Optimization of the energy management of low-energy houses with a solar heating and hot water system

Citation for published version (APA):

Document status and date:
Published: 01/01/1982

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
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OPTIMIZATION OF THE ENERGY MANAGEMENT OF LOW-ENERGY HOUSES WITH A SOLAR HEATING AND HOT WATER SYSTEM

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report WPS - 82.09.R334
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Summary

In the field of energy conservation many options are presently competing. This study aims at providing more rational criteria for selection between these options. It is directed towards residences and the options considered are: insulation of the walls, regeneration of the heat in the waste air, double glazing, enlarging the south facing window area, adding internal thermal mass, applying night shutters, solar water heating, solar space heating and applying a high performance heater.

For each option the investments are defined and subsequently each option is internally optimised, as far as applicable, and a comprehensive computer program is used which enables selecting the optimal combination of the options. Such is considered to be the combination leading to the minimum auxiliary energy need for a given total conservation investment. The decision regarding the latter is left to the user, but some aids to this end are provided. For the Dutch conditions the sequence of preference appears to be: wall insulation, heat regeneration, double glazing, high performance heater, solar water heating, solar space heating and enlarging the window area. At today's costs the other options do not enter into the optimum combination for the average dwelling up to a total conservation investment of Dfl. 25,000,--.

This study is part of the Dutch national solar-energy research program (NOZ) and was supported by the Project Office for Energy Research (BEOP) of the Netherlands Energy Research Foundation (ECN).
2 Introduction

An optimum design of a house and its heating system can be anything, depending on where, when and for whom it is assessed. As an optimization study should have a wider applicability than for one person, one location and one date, we decided to split the problem in two parts, an objective and a subjective, individual one.

In the first part we assess for a range of investments the system configurations and sizes with the lowest remaining auxiliary energy consumption. In the second part it is left to the user to fix the investments he is prepared to spend on energy savings, but the consequences of his decision in terms of the marginal energy saving/investment ratio are given.

The first part still depends on prices, longevity and similar features, but avoids the individual and unpredictable parameters like energy prices, tax incentives, loan and other interest rates, security of energy supply, regulations, aesthetics etc. The user can choose his own economical optimization criterion, which may range from some present day value method to just a certain amount of money (s)he is prepared to spend.

In this study we try to make a synthesis of all major energy conserving options in the built environment, with the objective to minimize the use of primary energy for a given comfort level.

As regards the mathematical aspects of the optimization a well known search algorithm is used to find a minimum of the non-linear auxiliary energy function under the constraint of the non-linear costfunction and other constraints (e.g. a minimum window area).

The intention of this study is to disclose the position of a solar system among its competitors like insulation, regeneration of heat from the waste air and enlarged windows.

As a spin off, however, the ranking of these competing conservation options is also obtained. The work is still in the explorative phase and needs continuation, in particular as regards the effects of a better defined costfunction.
3 Optimization method

Opinions about optimization of a solar energy system differ widely. In fact an optimum system is different not only for every individual, but also for every location and every point of time. Further the optimization criteria range from sophisticated economical models with energy scenarios to the highest degree of selfreliance. As a consequence it is impossible to calculate the optimum for every individual case, without creating a huddle of numbers from which a decision is difficult to derive.

3.1 Bissection of the optimization problem

To resolve this problem we try in this study to eliminate the part that is determined by the individual and to keep the part that is common to nearly everyone. This is possible because the costs or, better, the ratios of the costs of the parts of the system are roughly the same in most situations. Starting from the costs of all energy conserving options (as a function of their size) we subsequently try to find the optimal distribution of a certain investment among them, i.e. the distribution for which the associated auxiliary energy is minimum. For a range of investments we thus obtain the auxiliary energy and the sizes of the energy conserving options. On the basis of these data the user is then free to decide how much he wants to invest for the energy saved, using the economical optimisation criterion, or any other criterion of his own choice. Basically the method used is rather similar to the method followed by den Ouden [7]. However its scope is much wider because the solar systems are always internally optimized and the important interactions between passive and active solar gains are taken into account.

3.2 Restrictions

A house and a heating system serve the comfort and, in view of this we restrict the optimum to a solution for a given comfort level. This implies, for instance, that the window area is not too small, the air temperature in the heating system is not too high and the collector area is not excessively large. Most restrictions of this kind follow directly from the thermal comfort requirements, but some, e.g. the minimum window area, are rather subjective. For such individual restrictions we consider in this study only extremes. Summarising the object of the optimization is to minimize the auxiliary energy under the restriction of a certain investment and additional restrictions related to human comfort.

3.3 Technical optimization

In previous work [1,2] we performed a technical optimization of a system with a solar energy installation. In these studies we investigated the
optimum values of the technical parameters, which do incur minor or no costs. The most important results of this optimization were:

- A solar heating system performs best at a relatively low flow through the collectors and the heating system and a low recirculation rate of the indoor air (about 0.5 h⁻¹).
- Thermal stratification of the storage has to be promoted as much as possible.
- A fixed, but well chosen, collectorflow and on-off control is a good approximation of an optimum, variable flow, control (difference < 1%) and, as regards the costs, it is optimal in small systems.
- A simple, load dependent, control of the heater performs close to the optimum, and
- Recirculation rate, flow through the heating system and collectorflow are strongly coupled in the optimum configuration.

The just mentioned optimization of the flows has been implemented in the program SISOEN [3]. This program calculates the auxiliary energy for the setting of the optimum flows through the heating system and the collector in a system with a stratified storage.

3.4 Elimination of variables

In a complete optimization many parameters have to be considered. From a more practical point of view, however, several variables can be eliminated. To simplify the optimization we decided to eliminate the following ones:

- The orientation of the house and the collector are not considered in the optimization, because on the one hand the optimum is well known and flat and on the other hand the orientation is by nature mostly not a free parameter but, in some cases, only a restriction.
- From the technical optimization it follows that the difference in performance between a system with the auxiliary heater in series or parallel with the solar system (storage) is negligible as long as the setting of the flows is optimum in both systems (see fig. 1).
- An air heating system appears to be the better system for a solar energy system, so we didn't implement other heating systems, though in some situations other systems might be preferable.
- As water is a cheap and easy to handle working medium we only implemented a system with a water collector and storage (though an all-out air system might be a good competitor).
- The prices of an evacuated tubular collector and a good flat plate collector are expected to become roughly equal when mass produced. This implying that the evacuated collector will have a better cost/performance ratio, we only considered the evacuated collector.
- Because a good model of a seasonal storage is not yet available, we restricted the study to short term storage.
In this way we have eliminated from the optimization all variables, which are not associated with costs or for which the choice is trivial or as yet impossible.

Figure 1 Global schematic of the solar heating and hot water systems considered (c = control).

3.5 Remaining variables

The remaining variables are all more or less discrete. As a discrete optimization would be rather specific for the particular brands and the associated calculation effort would be enormous anyhow, we considered most variables to be quasi-continuous. The variables we considered in the
optimization are:
- the insulation thickness in the walls quasi-continuous
- the heat exchanging capacity of the regenerator quasi-continuous
- the window area quasi-continuous
- the quality of the windows discrete
- the insulation thickness of the night shutters quasi-continuous
- the thickness of the interior walls quasi-continuous
- the collector area quasi-continuous
- the insulation thickness of the storage quasi-continuous
- the heat exchanging capacity of the HSW coil quasi-continuous
- the heat exchanging capacity of the water-air heater quasi-continuous
- the connection of the heating system to the solar system (DHW or DHW + space heating) discrete

3.6 Splitting up of the problem

Also the costs, associated with the variables, except the quality of the glazing and the connection of the heating system, are considered as quasi-continuous. The initial (fixed) costs, however, cause a discontinuity at the origin of the cost curve. This discontinuity is difficult to handle mathematically in most optimization methods. To ensure that the real optimum is found, we first considered a set of optimization problems in which one or more of the variables are zero. Subsequently a simple comparison provides the real optimum (at the same time information is obtained on the optimum for the case that one or more of the variables is zero, for whatsoever reason).

3.7 Optimization algorithm

For the optimization we used the algorithm MINIFUN [5], which minimizes a non-linear function under the constraints of a set of non-linear functions. The constrained problem is solved by sequential unconstrained minimization of a so-called penalty function. The search directions in the process of minimizing the penalty function are generated with the Gauss-Newton method.

3.8 System model

The object function is the auxiliary energy as calculated by the model SISOEN, a result of previous work on the optimization of the flows in a solar system. Stratification and a near optimum control of the flows are incorporated. The model uses daily weather data and is about 1000 times faster than the model using hourly data. Nevertheless the results are very accurate [3]. Depending on the configuration of the system the process time on a fast machine (Burroughs 7700) ranges from 10 - 1000 ms for the calculation of a reference year.
3.9 Convergence of the optimization

Although the model is rather fast, the optimization of the complete configuration can easily take several thousand calculations for the reference year, or more than an hour processing time. This is caused mainly by the fact that a year has to be calculated twice to obtain a smooth function for the storage size and by the nearly dependence of the objectfunction with regard to the collector- and windowarea.

To make sure that the global minimum is found, the auxiliary energy function has to be smooth and no local minima should occur. For most variables this is the case, but for the storage size local minima may occur. Normally those small minima are overlooked by the search algorithm, because initially the steplength is larger than the region in which the local minimum can be detected. A higher certainty, however, can be obtained by starting the search from two sides of the optimum with respect to the storage capacity. An equal result gives confidence that the optimum is global.

Another problem originates from the initial conditions of the system, namely the wall and the storage temperature. Because the consecutive steps in the search are rather small it seems plausible to use the end conditions of the former run as the initial conditions for a new calculation of a year. Mostly this leads to good results, but sometimes the search becomes cyclic. Calculation of the year twice has proved to be sufficient to solve this problem; unfortunately it leads to double the costs.
4 The restrictions

4.1 The house

In this study we have only considered a typical Dutch detached dwelling. This means:

- volume of the house \( V_H = 270 \text{ m}^3 \)
- facade, roof and floor area \( A_H = 234 \text{ m}^2 \)
- brick cavity walls (\( U = 2.75 \text{ Wm}^{-2} \text{K}^{-1} \) if uninsulated)
- indoor wall area with thermal capacity equivalent to brick, with a minimum thickness of \( D_M = 0.105 \text{m} \) \( U = 2.75 \text{ Im}^{-2} \text{K}^{-1} \)
- internal heat production \( Q_I = 330 \text{ W} \)
- heating air inlet temperature maximum 60 °C
- hot domestic water load, daily \( Q_T = 36 \text{ MJ} \)
- hot waterflow (intermittent) \( C_A T = 0.6 \text{ m}^3 \text{h}^{-1} \)
- hot water temperature \( T_{TS} = 50 \text{ °C} \)
- ventilation rate \( V_R = 0.8 \text{ h}^{-1} \)
- infiltration rate \( I_R = 0.2 \text{ h}^{-1} \)
- recirculation rate (through air heater) \( R_R = 0.5 \text{ h}^{-1} \)
- maximum temperature indoor \( T_{RM} = 25 \text{ °C} \)
- roomset temperature (double glazing) \( T_{RS} = 18 \text{ °C} \)
- * (single glazing) \( T_{RS} = 20 \text{ °C} \)

For simplicity we only investigated the orientation due south, with windows only in the south facade and a collector tilt of 53°.

4.2 The energy conserving options

The properties of the energy conserving options are listed below;

- evacuated tubular collector, \( U_L = 1.8 \text{ Wm}^{-2} \text{K}^{-1} \), \( (\tau a) = 0.68 \), \( F = 0.96 \)
- collector loop: water, \( q.c = 4131250 \text{ Jm}^{-3} \)
- storage : water, \( q.c = 4131250 \text{ Jm}^{-3} \)
- maximum temperature in the storage = 80°C
- conductivity of insulation of storage = 0.036 \( \text{ Wm}^{-1} \text{K}^{-1} \)
- surface area storage = \( 5.6 \times \text{(storage volume)}^{2/3} \text{ m}^2 \)
- heat exchanging coil for hot water, running from bottom to top of the storage
- water-air heat exchanger operating in counterflow
- conductivity of insulation of walls \( \lambda = 0.036 \text{ Wm}^{-1}\text{K}^{-1} \)
- single pane windows \( U = 5.8 \text{ Wm}^{-2}\text{K}^{-1}, \tau = 0.84 \)
- double pane windows \( U = 3 \text{ Wm}^{-2}\text{K}^{-1}, \tau = 0.69 \)
- conductivity of insulation of night shutters \( = 0.36 \text{ Wm}^{-1}\text{K}^{-1} \)
- waste air heat regenerator, operating in counterflow

4.3 The variables

The variables considered in the optimization study are:

- collector area, \( A \) \( \text{m}^2 \)
- volume of the storage, \( V_S \) \( \text{m}^3 \)
- thickness storage insulation, \( D_S \) \( \text{m} \)
- heat exchanger capacity of hot water coil, \( U_T \) \( \text{WK}^{-1} \)
- heat exchanger capacity of air heater, \( U_H \) \( \text{WK}^{-1} \)
- heat exchanger capacity of regenerator, \( U_R \) \( \text{WK}^{-1} \)
- thickness insulation in cavity walls, \( D_D \) \( \text{m} \)
- window area, \( A_W \) \( \text{m}^2 \)
- thickness insulation of night shutters, \( D_L \) \( \text{m} \)
- thickness of interior walls (equivalent to brick), \( D_M \) \( \text{m} \)
- heating system connected (yes or no), \( H_S C \)

4.4 The costs

The cost functions used in this explorative study are rather rough, as a special investigation of this subject has still to be made. The longevity of all materials used is supposed to exceed 25 years, so the costs of the normal mortgage on the base of annuity are mainly determined by the investment and hardly by the longevity. The assumptions on the costs are listed below (1Dfl = 0.37 US $ = 0.22 £ (Brit)):

- initial costs of the collector array \( SKC = \text{Dfl} \ 1000,- \)
- collector costs, variable \( KC = \text{Dfl} \ 500,- \text{m}^{-2} \)
- storage costs per unit of surface area \( KS = \text{Dfl} \ 25,- \text{m}^{-2} \)
- insulation costs of storage, variable \( KIS = \text{Dfl} \ 300,- \text{m}^{-3} \)
- initial costs of hot water coil \( SKT = \text{Dfl} \ 100,- \)
- costs of hot water coil, variable \( KT = \text{Dfl} \ 3,- \text{W}^{-1}\text{K} \)
- initial costs of air heater
  \[ \text{SKH} = \text{Dfl 100,-} \]
- costs of air heater, variable
  \[ \text{KH} = \text{Dfl 4,-} \text{W}^{-1} \text{K} \]
- initial costs of regenerator
  \[ \text{SKR} = \text{Dfl 300,-} \]
- costs of regenerator, variable
  \[ \text{KR} = \text{Dfl 8,-} \text{W}^{-1} \text{K} \]
- initial costs of insulation of walls
  \[ \text{SKI} = \text{Dfl 1,-} \text{m}^{-2} \]
- costs of insulation of walls, variable
  \[ \text{KI} = \text{Dfl 200,-} \text{m}^{-3} \]
- costs of double glazing
  \[ \text{KW} = \text{Dfl 200,-} \text{m}^{-2} \]
- costs of single glazing
  \[ \text{KW} = \text{Dfl 75,-} \text{m}^{-2} \]
- initial costs of night shutters
  \[ \text{SKIL} = \text{Dfl 250,-} \text{m}^{-2} \]
- costs of insulation of night shutters, variable
  \[ \text{KIL} = \text{Dfl 300,-} \text{m}^{-3} \]
- costs of mass added to the interior walls
  \[ \text{KM} = \text{Dfl 400,-} \text{m}^{-3} \]
- costs of connecting the heating system to the solar system
  \[ \text{SKCH} = \text{Dfl 500,-} \]

4.5 The cost function

With the listed values the cost function reads:

Cost function = Investment -
\( (\text{SKC} + \text{KC} \times A) - \)
\( (\text{SKS} + 5.6 \times (\text{KS} + \text{KIS} \times \text{DS}) \times \text{VS}^{2/3}) - \)
\( (\text{SKT} + \text{KT} \times \text{UT}) - \)
\( (\text{SKH} + \text{KH} \times \text{UH}) - \)
\( (\text{SKR} + \text{KR} \times \text{UR}) - \)
\( (\text{SKI} + \text{KI} \times \text{DD}) \times (\text{AH} - \text{AW}) - \)
\( \text{KW} \times \text{AW} - \)
\( (\text{SKIL} + \text{KIL} \times \text{DL}) \times \text{AW} - \)
\( (\text{if DM less SDM then 0 else KM} \times (\text{DM} - \text{SDM}) \times (\text{AH} - \text{AW})) - \)
\( (\text{if HSC then SKCH else 0}) \)

In the cost function only extra investments for energy conserving options are calculated which exceed the normal investments in the standard house without (!) windows but with a marginal heating system. As a normal house has at least some windows, the energy saved is not the difference between the auxiliary energy for a zero investment and the investment considered, but between the auxiliary energy for a normal house and a house in which the considered investment is made.
4.6 The constraints

The most important constraint to the optimization problem is the cost function. Further constraints used are:
- a minimum window area of 5 m²
- a maximum collector area of 50 m²
- a maximum storage size of 10 m³, and
- a minimum air heater capacity of 100 W K⁻¹

Implicit in the auxiliary energy function are constraints regarding the maximum temperature of the dwelling (25°C) and of the storage (80°C) and of the minimum temperature in the air heater and the regenerator.

4.7 Comments

In this study we considered the envelope of the house as consisting of a wall with insulation and a window. In a normal house, however, the envelope is not uniform and many heat leaks to the environment occur. For the optimization of a house without a solar heating system this leads to a systematic underestimation of the auxiliary energy demand, but it does hardly affect the position of the optimum. If, however, a solar energy system for heating is attached, the heat demand will be somewhat too low, and this influences the position of the optimum. Consequently the benefits of a solar heating system are slightly underestimated in this study.

Two important energy conserving options are not considered in this study, namely the reduction of the infiltration rate and the reduction of the heat losses caused by the heat leaks just mentioned. The model is capable of handling these features, but too little data on the costs were available to include them here.

4.8 The auxiliary heater

Improving the auxiliary heater, a good energy conserving option as such, is not included in the optimization, because it does not influence the behaviour of the system and can be treated separately.

After the optimization is finished, the quality of the auxiliary heater can simply be taken into account by dividing the auxiliary energy (heat) by the efficiency of the heater and subsequently adding the difference in price with a conventional heater to the investment.
4.9 Scaling up

Although the optimization is performed for a single rather small house only, the results can be applied to a wide range of houses with approximately the same ratio of envelope area to volume for the following outcomes:
- the ratio of auxiliary energy to investments as function of the insulation thickness
- the effectiveness of the heat exchangers
- the ratio of the collector- and window area and the storage size to the envelope area (or volume) of the house.

It is assumed here that the hot water load, the internal heat production and the initial costs are proportional to the size of the house (see chapter 5.5).
5 Results and discussion

5.1 The scope of the study

To keep the process time within our budget (200,000 s) we had to curtail the number of calculations. For the house as mentioned we investigated the value and the position of the optimum for a range of investments from zero to Dfl. 25,000,-. A sensitivity study, though giving the most valuable information, is still not made for lack of time. Because some variables are not considered and because the cost function is rather rough, this study has to be considered as a first exploration.

5.2 Combinations investigated

We investigated the following combinations of energy conserving options;
1. * insulation of walls, roomsettemperature 20°C,
2. + insulation of walls, roomsettemperature 18°C,
3. o insulation of walls, double glazing, roomsettemperature 18°C,
4. o insulation of walls, regeneration, roomsettemperature 20°C,
5. x insulation of walls, regeneration, roomsettemperature 18°C,
6. + insulation of walls, double glazing, regeneration, roomsettemperature 18°C,
7. x insulation of walls, regeneration, solar hot water system, roomsettemperature 18°C,
8. z insulation of walls, double glazing, regeneration, solar hot water system, roomsettemperature 18°C,
9. v insulation of walls, double glazing, regeneration, solar hot water and heating system, roomsettemperature 18°C, and
10. * insulation of walls, double glazing, regeneration, solar hot water and heating system, night shutters, roomsettemperature 18°C.

The results of these investigations are presented in fig. 2. Each separate curve represents the auxiliary energy for the combination of options considered (see legend in figure; symbols correspond to list just mentioned).
Figure 2 Minimum auxiliary energy as a function of the investments for several energy conserving combinations.

If there are no restrictions to the use of any of the energy conserving options, the combination, that leads to the lowest auxiliary energy for a certain investment is the optimum combination for that investment (1 KF = Dfl. 1000,-).
5.3 Roomtemperature independent of windowtype

We first suppose that a roomtemperature of $18^\circ\text{C}$ (convection only) is sufficiently comfortable, regardless of the windowtype. Fig. 3 shows the results obtained for the various combinations just mentioned. The fat curve is the enveloping curve for lowest auxiliary energy needs. It shows kinks (often weak) at the intersection points of the several combinations. At these points a new option becomes economically more attractive than just "more of the same" in the "old" combination.

Figure 3 The optimum combinations and their auxiliary energy need as a function of the investment, for a roomsettemperature of $18^\circ\text{C}$ (fat curve). Effects of wall insulation are included.
5.3.1. sequence of combinations

The sequence of the optimum combinations starts with $5 \text{ m}^2$ (the minimum area) of single glazing for an investment of Dfl. 375,-. For an investment higher than Dfl. 600,- insulation of the walls becomes attractive. A regenerator has to be added if the investment is higher than Dfl. 2050,- and a solar hot water system for an investment higher than Dfl. 9300,-. For an investment beyond Dfl. 12.900,- double glazing comes into play. Finally the heating system has to be connected to the solar system if the investment exceeds Dfl. 21.000,-. Night shutters never form part of the optimum combination and neither does adding mass to the interior walls.

The investment at which solar heating becomes favourable is very dependent on the initial (fixed) costs of it (i.e. for connecting the heating system). Zero initial costs would bring the solar hot water system and the solar hot water and heating system in about the same position and make solar heating favourable at a total conservation investment beyond Dfl. 10.000,-. Further it is noteworthy that for an investment beyond about Dfl. 15.000,- the addition of solar heating has only a marginal effect on the auxiliary energy. The cause being that the hot water system and the heating system share the same energy source and that in this region the investment associated with enlarging the hot water system is traded off against implementing the heating system. Each optimum as such has its own optimum values of the variables.

The optimum values of the various variables as a function of the total investment are dealt with in the next sections.
5.3.2 insulation thickness in the walls

The optimum insulation thickness in the walls is a discontinuous function of the total investment (see fig. 4). The discontinuities are caused by the initial, fixed, costs going with the introduction of new options. The optimum insulation thickness is independent of the roomsettemperature, because the differentials of the auxiliary energy and the thickness are independent of it.

Figure 4 Optimum insulation thickness in the walls (fat curve) as a function of the total investment (roomsettemperature 18°C).
Between the discontinuities the optimum thickness changes nearly linearly with the investment because the change in auxiliary energy as a function of the insulation thickness is independent of other variables (except the windowsize). The slope of the curve in fig. 4 changes to a lower value as a new option becomes part of the optimum combination, in such a way that the partial differentials of the auxiliary energy with the investment in the energy conserving options are all equal. The insulation thickness starts from zero, because initially there are no competitors. When the regenerator comes into the optimum combination the insulation thickness jumps from 3.3 to 2.3 cm and a jump from 16.9 to 11.4 cm occurs when the solar hot water system comes in. The insulation thickness is 14.8 cm when double glazing becomes favourable and jumps from 24.3 to 21.7 cm when solar heating emerges.
5.3.3 regenerator size

![Graph showing heat exchanging capacity as a function of total investment.]

**Figure 5** Optimum heat exchanging capacity of a regenerator (fat curve) as a function of the total investment (roomset temperature 18°C).

Because of its initial, fixed, cost, the regenerator comes into the optimum combination at a, non-zero, heat exchanging capacity of 145 W K^-1. See fig. 5.

At a heat exchanging capacity of 980 W K^-1 a solar hot water system becomes more attractive than simply enlargement of the regenerator and the capacity drops to 680 W K^-1. The heat exchanging capacity is 860 W K^-1 when double
glazing becomes favourable and jumps from 1440 $\text{WK}^{-1}$ to 1320 $\text{WK}^{-1}$ at the introduction of a solar heating system. The relation between capacity and investment is nearly linear between the discontinuities, because the decrease of auxiliary energy with increasing regenerator size is nearly independent of other variables.
5.3.4 collector area

At an investment of Dfl. 9,300,- the solar hot water system comes into the optimum combination with a collector area of 2.6 m$^2$. See fig. 6. When double glazing enters the optimum combination the collector area jumps back from 5.6 to 4.7 m$^2$. If the connection of the heating system to the solar system becomes favourable, the collector area jumps upward from 9.9 to 11.7 m$^2$. The exceptional jump upward goes with a jump downward of the window area, the
causes being the better capturing of solar radiation by the collector as compared to the windows and the increase of the solar heat gain per unit collector area when the heating system is connected.
5.3.5 hot water coil size

Figure 7 Optimum heat exchanging capacity of the hot water coil as a function of the total investment (fat curve), (roomsettemperature $18^\circ$C).

At an investment of Dfl. 9300,- the solar hot water system comes into the optimum combination. One of the associated variables is the heat exchanging capacity of the coil, which starts at $210 \text{ WK}^{-1}$.

When double glazing becomes favourable, the heat exchanging capacity jumps from $520 \text{ to } 440 \text{ WK}^{-1}$ and when the solar heating system comes in, the
capacity of the coil jumps from 630 to 560 W/K. Contrary to the aforementioned energy conserving options, the heatexchanging capacity of the coil is a non-linear function of the investment and there appears to be an upper limit for about 700 W/K. This is caused by the fact that the efficiency of the hot water coil is an inverse exponential function of the heatexchanging capacity and for the given hot water flow approaches 100% for a heatexchanging capacity of 700 W/K.
5.3.6 window area

Figure 8 Optimum window area as a function of the total investment (fat curve).

Beyond an investment of about Dfl. 15,000,- the optimum window area starts increasing slowly. See fig. 8. The thin curves in fig. 8 suggest that limits are set to the window area of about 10 m² for single glazing and about 20 m² for double glazing. However further research is required to settle this point.
5.3.7 storage capacity

The optimum storage capacity as calculated is not a smooth function of the total investment. If the collector area is less than about 3 m² (investment less than Dfl. 10.000,-), the optimum storage capacity is close to zero, because any solar gain is consumed immediately and the storage is used only incidentally (such provided the draw pattern holds). Too little data are still available, but it seems that the optimum storage volume is about .2 m³ (the assumed daily consumption of hot water) for a collector area (hot water system) of 3-8 m² (investment ≈ Dfl. 10.000,- - 17.000,-). For a collector area of ≈ 8-10 m² (investment Dfl. 17.000,- - 21.000,-) the storage volume is a bumpy function and seems to approach a limit of .8 m³. When solar heating is introduced (collector area more than 12 m², investment more than Dfl. 21.000,-) the optimum storage volume is initially about .55 m³ and increases in steps. Further research is necessary to disclose more exactly the position of the optimum storage size.

5.3.8 insulation thickness of the storage

Also the optimum insulation thickness of the storage is not a smooth function of the total investment. Sufficient data are still not available, but it seems that the optimum insulation thickness is roughly 19 cm for a hot water system and 22 cm for a combined hot water and heating system up to an investment of about Dfl. 23.000,-. Further research is necessary to explain this somewhat surprising result.

5.3.9 air heater capacity

The optimum heat exchanging capacity of the water-air heat exchanger at low total investments is determined by the temperature limit of the air in the heater and the limit of the water temperature. For an investment of Dfl. 21.000,- i.e. when solar heating comes in, the heat exchanging capacity starts with 140 WK⁻¹; it further increases with .02 WK⁻¹ per Dfl. invested.

5.3.10 night shutters

Night shutters never enter the optimum combination. This is mainly caused by the high initial costs and the fact that collectors as compared to windows with night shutters perform better, because their night losses are zero. If no solar energy system is applied, night shutters come in the optimum combination at a total investment of Dfl. 15.000,- with an insulation thickness of the shutters of 14 cm.
5.3.11 thermal mass

Appending extra mass to the brick interior walls (by increasing their thickness beyond 10.5 cm) never becomes part of the optimum combination. For a low total investment extra mass does decrease the auxiliary energy, but is too expensive. For a high investment and consequently low auxiliary energy demand, the mass already available in the commonly applied wall construction is amply sufficient. Actually for such walls the wall area is the decisive factor.

5.3.12 conclusions

The sequence in which the energy conserving options have to be applied at a roomset temperature of $18^\circ$C is:
1. Insulation of the walls (beyond Dfl. 600,-)
2. Regeneration of the heat of the waste air (beyond Dfl. 2050,-)
3. Solar hot water system (beyond Dfl. 9300,-)
4. Double glazing (beyond Dfl 12.900,-)
5. Solar heating and hot water system (beyond Dfl 21.000,-)

Such provided the assumed costs apply. Within the range of investments investigated, night shutters and extra thermal mass are never preferable to these five options.

5.4 Roomtemperature dependent on windowtype

In the preceding section we assumed the comfortable roomtemperature to be independent of the windowtype. However, it is well known that the comfort level in a room depends on both the radiative temperature, mainly determined by the temperature of the walls (including the windows), and the air temperature. As a consequence a given comfort level requires a higher air temperature when single glazing is applied, as compared to double glazing.

To investigate this effect we tentatively assumed single glazing to require an air temperature of $20^\circ$C and double glazing only $18^\circ$C, such on the basis of subjective experiences (in the meantime a calculation method for the comfort level has been included in the model SISOEN). Subsequently optimization calculations were made for the same cost function and following the same method as outlined before.

The results give some insight in the effect just mentioned and - probably more important - in the sensitivity of the optimization to changes in the assumptions (a complete sensitivity analysis would require an enormous additional computational effort).
5.4.1 auxiliary energy; ranking of the options

Figure 9 presents the auxiliary energy required (fat curve) for the various combinations as a function of the total conservation investment. The sequence in which the energy conserving options have to be applied and
the investments at which they become attractive are:
1. Insulation of the walls (beyond Dfl.600,-)
2. Regeneration of the heat in the waste air (beyond Dfl 2.050,-)
3. Double glazing (beyond Dfl 3.800,-)
4. Solar hot water system (beyond Dfl 9.900,-)
5. Solar heating and hot water system (beyond Dfl 21.000,-)

A striking change, as compared to the former case of constant
roomsettemperature, is the large shift forward of double glazing. The
magnitude of this shift strongly depends on the tentative assumption about
the required air temperature and therefore should be considered with some
care. However the sensitivity of the results to minor changes in the
assumptions is clear. As we believe the differentiated approach to the
required temperature, aiming at constant comfort, to be more realistic than
the earlier one(section 1) we continue our investigations with only that
approach.

Night shutters and extra thermal mass never enter the optimum combination as
before.
5.4.2 sizes of the options

The optimum sizes of the insulation thickness of the walls, the regenerator, the collector and the hot water coil as a function of the total investment are depicted in figures 10 - 13.

Figure 10 Optimum insulation thickness of the walls as a function of the total investment (fat curve). The points at which the curve is discontinuous follow from the ranking of the options given at p. 32.
Figure 11 Optimum heat exchangeling capacity of the regenerator as a function of the total investment (fat curve). The points at which the curve is discontinuous follow from the ranking of the options given at p. 32.
Figure 12 Optimum collector area as a function of the total investment (fat curve). The points at which the curve is discontinuous follow from the ranking of the options given at p. 32
Figure 13 Optimum heat exchanging capacity of the hot water coil as a function of the total investment (fat curve). The points at which the curve is discontinuous follow from the ranking of the options given at p. 32.

At an investment beyond Dfl 12.900, the optimum combinations are the same as found earlier for the constant roomset temperature of 18°C, irrespective of the windowtype.

From the results it is obvious that accounting for the comfort level by making the roomset temperature dependent on the windowtype mainly leads to a much better viability of double glazing. This is in agreement with a widespread but as yet poorly documented belief that the benefits of double
glazing are considerably larger than those associated with the better thermal insulation as such. The points where the other options enter the optimum combination are only slightly affected by the more differentiated approach to the matter of comfort level.

5.5 Scaling up

The solution to the optimization problem we obtained gives us the solution for a wide range of dwellings, provided the following parameter set remains the same:

- the ratio of the envelope area to the volume of the house
  \[ \frac{AH}{VH} = 0.87 \text{ m}^{-1} \]
- the ratio of internal heat production to the volume of the house
  \[ \frac{QI}{VH} = 1.23 \text{ W m}^{-3} \]
- the ratio of the average hot water load to the volume of the house
  \[ \frac{QT}{VH} = 1.56 \text{ W m}^{-3} \]
- the ratio of internal brick wall area to the volume of the house
  \[ \frac{(AH + AH)}{VH} = 0.87 \text{ m}^{-1} \]
- the type of the house (i.e. brick cavity walls etc.), its orientation, the climate and the restrictions to temperatures
- the specific initial investments II/VH

The solution then is valid for the following variables:

- the specific investment in energy conserving options
  \[ \text{Investment/VH, Dfl m}^{-3} \]
- the specific auxiliary energy need (yearly)
  \[ \frac{Qaux}{VH}, \text{ J m}^{-3} \]
- the insulation thickness of the walls
  \[ DD, \text{ m} \]
- the specific heat exchanging capacity of the regenerator
  \[ \frac{UR}{VH}, \text{ W k}^{-1} \text{ m}^{-3} \]
- the specific collector area
  \[ \frac{A}{VH}, \text{ m}^{-1} \]
- the specific heat exchanging capacity of the hot water coil
  \[ \frac{UT}{VH}, \text{ W k}^{-1} \text{ m}^{-3} \]
- the specific storage volume
  \[ \frac{VS}{VH}, \text{ } \]
- the specific insulation thickness of the storage
  \[ \text{DS} \times \sqrt[3]{VH}, \text{ m}^2 \]
- the specific heat exchanger capacity of the water-air heat exchanger $U_{H/VH}$, $\text{WK}^{-1}m^{-3}$
- the specific window area $A_{W/VH}$, $m^{-1}$
- the thickness of the insulation of the night shutters $D_{L}$, $m$
- the thickness of the brick interior walls $D_{M}$, $m$

5.6 The differential of energy saved with investment

Many investment policies assess the differential of the energy saved with the investment, $\Delta E/\Delta I$. In figure 14 the specific investment is given as a function of this differential (for the constant comfort case). Multiplying the specific investment with the volume of the house ($270 \text{ m}^3$) gives the absolute conservation investment for the case considered in this report.

\[ \Delta E/\Delta I \text{ [MJ df1}^{-1}] \text{ differential of energy savings with the investment} \]

Figure 14 Specific investment as a function of the differential of the energy saved with the investment.

As far as the scaling up mentioned in section 5.6 applies the curve of fig. 14 can be generally utilised to decide on the energy conservation investments.
5.1 Example

Suppose that a house of $500 \text{ m}^3$ ($= 1.85 \times 270$) has to be designed and that the principal is prepared to spend on energy saving options up to a differential of heat saved with investment of $\Delta E/\Delta I = 2 \text{ MJ/Dfl}$ (the ratio of energy saved with the investment is of course much higher). If the parameters of the house etc. are equal to those afore mentioned, the permissible specific investment equals 42 Dfl $\text{m}^{-3}$ and the absolute investment ($42 \times 500) = \text{Dfl 21,000,-}$. The corresponding investment for the house of $270 \text{ m}^3$, as considered in this report, $(42 \times 270) = \text{Dfl 11,300,-}$. From figure 14, figures 9-13 and section 5.5 then follows:

- Total conservation investment: $42 \times 500$ Dfl 21,000,-
- Insulation thickness of the walls: 13 cm
- Heat exchanging capacity regenerator: $750 \times 1.85$ 1400 WK$^{-1}$
- Windows, double glazed: $5 \times 1.85$ 9.3 m$^2$
- Collector area: $3.5 \times 1.85$ 6.7 m$^2$
- Heat exchanging capacity hot water coil: $310 \times 1.85$ 570 WK$^{-1}$
- Storage volume: $21 \times 1.85$ .4 m$^3$
- Insulation thickness storage: $19 \times 1.85^{-1/3}$ 15 cm
- Auxiliary energy (heat) yearly: $19 \times 1.85$ 35 GJ

Normal Dutch building practice is that only two of the conservation options are used: insulation of walls (thickness $\approx 6$ cm) and double glazing (ratio of window area to envelope area $\approx .09$). The total conservation investment for the $500 \text{ m}^3$ house then is Dfl 13,000,- and the auxiliary energy demand about 120 GJ. Noteworthy is that this normal investment in energy conservation (regarded by many as too low) has to be increased by only 40% to make solar water heating feasible.

5.8 Auxiliary heater

The price and performance of the auxiliary heater have to be accounted for in the optimization. Because the auxiliary heater does not influence the thermal behaviour of the system, the optimization of the auxiliary heater can be dealt with separately. If, for example, the standard heating installation comprises an auxiliary heater with an efficiency of 70% and a comparison is wanted with a high performance heater with an efficiency of 90% and costing Dfl 1,500,- more, installation included, then figure 9 can easily be transformed by dividing the auxiliary energy by the efficiency and by adding the extra investment. The result of this is presented in fig. 15.
Figure 15 The minimum auxiliary energy (in primary energy), (fat curve) as a function of the total investment for both a standard and a high performance heater (latter curves shifted to the right and downwards relative to the former, same legend as in former figures).

A simple comparison shows the high performance auxiliary heater to become attractive at an investment beyond Dfl 6,000,-. The sequence in which the energy conserving options have to be applied and the associated investment thresholds become (for the constant comfort case);
1. Insulation of the walls (beyond Dfl 600,-)
2. Regeneration of the heat in the waste air (beyond Dfl 2.050,-)
3. Double glazing (beyond Dfl 3.800,-)
4. High performance heater (beyond Dfl 6.000,-)
5. Solar hot water system (beyond Dfl 11.400,-)
6. Solar heating and hot water system (beyond Dfl 22.500,-)

5.9 Heat leaks in the envelope

In this explorative study the envelope of the house was assumed to consist of only a brick cavity wall and a window. Actually houses have doors and many other points where the insulation is interrupted. All these "coldbridges" increase the heat demand of the "superinsulated" house and consequently lead to a better specific performance of the solar heating installation. Accounting for the "coldbridges" will, therefore, considerably reduce the investment at which solar heating appears in the optimum combination. More data are required to settle this point.

5.10 Pumping and fanpower

The pumping and fanpower are not accounted for in this study. With regard to the solar system this is a good approximation as the pumping energy in a well controlled system with stratified storage represents less than 1% of the energy displaced [2]. With regard to the extra fanpower induced by the waste air heat regenerator this approximation is usual not correct as for most nowadays regenerators the fan energy is a substantial portion of the energy displaced. This point has to be studied further.

5.11 Sensitivity of the optimization

Some indications on the sensitivity of the optimization have been given earlier. From the case of the solar heating installation (section 5.3.1) it appears that the investment at which an energy conserving option enters the optimum combination is rather sensitive to the initial costs of that option. Because of the still rough cost function, the results of this study have to be applied with great care and have to be considered as a first estimate only.

The approximate nature of the cost function does, however, not imply that the sequence in which the energy conserving options enter the optimum combination is expected to change essentially for a sharper defined and better founded cost function.
5.12 Future work

5.12.1 construction of a design aid

The final aim of this study is to supply an easy design method for architects and consulting engineers. To this end further research is required to disclose the influence of the parameters (section 5.5) and the cost function. Further the important energy conserving options of reduction of the air infiltration rate and elimination of the heat leaks in the envelope have to be incorporated in the study. Other wall constructions than the brick cavity wall may also have to be implemented. For the design of new dwellings a simple graphical design aid is then obtained, consisting of a set of curves, like figures 9-14, for several parameter sets and cost functions. An approximation for intermediate values then can be obtained by proper interpolation. The optimum values of the setting of the collector and loadflow can subsequently be found by running the program SISOEN with the parameter values obtained with the simple design aid. For this purpose the program SISOEN has recently been implemented on the pocket calculator HP-41C[4].

5.12.2 improvement of the optimization procedure

The optimization procedure in its present form takes too much processor time to be of practical value as a design tool (about 150,000 s on a fast machine for one set of restrictions and a range of investments).

A significant reduction of the processor time seems possible by investigating the following subjects:

- reduction of the number of weather data; investigation of the applicability of the short reference year [6] (a sixfold reduction)
- a much shorter period for the initialisation of the temperatures for the short term storage (a nearly twofold reduction)
- a better estimate for the start of the optimization search (mostly a minor improvement)
- more compact programming of the model SISOEN (reduction \( \approx 1.5 \))
- accelerating the iterations in the model SISOEN by using a more sophisticated iteration scheme (reduction \( \approx 1.5 \))
- application of a faster optimization algorithm than MINIFUN (reduction unknown, but an order of magnitude seems possible).
- calculation of the several combinations of options only in the regions where they are optimum (a twofold reduction).

Considering also the increasing speed and decreasing prices of computers, these improvements may eventually result in an optimization procedure that is suitable for design offices.
5.12.3 extensions to SISOEN

As the optimization procedure is based on the model SISOEN all extensions to SISOEN have a direct bearing on the range of options that can be included in the optimization. In this connection the following extensions of SISOEN deserve attention:

- the dependence of the efficiency of a condensing high performance heater on the temperature of its supply fluid
- a radiator and floor heating system
- a constant comfort level control of the room temperature
- a heatpump for auxiliary heating
- cooling
- integration of the auxiliary heater in the storage
- seasonal storage

Except for seasonal storage, cooling and a heatpump the modifications are presumably quite simple.
The following conclusions hold only for the parameters and cost function mentioned, under Dutch conditions and for a total energy conservation investment below Dfl 25,000,- for an average house.

- The rational sequence for the application of energy conserving options in a house is:
  - insulation of walls
  - waste air heat regenerator
  - double glazing
  - high performance auxiliary heater
  - solar hot water system
  - enlarging the south facing windows (double glazed)
  - solar heating system

- Night shutters are never attractive because of their high initial costs.

- The thickness of the usual interior brick walls with regard to their thermal mass is amply sufficient.

- 'Active solar' (hot water system) precedes enlarging south facing double glazed windows.

- The specific investment above which the energy conserving options become attractive, and the associated incremental energy saving/investment ratios are respectively:

1. insulation 2.2 Dfl m\(^{-3}\) , 110 MJ Dfl\(^{-1}\)
2. regenerator 7.6 Dfl m\(^{-3}\) , 69 MJ Dfl\(^{-1}\)
3. double glazing 14 Dfl m\(^{-3}\) , 16 MJ Dfl\(^{-1}\)
4. high performance heater 22 Dfl m\(^{-3}\) , 5.2 MJ Dfl\(^{-1}\)
5. solar hot water system 42 Dfl m\(^{-3}\) , 3.1 MJ Dfl\(^{-1}\)
6. larger south facing windows 61 Dfl m\(^{-3}\) , 1.4 MJ Dfl\(^{-1}\)
7. solar heating system 83 Dfl m\(^{-3}\) , .9 MJ Dfl\(^{-1}\)

- These conclusions follow from a newly developed optimization method which determines the lowest amount of auxiliary energy possible at a given total conservation investment, and the associated best combination of options. The method lends itself to further development into a device for computer aided design.
References


### List of symbols

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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>A</td>
<td>collector area</td>
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<td>ΔE/ΔI</td>
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<td>--------------------------------------------------</td>
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<tr>
<td>U</td>
<td>heat transfer coefficient</td>
<td>$\text{Wm}^{-2}\text{K}^{-1}$</td>
</tr>
<tr>
<td>UH</td>
<td>heat exchanging capacity air heater</td>
<td>$\text{WK}^{-1}$</td>
</tr>
<tr>
<td>UR</td>
<td>heat exchanging capacity regenerator</td>
<td>$\text{WK}^{-1}$</td>
</tr>
<tr>
<td>UT</td>
<td>heat exchanging capacity hot water coil</td>
<td>$\text{WK}^{-1}$</td>
</tr>
<tr>
<td>VH</td>
<td>volume of the house</td>
<td>m$^3$</td>
</tr>
<tr>
<td>VR</td>
<td>ventilation rate</td>
<td>h$^{-1}$</td>
</tr>
<tr>
<td>VS</td>
<td>volume storage</td>
<td>m$^3$</td>
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<td>$\lambda$</td>
<td>heat conduction coefficient</td>
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<td>specific heat capacity</td>
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