about the net present value method. In [4] the cost for a water heat store is assumed to be of the magnitude of 7000 SEK/m^3 or 150 SEK/kWh. A 60 kWh heat store should therefore cost about 9000 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 store will be still higher.

CONCLUSIONS

When time-of-use rates become 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 and 0600, and it is discharged during the rest of the day. It is shown that it is profitable to install a store 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 store cannot be fully charged during the cheap hours in the tariff. If it is too large no extra benefits occur. The store 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 store could be totally charged because of the long interval of cheap hours even if a very low power is implemented for charging. The store must then be used more or less on a weekly basis which means that the contents are discharged during a longer period of time. In spite of the charging between 2200 and 0600 the store will contain less heat for each working day at 2200. It is also shown that the benefits from the lower electricity cost will add 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.

Acknowledgement—The research behind this paper has been financed by the foundation of Bengt Ingeström, Sweden.

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Volume 12, Number 4 **July 1992**

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Announcement

Pergamon Press

HRSCEQ 12(4) 289–376 (1992)

Indexed/Abstracted in: *Appl. Mech. Rev., Curr. Cont. ASCA, Cam. Sci. Abstr., Chemical Abstracts Service, Curr. Cont./Eng. Tech. & Appl. Sci., Curr. Tech. Ind., EIC Intell., Eng. Ind., Metals Abstr., Curr. Cont. SCISEARCH Data., TCEA*

Typeset in Great Britain by BPCC Techset Ltd, Exeter. Printed by BPCC Wheatons Ltd, Exeter. **630**