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PRODUCTION OR CONSERVATION IN CHP NETWORKS?

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Abstract—In Sweden, Combined generation of Heat and Power (CHP) is in common practice. Different fuels are burnt in a boiler and the steam is used for generating electricity. The heat that has to be transferred from the condenser in the plant is used in the district heating grid. This grid is thus used as a cooling facility necessary for electricity production. However, energy conservation in the Swedish building stock is also encouraged, and if this is utilized in district heated buildings it results in fewer possibilities for electricity production. This might be a major drawback when nuclear power is abolished, as is the result from a consensus some years ago. This paper deals with the question of whether it is better to conserve both heat and electricity, to save only one of the energy forms or if it is cheaper to produce more energy, instead of saving. A case study is presented dealing with Malmö, in the South of Sweden, and it is shown that energy conservation in district heated buildings cannot yield profitability: neither can conservation in the electricity grid, even if it gets closer to profitable savings. It is assumed that the total cost of heating, insulation and electricity is paid by the society and the minimum point for this cost will characterize the best solution.

INTRODUCTION

A major part of Malmö is heated by district heating. The same utility also provides the inhabitants with electricity. Some of this electricity is purchased from a company called Sydkraft and some of it is generated in a combined heat and power plant owned by the municipality. Up to now, Sydkraft, which owns several power plants, some of them heated by nuclear power, could sell the electricity at a very low price. Cogeneration by the municipality has thus been of no interest.

However, nuclear power in Sweden is to be abolished and it could thus be expected that the prices from Sydkraft will increase when alternative electricity production must be used. The municipality might thus be able to produce the electricity cheaper than buying it from the company.

In an earlier research project, dealing with the OPERA model, which finds optimal energy retrofits in multi-family buildings, it was found that it could be optimal for the proprietor of the building to abandon district heating and implement other heating devices such as bivalent heat pumps and oil-boilers [1]. Insulation measures and weatherstripping were other energy conservation measures that were found occasionally to be optimal. Strategies like that were, of course, not very popular from the municipality's point of view.

The savings made by the owner of the building led to the loss of income for the district heating plant which was not balanced by the same decrease in its costs. Further, the savings of heat led to an increase in electricity purchases from Sydkraft which, in the future, might lead to an increase of the electricity prices. The electric drive heat pump used in the, assumed, optimally retrofitted building will thus have its profitability decreased. Therefore, the proprietor will not be satisfied with the situation; it will lead to suboptimations in the retrofit strategy of the building.

The problems found above made it of interest to examine how the supply side should act, in order to provide the end user of energy with correct information, so as to encourage the best strategy for them all. This is a major task to evaluate, and thus the municipality of Malmö has applied for research funds from the National Energy Administration in Sweden. However, the town found the question of great importance and thus an initial project was started immediately. This was funded by the municipality itself, using a subsidiary called Malmö Energy Research and Development Company, in Swedish abbreviated MEUB. The paper deals with the result from this initial project.

COGENERATION

In ordinary thermal power plants the pressure difference between turbine inlet and outlet should be as high as possible, and thus a condenser is used which is cooled by, e.g. cold sea water. The thermal laws, however, say that only about 40% of the energy in the fuel can be utilized as electricity while 60% must be led away as lukewarm water into the sea. This waste water cannot be used for, e.g. heating premises because of its low temperature. If the temperature must be increased, this will lead to a smaller difference in the saturation pressure and thus less electricity can be produced. This decrease in electricity power is, however, rather small. Information from [2] shows that the efficiency will decrease from about 40% to 35% if the temperature is increased from 10 to 50°C and to about 27% if the condenser temperature is raised to 100°C. The figures are very approximate but they show the magnitude of the influence. Extensive reading about cogeneration and powerplants can be found in [3] and [4].

PRICING ELECTRICITY AND HEAT

Consider once again an ordinary thermal electricity plant. The lukewarm water that is generated in the plant must be considered as useless and thus the price for it equals zero. Increasing the temperature in the condenser makes it possible to use the now somewhat warmer water. When the water is as hot as it is in the district heating grid, 120°C in Sweden during the winter, the water can be priced as coming from the ordinary hot water boiler, used for district heating generation. The price for the waste water must thus depend on its temperature and varies from zero to the district heating price during the winter season. In Malmö this means that the heat will be worth about 190 SEK MWh^{-1} (6 SEK = 1 U.S.$).

During the summer the need for electricity is lower, and so is the price for purchasing it. This means that it cannot be profitable for the municipality to produce electricity. However, heat must be provided to the district heating grid but this is much less than before. The temperature may also be reduced, and 70°C is common during the summertime in Sweden. The price for summer heat in Malmö is about 100 SEK MWh^{-1}.

Now consider the case where it is necessary to use ordinary thermal electricity plants in the national grid. The municipality could therefore also produce electricity, using the plant as an ordinary thermal power station, in a profitable way. However, the municipal plant has to provide hot water to the grid and subsequently its cost for producing the electricity is somewhat higher. This difference in electricity price should be paid by the district heating subscribers as the price for their use of the hot water. As is shown above, the increase in electricity production is rather small, if the plant is run ordinarily instead of as a cogeneration unit. This means that the price for heat, during peak demands for electricity, from the grid must be very low. In [5] this optimal price for heat was calculated to be 30 SEK MWh^{-1}. This also implies that heat should be sold more cheaply during winter time than during the summer. The opposite is valid today. See [6] for a more detailed discussion about pricing theories.

RETROFITTING BUILDINGS

In an earlier research project a mathematical model called OPERA was developed. Experience from this work showed that building retrofits, even low cost examples such as weatherstripping, were not profitable for prices of heat lower than approximately 0.10 SEK kWh^{-1}. From the discussion above, it is obvious that almost nothing could be done to the building if optimal pricing prevails. However, it could be profitable to conserve electricity in the buildings. In Sweden, where this form of energy has been very cheap due to our nuclear power program and the use of much hydroelectric power, a lot of buildings are heated with electricity. The magnitude of the electricity prices, valid for the consumers, during winter time is about 0.50 SEK kWh^{-1} and subsequently a lot of retrofitting must be profitable. More information about optimal building retrofits and electrical heating can be found in [7].

CASE STUDY

In order to clarify the situation, a case study has been elaborated. It deals with a simplified model of the situation in the municipality of Malmö. The model is presented in detail below, using some figures and tables to depict the energy system. The mathematical model is written in the

Table 1. Malmö as a district heated building

Building part	Area (Mm^2)	U-value (W m^{-2} K)	U-area (MW K^{-1})
Attic floor	3.1	0.5	1.55
External wall	9.7	0.7	6.79
Floor	3.1	0.5	1.55
Windows, 1.2 MPcs · 1.5 m^2	1.8	2.5	4.50
Total			14.39

Table 2. Power and energy demand in the district heating grid

Month	Load (MW)	Heat (GWh)	Month	Load (MW)	Heat (GWh)
January	438.7	326.0	July	94.3	69.7
February	442.6	309.5	August	104.0	77.0
March	401.8	298.5	September	166.3	120.2
April	312.2	225.3	October	255.8	189.9
May	214.9	159.5	November	333.7	240.7
June	137.1	99.2	December	390.1	289.8

programming language C, which has been run on a IBM compatible computer. The programming code, however, is not presented here.

The district heating load

When calculations are to be made for a big energy system such as Malmö, there is a need for many simplifications. As mentioned above, we have experience from previous building retrofit calculations and therefore it seemed convenient to simulate the total district heating load as a gigantic building sited in the South of Sweden. Of course the real load has been the base for the design of the model and the thermal properties of the "building" are shown in Table 1. The thermal losses from ventilation are assumed to total 5.07 MW K^{-1} and the heat for producing domestic hot water is set at 350 GWh year^{-1}. The dimensioning thermal load has been set to 720 MW, according to the Swedish building code. It is also necessary to present the district heating load due to the climatic conditions. This has been done using monthly mean values for the outside temperatures in Malmö. The power and energy demand are shown in Table 2.

Table 2 shows both the climatic load and the load for domestic hot water production. This latter demand was assumed to be 350 GWh annually (i.e. per 8784 h) and the load will thus be about 39.8 MW. The load is depicted in Fig. 1.

The electricity load

The electricity load is not influenced as much as the district heating load by the climate. Thus, the real load has been used as it is monitored by the municipality. The fact that the mathematical

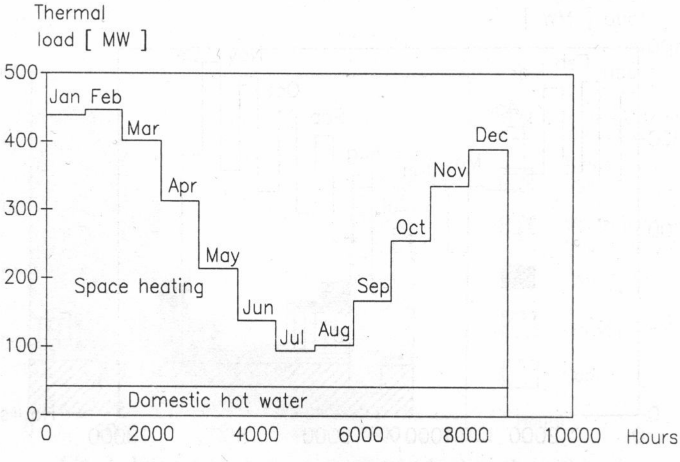

Fig. 1. Thermal load graph. District heating grid.

Table 3. Electricity demand in Malmö, 1988

Month	Peak (GWh)	Base (GWh)	Month	Peak (GWh)	Base (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

model must calculate the cost for buying the electricity makes it necessary to split the load due to the applicable tariff used by Sydkraft. The tariff, which is presented under a separate heading, uses peak load and base load divisions during each month. The peak load is supposed to emerge during 0600–2200 every working day, while the base load emerges during 2200–0600 on working days and during the full 24 h during Saturdays and Sundays. The monitored load is found in Table 3.

The maximum demand has been monitored to 455.3 MW in December.

The values in Table 3 have been depicted in Fig. 2. Note that the use of electricity is highest during December while district heating has its maximum during February. The electricity load thus cannot be predicted only by use of the climate.

Production of heat and electricity

In Figs 1 and 2 the demand for heat and electricity are shown. To start with electricity, it can be purchased from Sydkraft or it can be produced in the CHP plant. However, there is a limit for electricity production. When the district heating grid cannot act as a cooling device for the condenser in the electricity plant, it is not possible to produce any electricity at all. In this case study the electricity plant is sized at 100 MW_{el}. The ratio between electricity and heat production is assumed to be 0.33. In our case there must firstly be a calculation of how much electricity, and subsequently heat, that can be produced by the municipality. The values are shown in Table 4. The figures in parentheses show the months when the heating load is insufficient for electricity production (see Table 2). During November to April it is thus possible to produce electricity in the CHP plant. The electricity deficit must be purchased from Sydkraft. The tariff for doing so is shown in Table 5. To these prices shall be added annually a fixed fee of 0.4 MSEK, a connection fee of 15 SEK kW^{-1} and a power fee of 160 SEK kW^{-1}.

The heat demand that cannot be provided by cooling water from the electricity plant must be produced using the ordinary district heating utility. Different energy sources are used for this and those in Malmö are listed in Table 6. The first heat source arises from garbage burnt in an incineration plant. The next two are waste heat in the form of hot water and gas from the Swedish

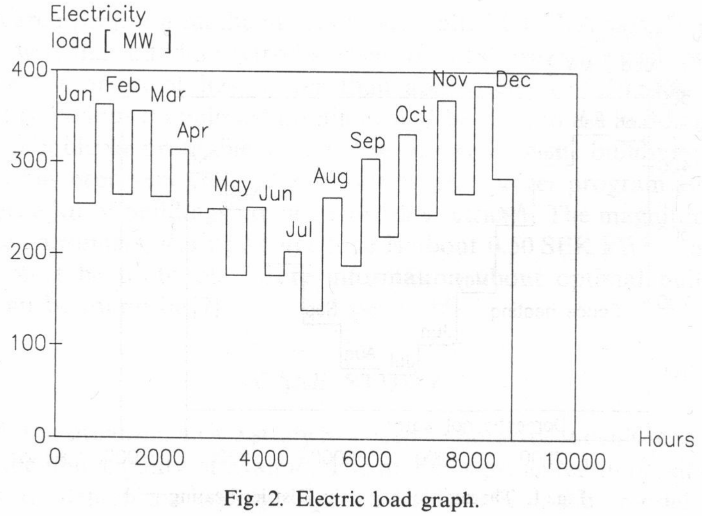

Fig. 2. Electric load graph.

Table 4. Heat and electricity production by Malmö

Month	Heat (GWh)	Electricity (GWh)
January	744.0	223.4
February	696.0	209.0
March	744.0	223.4
April	720.0	216.2
May	(744.0)	(223.4)
June	(720.0)	(216.2)
July	(744.0)	(223.4)
August	(744.0)	(223.4)
September	(720.0)	(216.2)
October	(744.0)	(223.4)
November	720.0	216.2
December	744.0	223.4

Table 5. Electricity prices from Sydkraft

Month	Electricity price ($SEK\ kWh^{-1}$) Peak	Off-peak
November–March	0.240	0.165
March, Sept.–Oct.	0.165	0.130
May–August	0.112	0.092

Table 6. Energy prices for district heating production

Source of energy	Priority	Size (MW)	Energy price ($SEK\ MWh^{-1}$)	Efficiency	Taxation ($SEK\ MWh^{-1}$)
Garbage	1	75	54	1.0	—
Waste SSA	2	22	100	1.0	—
Waste SCR	3	60	120	1.0	—
Heat pump	4	40	198	3.0	50
Coal	5	260	42	0.8	55
Nat. gas	6	120	85	0.85	29
Oil	7	240	57	0.8	89

Sugar and Swede Chrome companies. The heat pump takes part of its heat from sewage water while heat producers 5–7 are ordinary hot water boilers.

In Fig. 3 the different heat sources have been located in the thermal load graph and it is shown that almost all of the necessary heat comes from very cheap sources like refuse and process waste heat. Note that it is assumed that electricity production is to be maximized, which might not be an optimal solution.

Only during May and October coal has to be used as a fuel if electricity production is maximized. Oil or natural gas are never needed. However, it should be noted that the CHP plant is run on natural gas or oil, but this is primarily for electricity production. Note also that the peak load is

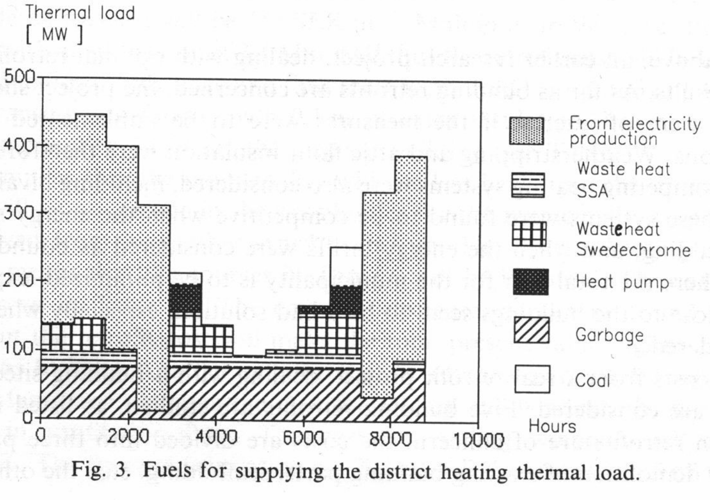

Fig. 3. Fuels for supplying the district heating thermal load.

Table 7. Fuel supply to district heating grid

	CHP		Garbage		Waste SSA		Waste SCR		Heat pump		Coal	
Month	(MW)	(GWh)	(MW)	(GWh)	(MW)	(GWh)	(MW)	(GWh)	(MW)	(GWh)	(MW)	(GWh)
January	300	223.2	75	55.8	22	16.4	42	31.0	—	—	—	—
February	300	208.8	75	52.2	22	15.3	46	31.7	—	—	—	—
March	300	223.2	75	55.8	22	16.4	5	3.6	—	—	—	—
April	300	216.0	12	8.8	—	—	—	—	—	—	—	—
May	—	—	75	55.8	22	16.4	60	44.6	40	29.8	18	13.3
June	—	—	75	54.0	22	15.8	40	28.8	—	—	—	—
July	—	—	75	55.8	19	14.4	—	—	—	—	—	—
August	—	—	75	55.8	22	16.4	7	5.2	—	—	—	—
September	—	—	75	54.0	22	15.8	60	43.2	9	6.7	—	—
October	—	—	75	55.8	22	16.4	60	44.6	40	29.8	59	43.7
November	300	216.0	34	24.3	—	—	—	—	—	—	—	—
December	300	223.2	75	55.8	15	11.2	—	—	—	—	—	—
Total		1310.4		583.9		154.5		232.7		66.3		57.0

Table 8. Cost for district heat production

CHP	—
Garbage	31.5 MSEK
Waste SSA	15.5 MSEK
Waste SCR	27.9 MSEK
Heat pump	5.5 MSEK
Coal	6.9 MSEK
Total	87.3 MSEK

720 MW, which is not shown in Fig. 3. The cost for producing the heat can be calculated using the information in Table 7 and the thermal load in Table 2.

The cost for producing the heat is given in Table 8. The values in Table 8 have been calculated using the prices in Table 6 and the demand from Table 7. The costs include taxation, and the heat pump energy cost has been calculated as:

$$\text{Heat pump cost} = [(198 + 50)/3.0]\cdot 66.3/1000 = 5.48\ \text{MSEK}$$

where 198 is the energy price for the heat pump, 50 is taxation, 3.0 is the efficiency or *COP* and 66.3 the total need for heat pump energy. The cost for the electricity production, and the hot water resulting from it, is set to zero above, which of course is not true. The cost can be calculated as:

$$\text{CHP cost} = (1310.4 + 1310.4/3)\cdot(85/0.85)/1000 + [1310.4\cdot(29/0.85)]/1000 = 174.7 + 44.7 = 219.4\ \text{MSEK}$$

where 1310.4 is the amount of heat from the CHP and 1310.4/3 is the amount of electricity (see Table 7). The natural gas price is 85 SEK MWh^{-1} and the efficiency of the boiler is 0.85. The natural gas resulting in heat from the CHP plant is taxed at 29 SEK MWh^{-1} (Table 6).

Retrofit costs

As mentioned above, an earlier research project, dealing with optimal retrofitting of buildings, gave interesting results. As far as building retrofits are concerned, the project showed that only the cheapest retrofits were of interest if the measures were to be implemented only from energy conservation reasons. Weatherstripping and attic floor insulation were therefore possible retrofits.

In the project, competing heating systems were also considered, including bivalent oil-boiler–heat pump systems. These systems were found to be competitive when the energy system border was set around the building, and when the energy tariffs were considered as boundary conditions. In this case study, where the total cost for the municipality is to be minimized, expensive heat pump systems located close to the buildings seem to be a bad solution, especially when optimal pricing, as in [5], is considered.

Here, building costs from a real retrofit project, dealing with a building sited in the Ansgarius block in Malmö, are considered. Five building retrofits are studied, as listed in Table 9.

When insulation retrofits are of concern, the costs are divided into three parts. The first one shows the cost for demolition of existing building parts, scaffolding, etc., the other shows an initial

Table 9. Retrofit costs for the Ansgarius building

Building asset	Retrofit cost m^{-2} (SEK)
Attic floor insulation	$0 + 125 + 300t$
External wall insulation	$425 + 275 + 395t$
Floor insulation	$250 + 195 + 250t$
Triple glazed windows	$2350 + 790A$
Low emissivity triple glazing	$2850 + 1020A$
Gas filled low emissivity triple glazing	$3000 + 1300A$
Weatherstripping per asset	200

cost when the insulation is to be implemented, such as joists. The third part depends on the insulation thickness t. The window retrofit cost consists of an initial part and one that is dependent on the window area A, while the cost for weatherstripping is assumed to be reflected by a cost for each item to be sealed. The decrease in the ventilation flow is assumed to be 0.1 renewals per hour. A more detailed description of this method for calculating the retrofit costs can be found in [8].

Present value calculations

Building costs and operating costs for the building do not emerge at the same time. They cannot be added together without considering the time aspect. In this case study the present value method is used, as recommended by most economists today [9]. Unfortunately, the use of this method makes it necessary to introduce the real discount rate and the project life which cannot be chosen with absolute accuracy. Here, a 5% real discount rate and a 30 year operating life are used, which means that the annual operating cost should be multiplied by 15.373 in order to find the present value. See [1] for more details.

Production costs, existing load

In the model which has been developed for examining the cost for the municipality, the cost for electricity production is first calculated. Above, it has been calculated to total 219.4 MSEK each year, which yields a present value of 3375 MSEK.

The hot water from the electricity production is subsequently used in the district heating grid, where the cost for making up the heat deficit has been calculated to be 87.3 MSEK or as a present value 1342 MSEK.

The municipality was not able to produce all of the electricity used by the community. The required purchase from Sydkraft is calculated using Table 3, Table 4 and the tariff (see Table 5 and below). The cost was found to be 304.6 MSEK, or as a present value 4682 MSEK. The total annual cost is thus 611.3 MSEK, or as a present value 9398 MSEK.

Production costs, district heating conservation

When heat is to be conserved, this can be done by, e.g. attic floor insulation in the building stock. In Table 9 it is shown that the cost can be assumed to be $125 + 300t$ SEK. If 0.1 m of extra insulation is considered the cost will be 155 SEK m^{-2}. Malmö is, in this case study, considered as a gigantic building with an attic floor of 3.1 Mm^2 and thus the retrofit cost will be about 480 MSEK. The cost is assumed to occur only once and thus there is no need for multiplying by a present value factor. The new transmission factor, with 0.1 m of extra insulation, has been calculated to be 13.70 MW K^{-1}, compared to 14.39 for the original building (see Table 1).

This new value implies that the municipality will use less heat from the district heating utility. In this case there will be no change in the possibilities for the municipality to produce electricity, and it can be utilized from November–April as before. The district heating load is, however, decreased and this means that the sources in Table 6 will be less used. The cost for heat supply will now be as shown in Table 10. The cost will decrease, as can be found when comparing Tables 8 and 10, but the retrofit cost will make the total present value higher, increasing it from 9398 MSEK to 9765 MSEK. Another retrofit that is often a part of the optimal strategy is weatherstripping. Mentioned above is the cost for sealing one window, the number of windows and the decrease in ventilation flow. The cost for sealing windows will become $200 \cdot 1.2$, equalling 240 MSEK. The thermal ventilation coefficient will decrease from 5.07 to 4.82 MW K^{-1}.

Table 10. Cost, in MSEK, for district heat production, retrofitted building, 0.1 m attic floor insulation

CHP	—
Garbage	30.7
Waste SSA	13.6
Waste SCR	24.7
Heat pump	5.3
Coal	5.6
Total	79.9

The decrease has been calculated as:

$$0.1 \cdot 3.1 \cdot 2.4 \cdot 0.33 = 0.25\,\text{MW}\,\text{K}^{-1}$$

where 0.1 = the decrease in ventilation flow, 3.1 = the area of the building, 2.4 = the height of the building, 0.33 = the heat capacity of the air. If weatherstripping is implemented, the total production cost for generating heat and electricity will become 9597 MSEK and thus this retrofit will not become profitable.

If extensive retrofitting is implemented the result might be an increased use of e.g. coal in the district heating plant because of reduced possibilities of producing electricity. The neeed for oil or natural gas in the CHP plant is, however, decreased but the municipality must buy more electricity from Sydkraft. This is shown in Tables 11 and 12 where both weatherstripping, 0.2 m attic floor insulation and 0.1 m external wall insulation are introduced. From Table 12 and the preceding it is obvious that building retrofits saving heat from the district heating grid are of no interest.

Production costs, electricity conservation

The electricity load implemented in the model is the real one monitored in Malmö during 1988. It is hard to know how for example a building retrofit will influence this load. A slightly different method has thus been used in order to examine the influence of energy conservation. A percentage decrease of the load is coupled to a specified cost. Of course very cheap retrofitting will be profitable while more expensive systems are of no interest. The model deals with three different types of retrofitting:

peak load energy conservation;
base load energy conservation;
maximal demand conservation.

The peak load energy conservation has been examined using different percentages of savings and at varying costs. A 10–40% decrease of the peak load energy demand at a cost of 10–40 MSEK $\%^{-1}$ will yield the results shown in Fig. 4. As can be seen, the total cost will decrease due to increased

Table 11. Production cost for district heating with extensive retrofit strategy

Source of energy	Energy (GWh)	Cost (MSEK)
Garbage	601.2	32.4
Waste SSA	119.6	12.0
Waste SCR	229.3	27.5
Heat pump	108.9	9.0
Coal	133.5	16.2
Total	1192.5	97.1

Table 12. Total cost for electricity and district heating production with an extensive retrofit strategy

	Annual cost (MSEK)	Present value (MSEK)
Electricity production	147.2	2262.9
Electricity purchase	329.6	5066.9
District heat production	97.1	1493.2
Retrofit costs	7686.7	7686.7
Total		16,809.7

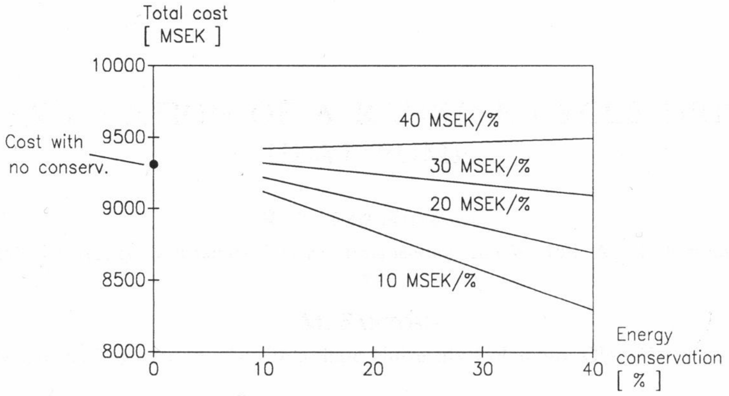

Fig. 4. Total cost as a function of conservation investments during peak load conditions.

energy conservation. This is valid as long as the investment is lower than about 40 MSEK $\%^{-1}$ of the peak load energy. When this border is passed the total cost will increase, showing that profitability has vanished.

In order to compare the investment for electricity conservation with the building retrofits dealt with above, a very simple method has been used. A 10% saving of the peak load electricity each year, i.e. 130.2 GWh as can be found from Table 3, must cost less than 400 MSEK if it is to be profitable. The investment is thus of the magnitude 3.1 SEK kWh^{-1} for each energy unit saved during one year. The attic floor insulation above saved 72.8 GWh during one year, for a cost of 480.5 MSEK or 6.6 SEK kWh^{-1}. In the same way weatherstripping, using the figures above, will cost about 9.3 SEK kWh^{-1}. It is thus obvious that none of the retrofits considered in this study will yield profitability.

If energy conservation is considered during the electricity base load, the investment must be of the order of 20 MSEK $\%^{-1}$ or less, which is about 1.9 SEK kWh^{-1} for the electricity saved during one year.

CONCLUSIONS

Energy conservation building retrofits are not profitable to install in the housing stock, when the costs for producing heat or electricity in Sweden are as low as today. If heat is to be saved in a CHP network only very cheap retrofitting should be considered. This is because of the reduced possibility of producing electricity. With the prices for building retrofits valid in Sweden, none was found profitable. The same is the case for building retrofits which influence the electricity load. The cheapest retrofit considered, attic floor insulation, could not compete against extra electricity production. When nuclear power in Sweden is abolished, the price of electricity is assumed to increase. This will primarily increase the interest in peak load savings in the electricity grid, while heat savings in the district heating grid will still be of minor importance.

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