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**Energy Conservation
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BIVALENT HEATING SYSTEM, RETROFITS AND MINIMIZED LIFE-CYCLE COSTS
FOR MULTI-FAMILY RESIDENCES.

AUTHORS:Msc Stig-Inge Gustafsson, Prof Björn G Karlsson
Institute of Technology, Dept of Mechanical Engineering,
Div of Energy Systems, S 581 83 Linköping, Sweden.

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Bivalent systems

Abstract:

In order to find the best retrofit strategy for an existing
multi-family building the minimized life-cycle cost can be used
as a ranking criterion. Our research have shown that it is
essential to use a low running cost heating system to achieve
such a minimized total cost. The bivalent system oil-boiler -
heat pump gives us a system with a very low running cost and at
the same time an acceptable installation cost. However it is
important to choose the optimal combination of the two heating
facilities and at the same time consider the energy conservation
measures that maybe shall be implemented at the building
envelope. Our paper shows how such an optimization can be
elaborated and also compares the bivalent system with ordinary
heating systems common in 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 /6/. 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 /2/ 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 /3/ 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 /4/ 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 /5/ 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.

P (kW)

Energy from the
oil- boiler

Energy from the
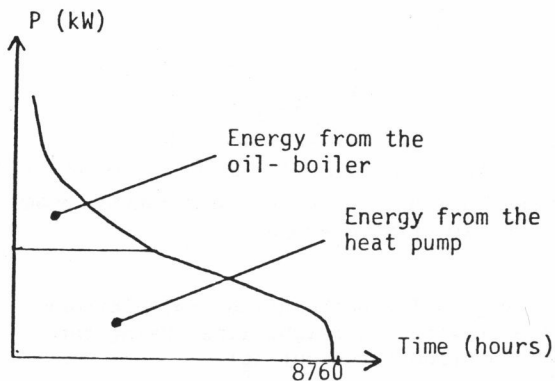heat pump

Time (hours)
8760

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:

$$((2\ 199 + 1\ 267) * 105\ 241 / 1\ 000) + 80\ 000 = 444\ 765 \text{ kWh}$$

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
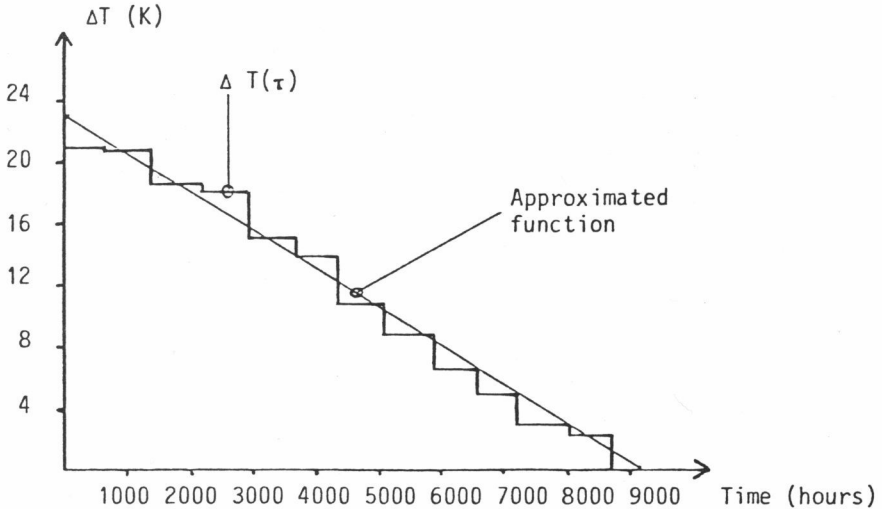can be found in /6/.

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:

$$\Delta T = - 0.00251 * \tau + 22.9 \qquad (F\ 1)$$

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.

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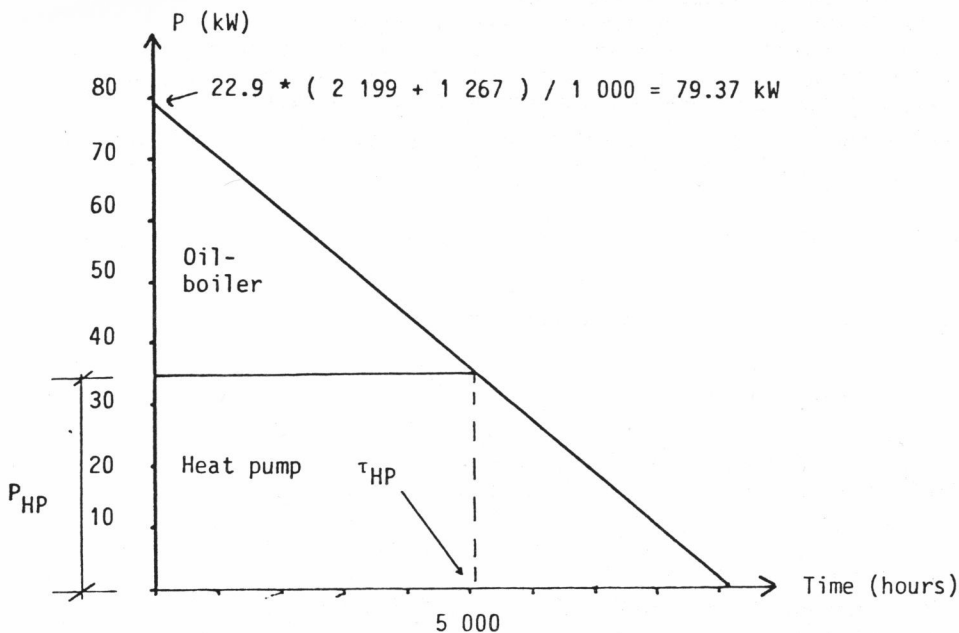depicted the duration curve for the bivalent system.

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

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:

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

The oil-boiler takes care of the peak load conditions and the heat
pump will be dimensioned to satisfy the thermal base load. In /6/
we have evaluated the installation costs for different heating
equipment. The costs are thus assumed to:

- $(20\ 000 + 350 * P_{OB})$ SEK for oil-boilers and

- $(30\ 000 + 3\ 300 * P_{HP})$ 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:

$$C_{OB} = (20\ 000 + (141.58 - P_{HP})) * 1.7655 \quad SEK \quad (F2)$$

$$C_{HP} = (30\ 000 + 3\ 300 * P_{HP}) * 2.3642 \quad SEK \quad (F3)$$

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

A heat pump of the power P_{HP} can supply the building with a
sufficient amount of energy up to the temperature difference:

$$\Delta T = P_{HP} * 10^3/ (2\ 199 + 1\ 267) \qquad (F4)$$

From (F1) we find that:

$$\tau_{HP} = (-\Delta T + 22.9)/0.00251 \qquad \text{and using (F4)}$$

$$\tau_{HP} = [-(P_{HP} * 10^3/(2\ 199 + 1\ 267)) + 22.9]/0.00251 \quad (F5)$$

From figure 3 we find the heat pump energy:

$$P_{HP} * \tau_{HP} + [P_{HP} * (9\ 163.6 - \tau_{HP})]/2 \qquad (F6)$$

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

$$E_{HP} = -57.5 * P_{HP}^2 + 9163.6 * P_{HP} \qquad (F7)$$

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

$$E_{OB} = (79.37 * 9163.6)/2 + 57.5 * P_{HP}^2 - 9163.6 * P_{HP} \quad (F8)$$

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 /6/. 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:

$$PVEC_{OB} = E_{OB} * 0.18 * 18.26 / 0.8 \qquad (F9)$$

$$PVEC_{HP} = E_{HP} * 0.30 * 18.26 / 3.0 \qquad (F10)$$

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

$$LCC = 1\ 687\ 807 - 13\ 375 * P_{HP} + 128.9\ P_{HP}^2 \qquad (F\ 11)$$

This function has its minimal value when :

P_{HP}= 13 375/(2 * 128.9) = 51.87   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 kW

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

$$C_{OB}= 90\ 744\ \text{SEK}$$

$$C_{HP}= 475\ 608\ \text{SEK}$$

$$C_{OE}= 176\ 409\ \text{SEK}$$

$$C_{HE}= 598\ 143\ \text{SEK}$$

Total cost =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.
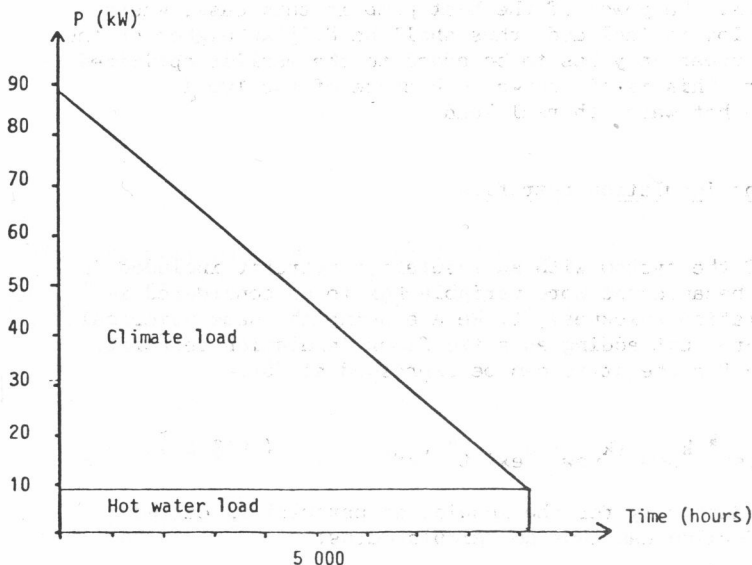
P (kW)

90
80
70
60
50
40
30
20
10

Climate load

Hot water load

Time (hours)

5 000

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

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

$$C_{OB} = [20\ 000 + 350 * (141.58 - P_{HP})] * 1.7655 \quad \text{See (F2)}$$

$$C_{HP} = [30\ 000 + 3\ 300 * P_{HP}] * 2.3642 \quad \text{See (F3)}$$

$$PVEC_{OB} = [80\ 000 + (22.9 * 3.466 * 9\ 163.6)/2 + 57.5 * P_{HP}^2 +$$

$$+ 57.5 * 8.73^2 - 2 * 57.5 * P_{HP} * 8.73 - 9\ 163.6] * 4.1085$$

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

$$PVEC_{HP} = [-57.5 * P_{HP}^2 - 57.5 * 8.73^2 + 2 * 57.5 * P_{HP} * 8.73 +$$

$$+ 9\ 163.6] * 1.865$$

After some calculations the LCC emerges as:

$$LCC = 2\ 026\ 312 - 15\ 625 * P_{HP} + 128.9 * P_{HP}^2 \quad (F12)$$

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 /6/:

$$U_{new} = U_{exist} * k_{new} / (k_{new} + U_{exist} * t_{af}) \quad (F13)$$

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

$$U_{new} = 0.8 * 0.04 / (0.04 + 0.8 * t_{af}) \qquad (F14)$$

The insulation cost has been evaluated to:

$$C_{ins} = 125\ 000 + 300\ 000 * t_{af}\ SEK \qquad (F15)$$

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:

$$TF_{new} = 2\ 199 - 0.8 * 1\ 000 + 0.8 *1\ 000 * 0.04/(0.04+0.8*t_{af})$$
$$= 1\ 399 + 32/(0.04 + 0.8 * t_{af}) \qquad (F16)$$

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

$$HLF_{new} = 2\ 666 + 32/(0.04 + 0.8 * t_{af}) \qquad (F17)$$

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

$$P_{TOT} = 141.58 - 0.8 * 1\ 000 * 36 + 32 *36 * 0.001 /(0.04 + 0.8 *$$
$$*t_{af}) = 113.5 + 1.152/(0.04 + 0.8 * t_{af}) \qquad (F18)$$

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

$$C_{OB} = [\ 20\ 000 + 350 * (113.5 + (1.152/(0.04 + 0.8 * t_{af}) -$$
$$- P_{HP})]\ * 1.7655 \qquad (F19)$$

$$C_{HP} = [\ 30\ 000 + 3\ 300 * P_{HP}]\ * 2.3642 \qquad (F20)$$

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:

$$LCC = 1\ 450\ 620 + 14\ 508 /(0.04 + 0.8 * t_{af}) - 13\ 375\ P_{HP} +$$
$$+ 4.487 * P_{HP}^2/(0.03465 + 0.5345 * t_{af}) + 89.74 * P_{HP}^2 *$$
$$* t_{af}/(0.03465 + 0.5345 * t_{af}) + 300\ 000 * t_{af} \qquad (F20)$$

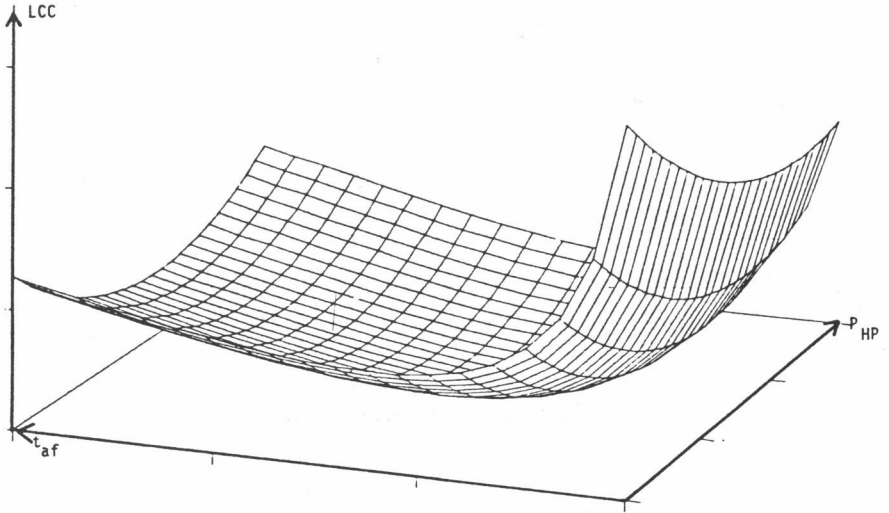The (F20) function is depicted in figure 5.

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

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

$$f(t_{af}^1, P_{HP}) = 0$$

$$f(t_{af}, P_{HP}^1) = 0$$

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 /6/ 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 /6/ 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
/6/ 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.

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

	Exist. oil	Electr- icity	Distr. heating	Heat pump	Bival. Oil-b. and a 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 hp	0.03	0.17	-	-	-
Total LCC	2.09	2.32	1.96	2.15	1.88

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.

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