Energy conservation in district-heated buildings[1]

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1. SYNOPSIS

In this paper the potential for energy conservation in space and water heating for three types of district-heated buildings in south-west Sweden is analyzed.

2. ABSTRACT

In this paper the potential for energy conservation in space and water heating for three types of district-heated buildings in south-west Sweden is analyzed. The energy savings for different conservation measures are estimated using a computer program which calculates daily building energy balances. The value of energy savings is estimated as the product of energy savings and the resulting avoided costs for district-heat production, summed over all periods with different costs. The cost differences among the several energy-conservation measures compared and the resulting avoided costs are low. Small changes in the assumptions could change results. Comparing costs between single conservation measures and the supply of district heat on a short term basis is insufficient. An extended analysis is needed to evaluate the effects on the total district-heat demand resulting from energy conservation and the connection of additional buildings to the system. Such an analysis indicates how energy conservation could reduce future investment needs in a district-heating system. The energy-conservation potential in analyzed buildings lies between 30 and 60% of final energy use when both avoided marginal operating costs and capital costs for peak-load and reserve boilers in district-heat production are considered together with an coordination of long-term planned building maintenance with energy-conservation measures.

3. INTRODUCTION

District heating systems (DHS) are an important component of the Swedish energy system. Two thirds of all Swedish multi-family buildings and half of the service buildings in 1987 were served by DHS, which delivered some 39 TWh - more than 10% of total national energy use. The rather low variable cost of district-heat production could be expected to reduce the economic potential for energy conservation in buildings with district heat compared to those with other heating systems. However, improved energy efficiency will help reduce emissions of acidifying gases and carbon dioxide, and thereby the environmental impact of energy extraction, conversion and use. A major increase in the energy efficiency of space and water heating, moreover, must be based on retrofits of existing buildings because the turnover rate of buildings is relatively low.

The energy-conservation potential in district-heated buildings can be analyzed in several ways to determine the economically feasible changes. An analysis considering both DHS capital and operating costs, together with changes in the building stock, may demonstrate a higher conservation potential than one which simply compares costs for a single energy-conservation measure with the yearly average variable operating cost for existing district-heat production. The energy-conservation potential for five district-heated buildings are estimated in this paper, considering, the marginal operating costs and capital costs for peak-load and reserve capacity for a DHS and coordination of energy-conservation measures with long-term planned building maintenance.

The buildings analyzed here were constructed in the 1960s to meet the then current Swedish building code standards and have a total heated area of 110 000 square meters, with an annual specific energy-use of between 170 and 310 kWh per square meter. These buildings are all connected to the Lund DHS. Changes in both the energy-use of the buildings and design heating requirements as a result of energy-conservation measures are analyzed in relation to the marginal operating costs for existing district-heat production and capital costs for peak-load and reserve capacity.

4. METHODOLOGY AND ASSUMPTIONS

The energy-conservation potential is defined as the energy savings resulting from energy-conservation measures where costs are equal to or lower than the resulting avoided cost in the DHS. The avoided cost is estimated utilizing two sets of information (1) marginal operating costs for existing production including energy taxes and (2) the information in (1) with the addition of capital costs for peak-load and reserve boilers.

The avoided operating cost for existing district-heat production as a result of energy-conservation measures is calculated as the product of energy savings and the operating cost for district-heat production summed over periods with different costs. The avoided capital costs of peak-load and reserve boilers are based on reduced building-design heating requirements through conservation measures.

The energy savings and the reduction of building-design heating requirements are estimated using a computer program which calculates daily energy balances in buildings (Munther 1986). The most profitable measure is applied first. Additional measures are applied in order of decreasing cost-effectiveness.

The cost of conserved energy for energy-conservation measure j, CCE_j (ECU/MWh), is calculated as

$$CCE_j=(CRF*C_{cp,j}+C_{op,j})/ES_j \tag{1}$$

where:

CRF = capital recovery factor (depends on discount rate and expected life-time of the investment)
$C_{cp,j}$ = Capital cost of energy-conservation measure j including administrative costs [ECU]
$C_{op,j}$ = operating cost of energy-conservation measure j [ECU]
ES_j = annual energy savings of energy-conservation measure j [MWh]

Costs resulting from the long-term maintenance or renovation needs of buildings are not included in the cost of energy conservation. *If*, for example, existing double-glazed windows are replaced because of building maintenance, the capital cost of energy conservation is the cost difference between new double-glazed windows and a new more energy-efficient type of window.

The avoided cost of the district-heat production resulting from energy-conservation measure j based on the existing marginal operating costs including energy taxes, $AC_{1,j}$ (ECU/MWh), is calculated as

$$AC_{1,j}=(\sum_{k=1}^{m} MOC_k*ES_{j,k})/ES_j \tag{2}$$

where:

m = annual number of periods with different marginal operating costs
MOC_k = marginal operating cost including energy taxes for period k (ECU/MWh).
$ES_{j,k}$ = energy savings for period k of energy-conservation measure j [MWh]

The avoided cost of the district-heat production resulting from energy-conservation measure j based on the existing marginal operating costs including capital costs for peak-load and reserve boilers, $AC_{2,j}$ [ECU/MWh], is calculated as

$$AC_{2,j}=AC_{1,j}+CRF*C_{cp,peak}*P_j/ES_j \tag{3}$$

where:

$C_{cp,peak}$ = capital cost of peak-load and reserve boilers [ECU/MW]
P_j = reduction of building-design heating requirement resulting from energy-conservation measure j [MW]

The energy-conservation potential i, ECP_i [MWh], when avoided cost of energy-conservation measure j is defined as $AC_{i,j}$, is calculated as

$$ECP_i=\sum_{j=1}^{n} ES_j*xj,\text{with}x_j=1\text{if}CCE_j\leq AC_{i,j}xj=0\text{if}CCE_j>AC_{i,j} \tag{4}$$

where:

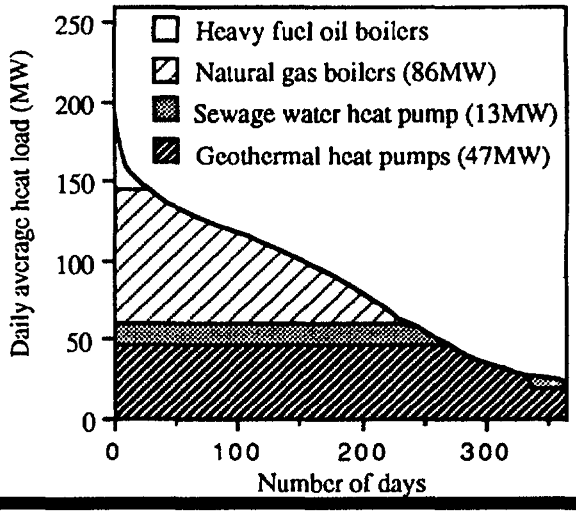
n = number of energy-conservation measures
$AC_{i,j}$ = avoided costs resulting from energy-conservation measure j calculated according to Equations (2) and (3) respectively.

The cost of conserved energy is often compared with the prices for the district heat, i. e. the district-heat tariff, to evaluate the cost-effectiveness from a consumer's point of view. This study, however, compares the costs of conserved energy with the resulting avoided costs for district-heat production, using rather the viewpoint of the production utility. The utility, however, can design the district-heat tariff so it reflects the avoided costs in the DHS, and thereby give consumers price signals in accordance with these avoided costs.

Energy-conservation measures that reduce buildings-design heating requirement can reduce future investments in peak-load and reserve boilers. An expanding heat load would result in immediate investments if the present production capacity is in balance with the design heat load. However, energy-conservation measures decreasing the design heat load will reduce the need for new investments. Energy conservation measures could even totally avoid the need for new capacity if the design heat load were constant or decreasing. The possible maximum avoided annualized capital cost for peak-load and reserve boilers is ECU11 per kW/yr (Gustavsson 1989).

Energy-conservation measures decreasing the return temperature in DHS result in better operation conditions for heat pumps and cogeneration plants and thereby lower production costs. These cost reductions as well as reduced investments in district-heating connections have not been included in the analyses, see also section 5.

Figure 1. ***Heat load-duration curve of Lund DHS for a yearly production of 800 GWh***



The price level refers to 1987 when the average exchange rate was ECU1 = SEK7,55 (IMF 1991). Fuel prices at the lower heating value per MWh_{fuel} are for natural gas ECU15 and for heavy fuel oils ECU9,5. Value-added taxes are excluded in the analyses because they will not change the results. Energy taxes, consisting of fuel taxes and electricity consumption tax are included. Fuel taxes at the lower heating value per MWh_{fuel} for heat production are for natural gas ECU4,2 and for heavy fuel oils ECU9,1. Electricity consumption tax per MWh is ECU6,7. All investment costs for energy-conservation measures are estimated by BPA, Building Production AB, Malmö. Electricity prices would influence the costs of district-heat production through electric heat-pumps. Electricity prices for consumers using high voltage are shown in Table 1. Costs for peak demand and demand charge are not included because electric heat pumps are not used during peak-load periods in the electricity system. The prices have been transformed to average weekly prices because the variation between day and night and between weekdays and weekends have no impact on the calculations (Gustavsson 1989).

5. ANALYZED DISTRICT-HEATING SYSTEM

The five buildings analyzed are connected to Lund DHS. District-heat production has been 800 GWh/yr during the eighties. The production based on large heat pumps, natural gas, and oil boilers and the heat-load-duration curve are shown in figure 1. The annual degree days for an average internal temperature of 17 °C is for Lund 3156 being calculated from measured out-door temperatures between 1961/62 and 1978/79.

Table 1. *Electricity prices for consumers using high voltage (130 kV) according to Lund's energiverk*

Period Date	Duration Days/yr	Electricity prices in 1987 ECU/MWh	
		Without taxes	With taxes
Nov-Mars	151	25,3	32,0
April, Sept, Oct	91	18,6	25,4
May- Aug	123	14,0	20,7

The heat-load-duration curve is based on district-heat production between 1971 and 1979 as analyzed by Werner (1984) after adjustment for decreased distribution losses to the level of 1987 which was some 70 GWh. Energy-conservation measures and the connection of new energy-efficient buildings can change the shape of the heat-load-duration curve and thereby the operating time for different production units. Such changes are not analyzed in this study. The marginal operating costs for Lund DHS (Figure 2) are based on the use of existing production that gives the lowest yearly operating cost and the heat-load-duration curve in Figure 1. The operating costs per MWh are for heavy fuel oil and natural gas boilers ECU22,2, for sewage water and geothermal heat pumps ECU7,9 and ECU7,1 respectively. The geothermal heat pumps are not operating for one to three weeks every second year because of normal maintenance. The maintenance of other plants is carried out during periods when they are not needed.

The annual marginal capital cost for district-heating connections of subscribers was calculated to about ECU1 per kW/yr for the buildings analyzed. The cost is low because the large capacity of connections required have a low marginal investment cost. The costs for avoided future investments in district-heating connections resulting from energy conservation has not been considered because it would have a minor impact on the results.

6. ANALYZED BUILDINGS

The main data for analyzed buildings are shown in Table 2. These buildings are quite typical of constructions during the 1960s and 70s in Sweden. More than half of the heated floor area of buildings within the geographical area of Lund DHS, in fact, were constructed between 1961 and 1977. Earlier buildings have a lower energy efficiency, being determined by changes of the building codes and, therefore, may have a higher specific energy-conservation potential than later constructed buildings.

Measured energy-use for the buildings correspond to the calculated values except for the Residential - C building (Gustavsson 1989). This building had extensive damage to the building envelope, and the measured energy-use was therefore 50 % higher than the calculated one. The building is included in the analyses to show the energy-conservation potential for buildings reconstructed in accordance with the current Swedish building code. The costs of the higher energy efficiency in this building, however, proved difficult to separate from renovation costs of the building. The costs of the energy conservation for this building, thus, could not be shown.

7. RESULTS

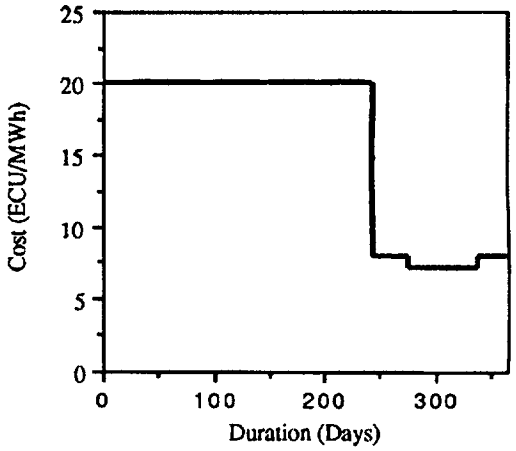
The cost of conserved energy (CCE) varies strongly among different conservation measures (Table 3). However, several measures have a CCE in the same magnitude as the avoided marginal operating cost for the district-heat production including capital costs for peak-load and reserve boilers, AC_2 (Figure 3). Conservation measures are displayed in order of cost-effectiveness in the figure. Already applied measures for residential building A are: adjustment of ventilation and heating systems, replacement of hot water fixtures in kitchen, and replacement of windows in the south and west facades. Measures with low conservation costs or without any costs for residential building A are: replacement of entrance doors and replacement of remaining hot water fixtures and windows; and for residential building B: replacement of entrance doors and hot water fixtures (figures 3 and 4). The yearly average variable cost is some ECU17 for the district-heat production in Lund.

Energy savings for different measures are shown in Figure 4. Heat recovery from exhausted air and the time controlled operation of ventilation systems led to large savings in both the industrial and school buildings. These buildings are used only during the day and have a high rate of air-exchanges.

7.1. Industrial building

Roof insulation and heat recovery from exhausted air reduced energy-use by about 60%. The CCE for roof insulation with existing U-value 0,80 W/m^{2}K and heat recovery from exhausted air were slightly higher than AC_2. These measures and roof insulation with existing U-value 0,92 W/m^{2}K as well as reduced window area, however, were obviously economic to implement if the discount rate was 3%, but clearly uneconomic if the discount rate was 12% (Figure 5).[2]

Figure 2. ***Marginal operating costs of Lund district-heat production based on the heat-load-duration curve and production units in Figure 1***



7.2. School Building

Replacement of double-glazed windows to triple-glazed windows reduced energy-use by 10%. The CCE was low because existing windows were severely damaged and were necessarily replaced for reasons of maintenance. The time controlled operation of the ventilation system had a low cost and reduced energy-use by 45%. The CCE for attic floor insulation was slightly higher than the resulting avoided cost AC_2.

Table 2. *Main data, final energy use, and design deating requirement for analyzed buildings*

Type of data	Building				
	Industrial	School	Residential - A	Residential - B	Residential - C
Year of construction	1966-1971	1962-64	1968	1963	1969
Heated floor area (m^2)	13 000	4 580	2 760	1 780	1 570
Floor/basement levels	1/0	2/0	3/1	4/0	2/0
Envelope surface area (m^2)	30 300	6 780	2 830	1 970	2 290
Outer wall 1, U-value (W/m^2,K)	1,7	0,80	0,50	0,51	0,50
Outer wall 2, U-value (W/m^2,K)	0,92	0,53	0,46	-	-
Outer wall 3, U-value (W/m^2,K)	0,61	0,50	0,41	-	-
Outer wall 4, U-value (W/m^2,K)	0,50	-	-	-	-
Attic floor/roof 1, U-value (W/m^2,K)	0,92	0,60	0,28	0,41	0,40
Attic floor/roof 2, U-value (W/m^2,K)	0,80	0,42	-	-	-
Lowest floor, U-value (W/m^2,K)	0,50	0,50	0,50	0,50	0,50
Windows, U-value (W/m^2,K)	3,1	3,1	3,1	3,1	3,0
Doors, U-value (W/m^2,K)	2,0	3,1	2,0	3,4	2,0
Ventilation volume (m^3)	109 100	11 400	6 610	4 260	3 920
Base ventilation rate (m^3/hour)	38 000	26 800	3 980	2 560	2 350
Forced ventilation rate (m^3/hour)	232 000	26 800	3 980	2 560	2 350
Indoor temperature (°C)	19	20	22,5	22,5	22,5
Calculated energy-use					
Total (MWh/yr)	4 020	1 300	354	319	255
Per squaremeter (kWh/m^2,yr)	310	280	171	180	218
Calculated design requirement (kW)	2 220	530	117	78	76
Total heated floor area for similar buildings† (m^2)	13 000	10 600	47 000	21 000	19 000

†The buildings are built in the same area with the same type of design and construction.

7.3. Residential Building - A

The owner of this building had adjusted the ventilation and heating systems, replaced hot water fixtures in the kitchen, and replaced windows from double to triple glazed in the south and west facades. These measures reduced the energy-use by 15%. Entrance doors, remaining hot water fixtures, and windows will be replaced because of maintenance needs and would reduce energy-use further by 16%. Attic floor insulation reduced the energy-use by 3%, but the CCE was higher than the resulting avoided costs.

7.4. Residential Building - B

Entrance doors and hot water fixtures will be replaced because of maintenance needs. These measures would reduce the energy-use by 7%. Attic floor insulation has a lower CCE, and adjustment of the ventilation system has a CCE about the same as the resulting avoided cost AC_2. Adjustment of the heating system and replacement of windows are not immediately profitable. These measures, however, could be coordinated with long-term planned maintenance measures and would then be cost-effective to implement. Taking into consideration such future maintenance measures, the total energy-conservation potential for the building would appear to be about 30% for the avoided cost AC_2.

7.5. Residential Building - C

The reconstruction of this building decreased energy-use by some 40% according to the calculations. Damage to the existing building envelope, however, seems to have increased existing energy-use by about 50%. The real savings, thus, may be around 60%.

8. CONCLUSIONS

The heat load in a DHS varies strongly over the year in Sweden because the largest fraction of the load is for space-heating and the energy use for this purpose mainly follows the outdoor temperature. District-heating production is therefore based on plants with varying costs, with higher marginal operating cost during peak-load periods and a lower marginal operating cost during base-load periods. The energy savings from different conservation measures also varies over the year. The conclusion to be drawn from the combination of these variations is that the value of a saved kWh/yr varies for different conservation measures. In other words, not all saved units of energy have same economic value. The value is equal to the product of energy savings and cost for the district-heat deliveries summed over all periods with different costs.

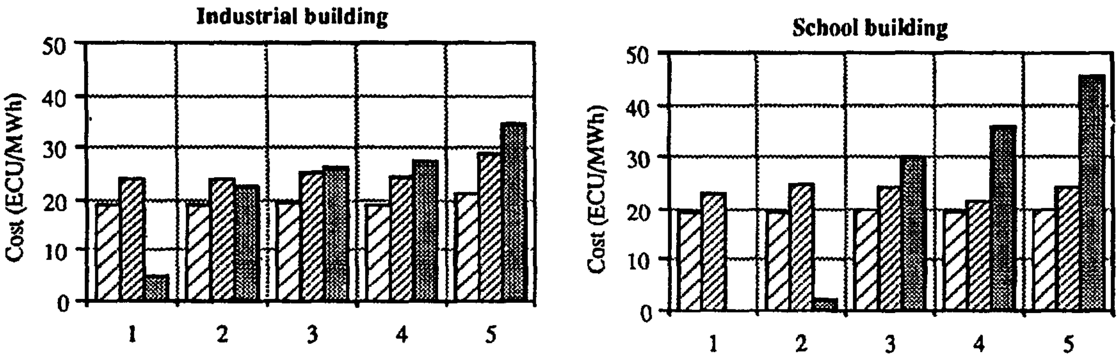
Table 3. ***Cost of conserved energy for analyzed energy conservation measures***

Measure	Life-time	Cost of conserved energy, ECU/MWh			
	year	*Industrial*	*School*	*Residential-A*	*Residential-B*
Adjustment of heating system	10	-	36	-	43
Adjustment of ventilation system	10	-	-	-	22
Time controlled operation of ventilation system	10	-	2,3	-	-
Heat recovery from exhausted air	15	26	71	-	-
Weatherstripping	10	5,0	-	-	-
Replacement of entrance doors	40	-	-	-	0[†]
Replacement of windows	40	240	0 (12-18)[†]	0 (12-18)[†]	-
Reduced window area[‡]	40	35 (0,23)	-	-	45 (0,25)
Attic floor/roof insulation 1[§]	40	23 (0,28)	30 (0,15)	35 (0,13)	25 (0,15)
Attic floor/roof insulation 2[§]	40	27 (0,27)	45 (0,24)	-	-
Attic floor/roof insulation 3[§]	40	-	75 (0,21)	-	-
External wall insulation 1[§]	40	69 (0,28)	330 (0,29)	90 (0,23)	-
External wall insulation 2[§]	40	120 (0,25)	600 (0,23)	210 (0,20)	-
External wall insulation 3[§]	40	210 (0,22)	-	330 (0,23)	-

[†] Windows and entrance doors must be replaced because of maintenance reasons. The Swedish building code has resulted in improved energy efficiency of entrance doors and windows. The costs for the improved energy efficiencies are uncertain and difficult to estimate. Building companies prefer uniform types of windows and entrance doors for production reasons, and imply that the price difference between standard windows/doors and windows/doors with a lower energy use is very low. However, a cost difference between new double and triple glazed windows of 27 ECU/m^2 had been used by Gustafsson (1992). This cost difference will result in a cost of conserved energy of ECU12-18 per MWh for both the school building and the residential building A for a U-value difference of 0,6-0,9 W/m^{2}K (Gustafsson 1986; Höglund et al. 1984). This cost is lower than the resulting avoided marginal operating cost.

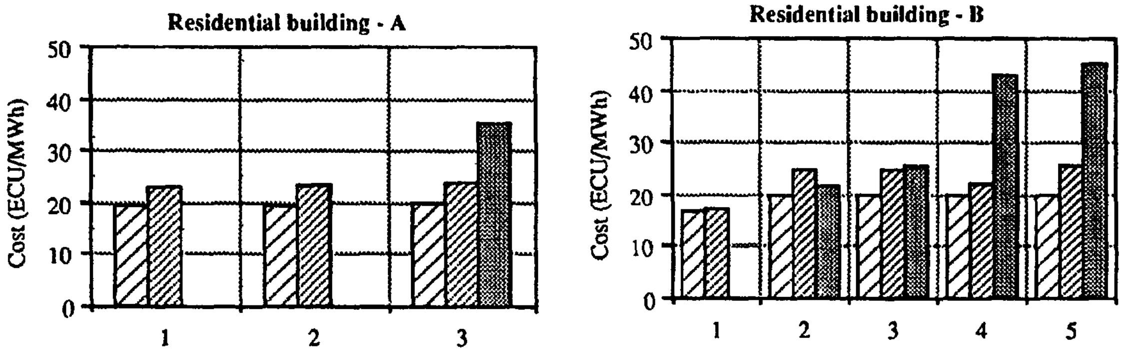
[‡] U-value (W/m^{2}K) for new wall in brackets.

[§] U-value (W/m^{2}K) after insulation in brackets.



1 = weatherstripping, 2 = roof insulation, existing U-value 0,92, 3 = heat recovery from exhausted air, 4 = roof insulation, existing U-value 0,80, 5 = reduced window area

1 = replacement of windows, 2 = time controlled ventilation, 3 = attic floor insulation, 4 = heating system - adjustment, 5 = roof insulation



1 = applied measures, 2 = measures without conservation costs, 3 = attic floor insulation

1 = measures without conservation costs, 2 = attic floor insulation, 3 ventilation - adjustment, 4 = heating system - adjustment, 5 = reduced window area

▧ Avoided cost based on the marginal operating costs for the production, AC1

▩ Cost of conserved energy, CCE

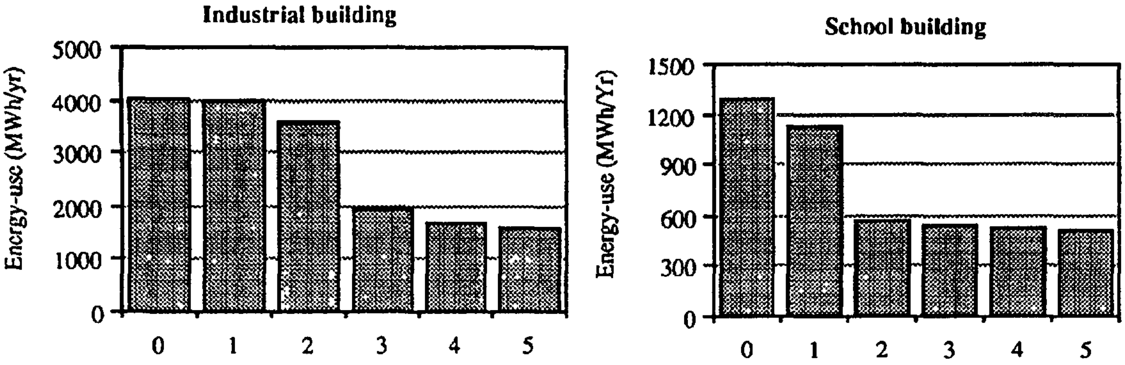
▨ Avoided cost based on the marginal operating costs for the production including capital costs for peak-load and reserve boilers, AC2

Figure 3. ***CCE for energy conservation measures and resulting avioded cost for district-heat production.***

For the conservation measures studied here, a saved kWh/yr resulting from reduced window area has the highest value since these savings will approximately follow the outdoor temperature. It should be noted that on days with a high solar radiation, mainly in the spring, the reduction of the radiation into the building will result in negative savings. In other words, a reduced window area will increase the heat demand on such days, which occur during base-load periods. Energy savings from the insulation of the building envelope have the next highest value and also mainly follow the outdoor temperature. Energy savings for hot water consumption, on the other hand, are spread nearly equally throughout the year and have the lowest value.

The value of a saved kWh/yr for space heating also depends on the duration of the heating season. In energy-efficient buildings, where there is also a shorter heating season, more of the energy savings for space heating will occur during peak-load periods when the cost for district-heat is higher.

The energy-conservation potential varied among the buildings studied here. The potential was 50-60% for both the industrial and school building, and about 30% for the residential buildings A and B if energy-conservation measures were coordinated with long-term planned maintenance measures. These conservation potentials are based on the resulting avoided marginal operating costs for the district-heat production including capital costs for possible avoided future investments in peak-load and reserve boilers, AC_2.



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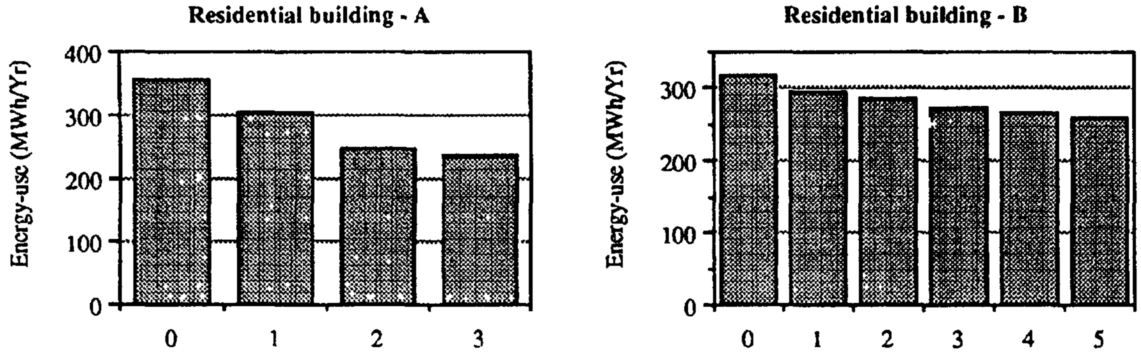

1 = applied measures, 2 = measures without conservation costs, 3 = attic floor insulation

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Figure 4. ***Energy-use before (referred to as 0) and after cumulatively implemented energy conservation measures***

9. DISCUSSION

The cost differences among the several energy-conservation measures and resulting avoided costs are low and small changes in the assumptions will change the results. Changed fuel prices would have a strong impact on the avoided costs for district-heat production and the development of fuel prices is uncertain and difficult to estimate over a longer period. The investment costs of energy-conservation measures have been calculated by a building company, and the uncertainties arising here can be approximately 10-20%, partly depending on the level of business activity. The uncertainties of energy savings mainly depend on the existing U-values and ventilation rates which have been estimated from construction documents and have not been empirically measured. The discount rate strongly change the annual costs for energy-conservation measures but would more weakly affect the avoided costs. The choice of discount rate, therefore, will change the economic energy-conservation potential.

Other studies of energy conservation for space and water heating in buildings show energy-conservation potentials in the same order as this study. According to the Swedish Counsil for Building Research (1987) energy-conservation measures in multi-family buildings can reduce final energy-use by 30-50% from an annual specific final energy-use of 250-300 kWh per squaremeter heated floor area. This conclusion is based

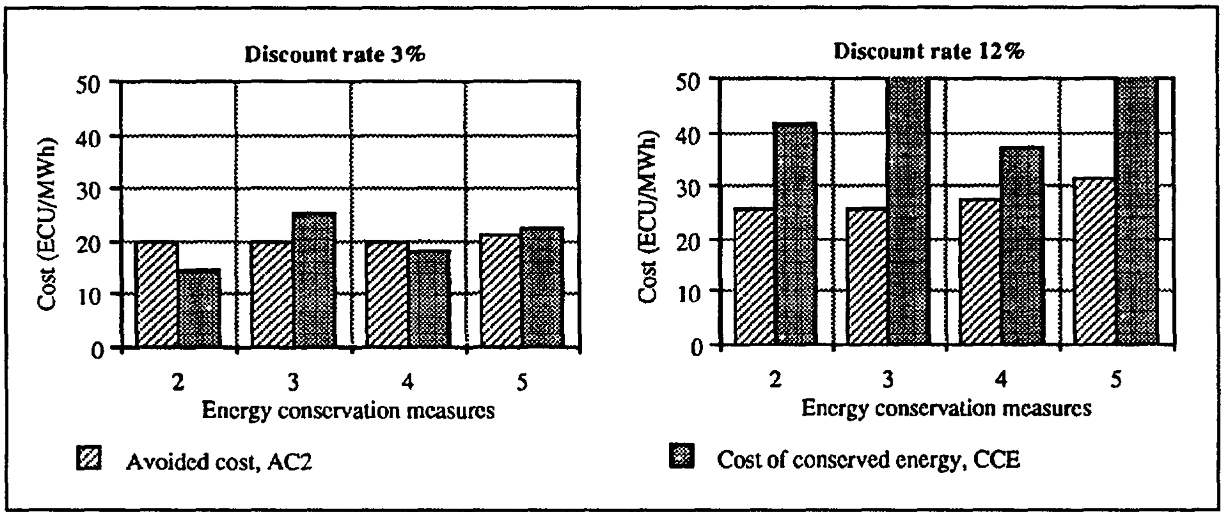

Figure 5. ***CCE for energy consrv. measures for industrial bldg. and resulting avoided cost*** AC_2.

on a number of studies carried out in recent years (Bjerking 1987; Franzén and Nylund 1987; Hansson et al. 1986; Högberg et al. 1987; Nilsson et al. 1987; Svarvare et. al 1987). Energy-conservation measures in four commercial buildings reduced district-heat deliveries by 30-50% (Sundbom et. al 1987).

Avoided future investments in peak-load and reserve capacity depend on the ratio between the design heat load and the existing production capacity. Therefore, the design heat load estimated and compared with the existing production capacity over the expected lifetime for energy-conservation measures would show the value of avoided future investments in peak-load and reserve capacity resulting from energy conservation. The design heat load depends on energy conservation in and demolition of districted-heated buildings as well as connection of additional buildings to the system. An ideal case appears to be when the production capacity is in balance with the design heat load and energy conservation in district-heated buildings allows additional buildings to be connected to the system, maintaining a constant design heat load. However, if the existing capacity is designed without regard to energy conservation, the conservation measures could result in less utilization of existing production capacity. In this case, the avoided future investments in peak-load and reserve capacity can be zero if the conservation measures have a shorter expected lifetime than the existing production capacity. For this situation, the avoided cost in district-heat production resulting from energy conservation is equal to the existing marginal operating cost, AC_1.

The costs of heat production varies among DHS, and the energy-conservation potential for the buildings analyzed here cannot directly be generalized to other systems. The production costs differ with the size of DHS. Lund DHS is a rather large system and smaller systems have normally higher costs. A DHS in nearby Eslöv, which is a tenth of the size of the Lund system, has about 20% higher production costs (Gustavsson 1989). The costs of different types of base-load production can also vary significantly among systems of the same size.

Analyses of the energy-conservation potential in district-heated buildings are complicated and the conservation potential depends strongly on the existing buildings and the existing DHS. The value of a saved kWh/yr is related to the variation of marginal operating costs and energy savings over the year as well as the resulting avoided future investments in the DHS. An evaluation of changes in building stock in relation to the existing DHS, thus, appears to be a necessary requirement in every case.

ACKNOWLEGEMENTS

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ENDNOTES

1. This paper is based on the article "District-heating Systems and Energy conservation - Part I" submitted to Energy - The International Journal.

2. Conservation measures : 2 = roof insulation existing U-value 0,92; 3 = heat recovery form exhausted air; 4 = roof insulation existing value-U value 0,90; 5 = reduced window area

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