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INTERNATIONAL JOURNAL OF ENERGY RESEARCH

Volume 12, No. 2 March–April 1988

Editor J.T.McMullan

WILEY
Chichester · New York · Brisbane · Toronto · Singapore
A Wiley-Interscience Publication

IJERDN 12(2) 189–378 (1988)
ISSN 0363-907X

INTERNATIONAL JOURNAL OF ENERGY RESEARCH, VOL. 12, 233–242 (1988)

WHY IS LIFE-CYCLE COSTING IMPORTANT WHEN RETROFITTING BUILDINGS

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SUMMARY

Using life-cycle costing (LCC) gives us a means to find the best retrofit strategy for an apartment block. This method also shows us how important it is to consider the whole existing building as an energy system. If the best heating system is put into the house almost every shield retrofit is unprofitable. Having heating systems, with high variable costs combined with exhaust ventilation air pumps, sometimes makes it unprofitable to caulk the windows and doors.

This article also shows the importance of using the accurate prices for the energy. Short-range marginal costs (SMRC) gives different retrofit strategies than normal tariffs used today. This also means that the retrofits do not correspond to the optimal use of the total national energy system and already scarce resources are used unnecessarily.

KEY WORDS Optimization Life-cycle cost Minimization Retrofit Energy system Building

INTRODUCTION

In Sweden, the production of new buildings has decreased during the last 10 years. Instead, society efforts have been emphasized upon retrofitting houses that already exist. In order to find out the best way to retrofit the different buildings, the Swedish Council for Building Research and the Community of Malmö, have initiated a project at the Institute of Technology, Division of Energy Systems in Linköping, Sweden. Some of the results from this project are discussed in this article.

Surprisingly little, among the huge amount of literature in this field, deal with the subject: 'How to find the best possible combination of a variety of retrofit measures?' One explanation to this is the fact that there are different guilds that construct and retrofit buildings. The building contractor, of course, wants extra insulation on the walls, new windows with three or more panes, and so on. At the same time the heating system contractor wants you to install a very sophisticated boiler with all facilities. Because of this it is common, at least in Sweden, that the boiler gives twice the real power need for the house. When retrofitting the house, it also happens that the newly installed boiler has the same power as the old one, despite the alterations done to the house to decrease its energy and power demand.

When we notice this problem, we have to find out an adequate way to choose between different retrofit measures and the amount actually needed. In this paper we claim that the best solution has been found *when the remaining life-cycle cost (LCC) for the house is as low as possible.*

LIFE-CYCLE COST

The life-cycle cost for a building consists of the sum of the building, maintenance, and the running costs. The cash flow for the entire life-cycle, may be 50 years, has to be considered during the calculations. This can be done by using the method of net present value (NPV). In this method the money paid in the future can be compared to the money paid today. (For a more elaborate discussion about the procedure, see *Life-cycle Costing* or Marshall and Ruegg, 1976/1977.)

0363–907X/88/020233–10$05.00

Received 1 July 1986

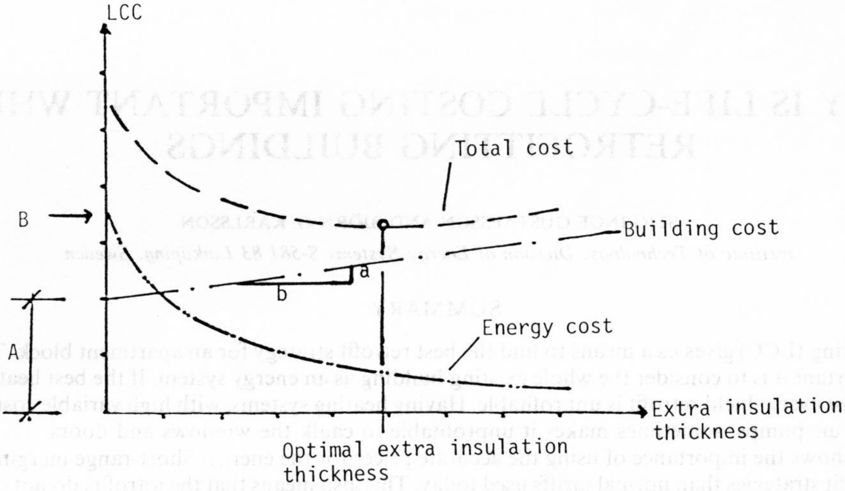

Figure 1

The formulae for the net present value (NPV) can be shown as

$$\mathrm{NPV} = A\cdot(1+r)^{-n}$$

$$\mathrm{NPV} = B\cdot\frac{1-(1+r)^{-n}}{r}$$

where

A = is the amount of money paid at a single occasion, e.g. the building cost
B = is the amount of money paid yearly, e.g. energy costs
r = discount rate
n = number of years

To make this more perspicuous we will illustrate the different types of costs using an extra insulated wall.

The present value for the building cost starts with an initial value A (Figure 1). In this value the costs for raising of scaffolding, demolition of the existing facade and so on, are included. The variable costs for the extra insulation are described by the ratio a/b. Also the NPV energy cost starts with a value B because of the existing energy demand. The graph shows that the building costs are increased if you choose a thicker insulation, but at the same time the energy cost is decreased. At one optimum point, t_{opt}, the sum of the two costs has its lowest value. Gustafsson *et al.* (1986) have shown how this point can be calculated.

One reason why life-cycle costing has not yet been accepted as a common tool for evaluation retrofit measures is the immense amount of calculations needed to find the optimal retrofit strategy. The method also requires adequate information about the existing house, the building, maintenance, and energy costs from now until the end of the optimization time. Furthermore, you have to implement the proper economical parameters to your calculations. However, it has been demonstrated, that it is possible to evaluate important results from these calculations, in spite of the uncertainties in the input data that are inevitable (Björk and Karlsson, 1984; Hall *et al.*, 1984).

By the use of modern computers, in our case a NORD 570 m, the need for time-consuming calculations can be reduced so much that it is possible to analyse important results with different discount rates, energy prices and so on.

NUMERICAL EXAMPLE (Existing house)

As mentioned above there are a lot of calculations behind an optimal retrofit strategy. It is therefore not possible to list all the results in an article of this type. Instead, we give examples from the results, calculated on a fictional apartment block.

For pedagogic reasons we have chosen different existing U-values for the attic, floor and external walls, viz. 0·8, 0·6 and 1·1 (W/m^2, °C). These values correspond to constructions common in Swedish houses that are now the subjects for renovation. Furthermore, we have chosen windows with two panes but with different U-values corresponding to different points of the compass.

When calculating the need for power the U-values during darkness have been chosen. In order to emphasize that the existing windows are bad we have chosen a darkness U-value as high as 4·0 (W/m^2, °C). (New two-pane windows have U-values of about 2·7 (W/m^2, °C)) (Jonsson, 1985).

The house has also a usual type of natural ventilation with a renewal of the air at 0·8 air changes per hour.

We have considered a small apartment block with a total net dwelling area of 2000 m^2.

With these, and other inputs, we have calculated the power need to be 158 kW and the yearly energy demand as 512 000 kWh.

The house is heated by oil where the existing boiler has to be replaced after 5 years.

Of course, the block also has a cost for renovation during its lifetime even if nothing was done to the house today, e.g. the windows would have to be replaced because of rot.

ECONOMIC PARAMETERS, CLIMATE, ETC.

As mentioned above it is hard to choose the proper economic parameters, i.e. the discount rate (r) and optimization time (n). In our case we have used $r = 0{\cdot}05$ and $n = 50$ years as a base case alternative.

The climate is of course very important to the result and in the base case we have chosen Malmö as the site location. In our calculations we used the 'degree hour concept' to describe the climate. For Malmö we have calculated with 105 000 degree hours per year. (There are several definitions for the degree hour. We are using the definition that degree hours generates when the mean outside temperature of one month is lower than +20°C, or the chosen inside temperature.)

In our base case the oil price is 0·30 SEK/kWh (1 US\$ = 7 SEK).

If the price on energy changes more than (or less than) the inflation, this can be considered using a different discount rate for the energy cost calculations (Gustafsson *et al.* (1986)). In our base case the prices are held constant.

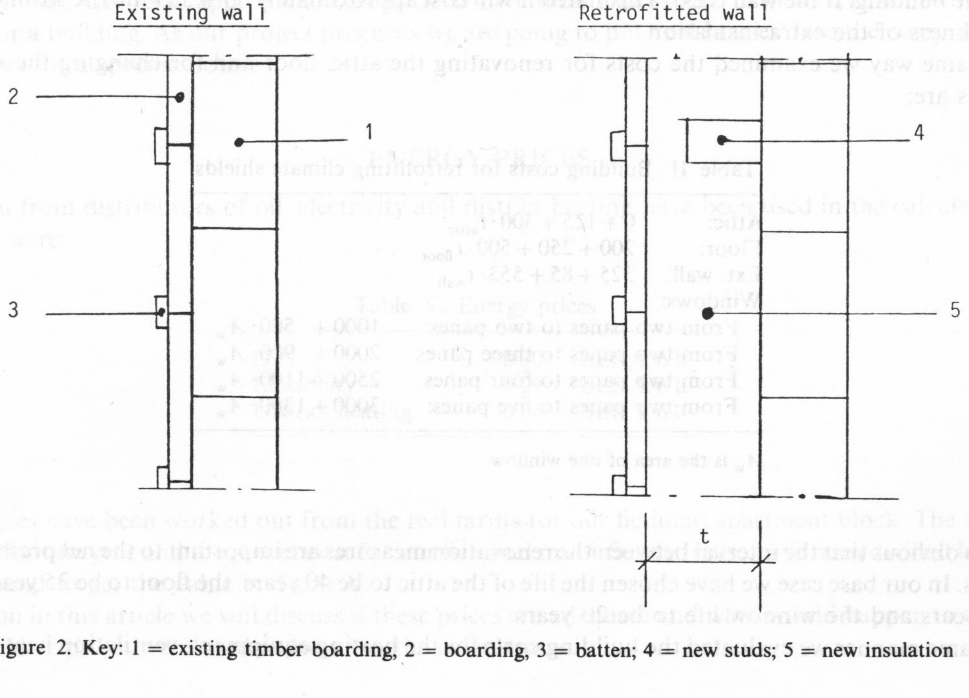

Figure 2. Key: 1 = existing timber boarding, 2 = boarding, 3 = batten; 4 = new studs; 5 = new insulation

BUILDING COSTS FOR RETROFIT MEASURES

As mentioned above we also calculated the cost for renovation of the climate shield. We give one example of how these costs have been worked out. Basic information has been taken from the *Price list for Renovating Buildings*. (Unfortunately this reference is in Swedish). Our example considers an external wall (Figure 2).

Table I. Building cost for retrofitting an external wall with extra insulation (Prices in SEK/m^2)

	Material	Time (n)	Wages	Sum
A. Scaffolding	15·20	0·25	14·50	29·70
B. 0·022 m existing boarding. (Demolished)	—	0·15	8·70	8·70
C. New boarding	47·20	0·98	56·84	104·40
D. Mineral wool thickness (t)	$230\cdot t$	0·12	6·96	$6{\cdot}96+230\cdot t$
E. New studs	$260\cdot t$	0·34	19·72	$19{\cdot}72+260\cdot t$
I Sum A + B + C	62·40	1·38	80·04	142·44
II Sum D + E	$490\cdot t$	0·45	26·68	$26{\cdot}68+490\cdot t$
Indirect costs 181% part I (wages)	144·87			
Indirect costs 181% part II (wages)	48·29			
Sum part I	287·31			
Sum part II	$74{\cdot}97+490\cdot t$			
Taxes part I 12·87%	36·97			
Taxes part II 12·87%	$9{\cdot}64+63{\cdot}06\cdot t$			
Total sum part I	324·28 (SEK/m^2)			
Total sum part II	$84{\cdot}61+553\cdot t$ (SEK/m^2)			

From Table I it appears that each time the outer part of the wall has to be substituted, it will cost about 325 SEK/m^2. This cost is called the inevitable renovation cost because it appears even if no energy retrofits are made to the building. If the wall is extra insulated it will cost approximately $85 + 553\cdot t$ SEK/m^2 more, where t is the thickness of the extra insulation.

In the same way we examined the costs for renovating the attic, floor and for changing the windows. The results are:

Table II. Building costs for retrofitting climate shields

Attic:	$0+125+300\cdot t_{\text{attic}}$
Floor:	$200+250+500\cdot t_{\text{floor}}$
Ext. wall:	$325+85+553\cdot t_{\text{wall}}$
Windows:	
From two panes to two panes:	$1000+\ 500\cdot A_w$
From two panes to three panes:	$2000+\ 900\cdot A_w$
From two panes to four panes:	$2500+1100\cdot A_w$
From two panes to five panes:	$3000+1300\cdot A_w$

A_w is the area of one window.

It is also obvious that the interval between the renovation measures are important to the net present value for these costs. In our base case we have chosen the life of the attic to be 40 years, the floor to be 35 years, the walls to be 30 years and the window life to be 20 years.

In the same manner we evaluated the building costs for the heating equipment, ventilation heat pumps, etc.

Table III. Building costs efficiency and life-cycles for heating equipment

	Cost in SEK	Efficiency	Life (yrs)	Ref.
Oil-heating	$13\,500+464E$	0·7	15	*
Electric boiler	$25\,000+85E$	1·0	20	*
District heating	$50\,000+182\cdot E$	1·0	30	*
Heat pump (lake)	$60\,000+2800\cdot E$	3·0	10	Mattsson *et al.* (1984)
Heat pump (earth)	$10\,000+4300\cdot E$	2·5	10	Mattsson *et al.* (1984)

E is the power for the equipment.
* *Different Pricelists from Dealers of Heating Equipment* and *Wages and Pricelists for Price-work for Heating Equipment Contractors.*

Table IV. Retrofitting costs for ventilation equipment and measures

	Cost (SEK)	Life-cycle (yrs)	Ref.
Caulking windows and sealing doors, etc. 0·8–0·5 air changes/h	200	10	Olsson-Jonsson (1980)
Ventilation air heat pump	$30\,000+1000\cdot E_p$	15	Sandqvist (1984)
Caulking the ventilation pipes and new pipes to the heat pump, etc.	$10\,000\cdot NA$	10	Karlsson and Lindgren (1983); Eriksson *et al.* (1985)

E_p is the power of the heat pump and NA is the number of apartments in the house.

Of course there are lots of approximations made in all of these expressions to make it easier to find the life-cycle cost for a building. As our project proceeds we are going to put 'real houses' into the computer and the actual figures for a specific house.

ENERGY PRICES

Information from distributors of oil, electricity and district heating have been used in the calculations. The prices used were:

Table V. Energy prices

Oil	0·30	SEK/kWh
Electricity	0·29	SEK/kWh
District heating	0·24	SEK/kWh

These prices have been worked out from the real tariffs for our fictional apartment block. The sum of the energy cost for one year and the power cost for our fictional multi-family house have been divided by the total energy demand to get the value in Table V.

Further on in this article we will discuss if these prices are adequate and what would happen to the retrofit strategy if other prices were used as input to the calculations.

LIFE-CYCLE COST FOR THE EXISTING HOUSE

As mentioned before our calculations are made in a Nord 570 computer. We have developed a FORTRAN program that among other things works out the life-cycle cost for the existing house. For the base case the cost consists of the following prices.

Table VI. Net present values in SEK

A. Cost for inevitable renovation of the climate shield	370 000
B. Cost for inevitable renovation of the heating equipment	117 000
C. Cost for energy	3 391 000
D. Total net present value	3 878 000

Notice that the net present value for the energy is almost 10 times higher than the other part of the total cost. Thus, it is obvious that it would be very profitable to try to lower the energy cost by investing money in energy conservation or heating equipment measures. We will start with changes in the heating system and leave the rest of the building intact.

LIFE-CYCLE COST WHEN CHANGING THE HEATING SYSTEM

(See Table VI for the abbreviations A, B, C and D.)

Table VII. Changes in the heating system. Net present values in 10^6 SEK. Base case

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
A	0·37	0·37	0·37	0·37	0·37	0·37
B	0·12	0·18	0·08	0·12	1·22	1·56
C	3·39	3·28	2·54	2·10	0·85	1·01
D	3·88	3·83	2·99	2·59	2·4	2·94

We see that the best retrofit strategy in this case would be to install a heat pump that takes its energy from a close lake. It is also interesting to notice that district heating has almost the same present value as the heat pump. When the net present values are as close to each other as in this case, it is, because of all the uncertainties of the input data, impossible to choose the proper system with any degree of accuracy. Other criteria have to be used to find the best system, e.g. the investment cost. If this is considered then the district heating system is superior. In the heat pump case the apparatus costs about 10 times the facilities for district heating, but the energy cost is at the same time much lower. The worst retrofit strategy would be, leaving the house as it is.

What will then happen to the LCC if there are different economical parameters?

Changes in the optimization time will not change the priority between the different systems. This is shown in Table VIII, where the optimization period has been changed from 50 to 10 years.

Table VIII. Changes in heating system. Optimization time = 10 years. Net present values in 10^6 SEK

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
A	0·01	0·01	0·01	0·01	0·01	0·01
B	0·03	0·10	0·06	0·08	0·54	0·68
C	1·50	1·39	1·07	0·88	0·35	0·43
D	1·54	1·50	1·14	0·97	0·90	1·12

Changes in the discount rate are more important to the result in our case. A lower rate will give advantages to the capital intensive equipment. Higher rates will make the cheap equipment competitive, and in our case the district heating will be the best choice when the rate is bigger than 7 per cent. Table IX shows the result for a discount rate of 15 per cent, where electrically-heated boilers are better than the heat pumps.

Table IX. Net present values in 10^6 SEK with different heating systems. Discount rate 15 per cent

	Existing oil	New oil	Electricity	District heating	Heat pump	
					Lake	Earth
A	0·12	0·12	0·12	0·12	0·12	0·12
B	0·05	0·13	0·07	0·11	0·70	0·91
C	1·28	1·20	0·92	0·77	0·36	0·37
D	1·45	1·44	1·11	0·99	1·12	1·40

Uniform increases/decreases of the energy prices will have the same effect as an increase/decrease of the discount rate (Gustafsson *et al.*, 1986), when calculating on the energy cost. A big increase will make this cost higher and will thus generate more profitable energy conserving retrofits.

The climate also has a big influence on the priority order. Table X shows this.

Table X. Net present values in 10^6 SEK with different heating systems. Climate 50 000 degree hours

	Existing oil	New oil	Electricity	District heating	Heat pump	
					Lake	Earth
A	0·37	0·37	0·37	0·37	0·37	0·37
B	0·12	0·18	0·09	0·13	1·22	1·56
C	1·90	1·85	1·42	1·18	0·48	0·57
D	2·39	2·40	1·88	1·68	2·07	2·50

In this mild climate the district heating has the lowest net present value.

RETROFIT MEASURES ON THE CLIMATE SHIELD ETC.

Up to now we have only considered what happens to the life-cycle cost when there are changes in the heat producing system in the house.

Now we will describe the situation when energy conservation measures are put into the building.

We have shown (Gustafsson *et al.*, 1986) that it is profitable to put much more insulation on bad shields than is common today. (Good shields, of course, should not be extra insulated at all.) In many cases it is optimal to put about 0·2 m extra insulation on the wall. Later in this article we will give more examples of this.

Unfortunately, it is very difficult to find an optimal window construction (Jonsson, 1985), so our program picks out the best solution from a number of alternatives.

Measures done to the ventilation equipment are chosen in the same way. If it is profitable the retrofit is used, otherwise not.

In Table XI we display the optimal retrofit strategy for our base case.

Table XI. Net present values in 10^6 SEK (base case)

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
No measures (LCC)	3·88	3·83	2·99	2·59	2·44	2·94
Savings (NPV)						
Attic insulation	0·30	0·29	0·16	0·10	0·09	0·19
Floor insulation	—	—	—	—	—	—
Wall insulation	0·21	0·20	0·09	0·04	0·02	0·11
Three-pane windows	0·01	0·01	—	—	—	—
Four-pane windows	—	—	—	—	—	—
Five-pane windows	—	—	—	—	—	—
Caulking	—	—	0·22	0·17	0·16	0·23
Exhaust heat pump	0·57	0·53	0·05	—	—	—
Total LCC with the optimal measures	2·78	2·80	2·47	2·28	2·16	2·41

In Table XI we can find some interesting things. Some of the retrofit measures are never chosen by the computer, no matter what the heating system is, i.e. extra insulation to the floor, four- and five-pane windows. Other measures are picked out sometimes, i.e. three-pane windows, caulking and exhaust ventilation heat pumps.

Insulation of the attic and the walls are picked out for every type of heating system. We also see that heating systems with high variable costs, e.g. oil boilers, makes it profitable to invest in more energy conservation measures. This is so, because the existing cost for energy (NPV) is higher than for the retrofit investment.

Furthermore, it is profitable to invest in 'demand conserving' measures. This is obvious because the insulation measures are picked out even for the heat pumps with high costs. (The heat pumps have the lowest variable costs of all the heating systems in our example.)

In those cases, where low demand costs and low energy costs are combined in the heating system, only a few shield retrofits are chosen.

Heat pumps that take the heat from the exhaust ventilation air, will not be picked out if the heating system has a low variable energy cost. The ventilation heat pump contributes too little to the demand of power in the house. Note! In such cases it is not profitable to caulk the windows because of the decrease in the amount of exhaust air. However, in this base case the lake heat pump combined with *optimal* attic insulation, *optimal* wall insulation and caulking the windows and doors, will give the best possible solution for this house.

In Table XII, we show how the optimal insulation on the attic varies between the different heating systems. Gustafsson *et al.* (1986) describe how the optimization is worked out.

Table XII. Optimal extra insulation thickness (m) for different heating systems

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
Attic	0·29	0·29	0·24	0·21	0·21	0·25
Floor	(0·19)	(0·19)	(0·15)	(0·13)	(0·13)	(0·16)
Ext. wall	0·21	0·21	0·18	0·16	0·15	0·18

The figures in parentheses show higher net present values than leaving the floor without the extra insulation. The reason for this is the high building cost and the low existing *U*-value. Insulating the floor is therefore not picked out by the computer (Table XI). The profitable amount of extra insulation to the attic varies between 0·21 m for the low energy cost systems and 0·29 m for the expensive ones. For the external wall the corresponding figures are 0·21 to 0·15 m.

Differences in the optimization time is very important for the retrofit measures. Tables XIII and XIV show this.

Table XIII. Net present values in 10^6 SEK for retrofits, optimization time = 10 years

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
No shield measures (LCC)	1·54	1·50	1·14	0·97	0·90	1·12
Savings (NPV)						
Attic insulation	0·02	0·01	—	—	—	—
Floor insulation	—	—	—	—	—	—
Ext. wall insulation	—	—	—	—	—	—
Three-pane windows	—	—	—	—	—	—
Four-pane windows	—	—	—	—	—	—
Five-pane windows	—	—	—	—	—	—
Caulking	—	—	0·09	0·07	0·07	0·1
Exhaust heat pump	0·24	0·21	—	—	—	—
Total LCC with optimal measures	1·28	1·28	1·04	0·90	0·83	1·02

Table XIV. Optimal extra insulation thickness (m) for different heating systems. Optimization time = 10 years

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
Attic	0·17	0·17	(0·14)	(0·12)	(0·11)	(0·14)
Floor	(0·10)	(0·09)	(0·07)	(0·06)	(0·06)	(0·08)
Ext. wall	(0·12)	(0·12)	(0·10)	(0·09)	(0·08)	(0·10)

When the optimization time is changed to 10 years a lot of the long-life retrofits will not be profitable, e.g. external wall insulation. With the district heating system it was only profitable to caulk. However, the lake heat pump were the best solution combined with one retrofit on the shield.

Changes in the discount rate are also very important. A discount rate of 15 per cent will make almost every shield retrofit unprofitable. Only caulking is picked out by the computer for all the tested heating systems. District heating gives the best solution because of the high capital costs for the heat pumps.

Uniform raising of the energy prices will make more shield retrofits profitable. Table XV describes this.

Table XV. Net present values in 10^6 SEK for retrofits. Uniform annual increase in energy costs = 3 %

	Existing oil	New oil	Electricity	District heating	Heat pump Lake	Heat pump Earth
No shield measures (LCC)	6·32	6·27	4·88	4·15	3·07	3·70
Savings (NPV)						
Attic insulation	0·66	0·65	0·44	0·33	0·18	0·30
Floor insulation	0·07	0·06	—	—	—	—
Ext. wall insulation	0·55	0·54	0·34	0·24	0·11	0·21
Three-pane windows	0·22	0·21	0·09	0·02	—	—
Caulking	—	—	—	—	0·23	0·31
Exhaust heat pump	1·42	1·38	0·92	0·65	—	—
Total LCC with optimal measures	3·40	3·43	3·09	2·91	2·55	2·87

Mild climate will, of course, make many retrofits unprofitable. For 50 000 degree hours the cheapest strategy was district heating and an exhaust ventilation heat pump. In very cold climates the retrofit strategy will be almost similar to that in Table XV (high energy prices).

Finally, we discuss the importance of accurate prices for energy. As is evident in the retrofit tables the lowest net present values come from the heating systems with a low energy cost even if they are very expensive to install in the house. However, the district heating has both rather low energy costs and low power costs. If the energy cost for district heating in some way gets lower than in the tariffs used today this heating system, with almost no shield retrofits, would be the cheapest possible solution.

In Sjöholm (1984) differential rates for heating systems are elaborately treated. The economic theory tells us that it is the short-range marginal cost, SMRC, that has to be used to get an optimal performance in the society energy system. With modern electronic equipment it is possible to make this energy cost known to the consumer, but it is hard to predict this cost in a project like this. Therefore, we have chosen to show what happens to the retrofit strategy when the next best tariffs are used to our house, viz. the time differential rate. We have, to some extent, examined this earlier (Gustafsson *et al.*, 1985) and interesting results have then been achieved. Among other things we could show that 'competing energy producing systems' in the house, e.g. exhaust air heat pumps and especially sun collectors, saved about half the money if a time differential rate was introduced.

In Malmö the SMRC for producing district heating energy was approximately

Table XVI. SMRC for district heating in Malmö (Gustafsson *et al.*, 1985) SEK/MWh

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
211	211	198	116	116	116	116	116	116	116	140	211

Taking notice of the climate for Malmö and the energy demand for our house we find that an average price for energy during the year would be 0·16 SEK/kWh. Using this price the district heated building with optimal attic insulation and caulking will be the best solution. The retrofit measures done to the climate shield lowers the net present value with about 200 000 SEK.

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