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Energy conservation conflicts in district heating systems

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SUMMARY

In Sweden, district heating of buildings is in common use. This paper deals with the district heating tariff. Many economists argue that the tariff should be based on short-range marginal costs, but in practice this never occurs. Traditionally instead, the prices are set so they are lower than the alternatives. A case study is presented dealing with a residential building in Navestad, Norrköping. For this building, the life-cycle cost with extra wall insulation and the introduction of a heat pump has been calculated. A comparison of two perspectives, the present tariff and a tariff-based short-range marginal cost, is done. It is shown that there is a conflict between the two perspectives. For the tariff based on short-range marginal cost, neither extra insulation nor an introduction of a heat pump is profitable. However, with the present tariff, a bivalent system with a heat pump and district heating is profitable. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: energy system; building energy; LCC; marginal cost pricing

INTRODUCTION

In combined heat and power (CHP) plants both electricity and heat are produced. In Sweden, the demand for both electricity and heat are strongly dependent on the time of year, and further on the time of day. For cold winter working days all hydro and nuclear electricity power stations are used and sometimes condensing power plants must be utilized. A few times a year, even gas turbines must be used to meet the demand. During summer nights, on the other hand, the demands for electricity and heat are very low and many a times it is possible to cover the electricity need with hydro electric plants and with water that must pass the station because of other than electricity generation reasons. It is therefore obvious that the cost for 1 kWh is dependent of the time of year. One crucial question is now, if this variation in cost should be reflected in the tariffs presented for the end user. If the price is levelled out, some energy conservation measures might be profitable which would not be so if a short-range marginal cost (SRMC) would have been used. Such a cost structure shows how much money must be spent, or could be saved, if one extra kWh is produced or not. This matter will be discussed in detail further down. In Bohman and Anderson (1987), these costs have been calculated for a district heating plant. During winter days, the optimal price for electricity was 0.171 SEK kWh^{-1} while

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it was 0.129 during the winter nights. For heat, the prices were calculated to 0.030 and 0.035, respectively (1$ is approximately 10 SEK). For summer days, electricity should be priced 0.11 and for nights 0.085 SEK/kWh while heat optimally should be priced 0.054 and 0.079 SEK kWh^{-1}. The prices in the reference are not up to date, but show how optimal pricing might look alike. Note that district heating should be cheaper during winter and the lowest price should be applied for winter days. The price for district heat in Navestad, Norrköping is today, 1999, about 0.30 SEK kWh^{-1}, VAT of 25% excluded, see the following. The owner of the building therefore might experience a district heating price that is 10 times higher than optimal, according to Bohman and Andersson (1987). The cheapest fuel available in a district heating plant is many times waste and garbage from the households. By incinerating this waste, useful heat can be produced. If the cost for district heating is too high, the proprietor wants to consume less heat which might result in a surplus of garbage at the incineration plant. For electricity there is today a deregulated market. It is in Sweden, possible to buy electricity on an annual basis for 0.15 SEK/kWh at least for industrial use. (The market is very volatile at the moment, so the price may vary.) This price is lower than the optimal cost above. If a consumer follows the price signals, he therefore will consume too much electricity and too less heat. It must be noted here that there is a debate going on among economists on how pricing of energy should be put into practise, see e.g. Kaye and Outhred (1989); Andersson and Bohman (1985); Della Valle (1988) and Turvey (1969) for some contributions.

If an owner of a building finds that the cost for electricity and heat is too high, there is a possibility to reduce the demand. By implementing energy conservation measures, such as extra insulation on the external walls, the energy bill will probably decrease, but investment is necessary in order to achieve this. Extra insulation will, however, decrease the energy demand over a number of years and therefore it is necessary to use a method which can transfer future reductions in energy costs to the present. This is fulfilled by so-called present value calculations, and if all these present values are added they result in the life-cycle cost (LCC). The LCC includes therefore building, maintenance and operating costs for a number of years. If, for example, extra insulation is added to the external walls, this measure is only profitable if the LCC becomes lower than the LCC without this insulation. By use of the so-called OPERA-model, see Gustafsson and Karlsson (1989) for a short description, such LCC calculations have been computerized. Further, the retrofit strategy was optimized, i.e. it should not be possible to find a strategy with a lower LCC. A peak load district heating system is, however, not presented in OPERA model and, hence another method is used here. In order to accurately calculate the LCC, it is necessary to use interest rates, energy costs, retrofit costs, etc. not only for conditions today but for the future. Sometimes, it has therefore been considered as a useless concept because of all uncertainties. But by use of a so-called sensitivity analysis the optimal strategy could be calculated for a number of interest rates, optimization periods, escalating electricity costs, etc. It is therefore possible to identify certain intervals where, e.g. extra insulation on the attic floor is optimal. It is also possible to calculate the difference in LCC if the proprietor withdraws from this optimal point, see Gustafsson (2000) for a recent study. Despite of all uncertainties, knowledge about the situation is therefore much better if LCC is used than if this concept is abandoned.

If the building owner implements e.g. solar panels in order to reduce the energy demand, the utility will loose money if the marginal cost is not reflected in the tariff. The very expensive equipment used in a district heating grid will therefore not be used as much as optimal because of this imperfection. This was to a part dealt with in Wene (1980) where linear programming

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(LP), was used for optimizing the retrofit strategy. Such an optimization method has, however, some drawbacks. One of the most obvious is that the mathematical model must be totally linear, but the introduction of fast computers made it possible to introduce integers in order to depict nonlinear functions. These so-called mixed integer linear programming (MILP), models must solve a number of LP problems which earlier made them tedious to use if the number of integers were large (Rardin, 1988). A recent study of a building and MILP programming can be found in Gustafsson (1998).

One of the main aims for restoration of the Navestad area is to create a more environmental-friendly energy system. One thing which would be interesting to study is, for example, how the CO_2 level is affected with this new system. This is, however, beyond the scope of this paper but is dealt with in Rolfsman (accepted for publication). Here the emphasize is on two perspectives: use of short-range marginal pricing or use of the existing district heating tariff.

CASE STUDY

The Navestad area is situated in the city of Norrköping, 200 km south of Stockholm at the eastern coast of Sweden. A number of blocks of flats were built in the early 1970s as part of a special programme initiated by the Swedish government. This in order to reduce the dwelling shortage by building one million new dwellings. The main emphasis was therefore not laid on energy efficient buildings but instead on the number of residences produced. The Navestad area consists of 1600 apartments built in large building blocks, of different heights, which form two large circles. In order to vitalize the area the large building blocks are now subject for down sizing and the circles will be opened up. Some buildings will contain offices and the number of apartments will be decreased to about 1200.

The Navestad dwellings are connected to the Norrköping district heating grid and use approximately 30 GWh of heat each year. In this case study, a test house is examined which has the same characteristics as one of the real buildings in the area, but it is somewhat simplified in order to make the calculations more transparent.

Nonetheless, it is assumed that the results of the study should be of significant relevance. The heating energy needed for ventilation is based on the values found in Table I, where the result is also presented.

In Figure 1, the duration graph for the test house is presented. The graph is calculated based on the values in Table II; the monthly mean temperatures for a normal year and an assumed indoor temperature of 20°C. The heating season is limited, thanks to the sun shining through the windows and the energy supplied by inhabitants and appliances, which is the lower curve in the duration graph. The free energy is based on assumed values but the contribution from the Sun is

Table I. Ventilation calculation. The ventilation ratio is an assumed value.

Ventilation ratio ($l\,s^{-1}$, m^{-2})	0.70
Area (m^2)	2310
Heat capacity of air C_p ($J\,kg^{-1}$, K^{-1})	1000
Density of air ($kg\,m^{-3}$)	1.20
Ventilation power needed ($W\,K^{-1}$)	1915

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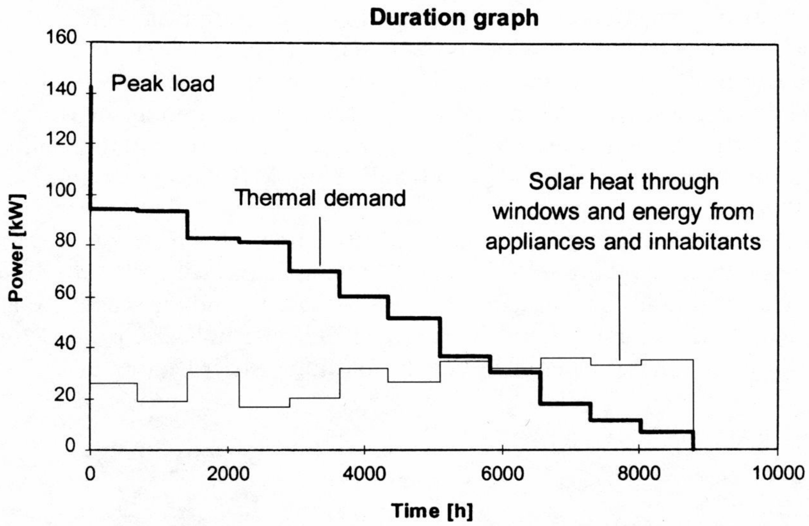

Figure 1. Duration graph for the test house in the Navestad area.

Table II. Building characteristics. Areas, U-values, heat transmission through the building parts and the demand for ventilation in $\mathrm{W\,K^{-1}}$.

	Area (m^2)	U-value ($\mathrm{W\,K^{-1}}$, m^{-2})	UA ($\mathrm{W\,K^{-1}}$)
Attic floor	770	0.38	293
Floor	770	0.25	193
External wall (windows excl.)	1215	0.46	378
Windows to the north	144	2.8	403
Windows to the east	0	0	0
Windows to the south	252	2.8	706
Windows to the west	0	0	0
The sum of *UA*	—	—	2153
Ventilation	—	—	1915
Total	—	—	4068

calculated with a computer program called SORAD (Gustafsson, 1990). The thermal demand graph do not include the need for the domestic hot water. The peak power demand is calculated for a dimensioning outdoor temperature of −15°C.

CHP AND DISTRICT HEATING IN SWEDEN

CHP—generation is rather common in Sweden and investments in the most expensive part of the district heating system, namely the network, has already been made in many cities. The conditions for CHP is particularly good due to the fact that district heating and electricity are

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Table III. District heating tariff for Norrköping, 1999.

Capacity price (SEK)	*E*-value	Flow cost (SEK m^{-3})	Energy cost (SEK kWh^{-1})
(234 × *E*)–1030	6–112	1.5 (November–March)	0.179
(204 × *E*)–4120	113–338	1.5 (November–March)	0.179
(170 × *E*)–15450	339–2100	1.5 (November–March)	0.179
(158 × *E*)–41200	2101	1.5 (November–March)	0.179

Table IV. Annual cost for district heating.

Capacity cost	37 200 SEK
Flow cost	8540 SEK
Energy cost	63 700 SEK
Total cost	109 400 SEK

needed at the same time. This is mainly explained by the wide use of electric resistance heating, which is a product of a rather low price of electricity.

THE DISTRICT HEATING TARIFF

The existing district heating tariff in Norrköping consists of four parts. The first two parts show the fixed capacity fee and a part depending on the capacity, or the so-called *E*-value. This value is calculated from the average energy usage in kWh, for the two, latest years divided by a category number 2200. The higher the *E*-value, the higher the fixed capacity fee.

The third part depends on the flow of water in the system and is priced as SEK/m^3. This fee is only charged during the winter, i.e. from 1 November to 31 March. The idea of this part is to keep the return temperature in the system down, which of course is good if you have a CHP plant and want to produce as much electricity as possible.

The last part is of course, the energy price. This price is independent of how much energy is used, however, with an exception for single family building owners who have a somewhat larger energy tariff.

First the *E*-value is calculated. In this calculation is an average year (with 0.356 GWh) used for the test house with no extra insulation. Hence, the *E*-value is 3.56×10^5 kWh/2200 = 162.

The capacity cost can then be calculated as $204 \times 162 + 4120 = 37\,200$ SEK, all according to the tariff (Table III).

The water flow cost must now be calculated (i.e. the water that passes the heat exchanger in the district heating grid). The temperature difference between the forward and return temperature in the district heating system is estimated to be 40°C and the heat capacity for hot water is 4.18 kJ kg^{-1} K^{-1}. The energy (2.62×10^5 kWh, which is the energy used in the test house during the period November–March) from the water in the district heating grid is calculated to 46 kWh/m^3, so the total flow is 2.62×10^5 kWh/46 = 5690 m^3 and according to the tariff the flow cost is 1.50 SEK/m^3. Thus, totally the flow cost is 8540 SEK. In Table IV the costs for district heating is summarized.

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A cost function is calculated, which will be used in the LCC calculations further on. The costs for district heating is divided into a fixed and variable part in the following cost function in which x is the energy in kWh. The fixed part (37 200) is the same as in Table IV and the variable part is the flow cost (8540) plus the energy cost (63 700) divided by the energy used (3.56×10^5 kWh).

$$37200-0.202x$$

THE SHORT–RANGE MARGINAL COST PERSPECTIVE

Apart from using the present district heating tariff in Norrköping, it can be interesting to study how the energy system in the test house would look like if pricing according to national economy theory and especially marginal cost pricing is used (Edsbecker, 1980). The point, by using marginal cost pricing according to Edsbecker (1980), is that the sum of the consumers surplus and the suppliers surplus is maximized if marginal cost pricing is used. The marginal cost is the cost for the last produced unit, i.e. the last produced kWh. It could also be noted that there is a long-range marginal cost (LRMC) and SRMC. For the SRMC, the investments are fixed and for the LRMC investments are variable. If the suppliers installation mix is optimal, the LRMC and SRMC is said to be equal (according to economic theory). Running the power plants according to the principle of SRMC means that power plants with the lowest marginal cost is operated first and then power plants with higher marginal cost and so forth. This means that the most expensive power plant is operated only in the coldest winter days. According to Andersson and Bohm (1981) a perfect tariff would reflect the SRMC. However, it is argued in Andersson and Bohm (1981) that a tariff based on costs for an alternative production, should be used. Reasons for this could be that of simplicity, i.e. it is impractical to use a tariff that varies very much during the year, reflecting the SRMC. Another reason could be that it is difficult to calculate the SRMC. However, one solution to these problems is presented here.

The marginal costs for a supplier can be calculated by use of linear programming (LP). When such a calculation is elaborated so-called shadow prices are generated (Williams, 1993), from which values can be interpreted as the marginal costs (Sherali *et al.*, 1982). One LP method used for the energy sector is MODEST (Henning, 1998), which has been used for Norrköping. The aim of the LP is to minimize an objective function, which is the cost of an energy system over a number of years, given a number of constraints. The objective function contains the costs, for example energy costs for different fuels in the power plants. It also contains income for sold electricity to the electricity market, as a negative cost. The objective function does, in this case, not include investments in new power plants. One constraint is the supply of district heating, which means that a certain amount of heat should be delivered. As a result, the optimal energy system is generated as well as how it should be run in different time steps. When the right-hand side in the supply constraint for district heating is increased one unit, in this case one MW during a certain time step, the system cost is altered by a certain amount. This amount is referred to as the shadow price. The shadow prices generated for each time step must be divided by the present value factor, which is in order to get the SRMC for 1 year, and the number of hours for the specific time step. (This is due to the fact that the MODEST model works with power levels in MW and it is desired to obtain the SRMC for an energy unit.) This procedure will result in a SRMC in [SEK/MWh].

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However, since the marginal cost pricing principle have not been used in Norrköping, the investments in production plants may not have been done optimally. Therefore, an additional fixed rate in the tariff is suggested along with the SRMC, in order to cover up the fact that the present production mix is not perfect. The rate is suggested to be of the same amount as it is in the district heating existing tariff. In order to fulfil the condition of simplicity, the price used is an energy weighted average which means that the SRMC for one time period is multiplied with the energy used that time period. The sum of all time periods is then divided by the energy used that year.

THE ELECTRICITY TARIFF

The electricity tariff is divided into two parts, one net tariff and one energy tariff. This is the new structure since the deregulation of the Swedish electricity market. The local energy companies had to split up into two parts; one responsible for the network and one for production of electricity. The net tariff have one fixed fee (3000 SEK/year), one that depends on the power that is used (225 SEK/kW) and one dependent on the amount of energy that is used. The energy dependent part is divided in one fee for the high cost period which is November to March between 6 a.m. and 10 p.m. (0.06 SEK/kWh), and the other part is for the low price period (0.05 SEK/kWh). The electricity energy tariff has only one part which is dependent on the energy used and it is not divided in a high and a low cost period (0.185 SEK/kWh + energy tax: 0.162 SEK/kWh).

SUGGESTED INVESTMENTS IN THE NAVESTAD ENERGY SYSTEM

There are different prospects, in the restoration project, of what the energy system in the Navestad area would be like in the future. The existing system with, for example, district heating is described above. For the building, e.g. thicker wall insulation is suggested together with new fenestration i.e. triple glazed windows with low emission coating. For the heating system heat pumps and solar heating panels together with a heat storage in the ground are suggested. In the energy system, district heating is supposed to cover the peak load. Two measures are studied in this paper: wall insulation and a heat pump.

Thicker insulation is the first measure to be investigated here. The new U-value can be calculated as (Gustafsson, 2000).

$$U_{\text{new}} = \frac{U_{\text{exist}} 0.0475}{0.0475 + U_{\text{exist}} t}$$

where 0.0475 is the thermal conductivity (W/m°C) for mineral wool, t is the insulation thickness in (m) and U_{exist} is the existing U-value. Then a cost function for insulation must be calculated. Prices are taken from Sektionsfakta ROT and a function is formed by linear regression. The linear regression is an adaptation of a straight line to a number of points, which in this case is prices for different levels of extra insulation. In the adaptation, the sum of the vertical distances from the line to each point is minimized. The result is the following function:

$$C_{\text{ins}} = 421t + 52\,\text{SEK m}^2$$

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Then, the life cycle cost (LCC) is calculated using the following formula:

$$\mathrm{LCC} = E \cdot \mathrm{PVF} \cdot C + C_{\mathrm{ins}} \cdot A$$

where E is the energy calculated using energy balances for the test house, PVF the present value factor with an interest rate of 8% and a economic life time of 20 years, C the energy cost and A is the Area.

The functions investment cost for insulation and LCC are calculated for a span of insulation thickness, which can be seen in Figures 2 and 3. In Figure 2, the energy price function for today's district heating tariff is used. In Figure 3 the marginal cost, as discussed above, is used. The marginal costs is calculated (as described in the section The Short Range Marginal Cost Perspective) in Gebremedhin (2000) together with Gebremedhin (personal communication) and the weighted average is 0.11 SEK/kWh.

The LCC curves in Figures 2 and 3 are rather flat, so adding extra insulation above the minimum would not cost so much. Figure 4 is shown in order to illustrate how the LCC curve would look like if the existing U-value was twice as high than it is for the walls of the building studied in this paper (the energy price is according to the existing tariff). In such case, the extra wall insulation would be of much greater use.

The interesting curve to study is the top curve in the three diagrams, i.e. the LCC curve. Note that the insulation cost curve in Figure 2 is not continuous, the cost is of course zero at zero extra insulation and therefore the LCC curve is not continuous, there is a step a the beginning of the curve (this step is due to the regression analysis approximation of the insulation cost curve). The LCC for the existing test building with no extra insulation is the lowest (in Figures 2 and 3), hence no extra insulation is profitable. However, if one would like to add insulation anyway the second minimum at 8 cm might be an alternative.

When one studies the same curve in Figure 3, the same thing as for the curve in Figure 2 applies, but in this case the second minimum is at 4 cm extra insulation. Adding extra insulation

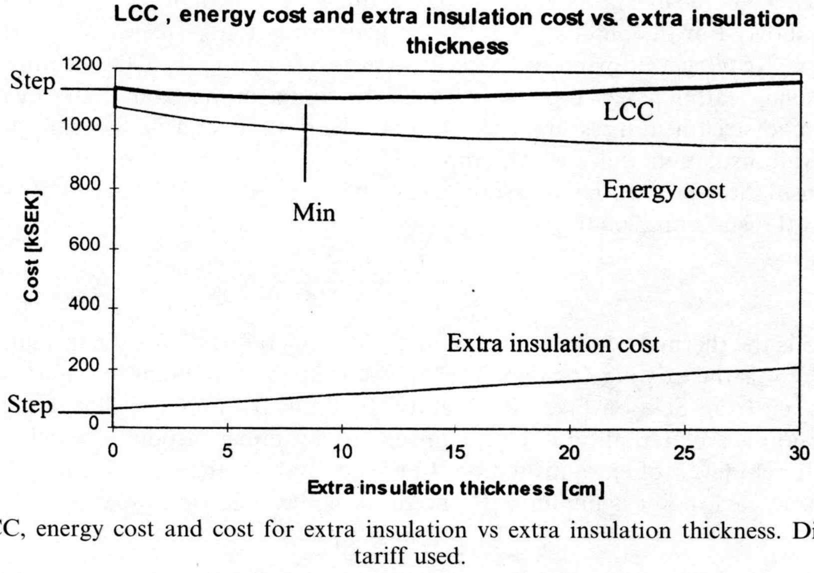

Figure 2. LCC, energy cost and cost for extra insulation vs extra insulation thickness. District heating tariff used.

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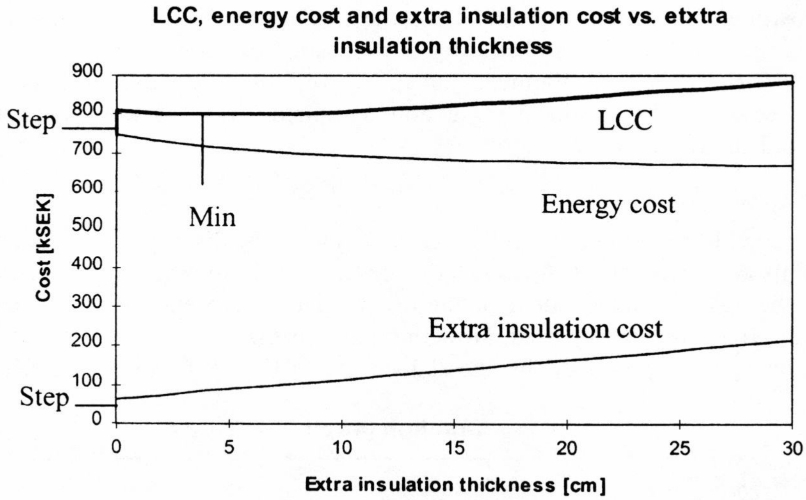

Figure 3. LCC, energy cost and extra insulation vs extra insulation thickness. Marginal cost used.

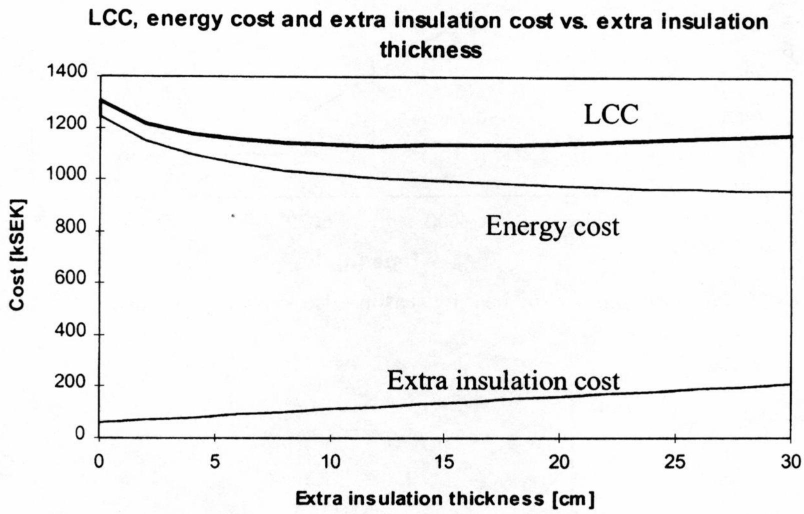

Figure 4. The same conditions as for Figure 2, but with an existing U-value (0.92 W m^{-2},K) which is twice as high as the test building.

is not profitable using either SRMC or the existing tariff. However, it seems that the economic incentive for insulation is somewhat greater with the existing tariff than the SRMC. Hence, there is a slight conflict between the two perspectives. When examining if a heat pump only is profitable in the system, or in a bivalent system together with district heating, a function $P(t)$ in a duration graph (which is an approximated duration graph) must be calculated. This is done in order to be able to calculate the energy provided by each energy supplier, i.e. the heat pump and

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the district heating. The duration graph is for the test house (Figure 5), which represents the energy needed for space heating and heating of domestic hot water.

The values are the same as in Figure 1, but in Figure 5 the hot water usage is also included. When that curve is established, linear regression is applied (the same way as for the insulation price curve) and the result is

$$P(t) = -0.0105t + 83.4$$

which is the sloped line in Figure 5. In the bivalent system the district heating is used on top of the heat pump which is the base load (the order is actually of no importance in these calculations, the result is independent of the order). The interpretation of the area under the power function $P(t)$ is the energy used. Now the function $E(P)$ can be calculated where E is the energy. This energy is represented by the shaded area ($A2 = P^*t^*$) in Figure 6 plus the little

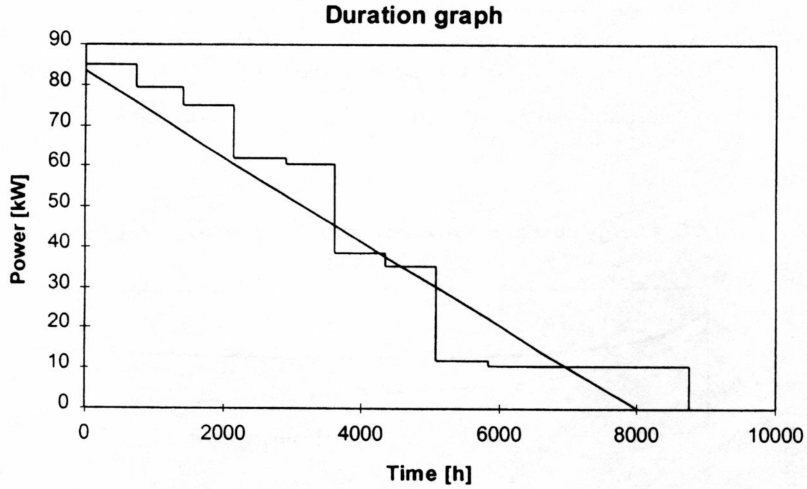

Figure 5. Duration graph for the heating season, also showing the linear regression line.

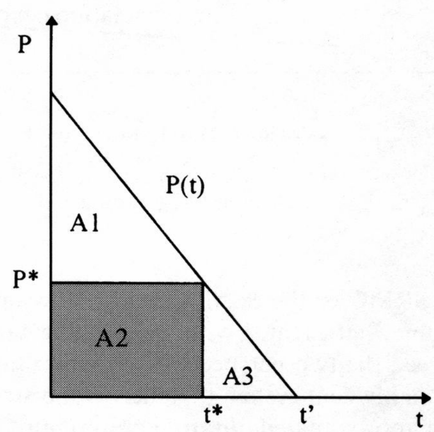

Figure 6. Principal figure showing how the energy for a certain power level is calculated.

triangle to the right of the shaded area ($A3 = 0.5P^*(t' - t^*)$). The result is

$$E(P) = P^* t^* + 0.5P^*(t' - t^*)$$

The energy calculated by the function $E(P)$ is the energy used by the heat pump. Rest of the area, i.e. the top triangle ($A1$ = Total energy-$A2$-$A3$) represents the energy from the district heating. These functions makes it possible to calculate the LCC for both the heat pump and the district heating. For the heat pump, the LCC is presented below. The first two terms are the cost function for the heat pump. The function is formed by a regression analysis based on prices from a sales company for heat pumps called IVT (Personal Communication). The prices are not further examined scientifically, but will hopefully be significant enough for this study. The third term is for change of compressor after 10 years. The cost is discounted to a present value. The interest rate is 8%. The cost is obtained the same way as for the investment in a heat pump:

$$\mathrm{LCC_{hp}} = 1400P + 119\,000 + (505P + 86\,500) \times 1.08^{-10} + \left(225\frac{P}{3} + \frac{E}{3}0.402\right)\mathrm{PVF}$$

The present worth factor is for 8% interest rate and 20 years of lifetime. The last term is the electricity cost, also shown above. (Note that the COP has been estimated to 3 for the heat pump.) The fixed fee in the electricity tariff is not included in the calculations for the heat pump, because this fee has to be paid anyway.

For the district heating, the LCC function is (This is of course for the existing test building. When the district heating is run on part load together with a heat pump, the E-value maybe have to be renegotiated. Here is it however assumed that the E-value is calculated based on the total energy usage of the building.) based on the calculations under the Section. The district heating tariff above. The first two terms are calculation of the E-value and the fixed part of the fee. The third term is the flow cost in the tariff, where r, is the part of the energy demand that is used during the period 1 November to 31 March. The value r, is based on the present situation. The fourth part is the energy cost

$$\mathrm{LCC_{dh}} = \left(\frac{E}{2200}204 + 4120 + \frac{Er}{46}1.5 + 0.179E\right)\mathrm{PVF}$$

Note that the energy E is the rest of the energy above $P(t)$ (stated above) in the duration graph, i.e. the energy not covered by the heat pump. The district heating is already installed in the existing building and dimensioned to be able to cover the peak load.

The curves in Figures 7 and 8 are not continuos. There is a step at the beginning and at the end of the curves since when one heat supply system is at full power the other is at zero. When one of the systems is at zero power there is still a cost, as can be seen in the two functions for $\mathrm{LCC_{hp}}$ and $\mathrm{LCC_{dh}}$ above. The comparison should however be done between the minimum of the curve for the summed LCC and the beginning of the step for each system. The sum of the LCC curves represents the situation when the total load is covered. The LCC curve for either district heating or the heat pump shows only how much of the total LCC is from the heat pump or district heating, respectively. On the abscissa is the heat pump power. Hence, when the power of the heat pump is zero, the energy is solely supplied by the district heating. Evidently, there is a minimum in Figure 7 at a HP power of 70 kW, ergo a bivalent system is profitable. If, however, the marginal cost is applied for the district heating, i.e. 0.11 SEK, a bivalent system is not profitable at all as can be seen in Figure 8.

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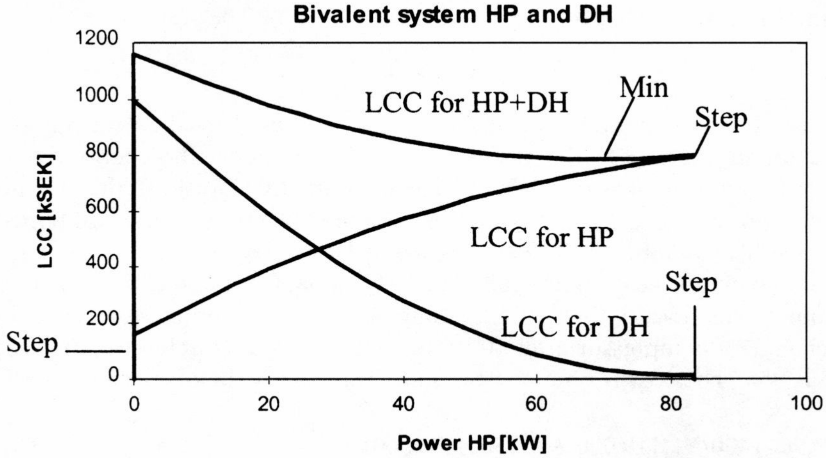

Figure 7. LCC for a heat pump and district heating, with the district heating tariff.

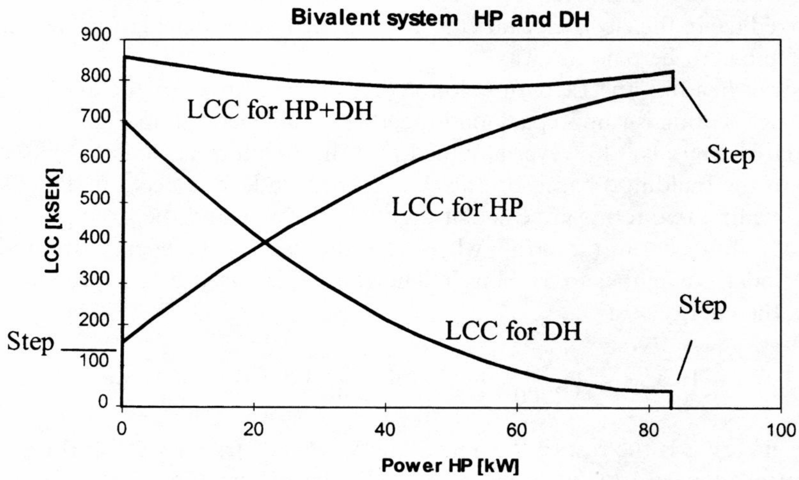

Figure 8. LCC for a heat pump and district heating, with marginal cost pricing.

CONCLUSIONS

When changing the energy system in Navestad, two different ways of pricing may be considered when studying the investments: the existing tariff and a tariff based on SRMC. Pricing based on SRMC does, according to economic theory, maximize the sum of the surplus for the supplier and the customer. There is a conflict between these two perspectives, i.e. the present tariff and a tariff based on SRMC. For example, when it comes to investment in a heat pump, the existing tariff shows that it would be wise to invest in a heat pump and use it together with the existing district heating system as a bivalent system. The marginal cost perspective points out that investment in a heat pump is not profitable at all.

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When it comes to extra insulation, it is not profitable no matter of which perspective that is used. However, when using the second minimum on the LCC curve, it seems that the incentive is somewhat stronger for extra insulation using the existing tariff.

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