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DIMENSIONING OF THE SOLAR HEATING SYSTEM IN THE ZERO ENERGY HOUSE IN DENMARK†

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Abstract—The paper describes the project for a Zero Energy House constructed at the Technical University of Denmark. The house is designed and constructed in such a way that it can be heated all winter without any "artificial" energy supply, the main source being solar energy. With energy conservation arrangements, such as 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-storied, one-family house built in Denmark, the corresponding heat requirement is 20,000 kWh. The solar heating system is dimensioned to cover the heat requirements and the hot water supply for the Zero Energy House during the whole year on the basis of the weather data in the "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 of mineral wool), and a heat distribution system. A total heat balance is set up for the system and solved for each day of the "Reference Year". Collected and accumulated solar energy in the system is about 7300 kWh per yr; 30 per cent of the collected energy is used for space heating, 30 per cent for hot water supply, and 40 per cent is heat loss from the accumulator tank. For the operation of the solar heating system, the pumps and valves need a conventional electric energy supply of 230 kWh per year (corresponding to 5 per cent of the useful solar energy).

INTRODUCTION

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

With energy conservation arrangements, such as high-insulated constructions, heat-recovery equipments and a solar heating system, the Zero Energy House is dimensioned to be self-sufficient in space heating and hot-water supply during normal climatic conditions in Denmark. Energy supply for the electric installations in the house is taken from the municipal mains.

The planning and construction of the experimental house is the result of a teamwork between three 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 was designed and constructed by Associate Professor Mogens R. Byberg, Civil Engineer Torben V. Esbensen and Professor Vagn Korsgaard.

The experimental house was 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.

The south facing upper vertical part of the atrium contains a flat-plate solar collector of 42 m^2 (12 m long × 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.

The measuring equipment was installed during the summer 1975, and a family occupied the house during the winter period to test the indoor climate and the habitability of the house.

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 hr of temperature, humidity, wind, direct solar radiation and diffuse radiation from the sky, cloud cover and cloud types [1]. In the calculation of heat requirement for the Zero Energy House, a variation is specified for the indoor temperature during the day. (See illustration on next page).

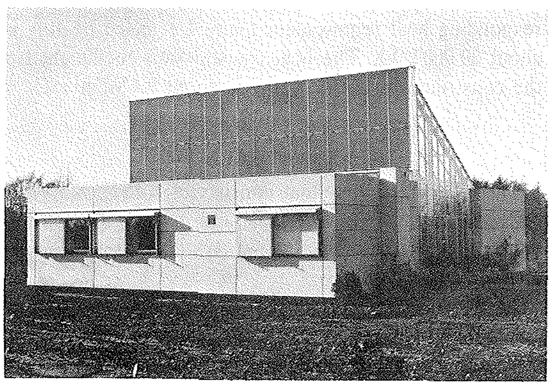
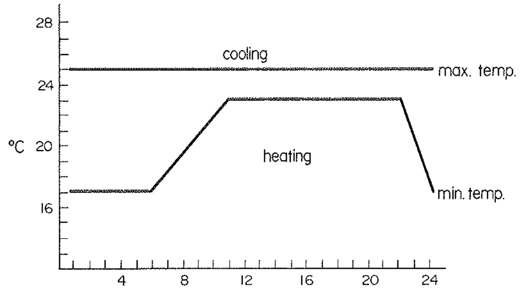


Fig. 1. The zero energy house, May 1975.

†Presented at the I.S.E.S. International Solar Energy Congress and Exposition, Los Angeles, California (28 July–1 Aug. 1975).



The variation in the specified indoor temperature during the day.

Energy conservation arrangements

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 a new type, specially developed for the Zero Energy House project. The heat transmission coefficient is 0.14 W/m^2 · °C for the walls and 0.10 W/m^2 · °C for the floor and ceiling construction.

The windows and the doors are provided with two layers of glass and with insulating shutters to increase the insulation value during the night. When the mobile insulation is active, the heat transmission coefficient is reduced from 3.10 W/m^2 · °C to 0.40 W/m^2 · °C. The windows facing south are furthermore provided with a Sun shading device.

The constructions have a minimum of air leakage, and to get an indoor climate optimum for both health and comfort, a fresh-air ventilating system was installed in the Zero Energy House. The amount of fresh air is determined to 100 m^3 per hr during 12 hr daily and 200 m^3 per hr during the remaining 12 hr daily.

The ventilating system is provided with an air-to-air heat recovery unit used for energy recovery from the exhaust air. In the laboratory, recovery degrees of 90 per cent at 100 m^3 per hr and 83 per cent at 200 m^3 per hr were measured.

Heat requirement

Given the above-mentioned energy conservation arrangements and taken into account the heat supply from persons, electric lighting and solar heat gain through the windows, the total heat requirement for space heating is calculated to 2300 kWh per yr.

For a typical one-storied, one-family house built in Denmark before the energy crisis in 1973, the corresponding heat requirement figure for space heating is about 20,000 kWh. The heat transmission coefficient for the constructions in this house is about 0.4 W/m^2 · °C.

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. 5.

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 × 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°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.

Hot water supply

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

The computer model later on was 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 l. per day.

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

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

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. 2).

A computer program was 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 was 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.

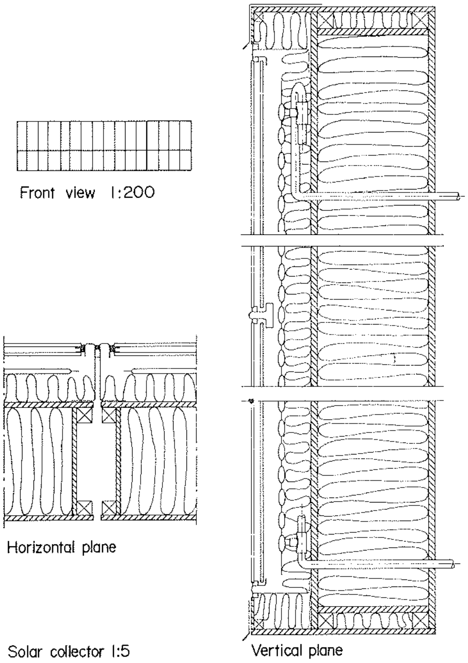


Fig. 2.

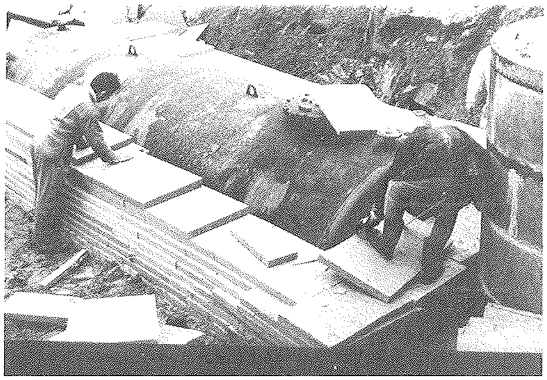


Fig. 3. The heat accumulator is insulated with 60 cm mineral wool.

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 l. storage tank for the domestic hot water was built into the accumulator (Figs. 3 and 4).

The heat conductivity coefficient for the mineral wool is 0.044 W/m·°C, and it is assumed that in the calculations of the heat loss the temperature of the surroundings (the ground) is constantly 15°C.

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

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

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

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°C.

Auxiliary heat

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

Working hours

In a Reference Year the amount of working hours for

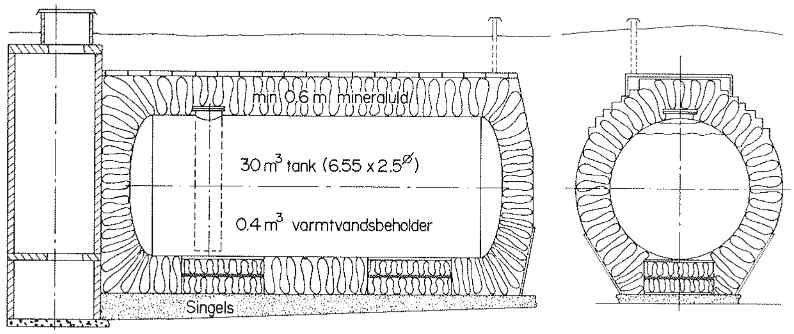


Fig. 4. Sketch of the accumulator buried just outside the house.

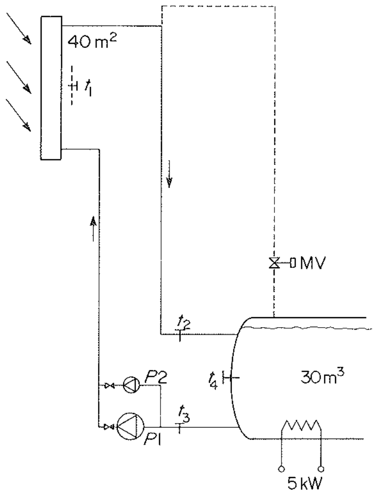


Fig. 5. Principle sketch of the solar energy system.

the solar collector is calculated to about 1100, which is 13 per cent of the total hours in the year.

In Fig. 6 the amount of working hours is set up for the various months. It varies from 42 hr in November to 127 hr 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 yr (31%)
Used for hot water supply	2260 kWh per yr (31%)
Heat loss from the accumulator	2770 hWh per yr (38%)
Totally	7330 kWh per yr

In Fig. 7 the calculations are shown graphically.

Example to illustrate the curve

During March, the useful solar energy gain from the 42 m² collector is 1300 kWh (curve 1). Heat requirement

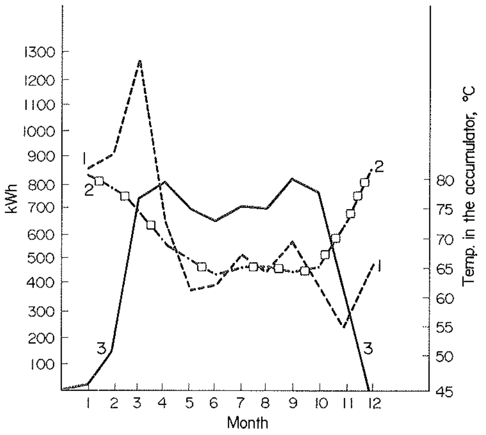


Fig. 7. Heat balance for the solar energy system.

Curve 1. Heat supply from 42 m² solar collector to 30 m³ heat accumulator.
Curve 2. Heat consumption from the accumulator (space heating, hot water supply, heat loss).
Curve 3. Accumulating curve for the accumulator.

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°C to 73°C (Fig. 7).

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°C to 63°C.

Temperature variation in the storage tank

In the calculations the temperature in the storage tank varies between 43°C in January and 80°C in October. The variation during the year is shown in Fig. 7, where the

	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. 6.

ordinate on the right following curve 3 is showing the temperature in the storage tank.

In Fig. 6 is shown the temperature rise of the water circulating through the solar collector. The maximum temperature rise is 8.6°C with a water flow through the collector of 1 l./min/m^2 collector area, corresponding to 25 kW in useful solar energy gain from the total collector.

Efficiency of the solar energy system

The efficiency 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°–50°C), the solar collector has an efficiency of about 30 per cent.

In the autumn months when the temperature in the tank is rather high (75°–80°C), the solar collector has an efficiency of only about 10–15 per cent. The variation during the months is shown in Fig. 6.

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 per cent of the reduction).

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

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3. J. A. Duffie and W. A. Beckman, *Solar Energy Thermal Processes.* University of Wisconsin, Madison (1974).
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Resumen—El artículo describe el proyecto de una Casa de Energía Cero construída en la Universidad Técnica de Dinamarca. La casa se diseña y construye de tal modo que se puede calentar todo el invierno sin ningún suministro "artificial" de energía, siendo la fuenta principal la energía solar. Con sistemas de conservación de energía, como son las construcciones altamente aisladas (30–40 cm de lana mineral), aislación móvil en las ventanas y regeneradores de calor en el sistema de ventilación, el total de calor requerido para calefacción de ambientes es calculado en 2300 kWh por año. Para una vivienda unifamiliar típica, bien aislada, de una planta, construída en Dinamarca, el calor requerido correspondiente es de 20,000 kWh. El sistema de calefacción solar es dimensionado para cubrir los requerimientos de calor para calefacción y agua caliente para la Casa de Energía Cero durante todo el año en base al dato del clima del "Año de Referencia". El sistema de calentamiento solar consiste en 42 m^2 de colectores solares planos y un tanque de 30 m^3 de acumulación de agua caliente (aislado con 60 cm de lana mineral) y un sistema de distribución del calor. Se determina para el sistema el balance total de calor y se resuelve para cada día del "Año de Referencia". La energía solar colectada y almacenada por el sistema es cercana a 7300 kWh por año. El 30% de la energía colectada es usada en calefacción del ambiente, el otro 30% para calentar agua y el 40% restante se pierde del tanque de acumulación. Para la operación del sistema de calefacción solar las bombas y válvulas necesitan 230 kWh de electricidad convencional por año, o sea, el 5% de la energía solar útil.

Résumé—Cette monographie décrit le projet d'une Maison Zero Energie construite à l'Ecole 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 Energie 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.