THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK

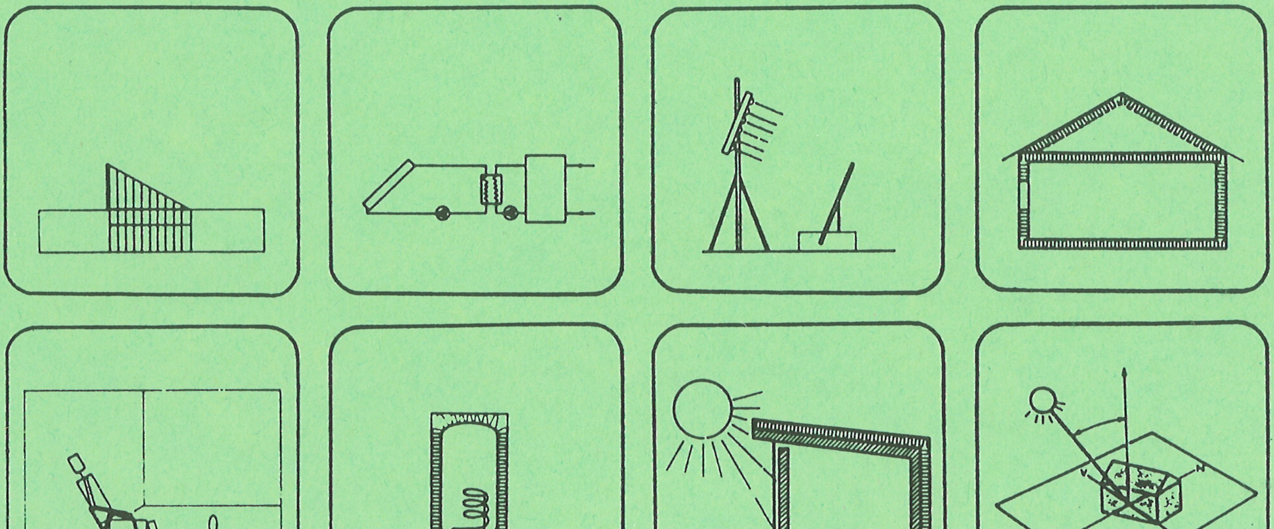
A SOLAR WATER HEATING SYSTEM FOR NORTHERN EUROPE

P. E. KRISTENSEN

SEPTEMBER 1983

REPORT NO. 140

PERFORMANCE MONITORING GROUP PMG - COMMISSION OF THE EUROPEAN COMMUNITIES



SOLAR SYSTEM CASE STUDY

A SOLAR WATER HEATING SYSTEM
FOR NORTHERN EUROPE

SEPTEMBER 1983

P.E. KRISTENSEN
THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK

PERFORMANCE MONITORING GROUP PMG
COMMISSION OF THE EUROPEAN COMMUNITIES

PREFACE

The CEC Performance Monitoring Group is one out of six concerted actions under project A of the CEC Solar Energy Recearch and Development Programme.

The Performance Monitoring Group consists of representatives from eight of the ten member countries of the CEC: United Kingdom, Belgium, Germany, Ireland, Italy, France, the Netherlands and Denmark. The members of the group are:

PROJECT CO-ORDINATION - UK

Richard Ferraro - Architect
Ramiro Godoy - Engineer
Energy Conscious Design
11-15 Emerald Street
London WC1N 3QL

GERMANY

Ulrich Luboschik
Engineer
IST Energietechnik GmbH
Kandern Wollbach

BELGIUM

Arnold Debosscher
Mechanical &
Electronics Engineer
Katholieke Universiteit
Leuven

IRELAND

J Owen Lewis
Architect &
Building Services Engineer
School of Architecture
University College Dublin

DENMARK

Poul Kristensen
Engineer and Building
Scientist
Thermal Insulation Laboratory
Technical University of
Denmark, Lyngby

ITALY

F Cecchi Paone
Engineer
Fidimi Consulting Spa
Rome

FRANCE

Gerard Kuhn
Professor and Engineer
CNRS - CRTBT
Grenoble

NETHERLANDS

Cees den Ouden - Engineer
Dick Brethouwer - Engineer
Institute of Applied Physics
TNO-TH Delft

The persons responsible for the project at the Commission are:

T. C. Steemers and W. Palz
Directorate General XII, Rue de la Loi 200, B-1049 Brussels

Scientific Adviser to the Commission: Cees den Ouden

From the start of the Performance Monitoring Group in 1979 and until 1982, the prime objective of the work was to collect and analyse data from solar houses around Europe. One conclusion drawn on this work was that all the solar heating systems seen so far were oversized, complicated and had poor economy. In the group it was felt that a much better performance to cost ratio could be achieved through careful design. Therefore a series of Performance Optimisation Studies were undertaken by the group in 1982/83.

The Performance Optimisation Studies were carried out by three groups of experts, each group being responsible for the design of a solar DHW system and a combined water and space heating system. In this report the work of one of these groups, the Northern European design group, is presented.

The other groups were the Northern/Central European design group based at TNO/TPO in Delft and the Southern European Design Group based at the University of Grenoble. Additionally an investigative study of a passive solar design for Central European climate was carried out by the UK representative of the group.

All the work carried out by the Performance Monitoring Group during the period January 1982 to October 1983 is reported in the following reports from the Commission of the European Communities:

1. Solar Heating - Performance and cost improvements by design.

2. Solar Heating - Performance of recent systems.

3. Solar Heating - Performance Monitoring 82/83
   - Executive summary and recommendations.

The three reports are edited by R. Ferraro and R. Godoy, and they were all published by the CEC in November 1983.

This report together with the parallel report on the combined solar heating system represent the work which was done by the design group based at the Thermal Insulation Laboratory.

Poul E. Kristensen

CONTENTS

List of figures

2.1 INTRODUCTION

This report outlines the findings of a system optimisation study for a solar water heater. The study was carried out under given constraints such as climate and local HVAC regulations.

The prime objective was to develop a solar heating system with a maximum output per invested ECU. Secondary objectives were to produce:

1. a system that would operate without any interference on the user´s part,

2. a high degree of reliability; since owing to the back-up heating system it would not always be possible to determine decreases in performance.

The work was carried out in 3 different stages. The first stage, referred to as "sketch design" represents a primary attempt based on conclusions drawn from previous experience.

The second or intermediate stage known as "initial or fist design" is discussed in sections 2.8 - 2.10 towards the end of the report.

The final design is presented in sections 2.2 - 2.7.

The system optimisation work was carried out by the following group of specialists:

Sten Melson, TIL (Modelling)

Poul E. Kristensen, TIL (System design)

Per Alling, Dansk Solvarme (manufacturer of solar systems, architect)

Torben V. Esbensen, Consulting engineer (Engineering Aspects)

Thanks are due to the following for assistance and encouragement:

- Roslev Houses, Skive who provided one of their standard model houses for the case study.

- Finn Straboe, architect, for invaluable advice on overcoming architectural problems and for illustrations of same. Finn Straboe is now working at the Technological Institute.

- Colleagues at the Thermal Insulation Laboratory, especially Ole Balslev Olesen (system modelling aspects), Svend E. Mikkelsen and Simon Furbo (system design aspects).

- Birthe Friis who typed the manuscript.

2.2 HOUSE DESCRIPTION

The system design was developed and adapted to the case study house. In section (2.2.1), a short description of the background to the selection of the house type will be given. A description of the case study house is given in section 2.2.2. Section 2.8 will give a further discussion of the initial choice of the case study house and the more general problems associated with integrating a solar system in a house. The specific problems and their solutions in the actual case study house are outlined in sections 2.2.3 and 2.2.4.

2.2.1 Introduction

Until the economic setback following the energy crisis in the seventies, the typical Danish single-family dwelling was a detached one-storey house of 130 m^2. The typical plot area was 700 - 1000 m^2.

In the late seventies and the beginning of the eighties, the building rate for dwellings dropped from 40,000 p.a. to approximately 20,000 p.a. The balance between detached and non-detached houses also changed so that now more than 50% of all houses being constructed are non-detatched.

The number of apartments being built remains stable at 6000 p.a. with an average floor space of 80 m^2. House size has dropped to an average 80 - 120 m^2. The rate of new houses being built is expected to incrase slowly throughout the eighties. The interest rate on loans for new housing has decreased significantly.

The typical plot area varies between 500 and 900 m^2, the lower numbers being typical for non-detached nouses, and areas from 700 to 900 m^2 being typical for detached houses.

The increase in new dwellings being built can be expected to restore the balance between detached houses and non-detached houses, i.e. a fifty-fifty balance could be expected. The plot area for a house is not expected to grow significantly, whereas the typical floor area may grow slightly.

A more detailed description of Danish housing is given in appendix 2.1.

2.2.2 The Case Study House

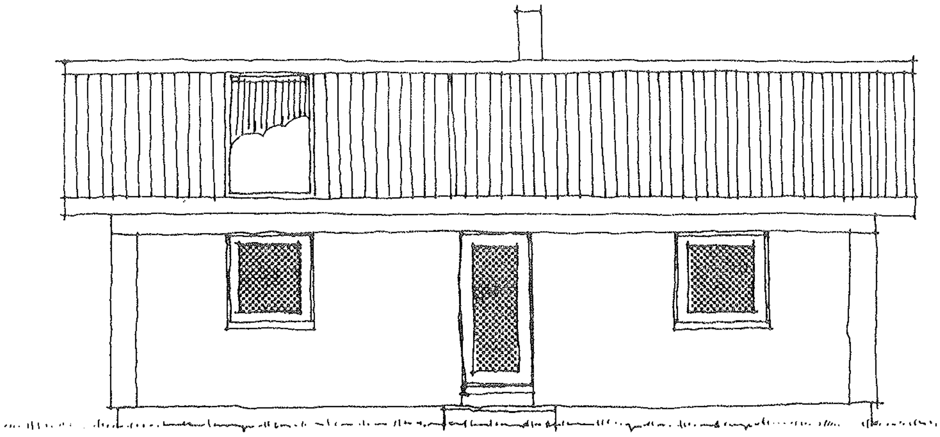
The house chosen for the case study is a typical single-storey detached house. Two houses (one laterally reversed) may be coupled together, or they could be clustered in a low rise-dense development plan. Each house may then take up a piece of land down to 500 m^2.

The groos floor area is 90 m^2, whereas the total living area within the exterior walls is 77 m^2. The volume is 180 m^3, see fig. 4.1.

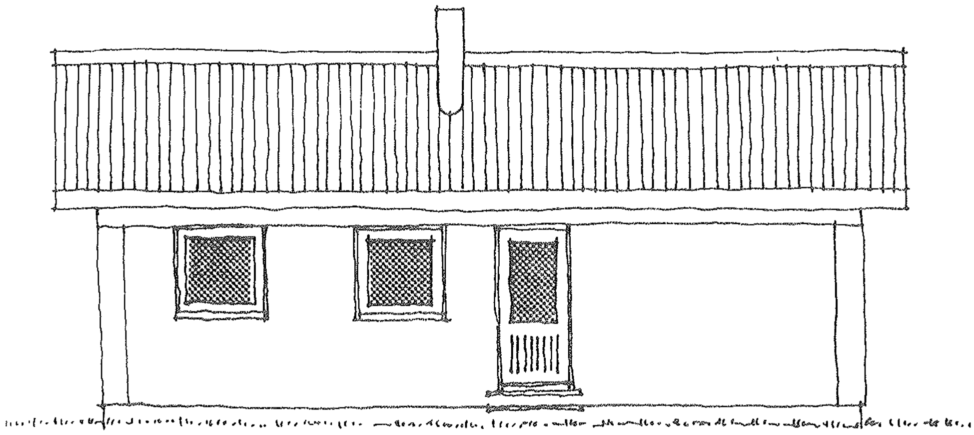
The U-values are:

exterior walls:	0.14	W/m^2 ^oC	
roof :	0.12	-	
floor :	0.12	-	
windows :	1.85	-	(glazing)
	2.20	-	(average for glazing and casement)

The house has a 20^{o} pitched roof with corrugated asbestos cement sheets. The standard plates have a black semi-glossy finish, but other colours are available. The loft space is not heated and is naturally ventilated.

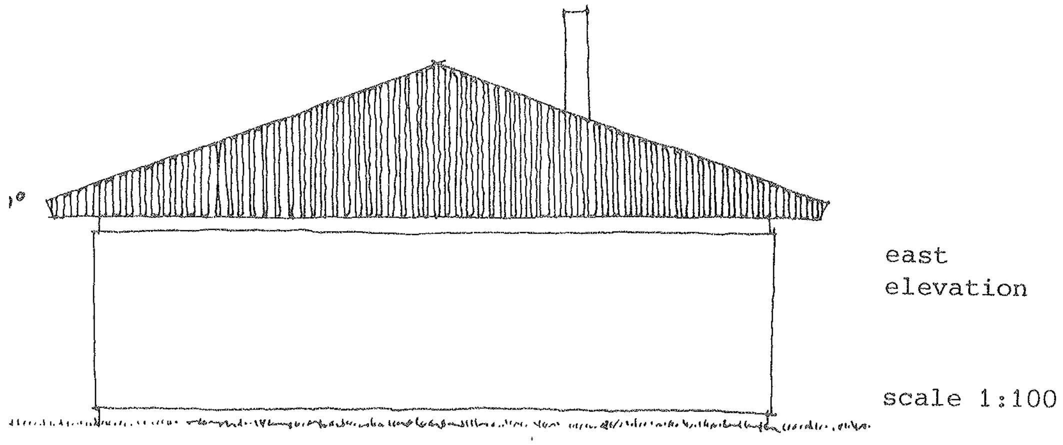


South elevation Scale 1:100



North elevation Scale 1:100

Fig. 2.1 The Case Study House, south and north elevations



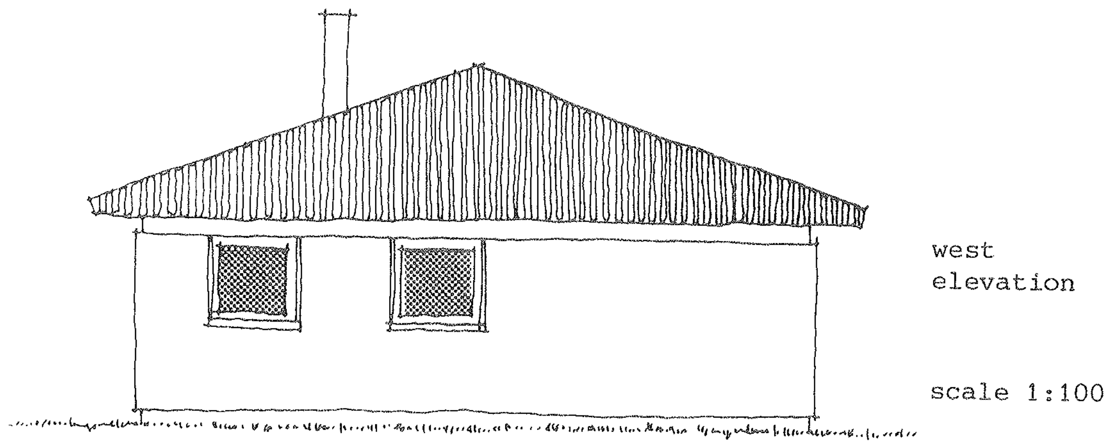


Fig. 2.2 The Case Study House, east and west elevations

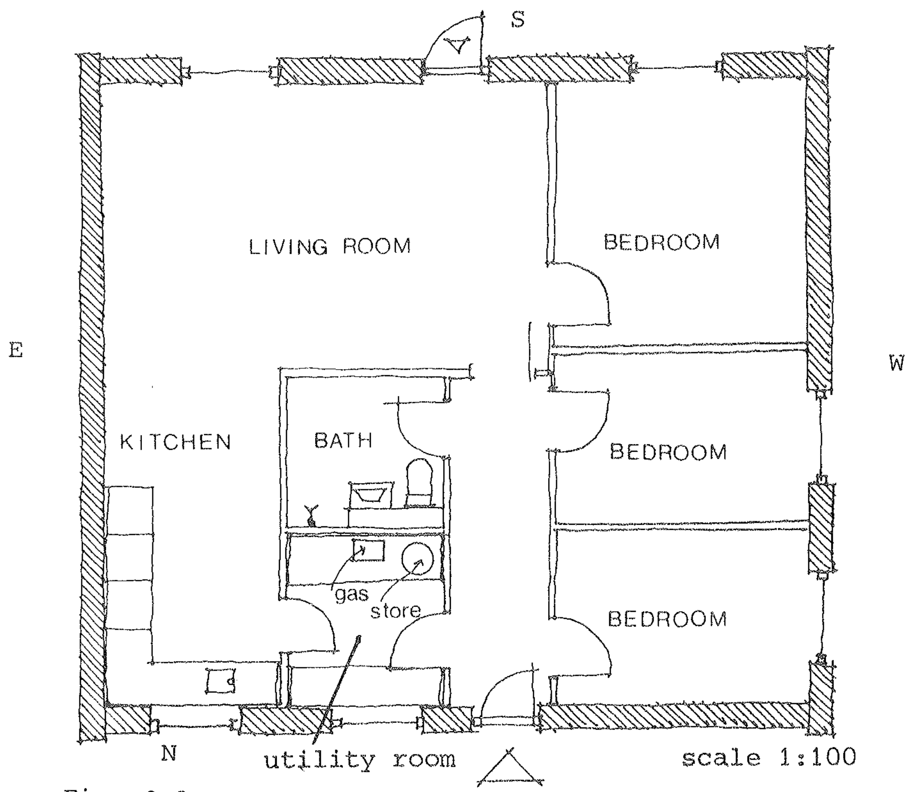


Fig. 2.3 The Case Study House, floor plan

2.2.3 Solar Collector

A solar collector in a single unit for solar DHW systems has been developed by Per Alling (Dansk Solvarme). The collector is prefabricated as regards casing and mounting of absorber in casing. Backside insulation is put into the casing on site. The glazing is fitted on site as well. The details of the collector construction are discussed in section 2.4.2.

Flashing

The glass and the flashing are fastened together by a standard greenhouse cap, see fig. 2.4 - 2.5. For this purpose the cap is a little bit higher than usual, and it has been filled with polyurethane foam. In this way the effect of the thermal bridge from the air in the absorber/glazing interspace to the ambient air is decreased. The greenhouse caps are fastened to the slot in the aluminium profile with thin screws made of stainless steel.

The flashing up to the ridge and to the lower end of the roof is shown in fig. 2.5. The ridge is normally covered by a plane plate of asbestos cement in a shape corresponding to the roof tilt. The roofing is corrugated asbestos cement sheets. The flashing is made of zink plates.

As shown in fig. 2.5 the space between the flashing and the aluminium frame is filled in with insulation material. Given the insulated caps described above, the perimeter insulation should be reasonably good.

Assembling on-site

The collector unit is mounted on the roof in the following way:

- The rafters on the area where the collectors are to be installed are covered by an 8 mm plywood board.

- A frame of 30 · 50 mm wooden laths is made corresponding to the collector dimension (1 · 5 m^2).

- 50 mm insulation is put into the frame.

- The aluminium/wood frame with the absorber is fastened on the lower wood frame.

- The glazing is put into place.

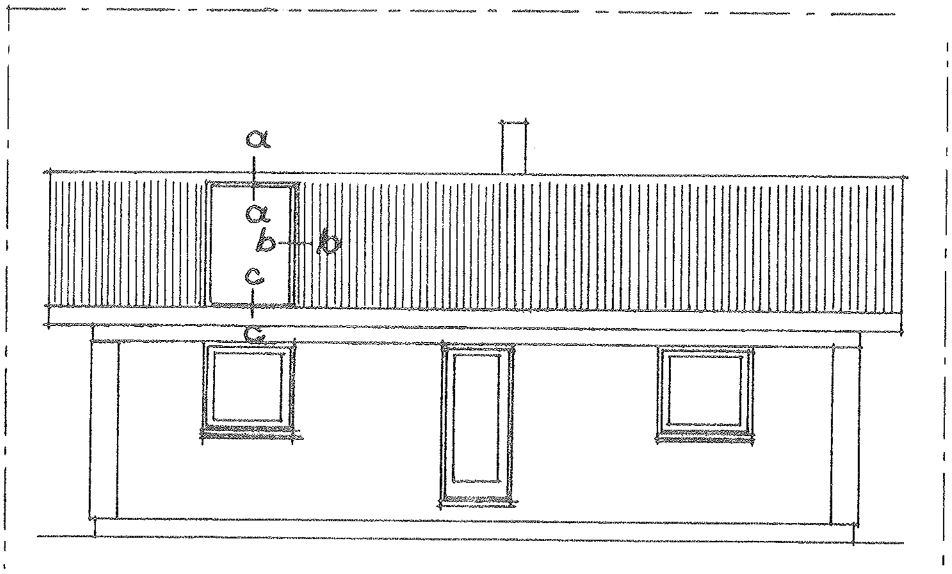
- The flashing is finished and edge insulation is put into place.

- The insulated caps are fastened with screws.

2.2.4 Integration of heat storage tank

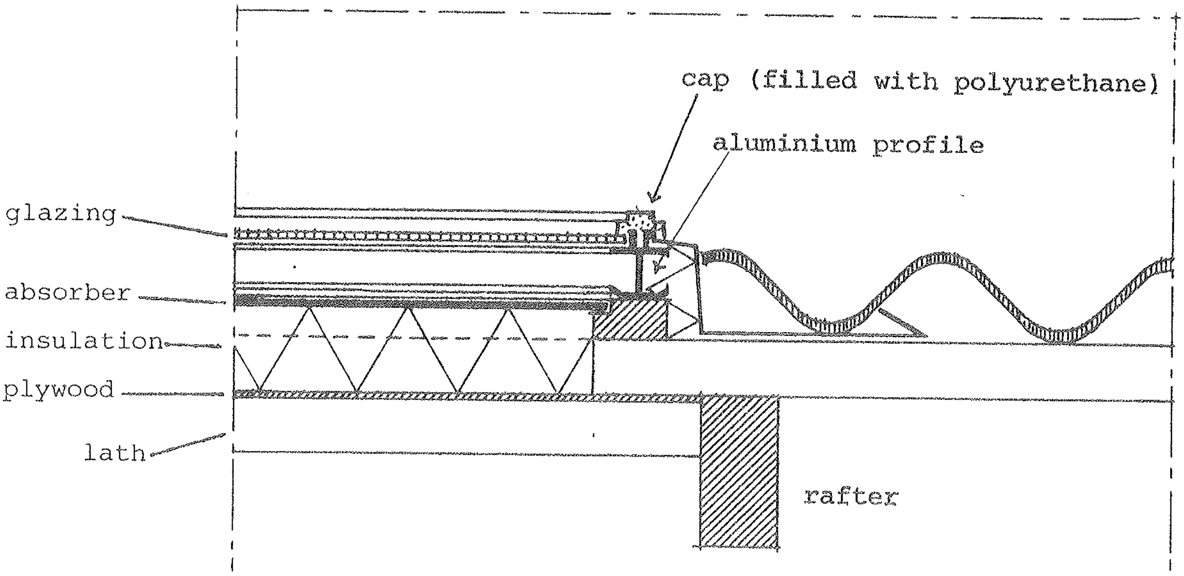
The storage tank should be situated close to the auxiliary boiler. Furthermore it should be as close to the hot taps as possible.

In the actual house (see fig. 2.3) the only place to situate the boiler is in the utility room. The heat storage tank should then preferably be situated here as well. This will leave very short pipe runs from store to taps.



south elevation

scale 1:100

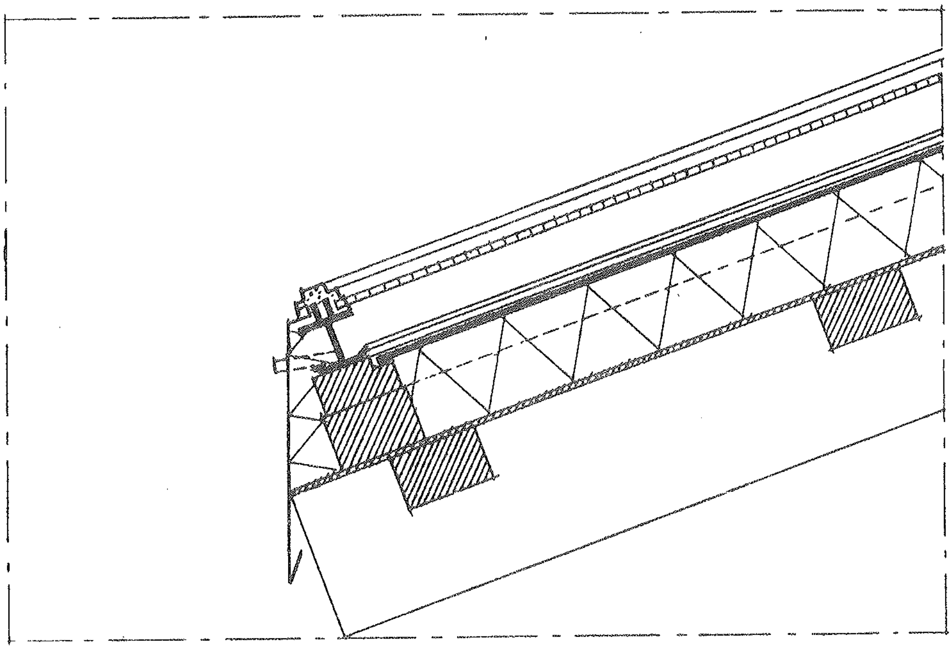


section b-b

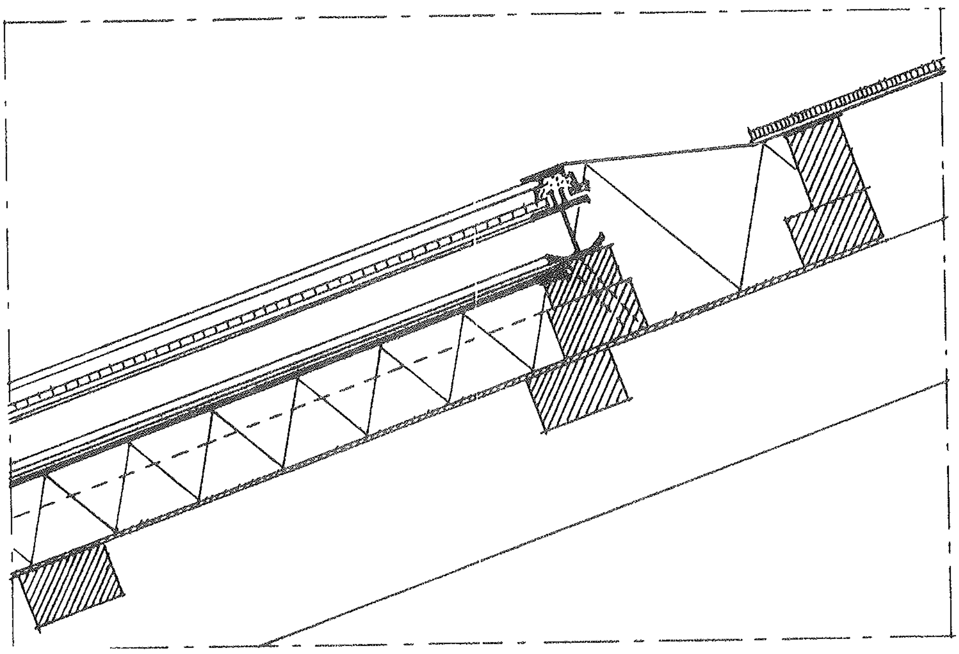
scale 1:5

Fig. 2.4 Solar collector built into the roof

The actual boiler chosen is very light (49 kg), and it is intended for mounting on a wall. It is mounted as close to the ceiling as possible, see fig. 2.6. The dimensions are: depth = 345 mm, width = 475 mm and height = 830 mm.



section c-c   lower end of collector



section a-a   upper end of collector

scale 1:5

Fig. 2.5 Sections in collector.
Reference drawing, see fig. 2.4

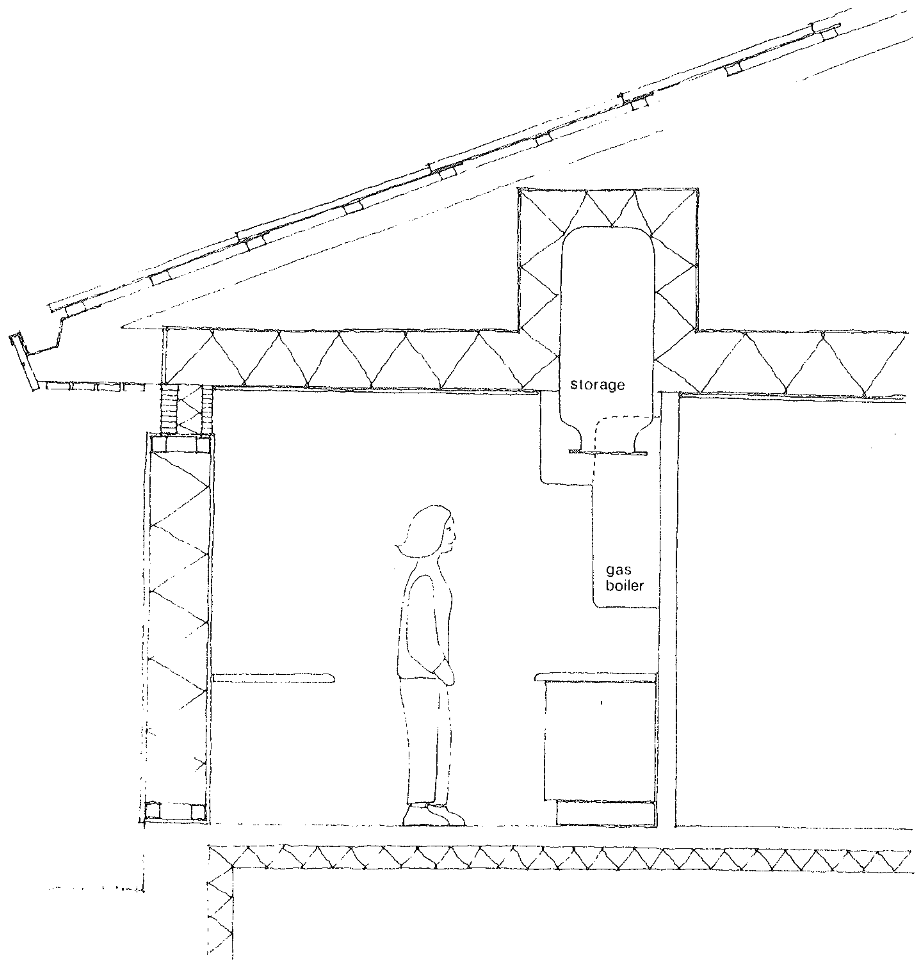


Fig. 2.6 Integration of the storage tank

The storage tank is mounted next to the boiler. Most of the store is situated in the roof space, but all of the connections appearing from the bottom lid are accessible from the utility room. The components and the piping connecting store and boiler are situated in an insulated cabinet. This cabinet is shown in more detail in figure 2.8 in section 2.4.4.

The normal work table of the utility room may be placed below the cabinets, as shown in figure 2.6. The use of the table will not be restricted too much.

2.3 SYSTEM DESCRIPTION

2.3.1 Introduction

The system design was derived on the basis of two major constraints:

- Solar energy production from the collector must be added to the lower part of the storage tank in order to benefit from the temperature stratification effect in the tank.

- Postheating of domestic hot water should happen automatically, and there should be no idle losses from the backup system.

These constraints have been met in the system layout shown in fig. 2.7.

2.3.2 System Diagram and Description

The basis for this case study is that auxiliary heating is supplied via oil or gas. The boiler chosen for this purpose is a boiler which condensates most of the water vapour in the flue gases. The actual boiler works

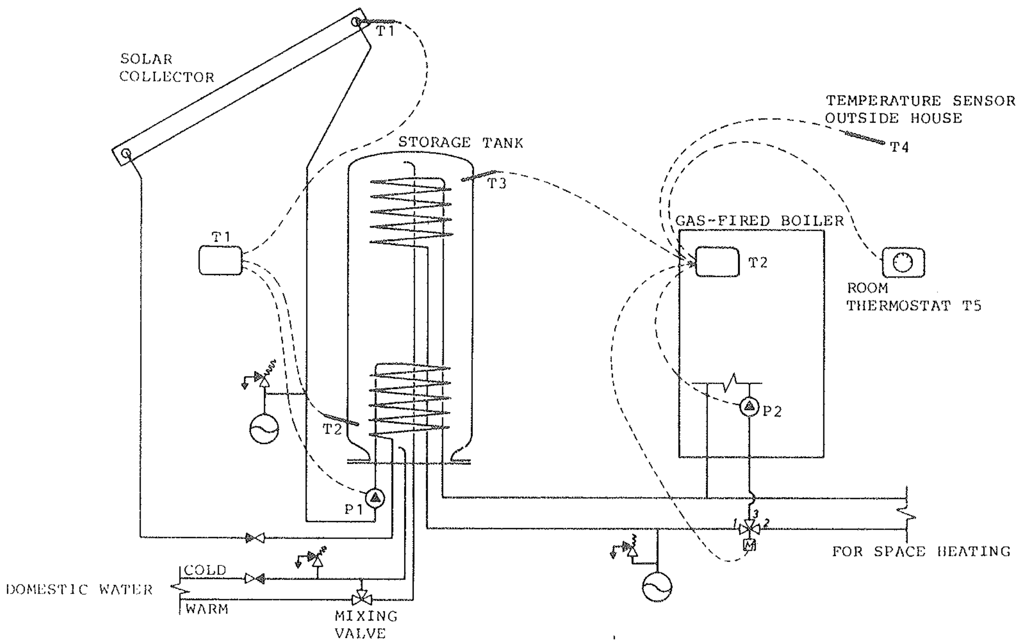


Fig. 2.7 System diagram, final design

on gas, but similar oil-fired boilers are becoming available. The advantage in both cases is that the efficiency of the boiler is improved considerably compared to that of conventional boilers. The actual boiler is a "Nefit Turbo". The maximum output of the boiler is 19 kW.

The required DHW temperature selected will normally be between 40°C and 50°C. If the temperature at sensor T3 drops below the setpoint, the motorized valve M is turned to position 1-3 (see fig. 2.7). The working temperature of the boiler is now controlled via a special thermostat with a setpoint of typically 60°C. When T3 is satisfied, both the gas burner and the pump P2 are shut off.

The boiler will work on space heating if the room thermostat T5 situated in a main room calls for heat. In that case the motorized valve M is turned to position 2-3. Pump P2 and the gas burner are switched on automatically, and the setpoint of the boiler temperature is chosen according to the ambient temperature.

If there is no need for either space heating or postheating of domestic hot water, pump P2 will not be working, and the boiler will be cold. This is considered to be a great advantage since the boiler will always be on standby for DHW postheating during summertime without there being any idle loss. Typically the idle loss from good, well insulated boilers on the Danish market is 200 - 300 W. During the five summer-months this will amount to about 1000 kWh.

The control strategy described means frequent heating and cooling of the boiler, and working temperatures in the region of between 30°C and 60°C, but the boiler is constructed to withstand these conditions. Furthermore the low working temperatures are a precondition to the good efficiences achieved by condensing the water vapour in the flue gases. The dimensions of the DHW coil in the storage tank are such that they allow for the amount of hot water needed for a shower where the flow required is 10/1 min. Given that the temperature in the lower part of the storage tank is an estimated 10°C and the desired DHW temperature is 38°C then the required performance is 12.5 kW. The details of the heat exchanger are dealt with in section 2.4.4 where the storage tank is described.

2.3.3 Operating modes

The control strategy of the system can be summarized as follows:

<u>Solar circuit</u>

The solar pump P1 is started if the temperature in the collector at T1 exceeds a level of 5 to 8°C higher than the temperature in the storage tank at T2. The pump is stopped when the collector temperature drops below a level of 1°C higher than the storage temperature.

<u>Overheating of primary circuit</u>

Overheating of the primary circuit and the storage tank is normally not a problem. The opening pressure of the relief valve in the primary circuit is 250 kPa, and the vapour pressure of 40% glycol-water fluid exceeds 250 kPa at 143°C.

The opening pressure of the relief valve of the storage tank is 600 kPa, giving a boiling temperature of over 143°C. The performance of the collector at this temperature is not higher than approx. 100 W/m^2. This is less than the heat losses from the primary circuit and the storage tank. Boiling is therefore prevented.

The control strategy for the interaction between the auxiliary coil in the top of the storage tank and the auxiliary boiler has been described previously and can be summarized as follows (reference is made to fig. 2.7):

1. When the temperature (T3) in the top of the storage tank drops below 50°C, the boiler will work exclusively on the DHW auxiliary coil. The boiler temperature has, in this case, a fixed setpoint of 60°C.

2. If the DHW auxiliary is not needed, the boiler is ready to satisfy the needs of the space heating system. If the room thermostat T5 in the reference room calls for heat, pump P2 will come on, and the setpoint of the boiler will, in this case, be determined according to the ambient temperature. A typical variation will be from 25°C at an ambient temperature of 20°C to 55°C at an ambient temperature of -10°C.

3. If neither the DHW auxiliary thermostat (T3) nor the space heating thermostat (T5) calls for heat, the boiler will be cold and pump P2 will be off.

2.4 COMPONENTS

2.4.1 Introduction

This section is devoted to a more detailed description of the components in the system. Primarily the storage tank and solar collector will be described.

2.4.2 The Solar Collectors

Absorber

The absorber is a double sheet construction, consisting of two 6 mm plates of stainless steel. The absorber size is $1.0 \cdot 5.0\ m^2$, and it is covered with selective foil (Maxorb). The collector fluid inlet is in one of the lower end corners, and the outlet is in the opposite higher end corner.

Casing

The casing consists of an aluminium frame fastened to an underlying wooden frame of $25 \cdot 50\ mm^2$, (see fig. 2.4 and 2.5). The absorber is mounted in a slot in this wooden frame. The aluminium frame is made of greenhouse-glazing welded together at the corners.

Glazing

The glazing consists of three panes, which are mounted with an overlap of approx. 40 mm. The overlap is sealed with silicone. The glass is 5 mm low iron.

Integration

The integration of the collector and on-site assembly are described in section 2.2.3.

2.4.3 Primary Circuit

The primary circuit is a traditional, closed, pressurized system. The heat transfer medium is a mixture of propylene glycol and water. Heat transfer to the storage tank is via a coil heat exchanger.

Piping

The heat exchanger in the storage tank and the primary circuit piping are made of copper. Copper piping is a little more expensive than steel piping, but this is to some extent counterbalanced by the fact that copper piping is more flexible to work with, and thus the overall installation costs are lower.

Components

The pump chosen is a Grundfos UPS 15/35. The performance of this pump may be controlled in three steps. The given primary circuit (collector, 15 m circuit, 8 m coil, components) requires a head of 31 kpa at 4 l/minute. The performance of the pump on step III is 34 kPa at 4 l/minute (corresponding to 0.8 l/minute x m^2 collector). The pump then requires 70 W of absorbed electricity. The counterflow valve selected is one with a spring to avoid natural circulation, and the materials are compatible with the influence of the propylene glycol.

The expansion tank has a volume of 10 l which is more than required given the total volume of 15 litres of glycol-water, but is has been found that the expansion tank should be a little oversized to avoid exessive variations in the pressure level of the primary circuit.

Heat exchanger

The heat exchanger consists of copper tubes with an inner/outer diameter of 13/15 mm.

The required flow from the solar collector (5 m^2) is 5 m^2 · 0.8 l/minute · m^2 = 4 l/minute. The heat transfer fluid is a 40% propylene glycol. The heat exchanger performance is requested to be 40 W/^{o}C · m^2 · 5 m^2 = 200 W/^{o}C. This figure is requested at a storage temperature of 40^{o}C. Under these conditions, the performance can be given to (2.4) approximately 17 W/^{o}C · m coil. The required coil length is then 200/17 m = 12 m.

The coil designed has a diameter of 275 mm with a distance between each torsion of 35 mm. The total height of the 12 m coil is then 560 mm. This is 40 mm more than 1/3 of the total height of the store (1550 mm), but it is found to be acceptable.

Because of the fact that the coil is immersed upright in the storage tank, the possibility of having an airvent at the highest point of the coil is eliminated. The speed of the fluid in the coil must therefore be high enough to allow for air bubbles to be carried along even in those pipe sections where downward flow takes place. In vertical sections speeds above 0.6 - 0.8 m/s are required. At a flow of 4 l/min, the actual velocity in the 13 mm tube is 0.55 m/s. However since, in our design, the downward flow occurs only in spirals that are diagonal rather than vertical, this figure is acceptable.

2.4.4 The heat storage tank

The storage tank is a pressurized steel tank containing domestic hot water (DHW). Its prime functions are:

1. to enable the solar collector to benefit from the temperature stratification effects arising from DHW consumption.

2. to postheat DHW, making an auxiliary DHW device unnecessary.

Via the current R&D work at TIL regarding small heat storage systems, references (2.1), (2.3) and (2.5), the following rules of the thumb have emerged:

- Good utilization of temperature stratification effects are achieved if

  1) The height of a cylindrical tank is 2 - 3 times the diameter,

2) The solar heat exchanger should be situated in the bottom of the tank, and it should be as flat as possible. In any case it should not exceed a height of more than approx. 1/3 of the total height of the store.

Furthermore, detailed modelling work has revealed that the heat exchanger capacity of the heat exchanger should be about 40 $W/^{o}C \cdot m^2$ collector.

The storage tank integrated in the roof construction is shown in fig. 2.8.

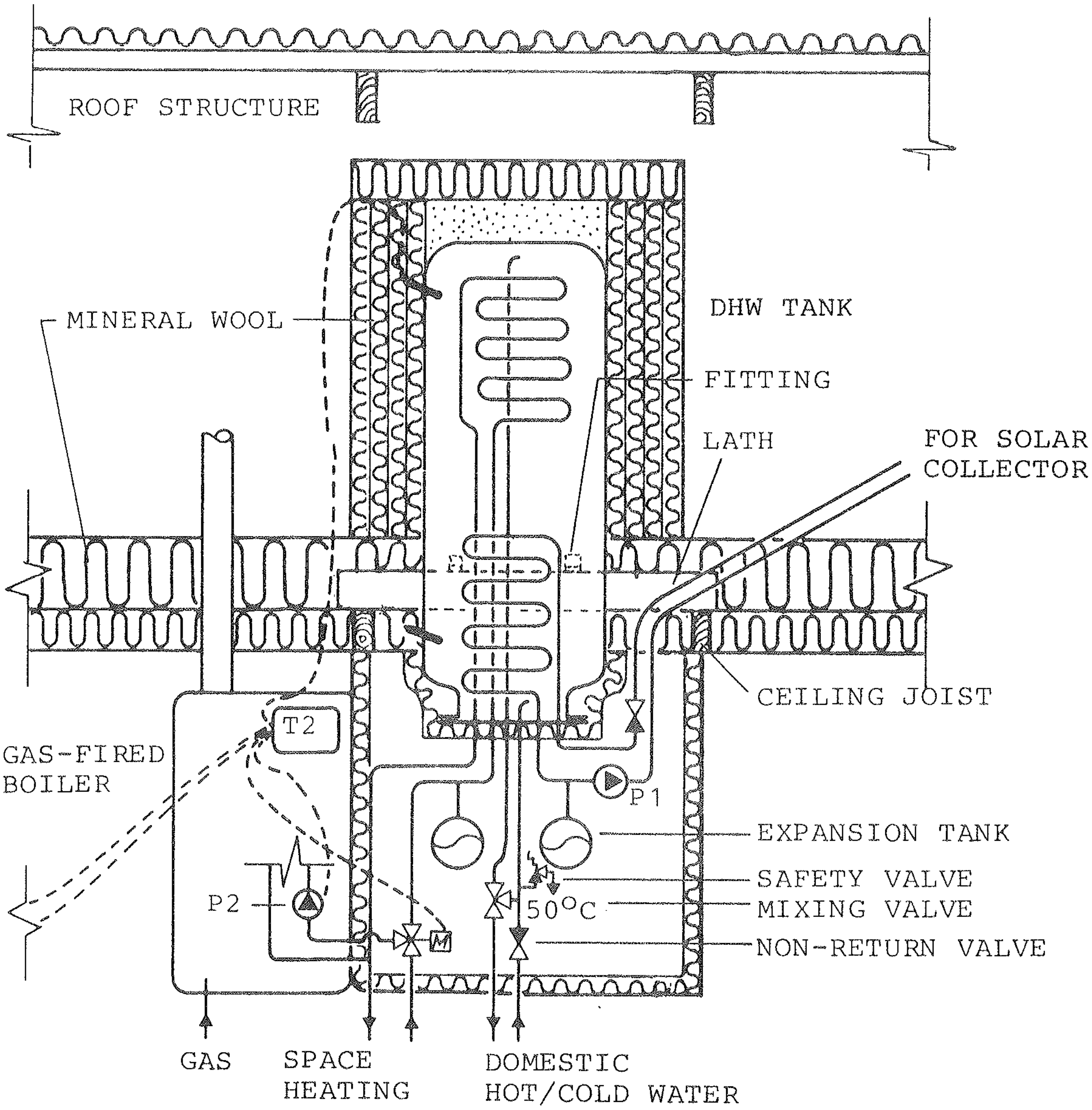


Fig. 2.8 Integration of the store in the house.
Front view/section in utility room.

The ideal tank is a slim, vertical, cylindrical tank with domestic water as the storage medium. It is then possible to use a standard tank construction (i.e. standard end plates), and it is still possible to benefit from the temperature stratification effect. Standard diameters of the end plate are 400 and 500 mm. If the height of the diameter ratio is taken as 3, this means a volume of 300 l for a 500 mm end plate, and 150 l for a 400 mm end plate.

All the pipes connecting the store to the DC/HW taps, the gas and the space heating unit pass through the lower end plate. Previous research has shown that if this is done the effect of the pipe connections as thermal bridges is very slight. Furthermore, when a small amount of cold water is present in the bottom of the tank, the heat loss from same is almost zero. Cold water is present in the bottom of the tank at all times except for relatively short periods beginning at the time when the collector is working and ending when the first of the subsequent DHW drawoffs takes place. Furthermore, experiments have shown that heat loss through a pipe going down from a hot tank is much smaller than through a horizontal pipe or a pipe going upwards. This is because of the fact that, in the first case, heat transfer occurs primarily through the pipe wall and not through the water. For a horizontal pipe or a pipe going upwards, heat transfer via convection of the water internally in the pipe increases the total heat loss considerably.

All the connections being mounted on a lid has the big advantage that all piping and heat exchangers in the store can be taken out by removing the lid. It is a general wish to minimize the height of the heat exchanger coils. This means that a large diameter is required, thus also a large diameter of the lid is required. A 400 mm tank will normally only leave a free opening of 200 mm in the lid, whereas a 500 mm tank will mean a lid of approx. 300 mm. One loop of a coil will, in the two cases, be 0.60 m and 0.90 m respectively. This is a critical point, resulting in a general wish for a 500 mm tank.

The basis for the following sections is a cylindrical tank of 500 mm diameter and a total length of 1300 mm. This gives a total volume of 250 l.

Furthermore, when reference has to be made to a collector area, an area of $5m^2$ is implied.

The tank has to conform to the national regulations regarding pressure of domestic water etc. The tank should be tested at a pressure of 1000 kPa. It is then certified for working pressures up to 600 kPa. This is sufficient since the pressure of the water mains supply is normally only 300 - 400 kPa. The relief valve (mandatory) is chosen to 600 kPa. Most of the standard cylindrical DHW tanks in Denmark have a metal thickness of 3 mm for tanks up to 300 l. This is the minimum thickness allowed by the regulations. For this purpose there is no reason to deviate from 3 mm metal thickness.

It is mandatory that a DHW tank should be protected against corrosion. There are different options as how to meet the requirements: coating with enamel or rilsan, and/or protection with a magnesium anode. Protection via rilsan treatment is chosen as a good and economical solution. It should nervertheless be noted that experiences with rilsan coating are sparse for temperatures above 90 - 95 ^{o}C, temperatures that may occur on rare occasions in this system.

The installation procedure of the storage system is described in section 2.4.7, "Assembly on site".

2.4.5 Auxiliary heating

The required performance of this heat exchanger is 12 kW, corresponding to the continuous consumption of a shower (10 l/min). Boiler flow/return temperatures are estimated to be between $60^{o}C/45^{o}C$. The DHW temperature, when entering the postheating region of the store, is expected to be $20^{o}C$, and the required DHW temperature is $38^{o}C$. Mean temperature difference across the coil is then $23.5^{o}C$.

A copper coil 16/18 mm is chosen, and based on (2.4) the performance of this coil at the given condition can be estimated to 30 $W/^{o}C \cdot m$ coil. The required coil length is then $12000/(30 \cdot 23.5) = 17$ m. Given a coil diameter of 275 mm and a distance between each single tube of 35 mm, the coil height will be 670 mm. This corresponds to 50% of the total height of the store, or 125 l out of a total of 250 l. This is regarded as too much of the volume being devoted to auxiliary heating. About 1/3 of the volume or 90 l is regarded as enough. This would decrease the coil length to 12 m (height 500 mm). The performance during continuous consumption of DHW $20/38^{o}C$ would then be about 7 l/minute.

A backup capacity of 80 l heated to $50^{o}C$, and a possibility of a continuous consumption of 7 l/minute heated $20/38^{o}C$ is regarded as acceptable. If the performance during continuous consumption should be increased, another coil construction (double coil) or a finned coil might be considered.

Pipes in the heat storage tank

Three vertical pipes run from the warm zone ($50^{o}C$) of the store down into the lower part of the store, which may be considerably colder (down to $10^{o}C$). The pipes will, in any case, increase the heat transfer from top to bottom. Furthermore, temperature stratification will be disturbed when either hot water is drawn or when heat is delivered via the upper coil. Consequently, the vertical pipes will act as heat exchangers between the warm upper part and the cold lower part of the store. The problem is solved by decreasing the capacity of the pipes to transfer heat. In this study two changes are made:

1. The hot water pipe is a 22/26 mm PEX-tube mounted on a copper pipe stub on the bottom lid. The PEX-tube is a polyethylene pipe approved for DHW applications.

2. The two copper pipes (16/18 mm) for the upper heat exchanger were covered with a 28/20 mm PEX-tube. The thermal resistance of the exterior surface layer of the 16/18 mm copper tubes is increased from approx. $0.002\ m^2 \cdot {}^{o}C/W$ to approx. $0.014\ m^2 \cdot {}^{o}C/W$. Substituting the copper DHW pipe with a PEX-tube will give similar results.

2.4.6 Controllers

The controller for the primary circuit is a traditional, differential thermostat with digital display. For our purposes, a thermostat with a third sensor has been chosen. This sensor may be mounted in the top of the store. Via the display it is then possible to have a reading of three system temperatures: the top storage temperature, the temperature of the lower part of the store, and the absorber temperature.

2.4.7 Assembly on site

The procedure for assembling the collector on site is described in section 2.2.3, "The Solar Collector".

The procedure for assembling the rest of the system is as follows (reference is made to fig. 2.8 in section 2.4.4):

- The storage tank arrives at the building site as an uninsulated unit with the heat exchangers installed. The total weight of the unit is 80 kg.

- The store is mounted on two wooden laths resting on the ceiling joist on each side of the tank. The tank has two fittings on each side, which makes mounting of the store on the laths easy.

- The gas-fired back-up boiler is now mounted on the wall. The piping between boiler and store is finished, and the connections to domestic hot and cold water are made. The piping for the solar collector is drawn from the bottom of the tank up into the loft.

- The installation job in the utility room is finished by mounting an insulated cabinet around the components. The front of the cabinet may be opened to facilitate access to the components.

The ceiling contractor will now install the ceiling, and the insulation contractor will insulate the loft. He will finish his work by insulating the part of the store penetrating up into the loft with 200 mm of mineral wool. The storage insulation consists of 4 $\cdot$ 50 mm of mineral wool (laminated tank insulation with kraft on one side, in rolls). A comparison between the costs and the reduction of heat loss from the top of the store showed that 200 mm are cost-effective.

It should be noted that there will be no thermal bridges from the store to the surroundings, apart from the piping in the bottom lid. The wooden laths on which the store is resting cannot be regarded as thermal bridges, and they are furthermore incapsulated in the building insulation.

The way in which the store is integrated in the house presents the following advantages:

- The store does not take up any floor space.

- The components (pumps - valves, etc.) are accessible, and the heat exchangers can easily be removed for inspection, cleaning, etc.

- Heat loss from the store is minimized since there are no thermal bridges except in the bottom lid. Furthermore, heat losses from components, pumps, etc. are decreased since they are gathered in an insulated cabinet.

2.5 SYSTEM PERFORMANCE

In this section the modelling work which is basis for the system optimisation exercise, section 2.6, is presented.

2.5.1 Introduction

A system performance of 300 - 400 kWh/m^2 can be regarded as a reasonnable target for solar water heating systems in Northern Europe. System performances below 300 kWh/m^2 will in most cases lead to system paypack periods that are not acceptable.

Under Northern European weather conditons, performances up to 700 kWh/m^2 may be achieved (2.2). This is achieved with a collector area of 1.5 - 2 m^2 for a solar water heater. Such a system is, on the other hand, shown not to be optimal, see section 2.6.4. This is caused by the high initial costs for the system, meaning that the investment per m^2 is relatively high for the first square meters of collector.

2.5.2 Description of the simulation model

The model work was done using a revised version of the SVS model that has been in use at TIL for several years. The revised version is capable of working with a stratified storage tank. The time-step is varied through the simulation, but it is typically less than one hour. A description of the SVS model is given in (2.10).

2.5.3 Predicted performance data

Simulation of system performance took place in order to assess the influence on performance of the main system data: collector area, storage volume and load.

The modelling work was performed using the performance equation obtained for an early version of the collector prototype (see appendix 2.2). As discussed in section 2.11, the performance of a new prototype recently tested is somewhat improved, and the performace of the system as a whole will then also be improved.

<u>Basis for the modelling work</u>

Collector: $\eta = 0.82 - 5.0(T_m - T_1)/E - 0.011(T_m - T_1)^2/E$

T_m = mean fluid temperature in collector (^oC)

T_1 = ambient air temperature (^oC)

E = incident energy (W/m^2)

tilt: $s = 20^o$ from horizontal

orientation: south

Storage tank: 250 l (reference value)

200 l

300 l

heat loss coefficient 0.95 W/^{o}C

Load: 200 l/day heated 10^{o}C to 50^{o}C (3400 kWh/year)

150 - - - - - (2550 kWh/year)

100 - - - - - (1700 kWh/year)

The predicted performance data are shown in fig. 2.9.

Influence of the storage tank volume is seen to be quite limited. For reasons explained in section 2.4.4, volumes smaller than 250 l are not considered. The modelling work shows, furthermore, that problems with overheating of the storage tank increases significantly with smaller storage volumes With a 200 l store, the model predicts storage temperatures higher than 100 ^{o}C 9 times/year, whereas the number with a 250 or 300 l storage tank is decreased to two respectively one time. These predictions are based on a situation with constant load, i.e. no holidays.

collector area m^2	storage volume l	Load 1/day	kWh/year	Gross load kWh	Solar to store kWh	Auxiliary kWh	Saved Energy kWh
5	250	200	3324	3674	1883	1653	2021
5	250	150	2491	2841	1599	1136	1705
5	300	150	2491	2841	1614	1128	1713
5	200	150	2491	2841	1581	1145	1696
4	250	200	3326	3676	1740	1782	1894
4	250	150	2493	2843	1489	1230	1613
3	250	150	2496	2846	1335	1365	1481

Fig. 2.9 Predicted performance data

The storage tank serves both as solar storage tank and auxiliary tank. This means that energy is added to the store both from the solar collector and from the auxiliary boiler. Whereas solar input to the store is straightforward to define, it is difficult to define useful solar output. In this case it was decided to solve the problem by considering a reference situation, i.e. the case where there is no solar water heater.

A typical domestic hot water tank on the Danish market has a heat loss coefficient of typically 2 - 3 W/^{o}C. Based on 2.5 W/^{o}C, the annual heat loss from the tank is approximately 700 kWh. Since the hot water tank will be situated within the insulation envelope of the house, the heat losses can be regarded as useful during the heating season. It is assumed that 50% or 350 kWh is not useful. The gross DHW load can now be defined as:

Gross load = net load + 350 kWh (1)

The energy savings due to the solar heating system can now be defined as:

S = Gross load - auxiliary input to the storage tank. (2)

It is noted that all heat losses from the combined solar/auxiliary storage tank can be regarded as non-useful. This is done since the main part of the store is situated in the roof space outside the heated envelope of the house, see fig. 2.8.

The solar system performance used in section 2.6.4, "Cost effectiveness", is defined as solar savings S according to equation (2) above.

2.6 SYSTEM COSTS AND COST EFFECTIVENESS

In this section both the overall and the more detailed costs will be discussed. The solar heating system has been costed on the basis of the case study house as described in section 2.2.

2.6.1 Introduction

The system costs have been analysed by the contractor, Dansk Solvarme. The company produces the solar heating system and undertakes the installation job as well. Experiences from other jobs indicate that the lowest total price is achieved if the installation job is undertaken either by the solar manufacturer or by a contractor who works closely with him.

System costs are shown for a 5 m^2 system in two cases. In section 2.6.2 the costs of a one-off system are presented, and in section 2.6.3 the costs of having 100 identical systems installed on one site are presented. Finally, it is indicated to what level the costs might be reduced if the manufacturer could utilize the full production capacity of the present facilities.

In section 2.6.4 the cost-effectiveness of the system is discussed. As a basis for this, a cost function for variations in system size is set up. The system size giving best performance per invested ECU is identified. Finally, the economical situation for the private consumer is discussed, using the actual fuel prices and the economical incentives presently available in Denmark.

The cost figures are given in dcrs. followed by the equivalent figures in ECU, where 1 ECU = dcrs 8.04. The price base date is January 1983. All prices are exclusive of VAT (22%).

2.6.2 Cost of the Solar Heating System

The detailed costs of components, etc. can be seen in section 2.6.3, where the cost breakdown for 100 systems is shown. In this section the cost predictions have been revised to indicate what the costs for at one-off system would be. The basis is still a newly built house. As in section 2.6.3, the system is a 5 m^2 system with a storage volume of 250 1.

	dcrs	ECU
A. Solar collector, 5.0 m^2	5.975	743
B. Storage tank, 250 1	5.060	630
C. Other components	2.565	320
D. Materials for installation of primary circuit	1.055	131
E. Transportation	460	57
F. Installation costs	4.345	540
G. Control of system function, etc.	900	112
H. Insulated cabinet to cover components	1.000	124
Total costs	21.360	2.657
Saved DHW tank, installed	4.300	535
Net overcosts for solar system	17.060	2.122

2.6.3 Cost of 100 identical systems

The cost of several identical systems being built on the same building site were originally based on 50 identical systems. The manufacturer has reviewed the costs, and no further reductions in costs can be identified by going from 50 systems to 100 systems at one site. This is because of the fact that 50 identical systems on one site are enough to overcome the extra costs of a one-off system. Furthermore 50 systems are enough to allow the contractor some on-site flexibility.

		dcrs	ECU
A.	Solar collector 1 element type KP 10, 5.0 m^2 aperture area		
	- Selective absorber, 5.0 m^2	3,600*	448
	- Casing, flashing inclusive	1,672	208
		5,272	656

*The investment for the same absorber with black coating (paint) would be 3050 dcrs.

		dcrs	ECU
B.	Storage tank 250 l steel tank, non-insulated coated with rilsan, with two heat exchanger 13/15 mm Cu, each 12.5 m	4,600	572
C.	Other components		
	- closed expansion tank (prim. circuit)	471	59.0
	- air vent	36	4.5
	- 2 closing valves, 3/4 "	42	5.2
	- dirt trap, 3/4 "	58	7.2
	- non-return valve, 3/4 "	44	5.5
	- pump, Grundfos UPS 15/35	512	64.0
	- differential thermostat, JN 105	951	118.0
	- 2 bottom cocks	39	4.9
	- 2 sensor pockets	55	6.8
	- mixing valve, Caleffi 520	230	29.0
		2,438	304
D.	Materials for installation of primary circuit: 10 m steel pipe 0.5 inch with fittings and insulation, storage insulation and 12.5 l glycol	960	119
E.	Transportation (approx. value)	400	50
F.	Installation costs		
	- Solar collector	1,800	224
	- Storage tank	280	35
	- Piping and insulation	960	119
	- Electrical connections	440	55
		3,480	433

G. Control etc. Filling up primary circuit with glycol, control of functions after 30 days and one year	600	75
H. Insulated cabinet to cover components in scullary (installed)	600	75
Total costs (prices A-H incl.):	18,350	2,284
Saved DHW tank, installed	4,300	535
Net overcosts for solar systems	14,050	1,749

Further cost reduction

The basis for the costs given above is the present annual production of the manufacturer, which is far below his full production capacity. Given full production, it is estimated that the costs of collector and storage tank can be reduced by 30%. The costs for other components (fittings, etc.) may be reduced by a factor of 15% because the necessary components may now be bought in larger batches. The on-site costs, items E-H incl., are not changed since the installation job is unchanged.

The total costs for 100 systems built on one site given full utilization of production capacity at the manufacturer is now:

Total cost (dcrs): = 14,050 - 0,3 (5272 + 4600) - 0.15 (2438)
= 10,720 dcrs.
= 1,330 ECU

This corresponds to a total cost reduction of 24%.

It should be emphasised that the above figures are based on the system construction and layout as described in this report. Further reductions in cost may result from future developments of solar heating systems.

2.6.4 Cost Effectiveness

In section 2.5.3 the system performance for variations in system size is shown. In order to identify the optimal system design (maximum output per invested ECU), a price function for variations in collector size must be established.

Price function

The major costs are connected to the collector and the storage tank. In both cases the price function is far from linear for changes in the system size. The price function shows major jumps at the point where the collector system changes from one unit to two.

Collector

Variations in the collector size may be achieved, primarily by varying the unit up to its maximum size.

If collector areas larger than this are requested, two units should be installed.

As described in section 2.2.2 the collector is built as a partly prefabricated unit. The maximum size of one unit is 5 m^2 ($1 \cdot 5$ m^2).

The limits defining the maximum area in one unit are:

Width: The present machinery for absorber production does not allow for a larger width than 1.0 m.

Length: The total length of the roof is approximately 5.3 m. The limit given by the absorber machinery is about 5.0 m. Transportation of units of a length of much more than 5 m is not easy with the type of small trucks normally used by the working team of a contractor. In practice the maximum length is 5.0 m.

The costs for one unit of $5.0 \cdot 1.0$ m^2 aperture area are 7072 dcrs., installation included.

If an area less than 5 m^2 is requested, the investment corresponding to the absorber price (720 dcrs/m^2) will be lowered almost proportionally to the decrease in area. The reduction of the other costs is on the other hand far from proportional since much of the rest of the collector price is composed of working expenses either in the factory or on the building site.

On the basis of the investment of the 5 m^2 unit it is reasonable to define the decrease in costs for smaller units to be 700 dcrs/m^2. The price function for the collector itself (up to 5 m^2) is then:

$$P = 3572 + 700 \cdot A \text{ (dcrs)}$$

where A is the collector area in m^2.

Storage Tank

Given the diameter of the end plates to be fixed at 500 mm, the influence of variations of the storage volume on the price is very small.

The basic price of a 250 l tank (height 1600 mm, diameter 500 mm) is dcrs. 4880, installation inclusive. This price is with the two heat exchangers installed as well.

The influence of changing the storage volume given for the same diameter has for small DHW tanks (200 - 300 l) been found to be about 150 dcrs/50 l. The price function for the storage tank can then be established as:

$$P = 4130 + V \cdot 3 \text{ (dcrs)}$$

The storage volume V is in litres.

The relative storage volume is 50 l/m^2, postheating section included. The price function can then be expressed as a function of collector area as:

$$P = 4130 + 150 \cdot A$$

The costs of the rest of the components and installation jobs are not influenced by small variations in system size (3 - 10 m^2).

The total costs for a 5 m^2 system is (in section 2.6.3) shown to be 14,050 dcrs. The variable costs can be obtained by adding the price function for collector and storage tank, i.e.

The total costs for a 5 m^2 system is (in section 2.6.3) shown to be 14,050 dcrs. The variable costs can be obtained by adding the price function for collector and storage tank, i.e.

$$
\begin{aligned}
P &= 3572 + 700 \cdot A \\
&\quad + 4130 + 150 \cdot A \\
P &= 7702 + 850 \cdot A
\end{aligned}
$$

The fixed investment not included here amounts to 6398 dcrs. If the investment of the DHW tank (saved) is included, dcrs 4300, the price function for the net overcosts can be established as:

$$P_{tot} = 7702 + 6398 - 4300 + 830 \cdot A$$

$$P_{tot} = 9800 + 850 \cdot A$$

This price function is valid for collector areas up to 5 m^2 (one unit of collector). If the system size exceeds 5 m^2, this will mean two elements. If the price function of the second collector element were the same as the first, it would be:

$$P_{s,2} = 3572 + 700 \cdot A \text{ (dcrs., A in m}^2\text{)}$$

If two elements each of 5 m^2 were installed, the total investment would be very close to the price of the total 5 m^2 system plus $P_{s,2}$, i.e.

$$
\begin{aligned}
P(10\ m^2) &= P_{tot}\ (5\ m^2) + P_{s,2} \\
&= (9800 + 850 \cdot 5) + 3572 + 700 \times 5) \\
&= 21{,}122
\end{aligned}
$$

It is assumed, however, that going from one element to two elements will result in a slightly larger coefficient to be multiplied by A, i.e. 700 should be increased a little. A coefficient of 1000 dcrs. is chosen, which means that the price function going from a 5 m^2 double collector system to a 10 m^2 double collector system will be:

$$
\begin{aligned}
P_{tot}\ (2 \text{ elements}) &= (9800 + 850 \cdot 5) + (2072 + 1000 \cdot A) \\
&= 16{,}470 + 1{,}000 \cdot A
\end{aligned}
$$

This equation is valid for a system using a collector of between 5 and 10 m^2. The collector area A of the second unit is accordingly varied between 0 and 5 m^2. If the variable A varies between 5 and 10 m^2, the equation is:

$$P_{tot}\ (2 \text{ elements}) = 11{,}470 + 1{,}000 \cdot A$$

The two price functions are plotted into the optimisation diagram together with the performance functions derived in section 2.5.3.

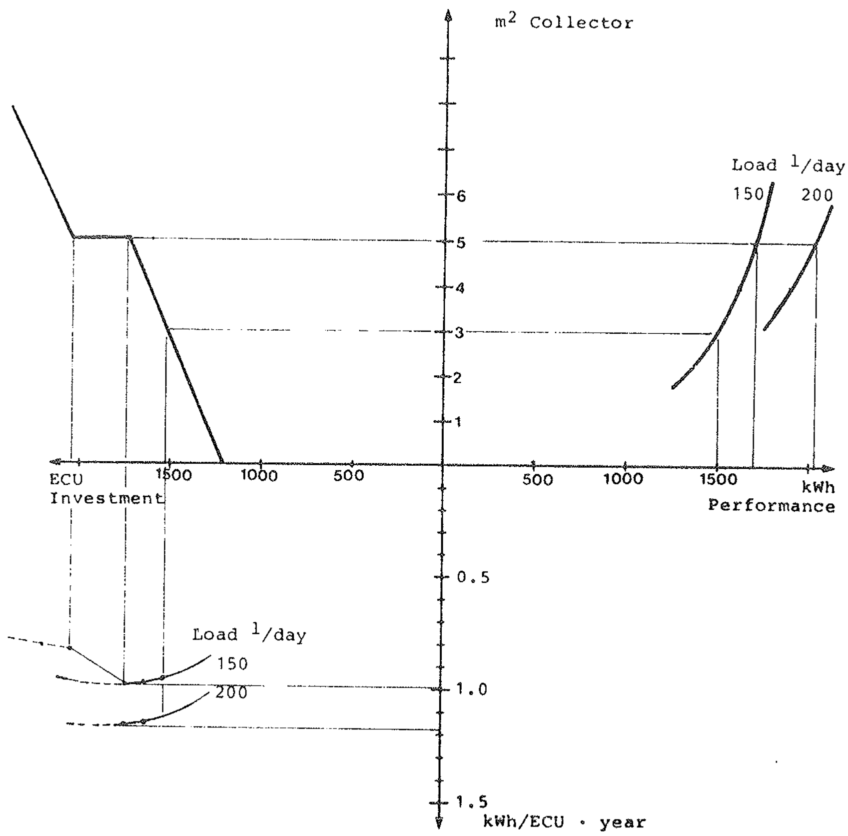


Fig. 2.10 Optimisation of DHW system.

It is seen that irrespective of the DHW load, the optimal system size is the maximum system size that can be achieved with one collector unit, 5 m^2. It can be seen that an even larger system size might be attractive, provided that it could still be supplied with a one-unit collector.

It should finally be mentioned that further system development might change the bias towards smaller system sizes being optimal. This is because further development is expected to bring down the fixed costs to a larger extent than the variable costs.

Costs versus savings for the consumer

Finally, the economic consequences for the private consumer will be discussed. The economic situation for a consumer buying a new house with a solar system has been assessed based on the present situation (spring 83) in Denmark, regarding tax rates, rates of interest, fuel prices and available incentives for installing a solar system.

The extra costs for the optimal 5 m^2 system has been shown to be 14,050 dcrs VAT exclusive. This price will be reduced in Denmark due to a 30% subsidy, which is given to people installing solar system. When 22% VAT and incentives are taken into account, the costs can be established as:

	costs inclusive VAT
Total cost for a 5 m^2 system 18,350 · 1,22 =	22,400 dcrs
Saved DHW tank installation 4,300 · 1.22 =	- 5,200 dcrs
Subsidy: 30% of total costs 22,400 =	- 6,720 dcrs
Net overall cost for private consumer =	10,480 dcrs

The extra annual costs for financing a net overall cost of 10,480 dcrs is 1,570 dcrs per annum based on a 14% loan over 30 years. When tax deduction of interest is taken into account, the net costs can be calculated to be 690 dcrs per annum for the first year of operation, based on a marginal rate of taxation of 60%.

With the present fuel prices of gas or oil corresponding to 3.4 dcrs/l oil, the cost of one kWh produced by the proposed high-efficiency boiler is approximately 0.40 dcrs/kWh. The annual savings of 1705 kWh then correspond to 680 dcrs. If backup heating was provided with electricity, the annual savings would rise to 1240 dcrs, based on the present electricity price of 0.73 dcrs/kWh.

If the boiler was not a high-efficiency one, the value of saved energy would increase. The high-efficiency boiler has almost no idle losses, whereas a typical boiler on the Danish market has an idle loss of 300 W or 1300 kWh during six summer months.

Out of this idle loss 350 kWh have already been accounted for in the calculation of gross DHW load (see section 2.5). A tradional boiler would therefore mean an increased annual saving due to the solar heating system of (1300 - 350) kWh = 950 kWh. The total annual savings due to the solar heating system would then rise from 1705 kWh to (1705 + 950) kWh = 2655 kWh. The value of this is then 2655 · 0.40 dcrs = 1060 dcrs.

2.7 OPTIMISATION METHOD AND SYSTEM SIZING

Generally, this present system design should be seen as a further development based on previous experiences with solar water heating systems, (2.2) and (2.7). Based on given constraints, the system has been designed and sized towards an "optimum design".

2.7.1 Introduction

In this case, optimum efficiency is defined as maximum output per invested ECU, i.e. kWh/annum • ECU should be as high as possible. Furthermore, the given constraints have some impact on the optimisation concepts. A given design cannot immediately be accepted as optimal if it is based on processes of manufacturing that are not yet developed. Similarly, the traditional way of installing hot water systems has some impact on system design. DHW systems in Denmark are, for instance, always pressurized systems, where possibilities for non-pressurized systems could lead to simpler and cheaper designs.

2.7.2 Optimisation method

The optimisation method is, as previously mentioned, based on the concept "maximum output per invested ECU", see (2.8). Such an optimum efficiency criterion is useful when discussing the situation for the private consumer. He will normally focus on the payback period or on the balance between extra expenses and savings during the first years after he has made an investment in an energy saving measure. If the situation in the immediate future is that extra expenses on loans, etc. are significantly higher than the value of fuel saved, he will be reluctant to make the investment. This may still be the case even if some present value calculations over a given period based on certain predictions re. inflation, fuel prices, etc. predict a positive balance in favour of the investment.

It should be noted that the optimisation criteria adopted would tend to be rather conservative. One could state that if the value of saved fuel can pay for the extra expenses the first year, this can surely be expected to be the case in the future, given that the fuel prices do not fall as measured in inflated ECUs.

2.7.3 System sizing

The system sizing has been done by using some rules of thumb for sizing components that are not critical to system cost-effectiveness. This applies, for instance, to insulation thickness of piping and storage tank, flow in solar circuit, size of heat exchanger, etc. If some minimum criteria are respected, the system performance will not be affected, and the costs in question are in any case not very high.

The main parameters of the system are collector size, storage size and DHW load. Those parameters exert large influence over cost and performance or both. They are therefore examined in more depth. This is done by using a simulation model to model the performance for a given system layout. Similarly the costs of both the collector and the storage tank are investigated in order to work out minimum costs.

2.8 HOUSE: INITIAL DESIGN AND REVISIONS

2.8.1 Introduction

The case study house was selected from among the new houses currently on offer in Denmark. The actual house used was chosen for its suitability to the installation of a solar water heater. The house was only modified when necessary to accomodate the solar heating system.

The case study house, both the original 1st design house and the final design house are standard houses from Roslev Houses, Skive, Denmark. The houses are of a light construction, and they are prefabricated in sections.

2.8.2 Initial design and revisions

The initial case study house used as a basis for the design study was the same house as being used in the case study for a combined system for space heating and domestic hot water (2.9).

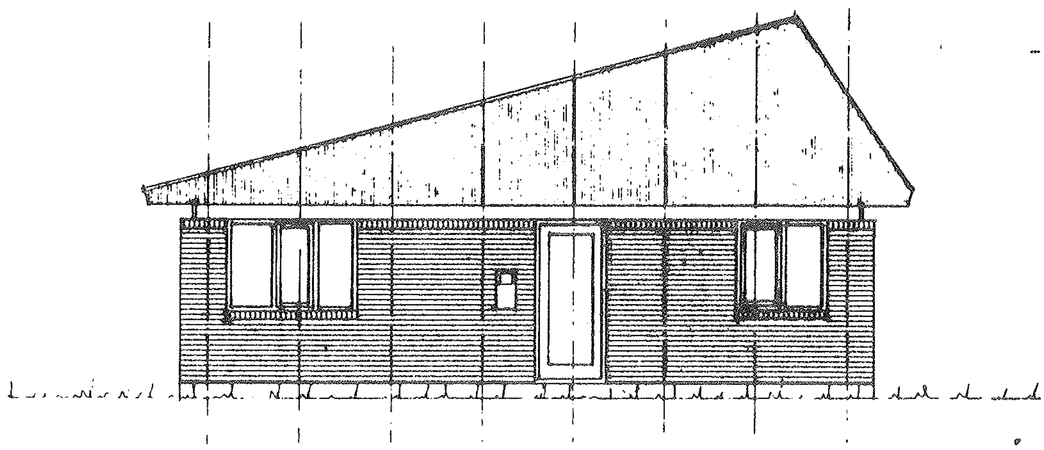


Fig. 2.11 Case study house, 1st design

This standard house has a roof tilt towards the south of 56^{o}, since the roof is meant for integrating a collector for a combined solar system.

The total living area of this single-storey house is 116 m^2.

2.8.3 Problems and Revisions

The case study house was changed to the final choice being described in section 2.2 because of two main reasons:

1. When scrutinizing the collector design it became evident that for a solar water heating system, the collector should preferably be in one unit. This is mainly in order to reduce production costs and installation costs. The south facing roof area of the house is 2.3 m · 13 m.

It was found that a one-unit collector could not be adapted to this area in an acceptable way. It was therefore decided to return to a more traditional roof construction with a 20 - 30 ^{o} roof pitch towards both south and north. With a typical house width of 9 m, it is possible to integrate a 1 · 5 m^2 collector in the roof.

2. The final case study house was smaller than that originally selected with a gross floor area of 90 m^2 rather than the initial 116 m^2. Houses with the former surface floor area are more typical of the present-day trend here in Denmark towards smaller single-family dwellings (see section 2.2.1 and appendix 2.1).

   It was felt that a house with a higher than average floor area in the low-medium cost housing range would be better adapted to the combined system in view of the greater space heating load. Consequently it seemed more appropriate for us to choose a smaller house that only required the DHW system.

2.9 SYSTEM: INITIAL DESIGN AND REVISIONS

2.9.1 Introduction

This section is devoted to a discussion of the background for the final system design and an account of the intermidiate design developed before the final design was reached.

Basically, the design is based on the BV 300 system concept, as described in references (2.2) and (2.7). The objective here was to develop a solar water heater for a single family dwelling with a performance exceeding 300 kWh/m^2 collector of a system covering approximately 2/3 of the annual DHW load. Monitoring of the system performance in a test rig and in a private house has shown that the objectives were met. The system was tested in a private house in the period January 1982 to December 1982, and the data are reported as part of the PMG data collection exercise 1982-1983 (project name: Holte).

The system layout for the BV 300 system is shown in fig. 2.12

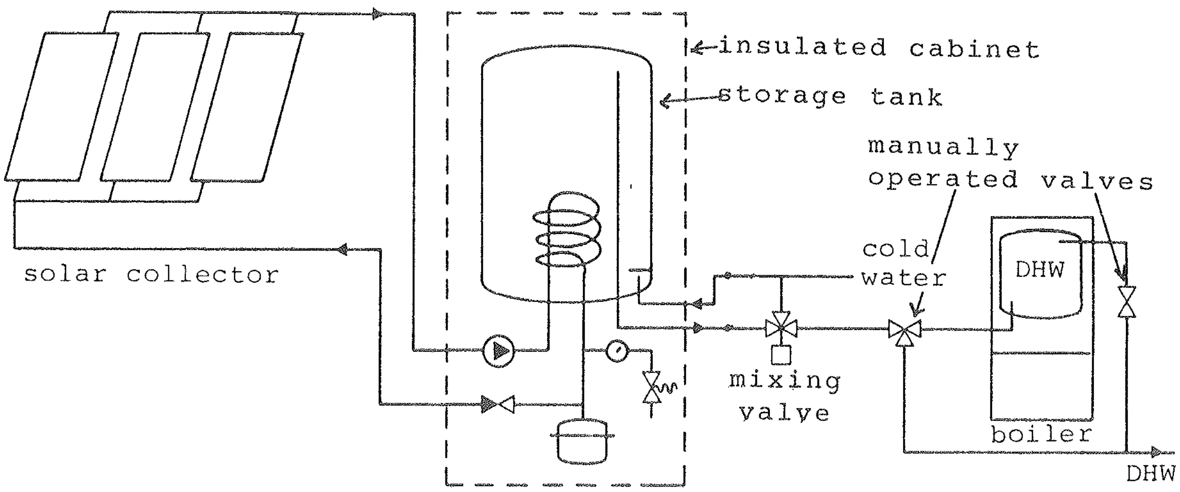


Fig. 2.12 System layout BV 300 system in Holte.

The system consists of 3 collectors with single glazing and selective absorber. The storage tank is pressurized with the solar heat exchanger situated in the lower part of the store. The primary circuit is a traditional pressurized system filled with a propylene glycol-water mixture.

Postheating of domestic hot water is achieved via the DHW tank, which is a standard feature of the traditional oil-fired boiler units. During the summer-time with ample sunshine, the boiler is manually cut off. By operating the three way valve shown, the hot water from the store is led directly to the taps. Very hot water from the store is not allowed to reach the taps, and a thermostatic mixing valve is therefore installed.

A main feature of the system is the well-insulated storage tank, which is shown in fig. 2.13.

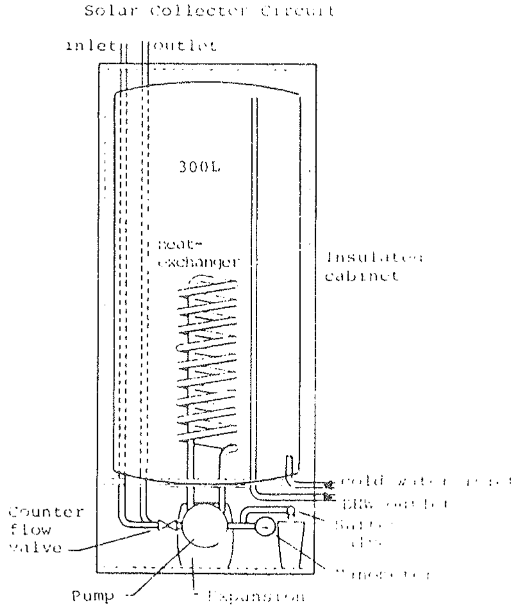


Fig. 2.13 Section through BV 300 store.

The storage tank is situated in an insulated cabinet, and all piping connections are situated in the bottom of the tank. In this way the effect of the piping connections as thermal bridges are almost eliminated, since the bottom of the tank in most cases will be filled with relatively cold water. Furthermore, all the components such as pumps, valves, etc. are situated inside the insulated cabinet beneath the store. The heat loss from these components is therefore decreased to a minimum (2.1).

The combination of an efficient collector and the well-insulated storage tank made it possible to reach the performance objective, i.e. 300 kWh/m^2. It is felt, however, that the design of the system could be improved on still more so that the interference from the user would not be necessary in order to cut off the auxiliary heating during the summertime and thereby save the standby losses from the boiler. Since the present case study is based on new-built houses, it is, more-over, desirable that the storage tank is combined with the DHW auxiliary heating device in one unit.

2.9.2 Initial Design and Revisions

The first design layout is shown in fig. 2.14. Postheating of domestic hot water is now achieved in a tank mounted on top of the solar storage tank, and the backup heating boiler is without DHW tank.

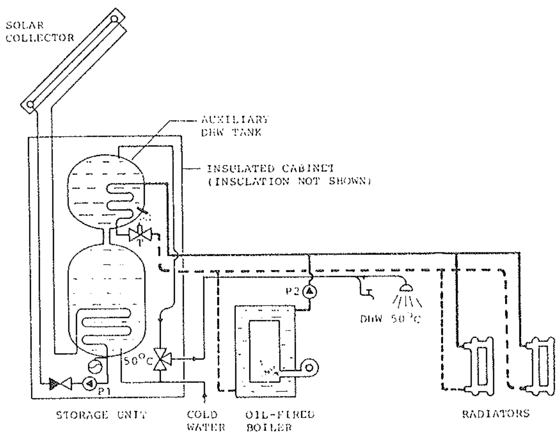


Fig. 2.14 System diagram, 1st design.

The boiler should have a fixed working temperature of at least 55°C in order to postheat DHW to 50°C. If the solar storage tank exceeds 50°C, the postheating tank will be heated by solar energy via convection through the thermal diode between the two tanks. The thermostatic valve T will then close the connection to the boiler circuit. It can be argued that valve T is not necessary. If the upper tank was heated to more than 50°C, energy would be transferred from the store to the heating system. Solar energy would then cover some heating load and/or it would cover some of the standby losses from the boiler. In both cases the heat extracted from the store can be regarded as useful.

During the summertime with ample sunshine and no space heating load, the oil-fired boiler and pump P2 are manually cut off.

The rest of the system is basically the same as the design shown in section 2.9.1, i.e. the primary circuit is pressurized and filled with glycol/water, and the storage tank is mounted in an insulated unit with pipe connections penetrating from the bottom and with pumps, valves, etc. mounted within the insulating jacket.

2.9.3 Problems and Revisions

As compared to the previous system layout, the operation of the system has been improved since few manual operations are required. The user only has to cut off the oil-fired boiler during the summer to save boiler standby losses. Furthermore, it would be desirable that a boiler temperature of 55°C should only be requested when there is a demand for DHW postheating. In a new house with a well-designed space heating system, the space heating load can often be covered with boiler temperatures between 30°C and 50°C Finally, it can be questioned whether the double-tank solution is desirable from a maintenance point of view. In any case allowances would have to be made for the possibility of cleaning the tanks and the heat exchangers of lime deposits. Domestic water in Denmark is generally quite hard. This is the reason why instant heating coils in boilers are not very commonly used, since they will need regular service (every 1-5 years) to remove the lime deposits.

The final design is presented in detail in section 2.3. In order to fulfil the description of the logical design development, the final design is also shown in fig. 2.15, and a short summary of the main features is here given:

Integrated design:	The domestic hot water system consists of only one tank which serves both as solar storage tank and as DHW postheating tank. All thermal bridges are situated in the bottom of the tank, and all components, such as pumps and valves, are gathered in an insulated cabinet in order to reduce heat loss, at the same time giving good accessibility.
Low boiler temp., no idle losses	The gasfired boiler covers space heating and DHW postheating. The boiler temperature is always as low as possible, i.e. for postheating of DHW 60°C and for space heating 25 - 55 °C, depending on ambient temperature. The boiler is always on standby for postheating of DHW or for space heating, but it is only hot if there is an actual load.

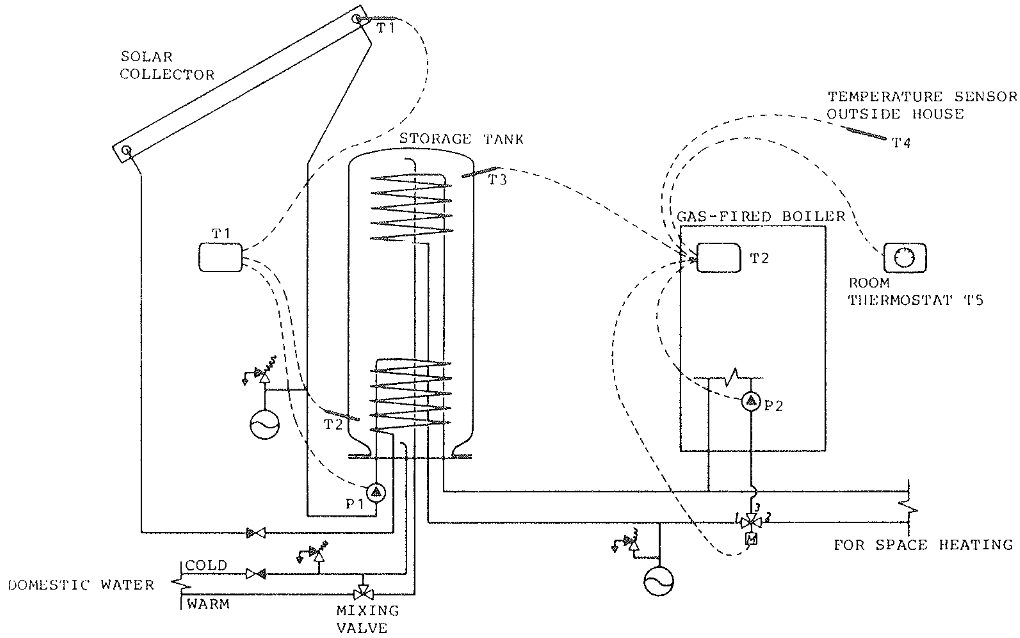


Fig. 2.15 System diagram, final design.

No manual functions	The user is not requested to interfere with the system operation in order to secure good performance.

The actual boiler has a DHW preference function, meaning that it will work exclusively on DHW when needed. If not, it will work exclusively on space heating.

2.10 COMPONENTS: INITIAL SELECTION AND REVISONS

In this section the selection of the main components will be discussed: The other components, such as valves, pumps, etc., were not a major issue and were not changed during the optimisation process.

2.10.1 Introduction

The collector elements presently available on the market all have an area of 1.5 - 2 m^2, see, for instance, appendix 2.2. A typical heat storage unit is shown in figure 2.12. The auxiliary system will typically be an oil or gas-fired boiler in a boiler unit which also includes a DHW tank, a pump, valves, etc.

2.10.2 Initial design

The first design was based on the following main components:

Collector: 2 · 1 m^2 units, single glazed with a selective absorber.

Store: A unit as shown in fig. 2.13, but with a DHW postheating tank on top of the solar store, see fig. 2.14.

Auxiliary: Oil-fired boiler.

2.10.3 Problems and revisions

The collector was changed for the reasons outlined in section 2.8.3, resulting in a collector unit of 1 · 5 m^2. The constraint limiting the size of the collector units is normally weight, and in this case the problem was solved by installing the glazing on the 1 · 5 m^2 unit on-site. This is not thought to be the final solution, but until a light collector cover with optical and durability qualities equivalent to glass has been found, it is accepted that the collector is finally assembled on-site.

The collector unit of 1 · 5 m^2 developed is shown to be quite useful, since it matches the height of a roof plane for houses with an occupied top storey. In fig. 2.16 the possibilities for integrating one, two or three 5 m^2 collector units in the roof of a typical Danish terrace house building is shown.

The basis for change in storage design from a two tank to a one-tank solution is discussed in section 2.9. Furthermore, it should be noted that where the storage tank in the original design takes up 1/3 m^2 of the floor space, the store does not take up any floor space in the final design, since it is integrated in the loft construction, see section 2.2.4.

In the case of a 1 1/2 storey terraced house as hown in fig. 2.16, the store could probably not be integrated in the loft space. In this case there are good opportunities to install the store under the staircase.

The auxiliary boiler was changed primarily due to the wish for a better control strategy and better fuel economy as discussed in section 2.9. Furthermore, the boiler was changed from a free standing unit on the floor to a very light unit meant for mounting on the wall in order to save floor space. The actual control strategy chosen means frequent heating and cooling between operating temperature and room temperature. A few of the

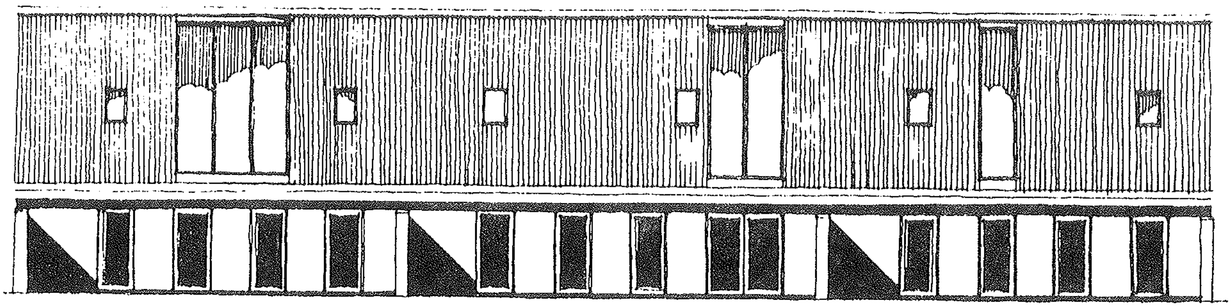


Fig. 2.16 1 1/2 storey terraced houses with 5, 10 and 15 m^2 collector.

the available boilers on the market can withstand those conditions. The boiler finally chosen was one which condensates the water vapour in the flue gases, which further heightens fuel economy.

2.11 PERFORMANCE: A COMPARISON OF ORIGINAL AND FINAL PERFORMANCE

2.11.1 Introduction

The main variables in a performance analysis are collector area and load. The influence of these parameters are seen in the optimisation diagram, fig. 2.10. Secondary variables, that still have some influence on performance, are: collector type, collector tilt and storage size. These parameters are influenced by the external constraints, especially the roof construction, which has an influence on collector tilt and the maximum storage height possible.

2.11.2 Comparison of initial and final design performance

The reference system is the system which was finally chosen to be optimal, i.e. the system on which cost considereations are based, see section 2.6. The reference system is characterized by the following figures:

Collector: $\eta = 0.82 - 5.0 \cdot (T_m - T_1)/E$

$$- 0.011 \cdot (T_m - T_1)^2/E$$

tilt = 20^o

area = 5.0 m^2

storage tank: volume 250 l

heat loss coefficient = 0.95 $W/^oC$

load: 150 l/day heated from 10^oC to 50^oC

The performance of the reference system is 1705 kWh/year ("saved energy", see definition in section 2.5).

1. If the collector tilt could be chosen to be optimal, it should be 45 - 60^o from horizontal. The performance for a 45^o tilt is improved by 9%.

2. If the collector performance was changed to the improved performance as measured on the 83 prototype (2 m^2 unit), see appendix 2.3, i.e.

   $$= 0.93 - 5.9\ (T_m - T_1)/E - 0.000\ (T_m - T_1)^2/E$$

   the performance would be 4% better than the reference performance.

3. If the tilt was 45^o and the collector was the improved 83 collector, the performance would be 1930 kWh/year, representing an improvement of 13%. This performance could be applicable for system integrated in a terraced house as shown in figure 2.16 of section 2.10.

2.12 COST EFFECTIVENESS: A COMPARISON OF ORIGINAL AND FINAL DESIGNS

One main factor has significant influence on the outcome of the performance/costs optimisation exercise. This factor is the maximum possible unit size of a collector element.

2.12.1 Introduction

The standard collectors have a unit size of 1.5 - 2.0 m^2. This means that a solar water heating system will normally have 3 units or 4.5 - 6 m^2 of collector. The collector element has, in this exercise, been developed so that a maximum of 5.0 m^2 is possible in one element.

2.12.2 Comparison of initial and final cost-effectiveness

In fig. 2.17 the optimisation curves for the initial design and the final design is shown. The performance is the same. The main difference is due to the difference in price function. The 1st design presupposes a linear price function, whereas the price function of the final design shows a break when going from one unit of maximum 5 m^2 to two units.

It is seen that the optimum system size of the 1st design is approximately 5 m^2, but this is not essential. In practice, the actual collector area will be defined by the number of collector elements giving an area of 4-5 m^2.

It should finally be noted that, as shown in section 2.6.4, variations in DHW consumption between of 100 and 200 l/day does not influence the optimum system size significantly.

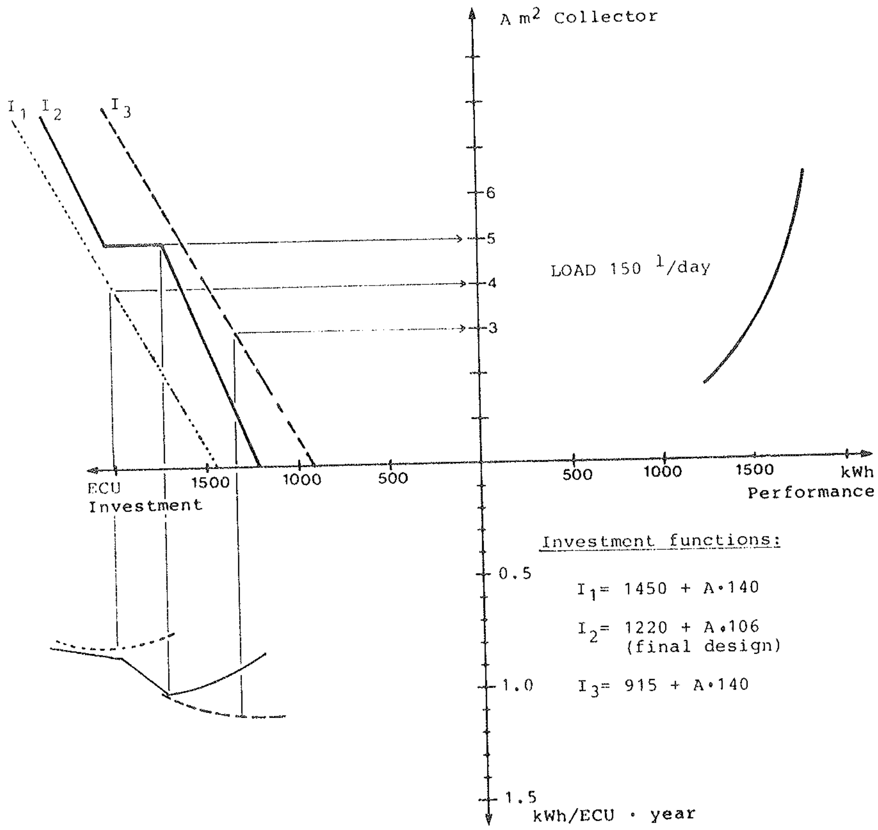


Fig. 2.17 System optimisation diagram, initial and final design.

2.13 CONCLUSIONS

The present solar water heating design was developed towards maximum output per invested ECU. The work was done under given contraints, such as actual climate, local regulations re. HVAC-systems, etc. The design can be regarded as a further development of earlier designs (2.2).

2.13.1 Principle lessons from the design exercise.

The conclusions are:

1. Major advantages re. system design and system cost-effectiveness are achieved by integrating the solar storage tank and the DHW postheating tank.

2. The auxiliary boiler chosen can be standby for postheating of DHW without having idle losses. This is of special importance in new, well-insulated dwellings where the part of the year with no space heating load is rather long (April/May to October/November).

3. Optimal system size depends heavily on the maximum size possible of one collector module.

4. Optimal system size, 5 m^2, has a specific performance of 0.97 kWh per invested ECU. Under present Danish economic conditions, the annual saving of 85 ECU compares with the extra annual costs for financing the system, 86 ECU per annum, taking installation incentives and tax deduction of interests into account. If backup heating were not gas, but electricity, the annual savings would rise to 154 ECU given the present fuel prices.

2.13.2 Future technical improvements

The present design concept still leaves scope for future improvements:

1. The collector unit should be developed towards lower weight, in such a way that it can be fully prefabricated and arrive at the site in one unit.

2. The storage tank could be made of stainless stell or synthetic materials. Primarily a reduction in weight is the objective but incidental cost reduction and improved performance could also thus be arrived at.

3. The primary circuit might be of a drain-down type (still with a heat exchanger). This may lower the investment in components, moreover, purchase and maintenance of glycol can be eliminated.

2.13.3 Future cost reductions and cost-effectiveness

The possible price reduction resulting from future technical improvements is very difficult to predict. One could perhaps expect a reduction of 25-50%.

Another possible price reduction applies to the number of units produced. If the actual manufacturer could utilize his full production capacity, the total price of the actual design could be lowered from 1750 ECU to 1330 ECU, thus improving the specific performance from 0.97 kWh/ECU to 1.28 kWh/ECU. (see section 2.6.3).

Installation of evacuated tubular collectors may improve the performance, but a possible improvement in cost-effectiveness is difficult to predict because of the uncertainty of future cost reductions for those collector types.

Finally, the new washing machines and dishwashers connected to hot water will increase the DHW load and thus improve the cost-effectiveness.

2.13.4 Other

Totally different design concepts will also be developed further. Those in question are especially:

- Solar thermosyphon systems

- Hybrid collector/storage systems

The thermosyphon systems offer some cost reduction possibilities. On the other hand, they impose restriction with regard to installation since the store should be sited above the collector.

Future development work will possibly also bring solar water heating systems where the collector and the store is an integrated unit.

Whether simpler systems than the present form design concept can be developed towards better cost-effectiveness is hard to predict. It is felt, however, that there will always be a market for solar water heaters of the present design concept, i.e. a pumped system with a pressurized DHW store, because of the installation and integration flexibility it offers.

REFERENCES

2.1 Test methods for small heat storages and experiences gained ("Prøvningsmetoder for mindre varmelagre og erfaringer fra prøvningerne")
In Danish
Simon Furbo, Jan-Erik Larsen
TIL November 1982

2.2 Solar Systems for Domestic Hot Water
Klaus Ellehauge
TIL November 1982

2.3 Solar Houses in Europe - How They Have Worked
Commission of the European Communities, 1981

2.4 Heat Exchanger coils ("Varmevekslerspiraler")
In Danish
Draft report by Søren Østergaard, part of current R&D work at TIL.

2.5 Test of heat storage units (DHW) for solar systems ("Prøvning af varmelagerunits til solvarmeanlæg")
In Danish
Simon Furbo
TIL April 1980

2.4 Thermal performance test done under the Danish Solar Energy R&D programme (in Danish)
S. Svendsen
Report no. 81-19
TIL June 1981

2.7 Solar Water Heating
Analysis of design and performance data from 28 systems.
Commission of the European Communities
December 1981

2.8 Performance Monitoring of Solar Heating Systems in Dwellings - Executive Summary and Recommendations.
Commission of the European Communities
December 1981

2.9 Solar System Case Study
Final design DHW + SP
Northern European Design Group
Commission of the European Communities
1983

2.10 Solar Energy Applications for Dwellings
Modelling and Simulation Part
Description of Simulation codes and Monthly tables
CEC, June 1979

APPENDIX 2.1

The Danish Dwelling stock

At present (beginning of 1983) it is difficult to predict how the market for new dwellings is going to develop in the near future.

The number of houses being built has dropped significantly since 1980, and most of the new housing reflects the constraints of the economic situation and is largely constructed with the aid of public subisdies.

New housing before 1980

The economic crisis which followed the "oil crisis" in 1973 did not really influence Danish housing before the end of the seventies. The dwellings being built in the seventies were to a large extent similar to those being built in the sixties. Most of them were detached single-family houses being built both by individuals and by standard-housing contractors. The gross floor area increased from 100 m^2 to approximately 150 m^2 throughout the sixties and until 1973/74. After that date a decrease in size to between 120 - 140 m^2 is noted.

The total stock of dwellings as of January 1st 1981 was:

	units	%
a. detached single-family houses	1,058,000	49
b. non-detached or semi-detached houses	164,000	8
c. dwellings in multi-family buildings	893,000	41
d. others	46,000	2
	2,161,000	100

The gross areas per dwelling were 130 m^2 for detached houses and 97 m^2 for non-detached or semi-detached houses.

Apartments have an average area of 74 m^2.

Housing in 1980 and 1981

As previously mentioned, the situation regarding new housing at the beginning of the eighties was greatly influenced by the economic set-back following the oil-crisis. However, this did not really affect the daily life of the Danes until the end of the seventies.

Throughout the sixties and at the beginning of the seventies around 40,000 dwellings per annum were being built, the major part of those being detached houses. In 1980 a total of 29,000 dwellings were completed. The figure for 1981 is only 21,000, and the figure for 1982 is expected to be even lower. The statistics for the two years are as follows:

	detached	non-detached or semi-detached	apartments
completed in 1980	15.207	7.297	6.783
approved* in 1980	9.036	7.461	5.457
completed in 1981	6.941	7.667	5.964
approved* in 1981	4.347	8.531	5.484

*i.e. Approved by the local municipality so that the dwelling may be built.

It can be seen from the chart that the number of non-detached single family dwellings is quite stable at 7-8000 per annum, whereas a dramatic decrease in the number of detatched houses being built is shown over the two years.

The gross floor area also fell significantly in the same period, going from 154 m^2 per single family house (detached and non-detached) in 1980 to 139 m^2 in 1981. Houses under construction at the end of 1981 had a gross floor area of 129 m^2 and houses approved in 1981, 124 m^2. These figures are representative of house size per single family home with regrettably no further breakdown into separate detached and non-detached categories.

The floor area for apartments is un-altered with an average of 80 m^2 per apt. over the two years.

Danish housing after 1983

Danish housing after 1983 will be influenced by at least two major factors. These are:

a. A growing optimism is felt as regards the prospects for economic stability. This will certainly affect the housing sector, especially since the rate of interest to be paid on loans for a new house has dropped from 22% at the end of 1982 to 15% in the spring 1983.

b. During the years of increasing pessimism as regards the economic prospects (1979-1982), many potential buyers of new houses hesitated because of the high rate of interest and the economic instability. Many of these people can be expected to realize their wish for a new house in the next couple of years.

The market for non-detached and semi-detached houses (and multi-family dwellings) is at present dominated by buildings receiving some kind of public financial support. This market may increase a little but the tendency is that the expected increase in new dwellings being built will primarily occur in the privately financed sector (as did the decrease at the end of the seventies).

House types and sizes

Almost all of the houses being built in the private sector are detached or semi-detached (terrace houses or cluster houses). The houses being built with public support vary from small detached houses to clustered houses and terraced houses. No one type seem to be more popular than the others.

Houses for rent

In 1983 a total of around 9000 dwellings, being publicly financed and for rent, will be built. These dwellings will primarily be built as multi-storey buildings, but some may also be characterised as low-density buildings.

Private houses with public support

The quota in 1983 for private co-operative associations receiving loans of low interest is 3,500 dwellings. This quota is expected to be fully exploited. An inquiry between contractors and architects working in this field shows that the house sizes vary between 60 and 130 m^2, typically between 70-110 m^2 with a medium around 90 m^2. The maximum area allowed is 95 m^2 (medium) with an absolute maximum of 130 m^2. The total expenses allowed vary from 5,600 dcrs/m^2 to 6,100 dcrs/m^2 all inclusive depending on location in Denmark. Actual expenses are normally very close to the limit allowed.

The inquiry did not give a very clear picture as to which types of houses one could expect in this sector (co-operative associations). However, it looks as though there are two main categories. The first category includes detached houses and cluster houses. The second category comprises terraced houses where two adjacent houses share an exterior wall. Both one-storey houses and 1 1/2 storey houses (one-storey houses with occupied roof) are very popular. The slope of the roof in the former is 13-25° and in the latter 40-55° from horizontal.

Private houses

Most of the houses being built in this sector are and will be detached. Both single-storey and 1 1/2 storey houses are very popular. The gross floor area can be expected to range from 80 m^2 to 130 m^2 (not including luxury houses). The average house is expected to have a gross floor area of 90-110 m^2.

The total cost for a house in this sector will be very close to the maximum cost allowed for a house receiving public support, i.e. 680 - 810 ECUS per m^2 gross area (22% VAT exclusive). The total investment for a 100 m^2 house will then be 75,000 ECUS with all expenses and site purchase included. The gross expenses per annum for such a loan will be around 11,200 ECUS (basis 14.5% interest rate). The net expenses when tax deduction of the interest is taken into account is around 5,000 ECUS per year.

APPENDIX 2.2

Datasheet for collector used in the case study.

DATASHEET ON SOLAR COLLECTOR EFFICIENCY	Date: 1982-07-30
Manufacturer: DANSK SOLVARME K/S, KABELVEJ 5, V. HASSING STRAND, 9310 VODSKOV	Type: KP IV R.S.
Test Laboratory: THERMAL INSULATION LABORATORY, TECHNICAL UNIVERSITY OF DENMARK	Solar collector id-no.: 144

Outside dim: 2,04 x 1,04 x 0,09 m

Weight: 76 kg

Transparent area: 1,93 m^2

Number and type of glazing: single, 4 mm glass

Absorber panel:

Type: channel plate

Material: stainless steel

Thickness: top/bottom: 0,9 mm/0,6 mm

Channelsystem: lengthwise with traversing connections

Headers: integrated in the absorber

Surface treatment: selective foil, MAXORB

Insulation, back: 50 mm mineral wool

Insulation, edge: 27 mm wood and aluminium foil

Solar collector frame: the frame is made of a galvanized steel profile with the dimensions 30 x 75 x 3 mm

Tightening: sealing strip between glass and frame

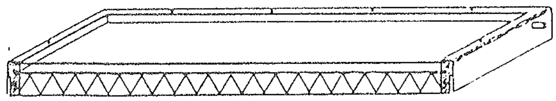
Recommended maximum pressure: 250 kPa

Pressure loss: 2,3 kPa at a fluid flow rate of 0,038 kg/s (50% propylene glycol)

Connection: can be made to the two out-sticking sockets in the upper part of the long sides

Mounting: The solar collector can be mounted on the roof or be integrated in the roof as a flashing system can be delivered. The fastening can be made with fittings or square-head screws from the back.

Section:

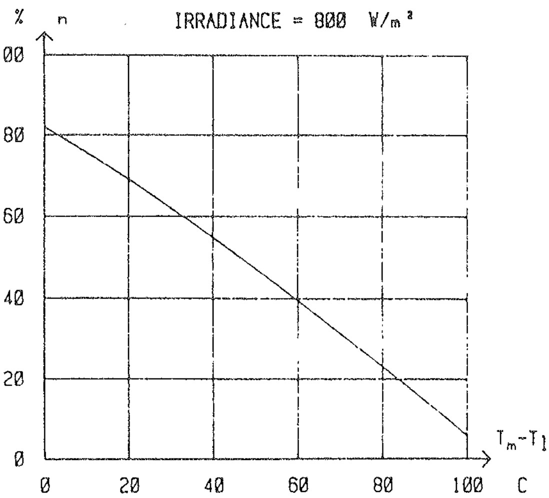


Efficiency expression under the following conditions:

Tilt 45°, fluid flow rate 0,038 kg/s
50% propylene glycol, wind speed 5 m/s

$$\eta = 0,82 - 5,0\frac{T_m - T_l}{E} - 0,011\frac{(T_m - T_l)^2}{E}$$

where η = efficiency
T_m = mean fluid temperature
T_l = air temperature
E = irradiance



Comments to the test:
None

APPENDIX 2.3

Datasheet for 1983 prototype collector

DATASHEET ON SOLAR COLLECTOR EFFICIENCY	Date: 05-05-1983
Manufacturer: DANSK SOLVARME K/S, KABELVEJ 5, V. HASSING STRAND, 9310 VODSKOV	Type: KP V
Test Laboratory: THERMAL INSULATION LABORATORY, TECHNICAL UNIVERSITY OF DENMARK	Solar collector id-no.: 174

Outside dim: 2,04 x 1,04 x 0,10 m

Weight: 63 kg

Transparent area: 1,93 m^2

Number and type of glazing: Single 4 mm glass

Absorber panel:

- Type: channel plate
- Material: stainless steel
- Thickness: top/bottom: 0,6 mm/0,6 mm
- Channelsystem: lengthwise with traversing connections
- Headers: integrated in the absorber
- Surface treatment: selective foil, MAXORB

Insulation, back: 60 mm mineral wool

Insulation, edge: 25 mm wood and aluminium foil

Solar collector frame: the frame is made of a aluminium profile with the dimensions 30 x 100 x 3 mm

Tightening: sealing strip between glass and frame

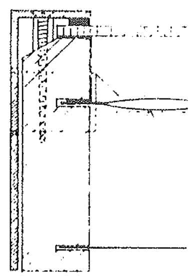
Recommended maximum pressure: 250 kPa

Pressure loss: 1,8 kPa at a fluid flow rate of 0,038 kg/s (50% propylene glycol)

Connection: can be made to the two outsticking sockets in the upper part of the long sides

Mounting: The solar collector can be mounted on the roof or be integrated in the roof as a flashing system can be delivered. The fastening can be made with fittings to the frame or squarehead screws from the back.

Section:

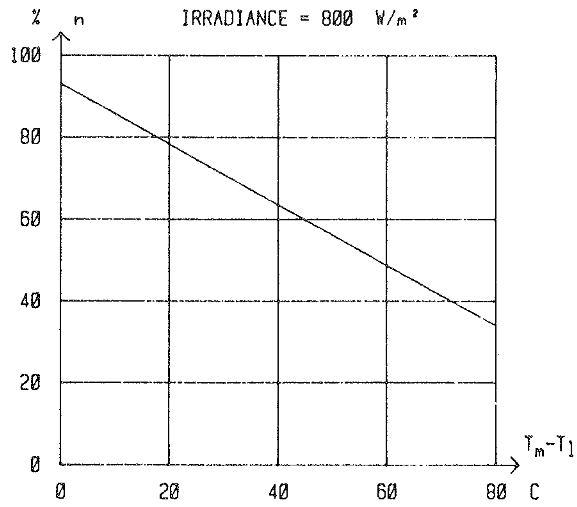


Efficiency expression under the following conditions:

Tilt 45°, fluid flow rate 0,038 kg/s
50% propylene glycol, wind speed 5 m/s

$$\eta = 0,93 - 5,9\,\frac{T_m - T_l}{E} - 0,000\,\frac{(T_m - T_l)^2}{E}$$

where η = efficiency
T_m = mean fluid temperature
T_l = air temperature
E = irradiance



Comments to the test:
When stagnation testing the solar collector the absorber plate bulged at the center of the lower third.