Bivalent heating system, retrofits and minimized life-cycle costs for multi-family residences

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Introduction:

Since spring 1985 a research project is running, financed by the Swedish Council for Building Research and the community of Malmö, Sweden. The aim of the project is to find out how existing multi-family residences shall be retrofitted in order to minimize the Life-Cycle Cost, LCC, for the building. An introduction to the subject LCC can be found in [1].

It is obvious that the optimal retrofit strategy will differ a lot according to the thermal status of the studied building. A very thoroughly insulated building can not be retrofitted in order to save energy with any profitability while houses in a bad condition can be the subjects for extensive retrofits. The latter cases will thus have a severe diminutation of the LCC and the retrofits will be very profitable.

However, the influence of the heating system in the building is very important [2]. A building heated with a heat pump which produces the heat to a very low running cost should of course not have the same envelope retrofits implemented as a building heated with eg electricity or oil. The running cost in the latter case is approximately three times higher. Making an insulation retrofit in a building with a low running cost heating system can increase the LCC and thus give the landlord a lower profitability than before the retrofit was made. The savings from a lower energy consumption can not compete with the cost for insulation. A lot of existent multi-family buildings are heated with oil, at least in Sweden. The oil-boiler is a heating system with a high running cost but has a low investment cost. In [3] we have shown that such heating systems implies an extensive envelope retrofit strategy if the LCC is to be minimized. Insulation measures, three-pane windows and exhaust air heat pumps etc are very profitable. However, changing the heating system to a low running cost system eg a heat pump, makes at least the exhaust air heat pump unprofitable. The insulation measures sometimes can be profitable because large heat pumps are very expensive. The insulation measures decrease the need for peak power in the house and a smaller heat pump may be chosen.

The best solution in most cases will be to install a heating system with low running costs and try to diminish the subsequent high installation cost. This can be provided with a district heating system if a cost accurate rate is used by the heating utility. Economic theory tells us that existing equipment is used in an optimal way, only if the energy cost in the rate is equal to the

Short Range Marginal Cost, SRMC, for producing an extra unit of heat. In [4] such rates are discussed both for district heating and electricity. The use of the SRMC implies that the energy cost differs during the year. In Sweden with a cold climate the cost for producing an extra unit of electric energy can be lower than 0.10 SEK/kWh for hydro electrical power during the summer.(1 US dollar = 7 SEK.) During the winter the cost can be higher than 0.50 SEK/kWh using gas turbines during peak periods. In [5] we have discussed the influence of differential rates for district heating on the retrofit strategy. Using a time-of-use rate for district heating where the peak fuel is oil makes the maximum energy cost approximately 0.20 SEK/kWh. Most envelope retrofits thus will be unprofitable. In [6] we have shown the influence of different energy prices etc on the optimal insulation thickness and where the profitability will vanish.

From the above discussion it is obvious that a low SRMC is essential if the optimal strategy shall be reached. The installation cost for the heating equipment has minor influence at least for facilities used today. The heat pump has a very low running cost but is also very expensive. A low installation cost can be provided by an oil-boiler and thus it is natural to combine the two systems. During peak conditions both of the systems are working while only the heat pump works during low demand periods. Figure 1 will depict the situation.

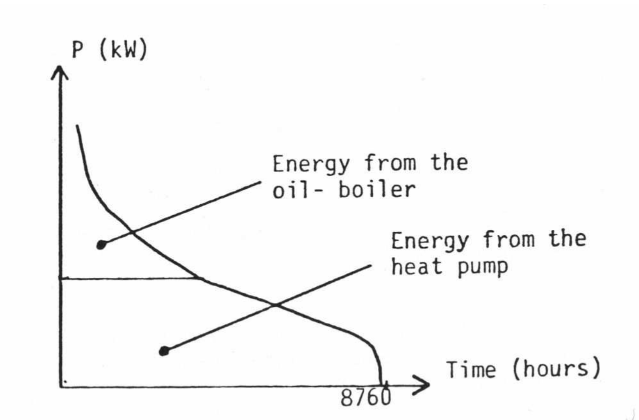

Figure 1: Schematic load duration curve for residential heating

The optimal distribution between the systems of course depends on the duration curve for the unique building, but also on the energy prices, the efficiency and the installation- and maintenance-costs for the two systems. One means to show the optimization procedure is to use a numerical example.

Construction of the climate duration curve

Our fictional building has a peak demand of 141 kW. This is reached when the outside temperature is - 16 degrees centigrade. The transmission factor for the building is 2 666 W/K while the ventilation factor is 1 267 W/K. However, using equivalent U-values for the windows in the building make the transmission factor for energy calculations slightly less or 2 199 W/K. The energy used in the building during one year is:

$$((2199 + 1267) \times 105241/1000) + 80000 = 444765 \text{ kWh}$$

The figure 105 241 shows the number of degree hours in Malmö, Sweden, and 80 000 equals the heat for hot water production.

However it is essential to find out when the energy is consumed during the year. Easy available meteorological information shows the monthly mean temperatures in Malmö and Figure 2 is depicted from this. The procedure and all the details about the building etc can be found in [2].

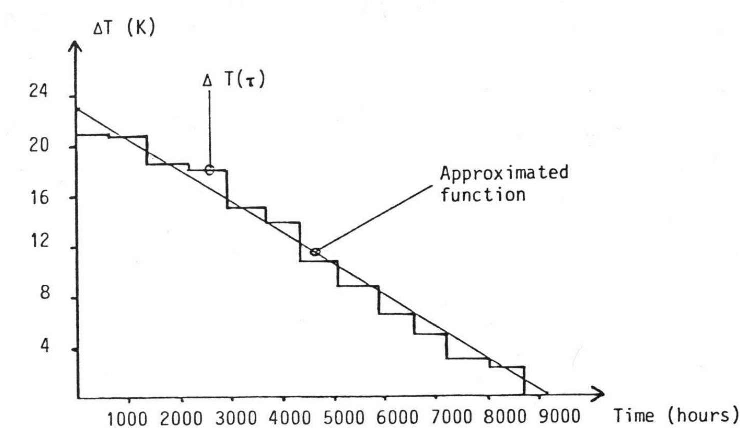

Figure 2: Difference between the inside (20 °C) and monthly mean outside temperatures in Malmö, Sweden.

The function $\Delta T(\tau)$ is not very good for mathematical calculations and thus we will approximate it with a straight line. Using the method of least squares the function turns out to:

$$\Delta T = -0.00251 \times \tau + 22.9 \quad \text{(F1)}$$

Figure 2 also shows this function. The number of degree hours calculated from this expression is 104 923 which shall be compared to the "real" value mentioned above.

The LCC function. Climatic load only

To find the optimal distribution between the oil-boiler and the heat pump it is necessary to examine the LCC function. This consists of four different parts ie:

- The oil-boiler investment,
- The heat pump investment,
- The oil energy cost,
- The heat pump energy cost.

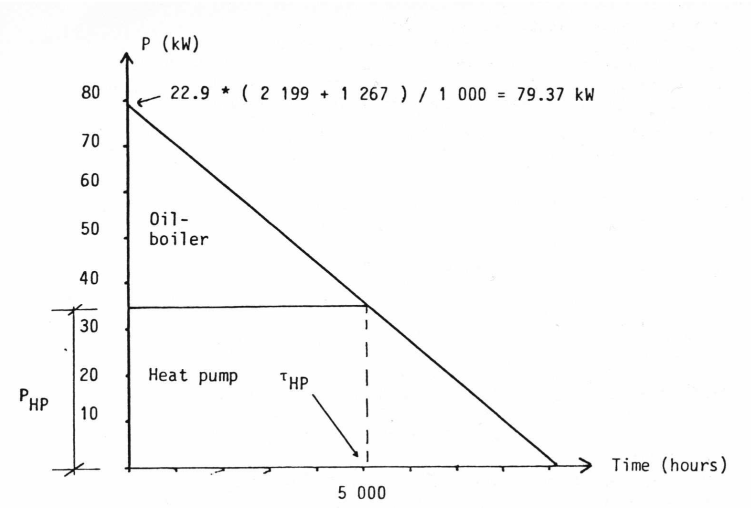

Figure 3: The need for heat evaluated from (F1)

Of course all of these values have to be calculated as present values for the total optimization period. In Figure 3 we have depicted the duration curve for the bivalent system.

In Figure 3 the need for power is approximately 80 kW and it shall be noted that this is only valid for monthly mean calculations. The total need still is about 140 kW. The oil-boiler power must thus be:

$$P_{OB} = 141.58 - P_{HP} \quad \text{kW}$$

The oil-boiler takes care of the peak load conditions and the heat pump will be dimensioned to satisfy the thermal base load. In Ref. [2] we have evaluated the installation costs for different heating equipment. The costs are thus assumed to:

- $(20000 + 350 \times P_{OB})$ SEK for oil-boilers and
- $(30000 + 3300 \times P_{HP})$ SEK for lake heat pumps

The economic life for the oil-boiler is assumed to be 15 years and 10 years for the heat pump. The discount rate eq 5 % and the optimization period is assumed to be 50 years. The present value costs for the two systems will be:

- $C_{OB} = (20000 + (141.58 - P_{HP})) \times 1.7655$ SEK (F2)
- $C_{HP} = (30000 + 3300 \times P_{HP}) \times 2.3642$ SEK (F3)

The annual heat production from the heat pump can be calculated from Figure 3 and (F1).

A heat pump of the power P can supply the building with a sufficient amount of energy up to the temperature difference:

$$\Delta T = \frac{P_{HP} \times 10^3}{(2199 + 1267)} \quad (\text{F4})$$

From (F1) we find that:

$$\tau_{HP} = \frac{-\Delta T + 22.9}{0.00251}$$

and using (F4)

$$\tau_{HP} = \frac{[-\frac{(P_{HP} \times 10^3}{2199+1267} + 22.9}{0.00251} \quad \text{(F5)}$$

From Figure 3 we find the heat pump energy:

$$P_{HP} \times \tau_{HP} + \frac{P_{HP} \times (9163.6 - \tau_{HP})}{2} \quad \text{(F6)}$$

Combining the two expressions (F5) and (F6) we can evaluate the heat pump energy to :

$$E_{HP} = -57.5 \times P^2{}_{HP} + 9163.6 \times P_{HP} \quad \text{(F7)}$$

The oil-boiler energy will thus be (from Figure 3 and (F7)):

$$E_{OB} = \frac{79.37 \times 9163.6}{2} + 57.5 \times P^2{}_{HP} - 9163.6 \times P_{HP} \quad \text{(F8)}$$

The net present value factor for 50 years, 5 % discount rate and annual recurring costs is 18.26. The efficiency of the oil-boiler is assumed to 0.8 and for the heat pump to 3.0. The oil price is assumed to 0.18 SEK/kWh and the electricity price for the heat pump to 0.30 SEK/kWh, see Ref. [2]. It shall be noted here that the efficiency for the heat pump here is assumed to a constant. This is not valid for all heat pumps eg outside-air-source machines which have an efficiency depending on the climate. It is now possible to calculate the present values of the energy costs:

$$PVEC_{OB} = E_{OB} \times 0.18 \times 18.26/0.8 \quad \text{(F9)}$$

$$PVEC_{HP} = E_{HP} \times 0.30 \times 18.26/3.0 \quad \text{(F10)}$$

Adding (F2),(F3), (F9) and (F10) combined with (F7) and (F8) we can find the approximated LCC:

$$LCC = 1687807 - 13375 \times P_{HP} + 128.9P^2{}_{HP} \quad \text{(F 11)}$$

This function has its minimal value when :

$$P_{HP} = \frac{13375}{2 \times 128.9} = 51.87 \quad \text{kW}$$

and the minimized LCC thus becomes 1 340 877 SEK. The oil-boiler shall have the power:

$$P_{OB} = 141.58 - 51.87 = 89.71 \quad \text{kW}$$

From (F2), (F3), (F9), (F10) we can calculate the different costs ie:

- $C_{OB} = 90744$ SEK
- $C_{HP} = 475608$ SEK
- $C_{OE} = 176409$ SEK
- $C_{HE} = 598143$ SEK

and the total cost hence equals 1 340 904 SEK. The figure is almost similar to the one calculated a few lines above.

LCC function. Climatic and hot water load

The energy need for hot water is assumed to have a 100 % durability. The situation is depicted in Figure 4. The hot water load of 80 000 kWh during 9163.6 hours will correspond to a power of 8.73 kW.

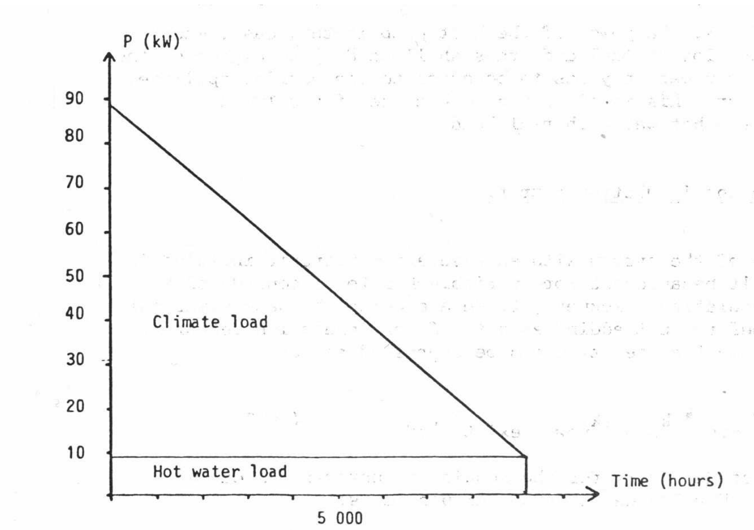

Figure 4: Duration curve for the building, hot water energy included

With the same technique as earlier we find the different costs:

$$C_{OB} = [20000 + 350 \times (141.58 - P_{HP})] \times 1.7655. \quad \text{See (F2)}$$

$$C_{HP} = [30000 + 3300 \times P_{HP}] \times 2.3642 \quad \text{See (F3)}$$

$$PVEC_{OB} = [80000 + \frac{22.9 \times 3.466 \times 9163.6}{2} + 57.5 \times P^2{}_{HP} + 57.5 \times 8.73^2 -$$

$$-2 \times 57.5 \times P_{HP} \times 8.73 - 9163.6] \times 4.1085$$

The expression can be evaluated from (F9) and figure 4. Using (F10) we find:

$$PVEC_{HP} = [-57.5 \times P^2{}_{HP} - 57.5 \times 8.73^2 +$$

$$+2 \times 57.5 \times P_{HP} \times 8.73 + 9163.6] \times 1.865$$

After some calculations the LCC emerges as:

$$LCC = 2026312 - 15625 \times P_{HP} + 128.9 \times P^2{}_{HP} \quad \text{(F12)}$$

The expression has its lowest value for $P_{HP} = 60.61$ kW and the value is 1 552 812 SEK. The power of the heat pump in this case, where the hot water flow is included, thus shall be 8.73 kW higher or the hot water flow power only has to be added to the earlier optimized heat pump power. This is of course so because of the 100 % duration of the hot water thermal load.

LCC function and insulation retrofits

Optimization of the system with an insulation retrofit included is more difficult because one more variable has to be considered ie the extra insulation thickness, t. We are using the same numerical example as before just adding an attic floor insulation retrofit. The new U-value for the attic can be expressed as [2]:

$$U_{new} = U_{exist} \times \frac{k_{new}}{(k_{new} + U_{exist} \times t_{af}} \quad \text{(F13)}$$

The thermal conductivity for the insulation material is called k_{new}. The new U-value can thus be calculated as:

$$U_{new} = \frac{0.8 \times 0.04}{0.04 + 0.8 \times t_{af}} \quad \text{(F14)}$$

The insulation cost has been evaluated to:

$$C_{ins} = 125000 + 300000 \times t_{af} \quad \text{SEK (F15)}$$

for a 1 000 m^2 attic floor.

The transmission factor mentioned above is 2 199 W/K. Excluding the existent attic floor and adding the new U-value in (F14) give us:

$$TF_{new} = 2199 - 0.8 \times 1000 + 0.8 \times 1000 \times \frac{0.04}{0.04 + 0.8 \times t_{af}} =$$

$$= 1399 + \frac{32}{0.04 + 0.8 \times t_{af}} \quad \text{(F16)}$$

Adding the ventilation factor gives us the new total heat loss factor:

$$HLF_{new} = 2666 + \frac{32}{0.04 + 0.8 \times t_{af}} \quad \text{(F17)}$$

Extra insulation also diminutes the need for power in the building and thus:

$$P_{TOT} = 141.58 - 0.8 \times 1000 \times 36 + \frac{32 \times 36 \times 0.001}{(0.04 + 0.8 \times t_{af}} =$$

$$= 113.5 + \frac{1.152}{0.04 + 0.8 \times t_{af}} \quad \text{(F18)}$$

The new cost functions (F2,3,9,10) will become:

$$C_{OB} = [20000 + 350 \times (113.5 + \frac{1.152}{0.04 + 0.8 \times t_{af}} - P_{HP})] \times 1.7655 \quad \text{(F19)}$$

$$C_{HP} = [30000 + 3300 \times P_{HP}] \times 2.3642 \quad \text{(F20)}$$

Changing the previous transmission factor in (F5) to that in (F17) makes it possible to calculate the heat produced by the heat pump. We will not repeat the tedious work but only give the final LCC function:

$$LCC = 1450620 + \frac{14508}{0.04 + 0.8 \times t_{af}} - 13375 P_{HP} + \frac{4.487 \times P^2{}_{HP}}{0.03465 + 0.5345 \times t_{af}} +$$

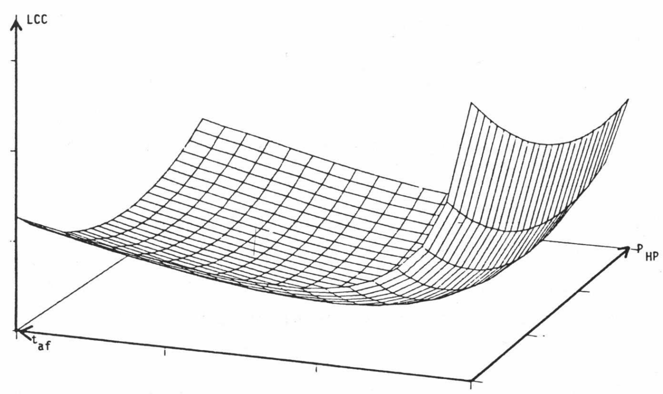

Figure 5: LCC - function for both insulation and bivalent system optimization

$$+\frac{89.74 \times P^2{}_{HP} \times t_{af}}{0.03465 + 0.5345 \times t_{af}} + 300000 \times t_{af} \quad (\text{ F21 })$$

The (F20) function is depicted in Figure 5.

This function has to be minimized and thus (F20) is derivated first with the emphasis on P_{HP} and then on t_{af}. However the system

$$\begin{cases} f(t'_{af}, P_{HP}) = 0 \\ f(t_{af}, P'_{HP}) = 0 \end{cases}$$

is rather cumbersome to solve in a strict analytical way and thus we have used a numerical method and found approximate values for P_{HP} and t_{af}, 42.6 kW and 0.17 m respectively. The minimimal LCC is thus 1 306 000 SEK. The value is lower than the LCC without the insulation and therefore it is profitable to insulate the attic. It is interesting to note, however not shown here, that optimizing the heating system without any heat loss at all through the attic floor give us a heat pump of 40 kW, almost similar the the one chosen above.

Caulking and sealing windows and doors

Caulking the windows changes the natural ventilation rate in the building. In our numerical example from Ref. [2] the rate changes from 0.8 renewals/hour to 0.5 renewals/ hour. Thus the ventilation factor above changes from 1 267 W/K to 792 W/K. The retrofit cost have been calculated, see Ref. [2] to 52 000 SEK. Optimization gives us a heat pump of 44.6 kW, and the total LCC is decreased by the measure and thus profitable.

Exhaust air heat pump

Using a heat pump to recover the heat from the exhaust air is in many cases a profitable energy retrofit. However this kind of equipment is very expensive and thus the heat recovered also has to be rather expensive if the measure shall be profitable. In this case where we already have a heat pump in the ordinary heating system this is not the sitation. The bivalent system produces the heat at a very low running cost and thus the exhaust air heat pump can not compete, the LCC gets higher than before the measure was implemented.

Bivalent systems compared with single heating systems

We have made a lot of calculations on ordinary heating systems common in multi-family buildings in Sweden. Those are described in Reference [2] and we will thus only show some LCC and present values of the savings, from different retrofit measures.This in order to compare the figures with those achived for the bivalent system described above. It shall be noted that also other costs are hidden in the figures below and thus they will not correspond to those calculated above. The situation is shown in Table 1.

	Exist. oil	Electr-icity	Distr. heating	Heat pump	Bival. oil-b. and heat pump
LCC with no env.retrofits	2.43	3.02	2.14	2.48	2.04
Savings PV					
Insul.attic	0.11	0.20	0.06	0.12	0.04
Ext. wall	0.03	0.10	-	0.04	-
Caulking	0.17	0.23	0.13	0.17	0.12
Exh. air h.p.	0.03	0.17	-	-	-
Total LCC	2.09	2.32	1.96	2.15	1.88

Table 1: LCC and savings with different retrofits in 10^6 SEK

It is obvious that the bivalent heating system is a very profitable one. Combining it with caulking and an attic floor insulation give the building the lowest LCC at least among the considered alternatives. The second best solution was the district heating system also this combined with an attic floor insulation and a caulking measure.

We have also implemented the optimization process of the bivalent heating systems in our earlier developed OPtimized Energy Retrofit Advisory - model (OPERA). Calculations have been made for a variety of discount rates, optimization periods etc. and the optimal retrofit strategy shown above for most of these cases will be the same.

Summary

Using the LCC as a ranking criterion gives us an opportunity to find an optimal retrofit strategy for each unique building. Our calculations show that choosing a low running cost heating system makes almost all of the envelope retrofits unprofitable. The bivalent system oil-boiler and a heat pump gives us the very low running cost and also at the same time an acceptable investment cost.

The optimal distribution between the heat pump and the oil-boiler power seems to be about 40 % for the heatpump and 60 % for the oil- boiler, of the total peak demand. Then the heat pump produces approximately 90 % of the heat used in the building.

(NOTE! Some of the references below were not published at the time of original publication of this paper)

References

[1] Ruegg R. et al. Life-Cycle Costing: A guide for Selecting Energy Conservation Projects for Public Buildings. Technical report, National Bureau of Standards, NBS BSS 113. Washington D.C., 1978.

[2] Gustafsson S-I. Optimal energy retrofits on existing multi-family buildings. Division of Energy Systems. Department of Mechanical Engineering. The Institute of Technology. Linköping, Sweden., 1986. Licentiate thesis no 91.

[3] Gustafsson S-I. and Karlsson B.G. Why is Life-Cycle Costing Important when Retrofitting Buildings. *The International Journal of Energy Research*, 12(2):233–242, 1988.

[4] Sjöholm Bertil H. *Influence of differential rates on heating systems. Dissertation no. 119 Division of Energy Systems.* PhD thesis, Department of Mechanical Engineering, The Institute of Technology. Linköping, Sweden., 1984.

[5] Gustafsson S-I, Sjöholm B. H. and Karlsson B. G. Differential rates for district heating - An analysis of the consequences for retrofit measures in multi-family residences. Technical report, Department of Mechanical Engineering. The Institute of Technology. Linköping University, Report no. LiTH-IKP-R-412. (In Swedish), 1985.

[6] Gustafsson S-I., Karlsson B.G. and Sjöholm B.H. Renovation of Dwellings - Life-Cycle Costs. In *Advancing Building Technology, Translating Research Into Practice*, volume 9, pages 3886–3893. CIB-86, September 1986.