DIMENSIONING OF THE HEAT BALANCE AND THE SOLAR HEATING SYSTEM IN THE ZERO ENERGY HOUSE IN DENMARK

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SUMMARY

The paper describes the project for a Zero Energy House constructed at the Technical University of Denmark. The house is designed and constructed with special reference to energy conservation.

With high-insulated constructions (30-40 cm mineral wool insulation), movable insulation of the windows, and heat recovery in the ventilating system, the total heat requirement for space heating is calculated to 2300 kWh per year.

For a typical, well insulated, one-story, one-family house built in Denmark, the corresponding heat requirement is 20.000 kWh.

The solar heating system is dimensioned to cover the heat requirement of 2300 kWh and the hot water supply of 2300 kWh for the Zero Energy House during the whole year on the basis of the weather data in the Danish "Reference Year". The solar heating system consists of a 42 m^2 flat-plate solar collector, a 30 m^3 water storage tank (insulated with 60 cm mineral wool), and a heat distribution system.

SOMMAIRE

Cette monographie décrit le projet d'une Maison Zero Énergie construite à l'École Polytechnique de Danemark. La maison est dessinée et construite spécialement au point de vue de la conservation d'énergie.

Avec des constructions hautement isolées (30-40 cm d'isolement de soie minérale), de l'isolement mobile des fenêtres et de la récupération de chaleur dans le système d'aération, la chaleur totale nécessaire pour le chauffage d'espace est calculée à 2300 kWh/an.

Pour une maison typique, bien isolée, à un seul étage, pour une famille seule, bâtie au Danemark, la chaleur nécessaire correspondant est de 20.000 kWh.

Le système de chauffage solaire est dimensionné à couvrir la chaleur nécessaire de 2300 kWh et la consommation en eau chaude de 2300 kWh pour la Maison Zero Énergie pendant toute l'année, en se basant sur les données météorologiques dans le "Reference Year" danois. Le système de chauffage solaire se compose d'un collecteur solaire plan de 42 m^2, une citerne pour la conservation d'eau de 30 m^3 (isolée par 60 cm de soie minérale) et un système de distribution.

INTRODUCTION

During the spring 1975 a one-family, one-story, experimental house, the Zero Energy House, has been constructed at the Technical University of Denmark.

The measuring equipment has been installed during the summer 1975, and a family will occupy the house during the winter period to test the indoor climate and the habitability of the house.

The planning and construction of the experimental house is the result of a teamwork between 3 institutes at the Technical University of Denmark: The Thermal Insulation Laboratory, the Institute of Building Design, and the Heating and Air Conditioning Laboratory.

The solar energy system has been designed and constructed by associate Professor Mogens R.Byberg, civilengineer Torben V.Esbensen and Professor Vagn Korsgaard.

The experimental house has been granted by the Danish Council for Scientific and Industrial Research.

The Experimental House

The house is designed as two "living-boxes" of 60 m^2 each, separated by a glass-roofed atrium of 70 m^2. The atrium is not heated, but it is protected against wind and rain, and therefore it may be used as a part of the living area at daytime during the main part of the year (Fig.1).

The south facing upper vertical part of the atrium contains a flat-plate solar collector of 42 m^2 (12 m long and 3.5 m high). The solar collector is connected with an insulated storage tank of 30 m^3 buried in the ground just outside the atrium.

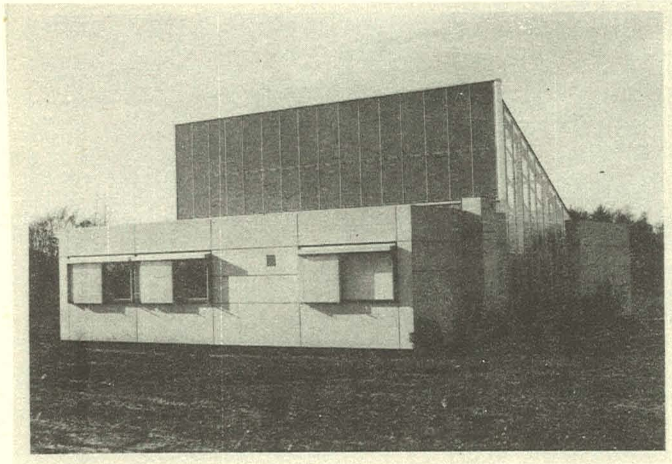

Fig.1: The Zero Energy House, May 1975

The two "living-boxes" are constructed of prefabricated units with 30 cm of mineral wool in the walls and 40 cm of mineral wool in the roof and in the floor. The construction elements are of a new type, specially developed for the Zero Energy House project.

The windows and the doors are provided with two layers of glass and with insulated shutters to increase the insulation value during the night. The windows facing south are furthermore provided with a sun shading device.

Method of Calculation of the Heat Requirement

A computer program "BA4" has been developed to calculate the hourly heat requirement for the house on basis of the meteorological data in the Reference Year [1]. Furthermore the program calculates the variation of the indoor temperature in the house during the year [2].

In the calculation the following heat flows are included:

SUPPLY OF HEAT

1. Solar heat gain through windows
2. Emission of heat from persons, electric lighting, cooking, etc.
3. Emission of heat from walls with a heat capacity

HEAT LOSS

1. Heat loss by transmission through walls, windows, floor, and roof.
2. Heat loss by air change
3. Heat flow to walls with a heat capacity
4. Heat loss by opening of doors

Reference Year

The basis of the dimensioning of the Zero Energy House and in particular of the solar energy system is the "Reference Year". This consists of a set of climatic data for environmental engineering, especially suited for computerized calculations of indoor climate and energy demands. It is a collection of data for Denmark, giving hourly values for 8760 hours of temperature, humidity, wind, direct solar radiation and diffuse radiation from the sky, cloud cover and cloud types [1].

Indoor Temperature

In the calculation of the heat requirement for the Zero Energy House made by the computer, a variation during the day for the indoor temperature is specified (Fig.2). The specification is 17°C at night rising to 23°C at daytime.

Furthermore an upper limit at 25°C is specified. The computer program calculates a cooling demand, if the temperature exceeds this limit.

There is, however, no mechanical cooling system installed in the house, and the cooling requirement is met by opening of windows and by solar screenings in front of the southfacing windows.

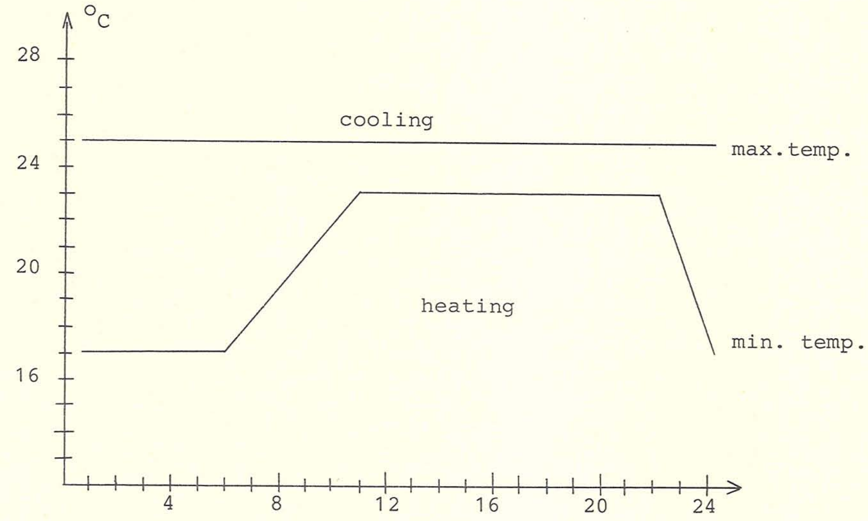

Fig.2: The variation of the specified indoor temperature during the day

Heat Loss by Air Change

To provide good living conditions in the house the indoor climate is optimum for both health and comfort. The amount of fresh air is determined with due consideration to energy consumption and good air quality.

The calculation of the heat loss by air change is divided into 3 parts:

1. A controlled ventilation with the amount of fresh-air specified to 100 m^3/h during 13 hours daily and 200 m^3/h during the remaining 11 hours daily.

   The Heating and Air Conditioning Laboratory has developed an air-to-air heat recovery unit used for energy recovery from exhaust air in the ventilating system.

   In the laboratory, recovery degrees of 90 per cent at 100 m^3 per hour and 83 per cent at 200 m^3 per hour were measured.

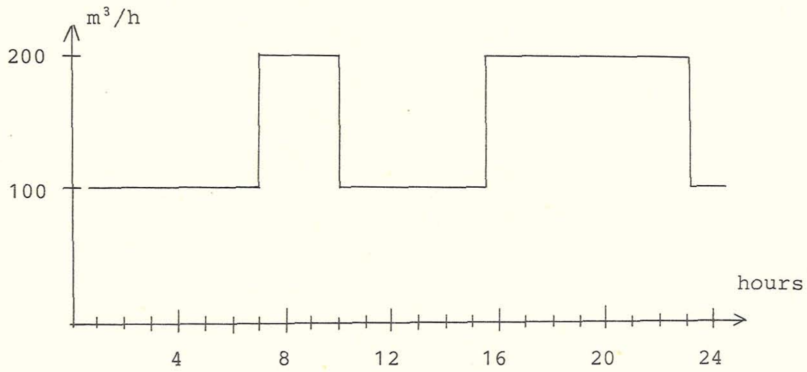

Fig.3: The variation in fresh air ventilation during the day

2. An uncontrolled air change through joints at the doors and the windows is dimensioned to 0.1 m^3 per hour per 1 meter of joints at a wind velocity of 5 m/sec.

   There are 75 meters of joints in the house, and the air change through joints is therefore 7.5 m^3 per hour, corresponding to an air change in the house of about 0.03 per hour.

3. Because of the living rooms being separated by an atrium which is not heated, a heat loss will occur by opening the doors between the "living boxes" and the atrium several times a day.

   The air change has been measured to about 5 m^3 per opening of a door, and with 4 persons in the house there is calculated with 130 openings during the day.

Emission of Heat from Persons

For the heat flow from persons calculations have been made with 4 sleeping persons for 8 hours per day, 4 persons in activity for 8 hours per day, and 1 person in activity for 8 hours a day.

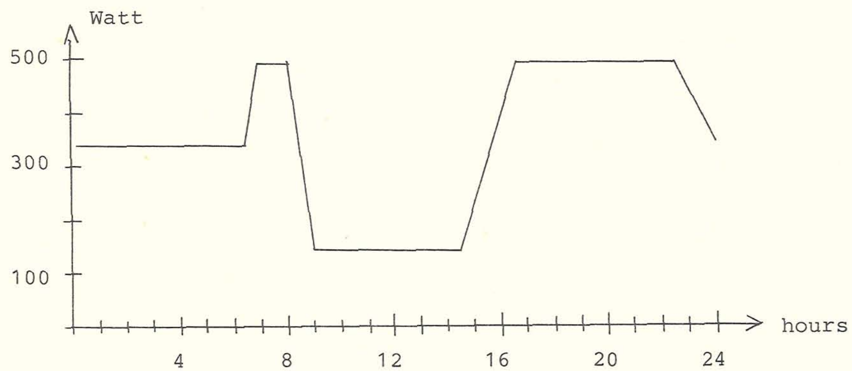

Fig.4: The variation in the heat flow from persons

The heat emission from persons totals 8 kWh per day.

In the calculation, 50 per cent of the emission from persons are supplied to the walls as heat radiation, and 50 per cent are supplied to the air in the rooms as heat convection.

Heat Emission from Electric Lightning, etc.

The heat flow from electric installations such as TV, kitchen machines, ventilators, etc., is calculated to totally 4.8 kWh per day.

The heat flow from electric lightning has the following variation during the day in the periods of the year, when the daylight does not fulfil the specified light intensity of 500 Watt:

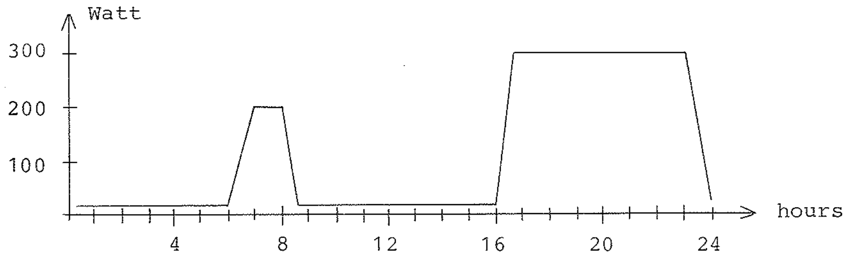

Fig.5: The variation in the heat flow from electric lighting

The heat emission from electric lighting is 2.5 kWh per day, 35 per cent being heat radiation and 65 per cent heat convection.

Solar Heat Gain Through Windows

The actual solar heat gain through windows is calculated on basis of the solar data in the Reference Year.

In the Zero Energy House there are 9.1 m^2 of windows facing south and 8.9 m^2 of windows facing north.

Heat Balance for the Zero Energy House

Given the above-mentioned arrangements with high-insulated constructions, with movable insulation in the windows, with heat recovery in the ventilating system, with heat supply from persons, electric lighting, solar heat gain through the windows, etc., the total heat requirement for space heating in the Reference Year is calculated to 2300 kWh, corresponding to 350 litres of fuel oil burner efficiency of 0.7.

To compare the heat balance for the Zero Energy House with the heat balance for a typical well insulated one-family house, calculations have been made for a house with the similar design and constructions as in the Zero Energy House, but without the special energy conservation arrangements.

The energy conservation arrangements for the two houses are shown in Fig.6.

Energy Conservation Arrangements		The Energy Zero House	A Typical Well Insulated House
Floorage	m^2	116	116
Volume	m^3	281	281
Windows	m^2	18	18
Insulation of walls	cm	30	10
K-value	$W/m^2 \cdot {}^oC$	0.14	0.39
Insulation of floor a. roof	cm	40	10
K-value	$W/m^2 \cdot {}^oC$	0.10	0.39
Insulation of windows, day	$W/m^2 \cdot {}^oC$	3.13	3.13
Insulation of windows, night	$W/m^2 \cdot {}^oC$	0.40	3.13
Fresh air ventilation		0.7/0.4 change/hour	1 change/hour
Heat recovery		83%-90%	none

Fig.6

An analysis for the heat balance for the two houses is shown in Fig.7, where the total heat loss is divided into the heat losses through the walls, the windows, and the ventilation. The total heat supply is divided into the supply from persons, the electric lighting, and the solar heat gain through windows.

In Fig.8 the calculations are shown graphically.

Comparative Heat Balance in kWh	The Zero Energy House	A Typical Well Insulated House
Heat loss through walls, roof, and floor	4720	14240
Heat loss through windows	2970	4420
Heat loss by fresh-air ventilation	1260	10100
Heat loss by opening of doors	660	
Total heat loss	9610 (100%)	28760 (300%)
Heat supply from persons	2050	2470
Heat supply from electric lighting, etc.	1770	2150
Solar heat gain through windows	3490	4690
Total supply of heat	7310	9310
Heat requirement for space heating	2300 (100%)	19450 (850%)

Fig.7

It should be noted that while the total heat loss for the zero Energy House is 1/3 of that of the typical house, the heat requirement is only approximately 1/9 due to the heat supply from persons, etc.

The Utilization of Heat Supply from Persons etc.

To obtain the maximum utilization of the heat supply from persons, electric lighting, etc., it is necessary to have an automatic regulation of the temperature in each room.

The total amount of heat supply in the Reference Year is calculated to:

From persons	2955	kWh
From electric lighting, etc.	2505	kWh
From solar heat gain through windows	5770	kWh
Totally	11230	kWh

From the comparative heat balance in Fig.7 it appears that the typical well insulated house can utilize a larger part of the free heat supply than the Zero Energy House. This is due to the larger heat loss, which means that more heat can be utilized before overheating occurs.

The typical insulated house utilizes 9310 kWh (83%) of the total heat supply, and the Zero Energy House utilizes only 7310 kWh (65%).

Reversed, the free heat supply is covering a larger part of the heat loss in the Zero Energy House than in the typical insulated house, being 76% against 32%.

The Influence of the Energy Conservation Arrangements

Without heat recovery in the ventilating system the heat requirement for the Zero Energy House rises by 150% from 2300 kWh to 5760 kWh per year.

Without insulated shutters in front of the windows at night the heat requirement for the house rises by 82% from 2300 kWh to 4160 kWh per year.

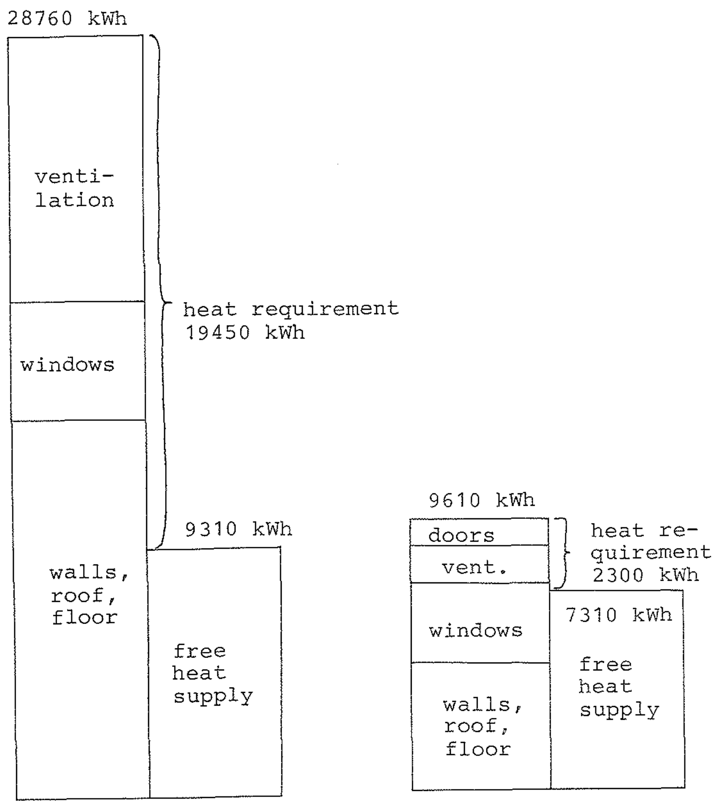

Fig.8: A comparative heat balance between a typical well insulated house and the Zero Energy House

The Solar Energy System

The solar energy system consists of a flat-plate solar collector, a heat storage tank and a heat distribution system. A sketch showing the system in principle is given in Fig.12.

The solar energy system is dimensioned on the basis of the following criteria:

1. For architectural reasons, it was decided that the area of the flat-plate collector should not exceed $42\ m^2$ (12 m long and 3.5 m high), and that the collector should be vertical.
2. Because the system is used also for hot water supply, the temperature in the storage tank must not be lower than $43^{o}C$.
3. With the area of the collector fixed at $42\ m^2$, the accumulator should be dimensioned in such a way that the solar energy system is able to cover the heat requirement for the house on the basis of the "Reference Year" and the hot water supply.

A computer program is developed to simulate the solar energy system.

Hot water supply

In the preliminary dimensioning of the solar energy system the amount of hot water supply was fixed to 350 litres per day, and the necessary volume of heat accumulator was calculated to $30\ m^3$.

The computer model later on has been corrected regarding the calculation of the diffuse radiation on a vertical collector.

This correction means a reduction in the total incident radiation on the solar collector. Therefore the absorbed solar energy is not enough to cover both the heat requirement for space heating and an amount of hot water supply of 350 litres per day.

The amount of hot water supply therefore was reduced from 350 litres per day during the whole year to 350 litres per day in the most sunny period from the middle of January to the end of September, and only 175 litres per day in the most cloudy period from the beginning of October to the middle of January.

A water-to-water heat recovery unit is installed in the house for energy recovery from waste water from baths, laundry machines, and automatic dishwashers. The installation is calculated to have an average recovery degree of 50%.

The Solar Collector

The collector is of the flat-plate type. The absorber is a roll -bond steel radiator painted with ordinary carbon black paint, insulated on the back with 25 cm of mineral wool. The front of the collector is standard hermetically sealed, double pains framed in steel bars, and sealed with a mastic (Fig.9).

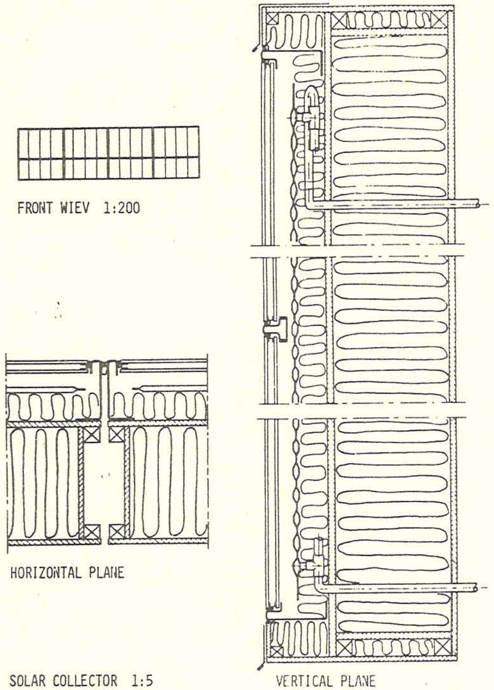

Figure 9

A computer program is developed to calculate the absorbed radiation in the solar collector and the accumulated energy in the storage tank.

On the basis of the data in the "Reference Year" for the solar radiation, the wind velocity and the outdoor temperature, the total useful energy gain of the solar collector is calculated hourly.

The so-called Hottel-Whillier equation is used in the calculations [3]:

$$Q_U = A_C F_R[S - U_L(T_{f,i} - T_a)]$$

Q_U = total useful energy gain of the solar collector
A_C = total collector area
F_R = collector heat removal factor
S = absorbed solar energy on the collector plate
U_L = overall heat loss coefficient for the solar collector
$T_{f,i}$ = water inlet temperature
T_a = ambient air temperature

The absorbed energy S is distributed to losses through the top, bottom and edges, and to useful energy gain. The overall heat loss coefficient U_L is the additional of the heat loss coefficients through the top, bottom and edges.

The effect of the heat removal factor F_R is to reduce the calculated useful energy gain from what it would have been, had the whole collector been at $T_{f,i}$ to what it actually is, using a fluid that increases its temperature, as it flows through the collector.

The Accumulator

The accumulator is designed as a cylindrical steel tank, 2.5 m in diameter and 6.5 m long with a volume of 30 m^3. The tank is insulated with 60 cm of mineral wool and buried in the ground just outside the house. The ground water level is far below the tank bottom. To prevent rain water from penetrating the insulation, an earth-covered roof is built on the top of the insulation separated by a mechanically ventilated air space.

A 400 litres storage tank for the domestic hot water is built into the accumulator (Fig.10 and 11).

The heat conductivity coefficient for the mineral wool is 0.044 $W/m\cdot{}^oC$, and it is assumed that in the calculations of the heat loss the temperature of the surroundings (the ground) is constantly 15^oC.

The heat loss is then calculated to $5.8(t_4-15)$ Watt, where t_4 is the actual temperature in the accumulator.

Fig.10: The heat accumulator is insulated with 60 cm mineral wool

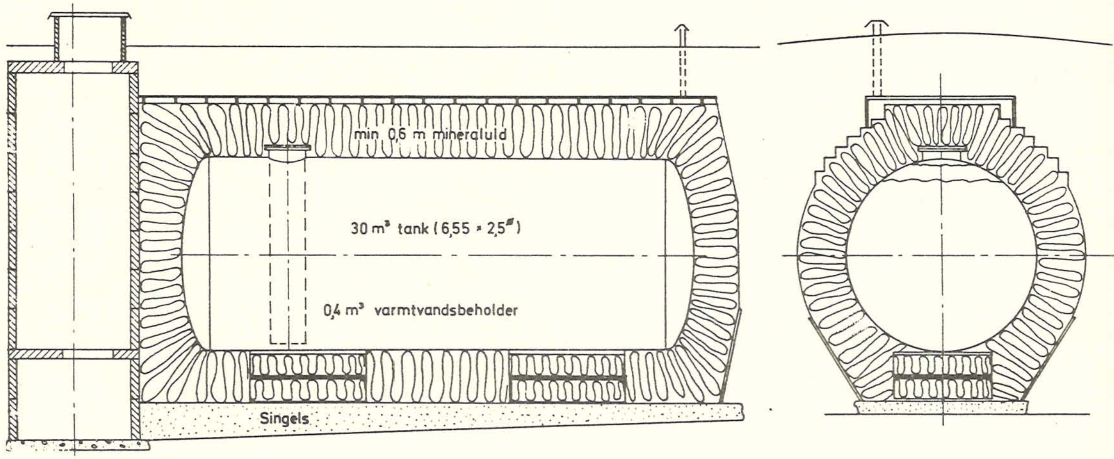

Fig. 11. Sketch of the accumulator buried just outside the house.

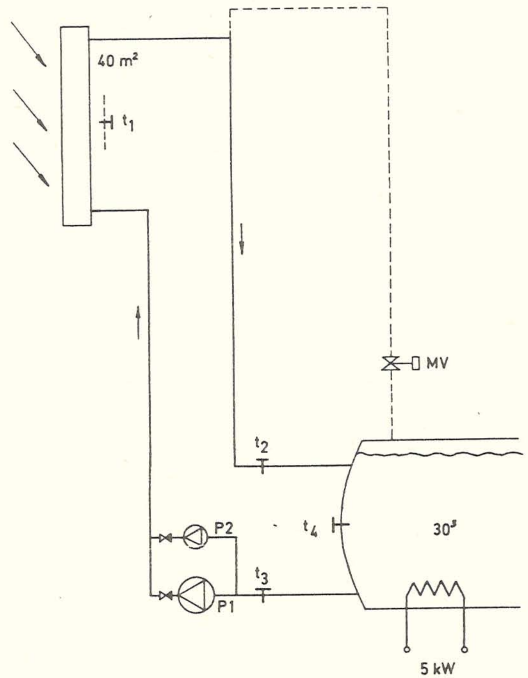

Fig. 12. Principle sketch of the solar energy system.

Method of working

To prevent the solar collector from freezing, the collector automatically will be drained for water in the night and in cloudy periods.

Accumulation in the storage tank (Fig.12)
When the temperature of the drained solar collector t_1 is about $5^{o}C$ higher than the temperature in the storage tank t_4, the two pumps P_1 and P_2 wil start filling the system with water. Then the magnetic valve is open for air-escape to the top of the tank.

When the system is waterfilled, the larger of the two pumps P_1 will stop, and the useful energy gain from the collector will be accumulated in the storage tank. The pump P_2 will stop when the temperature difference between inlet and outlet (t_2-t_3) is less than $1^{o}C$.

Auxiliary heat
If the temperature in the storage tank t_4 drops below $43^{o}C$ an electric heating element of 5 kW will automatically keep the temperature on $43^{o}C$. In a Reference Year, however, this might not be actual.

Working hours
In a Reference Year the amount of working hours for the solar collector is calculated to about 1100, which is 13% of the total hours in the year.

In Fig.13 the amount of working hours is set up for the various months. It varies from 42 hours in November to 127 hours in March.

Heat Balance for the Solar Energy System

Collected and accumulated solar energy in a Reference Year is 7330 kWh.

Used for space heating	2300 kWh per year	(31%)
Used for hot water supply	2260 kWh - -	(31%)
Heat loss from the accumulator	2770 kWh - -	(38%)
Totally	7330 kWh per year	

In Fig.14 the calculations are shown graphically.

Example to Illustrate the Curve in Fig.14:
During March, the useful solar energy gain from the 42 m² collector is 1300 kWh (curve 1). Heat requirement for space heating, hot water supply, and heat loss from the accumulator is 700 kWh (curve 2). Therefore there is an additional amount of solar energy of 600 kWh, and the amount of energy in the storage tank rises from 150 kWh to 750 kWh (curve 3), corresponding to an increase in the temperature from $52^{o}C$ to $73^{o}C$.

During November the useful energy gain from the collector is 250 kWh (curve 1). The heat requirement is 650 kWh (curve 2). Therefore there is a deficit of solar energy in November of 400 kWh, and the amount of energy in the storage tank drops from 800 kWh to 400 kWh (curve 3), corresponding to a decrease in the temperature from $75^{o}C$ to $63^{o}C$.

Temperature Variation in the Storage Tank

In the calculations the temperature in the storage tank varies between $43^{o}C$ in January and $80^{o}C$ in October. The variation during the year is shown in Fig.14, where the ordinat on the right following curve 3 is showing the temperature in the storage tank.

In Fig.13 is shown the temperature rise of the water circulating through the solar collector. The maximum temperature rise is $8.6^{o}C$ with a water flow through the collector of 1 litre/min/m² collector area, corresponding to 25 kW in useful solar energy gain from the total collector.

Efficiency of the Solar Energy System

The efciciency of the system depends on the temperature in the storage tank, because there is a direct circulation between the tank and the collector.

The efficiency is defined as the ratio of the useful solar gain to the total incident solar energy.

In the spring months when the temperature in the tank is rather low (45^{o}-$50^{o}C$), the solar collector has an efficiency of about 30%.

In the autumn months when the temperature in the tank is rather high (75^{o}-$80^{o}C$), the solar collector has an efficiency of only about 10-15%. The variation during the months is shown in Fig.13.

Energy Economy

The heat recover equipment in the ventilating system reduces the heat requirement in the house from 5760 kWh to 2300 kWh. To obtain this reduction, the ventilators need an electric energy supply of about 210 kWh (6% of the reduction).

The heat recovery equipment in the waste water system reduces the heat requirement for hot water supply by 2260 kWh per year. The energy supply to the pump is about 120 kWh per year (5% of the reduction).

The useful solar energy is 4560 kWh (2300 kWh + 2260 kWh) per year. The necessary electric supply to run the solar energy system is calculated to about 230 kWh per year (5% of the useful solar energy).

	Incident Solar Radiation kWh	Collected Solar Energy kWh	Total Efficiency %	Working Hours	Max. Temp. Difference over the Collector °C
Jan	2640	865	33	81	8.6
Feb	3315	931	28	100	6.2
Mar	4883	1298	26	127	6.8
Apr	5028	662	13	101	5.6
May	4637	389	8	95	4.1
Jun	4722	421	9	107	3.1
Jul	4743	534	11	119	3.8
Aug	4274	476	11	105	4.6
Sep	4049	588	14	104	4.8
Oct	2865	436	15	68	5.5
Nov	1793	246	14	42	4.7
Dec	2198	486	22	66	8.0
kWh	45147	7332	16	1111	8.6

Fig.13

HEAT BALANCE FOR THE SOLAR ENERGY SYSTEM

Curve 1 : Heat supply from 42 m^2 solar collector to 30 m^3 heat accumulator

Curve 2 : Heat consumption from the accumulator (space heating, hot water supply, heat loss)

Curve 3 : Accumulating curve for the accumulator

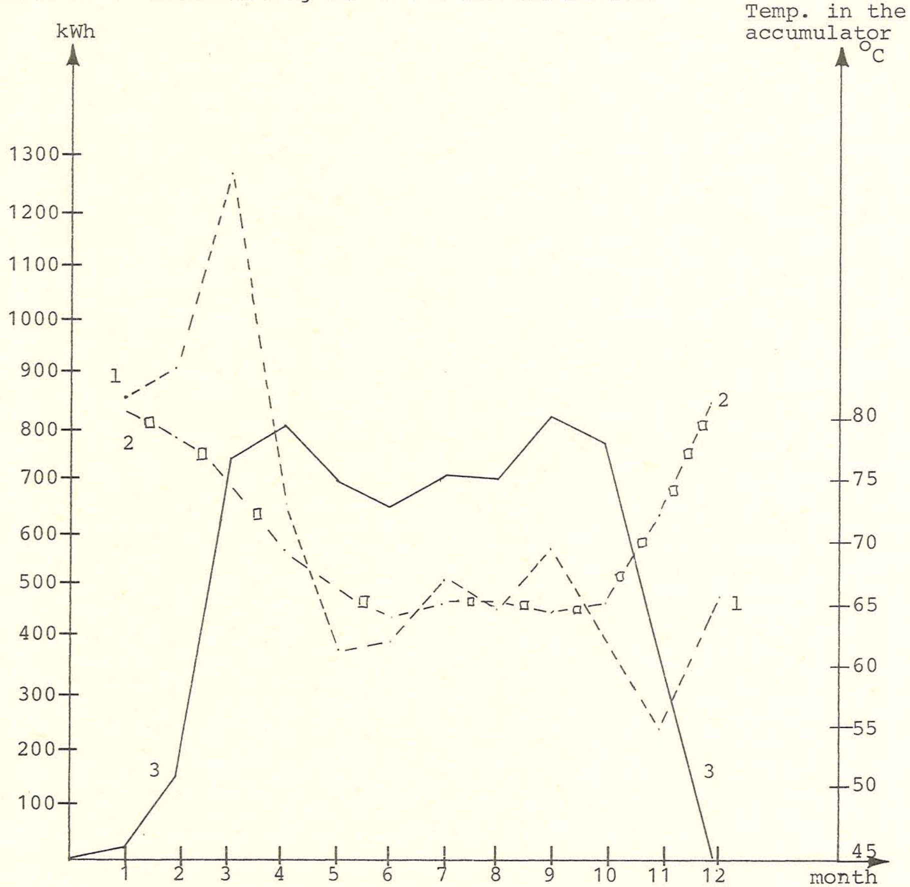

Fig.14

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