Solar Energy Vol. 52, No. 1, pp. 111-125, 1994
Printed in the U.S.A.

0038-092X/94 $6.00 + .00

THE SELF-SUFFICIENT SOLAR HOUSE IN FREIBURG

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Abstract—The Fraunhofer Institute for Solar Energy Systems has built a completely self-sufficient solar house (SSSH) in Freiburg, Germany. The entire energy demand for heating, domestic hot water, electricity, and cooking is supplied by the sun. The combination of highly efficient solar systems with conventional means to save energy is the key to the successful operation of the house. Seasonal energy storage is accomplished by electrolysis of water and pressurized storage of hydrogen and oxygen. The energy for electricity and hydrogen generation is supplied by solar cells. Hydrogen can be reconverted to electricity with a fuel cell or used for cooking. It also serves as a back-up for low temperature heat. There are provisions for short term storage of electricity and optimal routing of energy. The SSSH is occupied by a family. An intensive measurement program is being carried out. The data are used for the validation of the dynamic simulation calculations, which formed the basis for planning the SSSH.

INTRODUCTION

The Fraunhofer Institute for Solar Energy Systems is demonstrating for the first time in Germany, that a solar house can operate completely independently of other forms of energy [1,2]. The main problem at a high northern latitude (48°) is the strong variation of insolation between summer and winter. Since seasonal storage of large amounts of energy today is both technically and financially prohibitive for decentralized units, it was decided to reduce the energy demand by all available energy savings technologies without impairing the comfort of the occupants. Only the small remaining energy deficit in winter will be overcome with a modest storage capacity for high quality energy.

In conventional German residential buildings 80% of the energy demand is for space heating. On the other hand, the average amount of insolation energy falling upon the envelope of such a structure is greater than the heat transmission losses. Therefore, optimized use of passive solar heating technologies should make it possible to avoid seasonal heat storage. The institute has developed and demonstrated transparent insulation systems as a means of efficient utilization of solar radiation for space heating. Together with a highly efficient collector system based on transparent insulation for domestic hot water, and a photovoltaic generator in conjunction with a hydrogen/oxygen storage system, energetic self-sufficiency is achievable.

Planning of the project started in 1988, the start of the construction was in June 1991 and completion was in October 1992. A 3 year period of measurements in the occupied building with 145 m^2 living area will follow. Since no conventional energy sources are used, this house operates without emitting any pollution.

The goals of the project can be summarized as follows:

- use of solar energy to replace other, environmentally damaging energy carriers
- demonstration of new concepts of solar architecture integrated into an energetically optimized structure
- utilization of advanced technologies for energy conservation
- demonstration of new solar energy systems.

The intention of the project is to show the technical potential of solar energy to replace all environmentally damaging energy carriers in a dwelling. The demonstration of the technical potential is the basis for clarifying the economic potential. Many of the technologies and components applied in the SSSH will find their way into commercial application under the aspect of sustainable development in the future. Figure 1 shows the finished building in autum 1992.

COMPUTER SIMULATION

Formerly, all buildings with conventional energy supply systems were planned without considering the demand aspect at all. Apparently inexhaustible fossil fuels were present to cover any demand. Today, the building's energy demand is an issue again, because of the threatening destruction of our environment. Demand can be examined with simulation calculations before a building is erected. For a self-sufficient solar house without any conventional energy backup, computer simulation is the only way to plan such a house. The SSSH is a complex system of many mutually-dependent energy paths. System simulation is also necessary for the system optimization.

Drawing on the successful development of Transparent Insulation (TI) materials [3,4], it was decided to build a highly efficient TI wall heating system to cover the space heating demand (SHD) of the SSSH. To model the non-stationary temperature response of TI walls, a new simulation program was developed in the institute [5]. This program was the basis for a TI wall module [6] in the context of the TRNSYS sim-

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Fig. 1. The self-sufficient solar house in Freiburg in autumn 1992.

ulation program [7]. Typical dynamic behaviour of a TI wall is shown in Fig. 2 for Test Reference Year (TRY) data for days in January. The absorbed solar radiation causes temperature fluctuations on the outer surface of the wall. With a time delay of approximately 11 h, the inner wall surface releases the energy to the room behind. The heat flux through the wall is from outside to inside; the wall is heating the building. With the TRY weather data for Freiburg, fundamental simulation calculations were carried out to find a building ground plan with minimized SHD and maximized solar gains. Results are shown in Table 1. The effect of a south-orientated TI wall is significant, as the SHD for the square ground plan decreases from 100 to 17%.

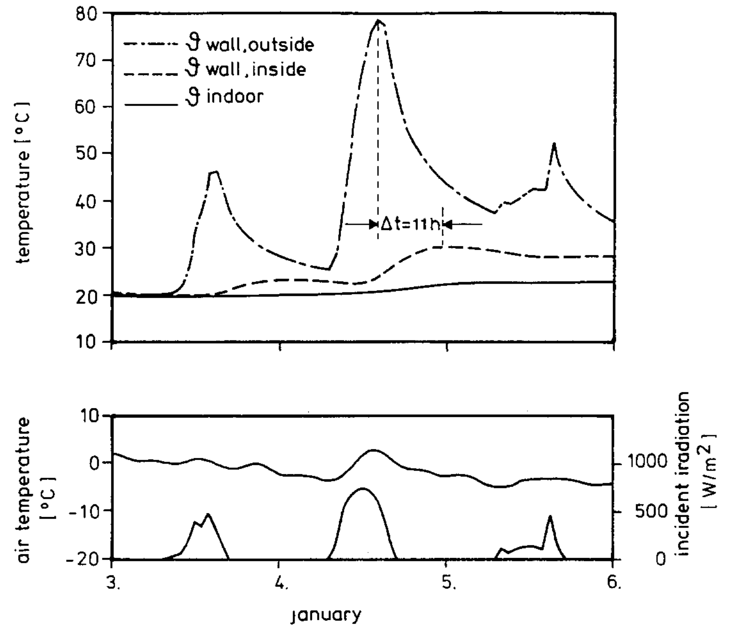

Fig. 2. Thermal dynamic behavior of a TI wall (top diagram) in relation to the TRY data for Freiburg (bottom diagram). The time shift between maximum outside wall temperature and inside wall temperature is approximately 11 hours.

Table 1. Simulated heating demand of modelled buildings in dependence on the ground plan and TI orientation (100% = 3500 kWh/year)

Ground plant	Heating demand (%)
Square 5 m × 5 m without TI	100
Square 5 m × 5 m with TI on south facade	17
Square 5 m × 5 m with TI on south, west and east facades	13
Rectangle 8 m × 12.5 m with TI on south, west and east facades	10
Rectangle 6.25 m × 15 m with TI on south, west and east facades	8
Semi-circle, radius = 8 m with TI on the south orientated curved facade	9
Segment of a circle, radius = 9.85 m with TI on the south orientated curved facade	7

Assumptions for the simulation calculations: TRY Freiburg, Germany, windowless building, single-zone model, constant volume, ground surface area 100 m^2, height 5 m, ventilation system with heat recovery, heat recovery factor 0.85, air exchange rate 0.75/h, internal heat sources 6.3 kWh/d, minimal indoor air temperature 18°C, U-value opaque wall 0.2 W/(m^{2}K), U-value TI wall 0.7 W/(m^{2}K), energy transmittance TI wall 0.6.

West and east-oriented TI walls cannot perform as well because of the lower insolation. Increasing the south-orientated wall area with a rectangular ground plan decreases the SHD further. The idea behind the curved ground plans was to increase the south-orientated TI wall area while simultaneously decreasing the north orientated wall area. As shown in Table 1, the negative heat flux through a TI wall changes one of the principles of low-energy building design: a small surface to volume ratio is not necessary for buildings with TI walls.

Different simulation programs have been used to find the collector system with the lowest auxiliary heating demand for domestic hot water (DHW). A recently developed, bifacially illuminated thermal collector with transparent insulation will be used. Besides SHD and DHW, electricity and high quality energy for cooking is needed. Efficient electrical household appliances are an obvious requirement for the SSSH. The following demands have been estimated as first input parameters for the total solar system design:

approx. 300 kWh/year auxiliary SHD
300 kWh/year auxiliary heating demand for DHW

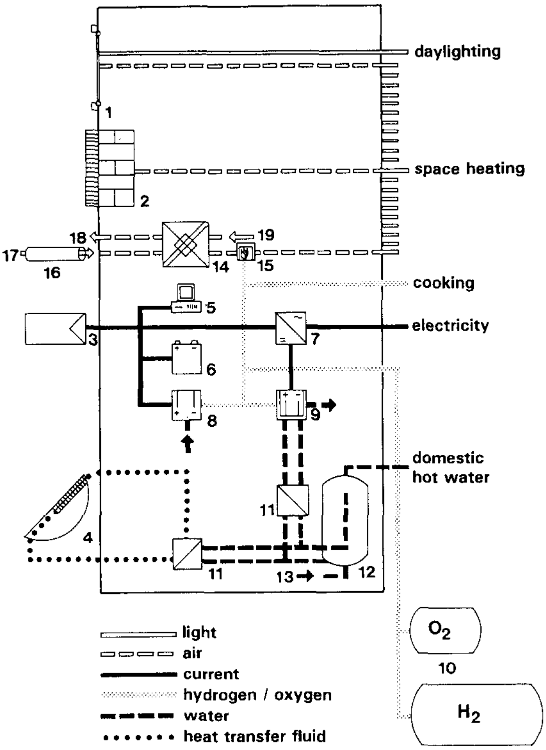

Fig. 3. Schematic diagram of the energy supply system. 1: windows, 2: TI wall, 3: PV generator, 4: thermal collector, 5: control and data acquisition, 6: battery, 7: inverter, 8: electrolyser, 9: fuel cell, 10: H_2 and O_2 storage tanks, 11: heat exchanger, 12: water storage tank, 13: mains water, 14: ventilation heat recovery, 15: heater, 16: subterranean heat exchanger, 17: ambient air, 18: exhaust air, 19: return air.

Table 2. Simulated annual energy totals (kWh/year)

	Input			Output	
	Radiation	Hydrogen	Electricity	Hydrogen	Electricity
PV generator	43540				4527
Electrolyser			2684	2048	
Hydrogen storage		1831		1715	
Cooking				701	
DHW auxiliary heating				300	
Auxiliary space heating				337	
Fuel cell		612			336
DC/DC converter			336		272
Battery			1182		986
Inverter			806		701
AC loads (household appliances)					701
DC fans					144
DC collector pumps					56
DC control and measurements					701
DC control fuel cell					134
DC control electrolyser					51

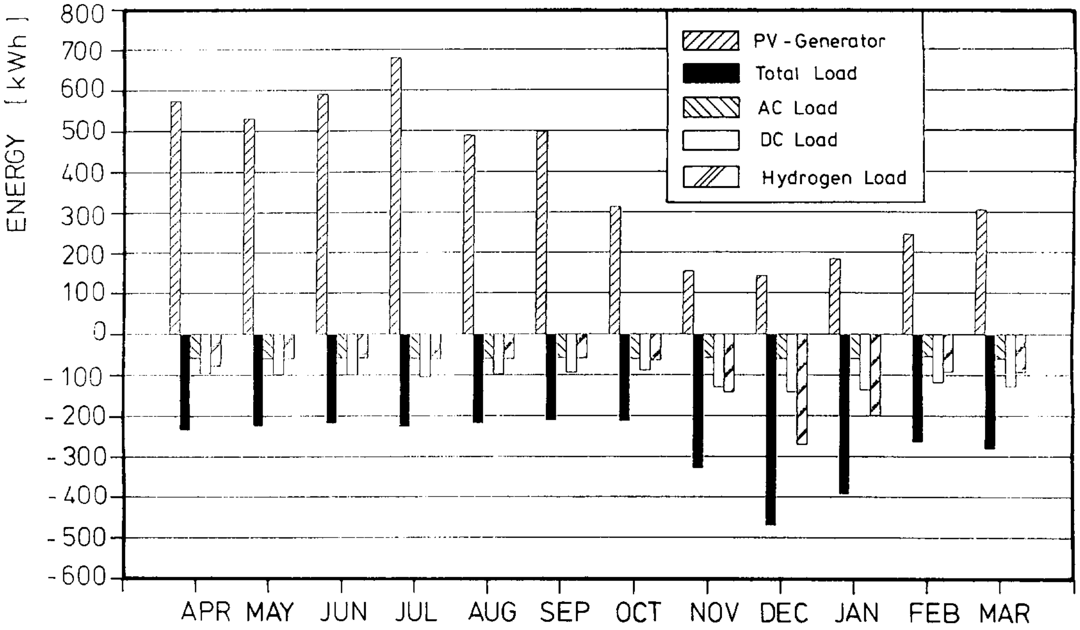

Fig. 4. Monthly sums of PV energy input and internal loads.

700 kWh/year for cooking (four-person household)
700 kWh/year electricity (four-person household)
1000 kWh/year for the system operation.

These energy totals are the absolutely lowest values which are attainable under realistic assumptions for the sizes and efficiencies of the thermal systems. The SSSH differs from other solar house projects in respect to the very low auxiliary SHD and DHW demand. This is due to the application of transparent insulation to utilize the winter insolation.

For the high quality energy demand, it is necessary that the SSSH be equipped with a PV generator. Insolation and demand, PV area and energy storage volume are the parameters for this very important optimization using computer simulation. The first results indicated that a seasonal storage volume of about 500 kWh will be needed. As shown above, an additional 500 kWh is needed for the low temperature energy demand. In a detailed evaluation, different storage solutions have been compared:

- sensible heat storage
- latent heat storage in the building construction

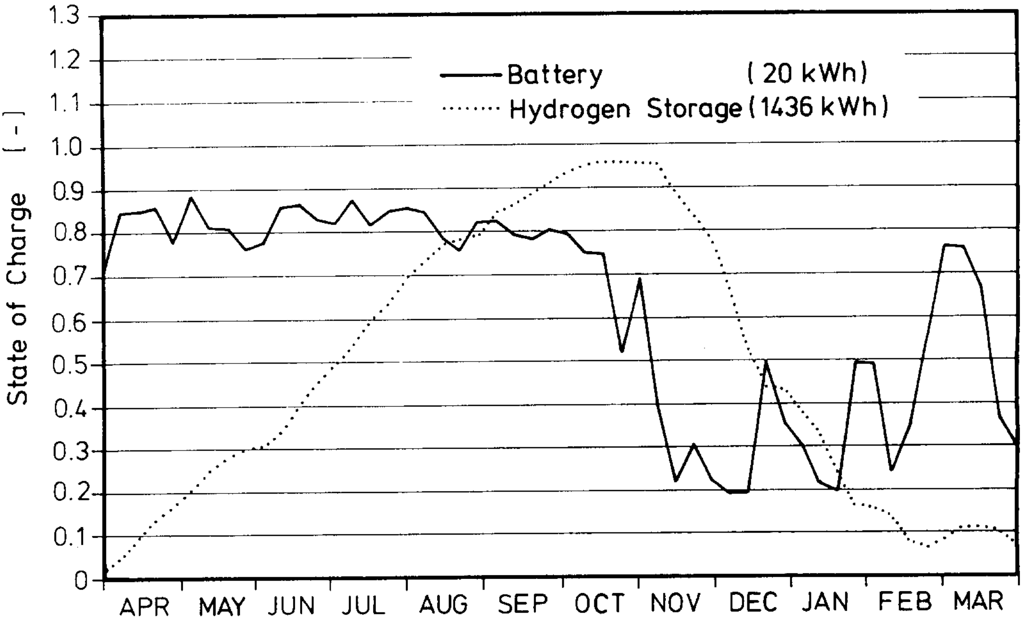

Fig. 5. Simulated battery charge state and hydrogen storage level.

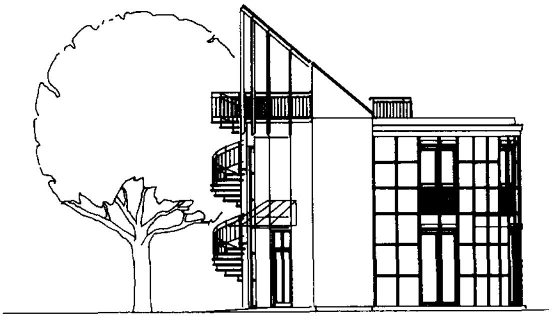

Fig. 6. Western aspect of the SSSH.

- latent heat storage in separate tanks
- electric batteries
- hydrogen storage.

The volume, cost and energy needed for production exclude electric batteries for seasonal storage. The decision was made to choose hydrogen storage for high energy demand. Consequently an electrolyzer and a fuel cell are needed. To avoid further large storage volumes and complicated operation, it was decided to use the hydrogen storage also for the low temperature energy demand to be stored seasonally. This simplifies the total energy system. The result of all these considerations is the schematic energy supply system shown in Fig. 3. For short-term storage, a small lead acid battery was added. The program TRNSYS was again used for the layout of this system [8]. TRNSYS allows the connection of many single components to form a complete energy supply system. Another reason for choosing TRNSYS is the possibility to include user-written component modules. For the simulation of the total system, several new components had to be developed: the electrolyzer, the fuel cell, the presurized tank for hydrogen storage, a DC/DC and a DC/AC converter, a catalytic heater and a central control unit. In addition, the TRNSYS lead/acid battery module was modified and a new PV array module was written. All these components were connected to a computer model of the solar energy supply system of the SSSH. This model was used as a tool to optimize the system. Simulation results were interpreted, system modifications followed and the experiment was then repeated with a new simulation run on the computer. The system is optimized for

- component variations
- auxiliary energy requirements of the subsystems
- short-term and long-term storage capacities
- sizing of system components
- influences of weather conditions and user behaviour control strategies.

The simulation program proved very valuable for studying the influence of changes of components, of climatic conditions and behaviour of the occupants. A summary of annual energy flows of the optimized system is given in Table 2. Beside the household demands already mentioned, operation of the system itself needs an additional 1086 kWh/year.

Figure 4 depicts the monthly totals of PV energy input and internal loads. It can be seen that the periods of maximum PV input and maximum load are displaced by approximately 6 mo. The increasing load in winter is due to hydrogen consumption for auxiliary SHD and DHW. The battery charge state and the hydrogen storage level shown in Fig. 5 correspond to this seasonal effect. During summer, the battery is always near 80%, the maximum state of charge that is allowed by the central control unit. Beginning in October, the battery is discharged down to the minimum allowed level of 20% by the beginning of December. In the middle of November, the hydrogen tank is beginning to be discharged after being continuously charged during spring, summer and fall. After the winter period, the tank is almost empty and ready to be filled again by the electrolyzer.

THERMAL CONCEPT

For the lay-out of the building, the facade with Transparent Insulation (TI) is of great importance. In a number of experiments, it could be demonstrated that TI not only minimizes heat transmission losses, but also converts the facade into a source of heat, compensating losses from other parts of the building and ventilation losses. Depending on the circumstances, the gain per heating period is 100–200 kWh/m^2. In combination with other already established means for minimizing heating demand, it is thus possible to heat a building exclusively with TI walls. On the basis of the simulation calculations, the ground plan of the SSSH was chosen to be in the form of a circular segment. The building (Figs. 6 and 7) consists of two

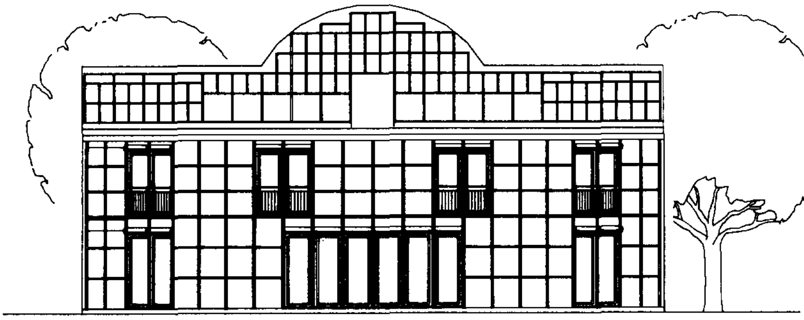

Fig. 7. Southern aspect of the SSSH.

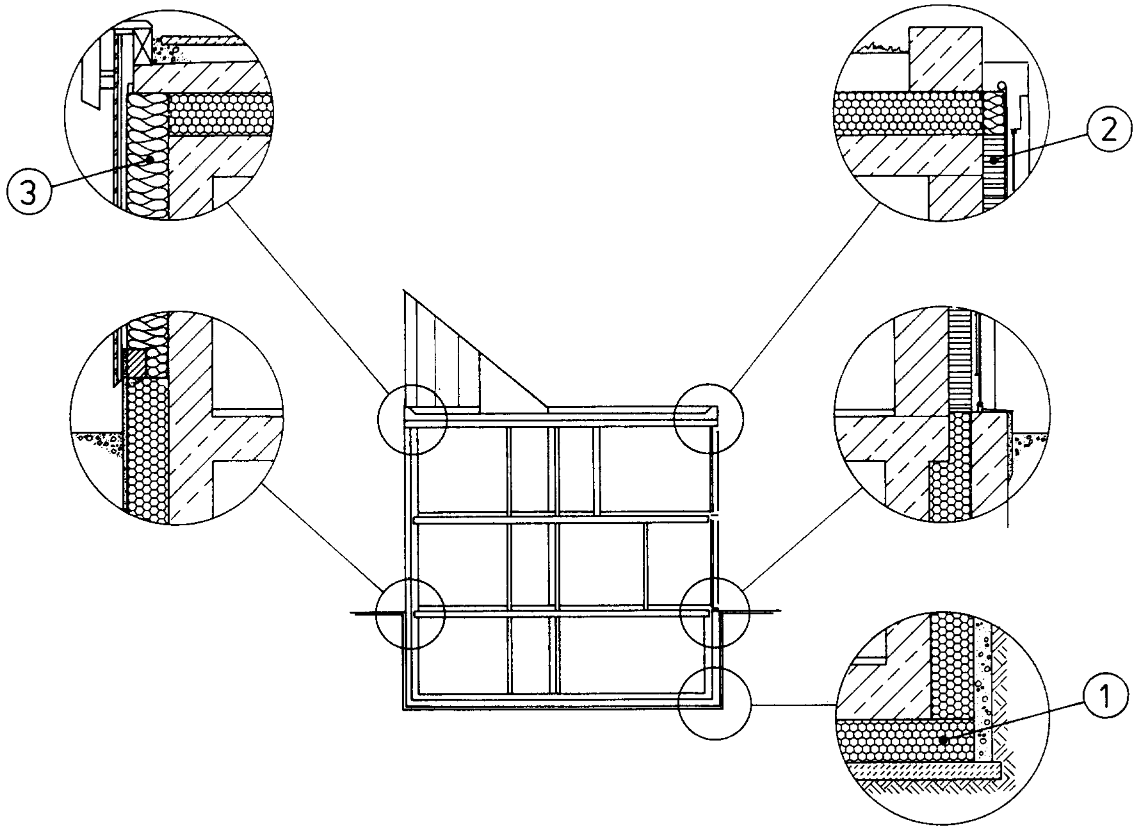

Fig. 8. Thermal insulation of the building facades. 1: foam glass, 2: transparent insulation, 3: opaque insulation.

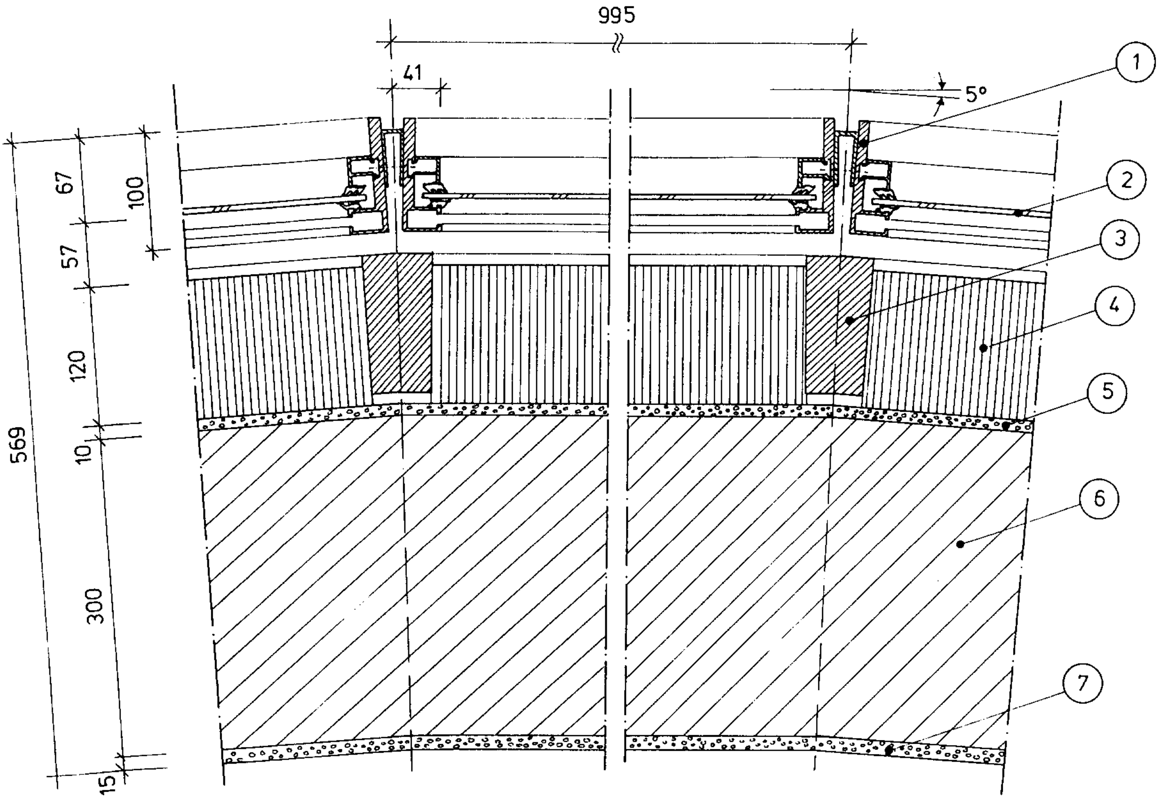

Fig. 9. Horizontal cross-section of the TI wall (dimensions in mm). 1: aluminium framework, 2: low iron containing security glass, 3: wooden framework, 4: transparent insulation, 5: absorber paint and plaster, 6: sand-lime blocks, 7: plaster.

Table 3. Physical parameters of building components (the structure of the components is listed from exterior to interior)

	d [m]	ρ [kg/m^3]	λ [W/(mK)]	g_{dif}	U** [W/(m^{2}K)]
Basement floor					
Weak concrete	0.10	2000	1.4		
Foam glass	0.26	110	0.05		
Reinforced concrete	0.30	2400	2.1		
Build floor	0.04	2000	1.4		
					0.18
Basement walls					
Foam glass	0.23	100	0.045		
Reinforced concrete	0.30	2400	2.1		
					0.19
Basement door					
Laminated wood	0.016	800	0.15		
Opaque insulation	0.04	300	0.02		
Laminated wood	0.016	800	0.15		
					0.60
Exterior walls					
Timber formwork	0.03	600			
Air gap	0.03				
Fibreboard	0.019	200	0.045		
Recycled waste paper	0.24	45–80	0.045		
Sand-lime stones	0.24	2000	1.1		
Interior plaster	0.015	1400	0.7		
				0.16	
				0.42	1.1
Door					
TI wall					
Safety glass	0.006				
Air gap	0.017				
Roller blind*					
Air gap	0.04				
TI material	0.12	25	0.09	0.68/0.03*	
Absorber coating					
Plaster	0.015	1400	0.7		
Sand-lime blocks	0.30	2000	1.1		
Interior plaster	0.015	1400	0.7		
					0.51/0.40*
Windows					
South facade					
Glass, low iron content	0.004				
Air gap	0.012				
Glass with IR-reflecting layer	0.004				
Air gap	0.19				
Glass	0.004				
Air gap	0.012				
Glass with IR-reflecting layer	0.004				
				0.39	0.6
North facade					
Glass	0.004				
Air gap	0.012				
Glass with IR-reflecting layer	0.004				
Air gap	0.012				
Glass with IR-reflecting layer	0.004				
				0.62	1.2
Roof					
Foam glass	0.23	100	0.045		
Reinforced concrete	0.30	2400	2.1		
Interior plaster	0.015	1400	0.7		
					0.19

* Values are given for roller blind open/roller blind closed.

** For doors and windows the U-values given include the frame.

storeys, a well-insulated basement and a flat roof which supports the structure for the thermal and photovoltaic collectors. Sharp corners and thermal bridges are avoided. The ground floor contains a lecture room and a combined kitchen/dining room. The first floor houses four rooms and two bathrooms. All occupied rooms are oriented toward the south, while floors and the staircase are facing north. All conventional means to conserve energy are considered in the building construction. All surfaces of the building are covered with

Table 4. Building parameters

Occupied ground area	111 m^2
Gross building area	332 m^2
Gross inner volume	1027 m^3
Weight	760 tons
Living area	145 m^2
Net living volume	365 m^3

either transparent or opaque insulation. A very unusual insulation detail is the foam glass layer under the concrete base of the building. Details of the insulation measures are shown in Fig. 8. Thermal bridges are almost totally avoided.

The south facade with a length of 22 m consists of transparently-insulated walls interrupted by optimized windows. The circular shape is constructed as a polygon with 22 segments, each 1 m wide. The orientation of the segments varies between 53 degrees southeast and 53 degrees southwest. A total of 35% of the main facade is made up of windows having a *U*-value of 0.6 W/(m^2K), and the other 65% consists of transparently insulated wall sections. The wall is 0.3 m thick and made of large sand-lime blocks. On the outer side of the wall, solar irradiation is absorbed by a black coating with an absorptivity of 0.95. The TI material is attached directly to the wall and held in place by a wooden frame. The outer glazing forms a separate curtain wall. The TI material was mounted on site in blocks of 0.8 m^2 directly before the glass was installed. As a shading device, electrically operated roller blinds are installed between the glazing and the TI material. Each blind has its motor at the top of the facade and shades a complete facade segment, 6 m high and 1 m wide. These large area blinds and a reduced framework width result in an aperture area of 90%. The cross section of the TI wall is shown in Fig. 9. Physical parameters of building components are given in Table 3 and building parameters in Table 4 [9].

Ventilation is achieved with a highly efficient heat recovery system. To preheat the incoming air, an subterranean heat exchanger is installed. The ventilation system is in operation only for three to four months in winter. Figure 10 is a schematic sketch of the system. A catalytic hydrogen heater belongs to the system. With a maximum power of 1.5 kW this is the device to cover the remaining SHD. After the principle architecture and construction questions had been settled further detailed simulation calculations were carried out. The building was divided into different zones, each zone having the appropriate internal heat sources etc. Figure 11 shows how solar gains through windows and TI walls affect the air temperature in the zone "living space." The air temperature cannot be improved when solar gains are made only through windows. The solar gains through the TI walls however result in a continuous increase in the air temperature level. The time delayed TI wall gains combine very well with direct gains through the windows. The heat energy demand of the building, excluding solar gains, is 3500 kWh/year which is comparable to the best low energy houses in the same geographic region. Solar gains reduce SHD for TRY weather data to 300 kWh/a. This results in a heating energy of 2 kWh per m^2 and year.

In accordance with the principles outlined above, the domestic hot water system was designed for the highest solar fraction. For this purpose, a collector having very high efficiency at low insolation was required. The limited space available for the collector had to be taken into consideration as well, since most of the roof area is taken up by the photovoltaic generator. In simulation runs, several types of collectors were tested, including a vacuum tube collector. The best performance was obtained with the new bifacially illuminated thermal collector developed in the institute [10]. This type of collector is used here for the first time in a practical system. A cross-section of the collector is shown in Fig. 12, while Fig. 13 depicts the DHW system. With 14 m^2 collector area and a 1000 l stratified storage tank, a solar fraction of 90% will be reached with an assumed demand of 190 l/day including hot water for the washing machine and dishwasher. The remaining 14% of the demand, amounting

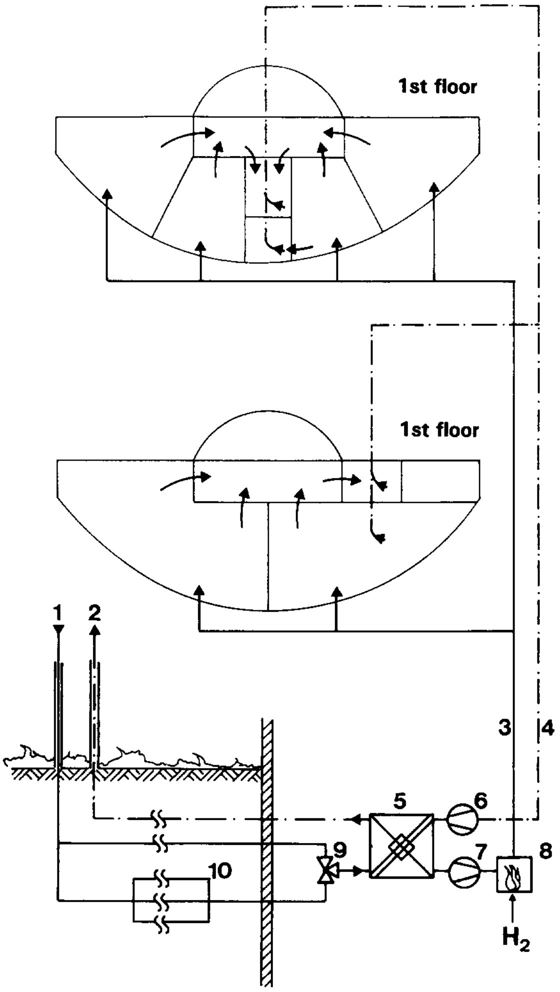

Fig. 10. Schematic diagram of the ventilation system. 1: fresh air, 2: exhaust air, 3: supply air, 4: return air, 5: heat exchanger, 6,7: fans, 8: heater, 9: valve, 10: earth heat exchanger.

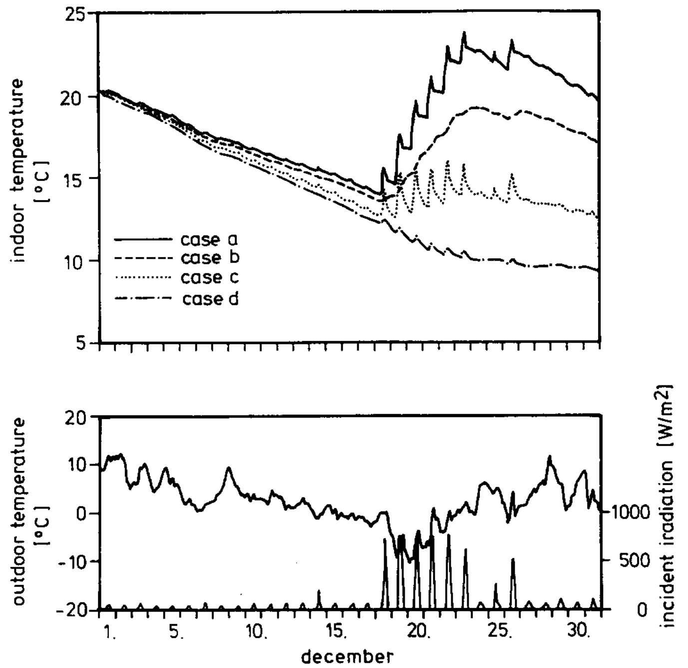

Fig. 11. Temporal dependance of the air temperature in the living spaces for the case of the unheated building (top diagram) in relation to the climatic conditions (bottom diagram). case a: actual case, solar gains with the TI walls and solar gains through the windows case b: solar gains with the TI walls, no solar gains through the windows case c: no solar gains with the TI walls, solar gains through the windows case d: no solar gains.

to 360 kWh, occurs in the months of December, January and February, and is supplied by the hydrogen storage system. Thermochemical and phase change storage was excluded because of the complexity and high auxiliary energy demand for pumps and controls.

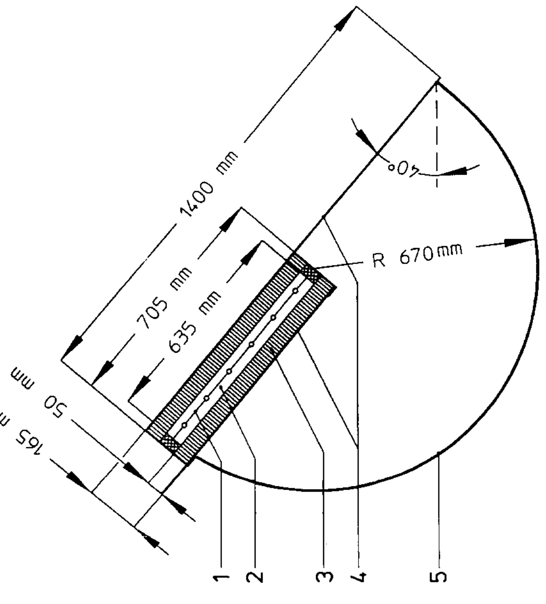

Fig. 12. Cross-section of the bifacially illuminated thermal collector with transparent insulation. 1: absorber, 2: air gap, 3: transparent insulation, 4: low iron containing glass, 5: reflector.

In Table 5 the parameters of the thermal systems are summarized.

ELECTRICAL SYSTEM

The electrical system of the self-sufficient solar house [11] consists of two main parts, the electrical power system and a control and measurement system to regulate and monitor the whole energy supply system. A block diagram of the electrical power system is given in Fig. 14, and the control and measurement system is shown in Fig. 15. The photovoltaic generator supplies the electrical energy to the consumer via an inverter. A lead-acid battery is used for short-term storage. The nominal storage capacity meets the need for electrical energy for 3–4 days without solar irradiation. The electrolyser and the fuel cell are components of the hydrogen system. The electrolyser is connected directly in parallel to the solar generator. Switch 2 is a rapidly switching transistor switch. The distribution of the solar electricity between the electrolyser and the battery, depending on its charging state, can be controlled by the ratio of the pulse to the pause. For moderate to high insolation values, the solar generator and the electrolyser are matched to 90% or more. The electrolyser is usually switched off during periods of low insolation by active solenoid valves because of its own power losses, so that the solar electricity then flows directly to the consumers and into the battery. Switch 3 is a shunt controller which is active when both the gas tanks and the battery are completely full. The diode between the battery and the electrolyser

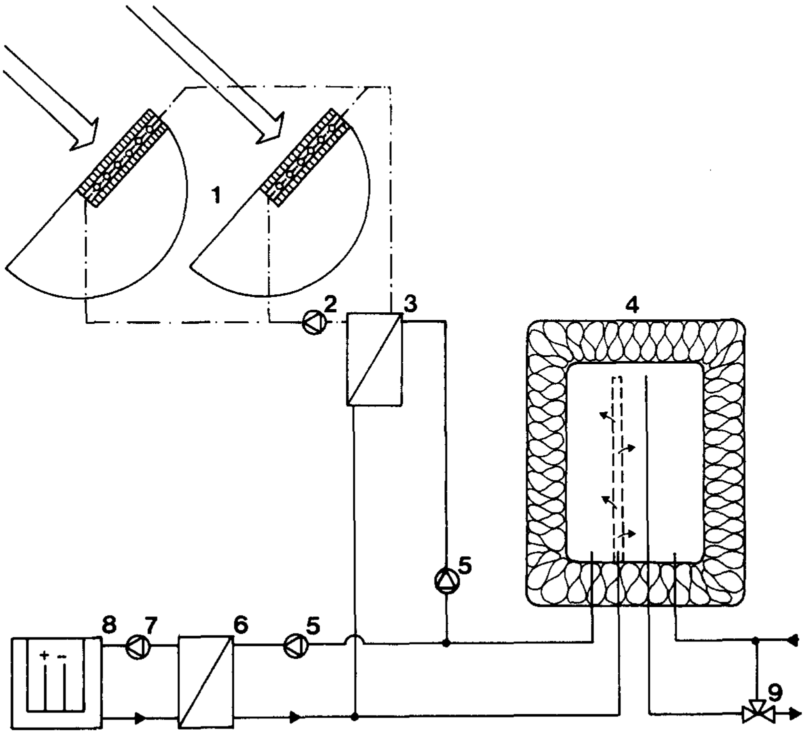

Fig. 13. Domestic hot water system. 1: collectors, 2,5,7: pumps, 3,6: heat exchangers, 4: storage tank, 8: fuel cell, 9: temperature control valve.

prevents discharge of the battery through the solar generator at low insolation. The fuel cell which compensates for the deficit in the solar-generated electricity during winter using the stored gases must be connected via a direct current transformer because fuel cells with the relatively low power of 500 W are available only with an operating voltage of 12 V maximum. As the fuel cell has a maximum efficiency of 55%, it is important that the direct current transformer used be as efficient as possible so that the fuel cell performance is not reduced further. The best efficiency value for commercially available 12 V/48 V direct current transformers is 80%, so a specially developed model was commissioned which achieved an efficiency value of more than 90%. To convert the direct current from the photovoltaic system to alternating current an inverter with very low open circuit losses must be used, as the average power consumption in a household is only 1/25 of the peak power [12].

When installing the electrical circuit in the hydrogen system, guidelines to reduce the explosion hazard have been observed. The regulation IEC 31 (CO) 43 (Electrical installations in explosive gas atmospheres) specifies the installation of an isolated circuit with an isolation monitor to identify short circuits through body contact or to the ground.

The household is equipped with energy-efficient electrical appliances using 230 V AC. All appliances are commercially available and are chosen according to the criterion of low power consumption. The resulting yearly energy consumption is given in Table 6. Using these appliances and the warm water heated by the solar DHW system (for the washing machine and dishwasher), it is possible to reduce the electrical power consumption to 700 kWh/a for a four-person household, compared to 3270 kWh/a as the average consumption of a four-person household in Germany in 1988.

In addition to the energy consumed by household appliances, further energy must be supplied, as itemised in Table 2. Thus, in order to cater for the complete power supply for the house, including cooking, additional heating, supplementary heating of warm water, control and measurement and the power consumed by the hydrogen-oxygen components, the photovoltaic system must supply much more energy than is required

Table 5. Parameters of the thermal systems

Windows	
Gross window area	55 m^2
Window aperture	
South facade	24 m^2
North facade	4 m^2
TI wall	
Gross TI wall area	89 m^2
TI wall aperture	70 m^2
Ventilation system	
Air exchange rate	200 m^3/h
Supply air heater	1.5 kW
Heat recovery factor	0.80
Earth heat exchanger area	34 m^2
Thermal collector	
Gross area	14 m^2
Aperture	12 m^2
Storage volume	1000 l

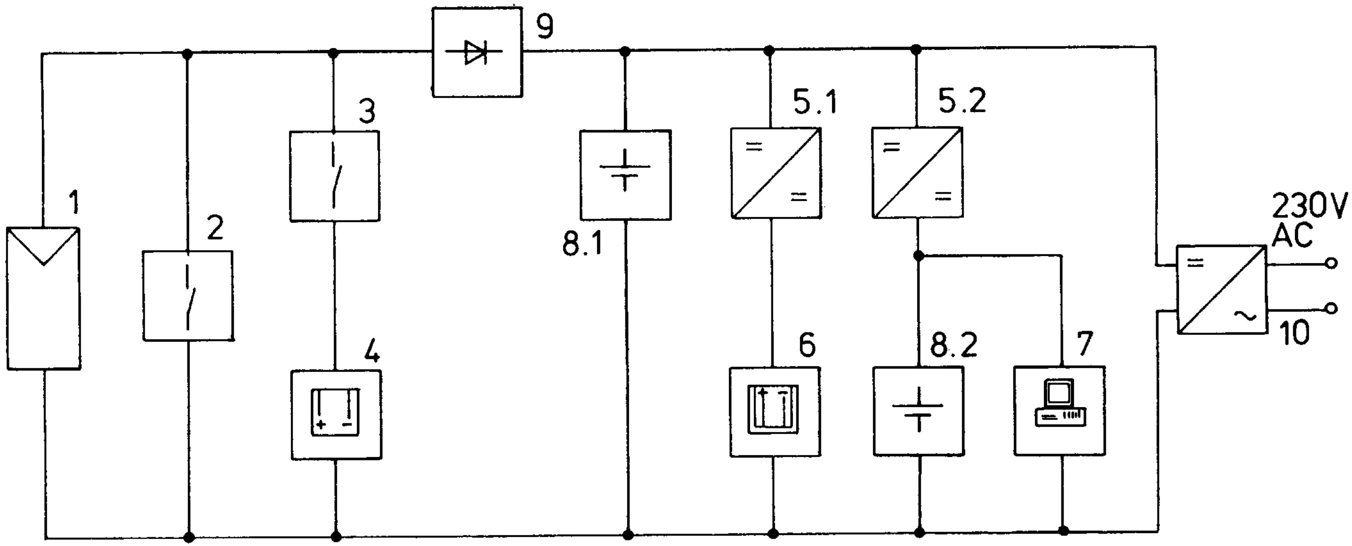

Fig. 14. Diagram of the electrical system. 1: PV generator, 2,3: switches, 4: electrolyser, 5.1, 5.2: DC/DC converters, 6: fuel cell, 7: control and data acquisition system, 8.1: battery, 8.2: battery for the control and data acquisition system, 9: diode, 10: inverter.

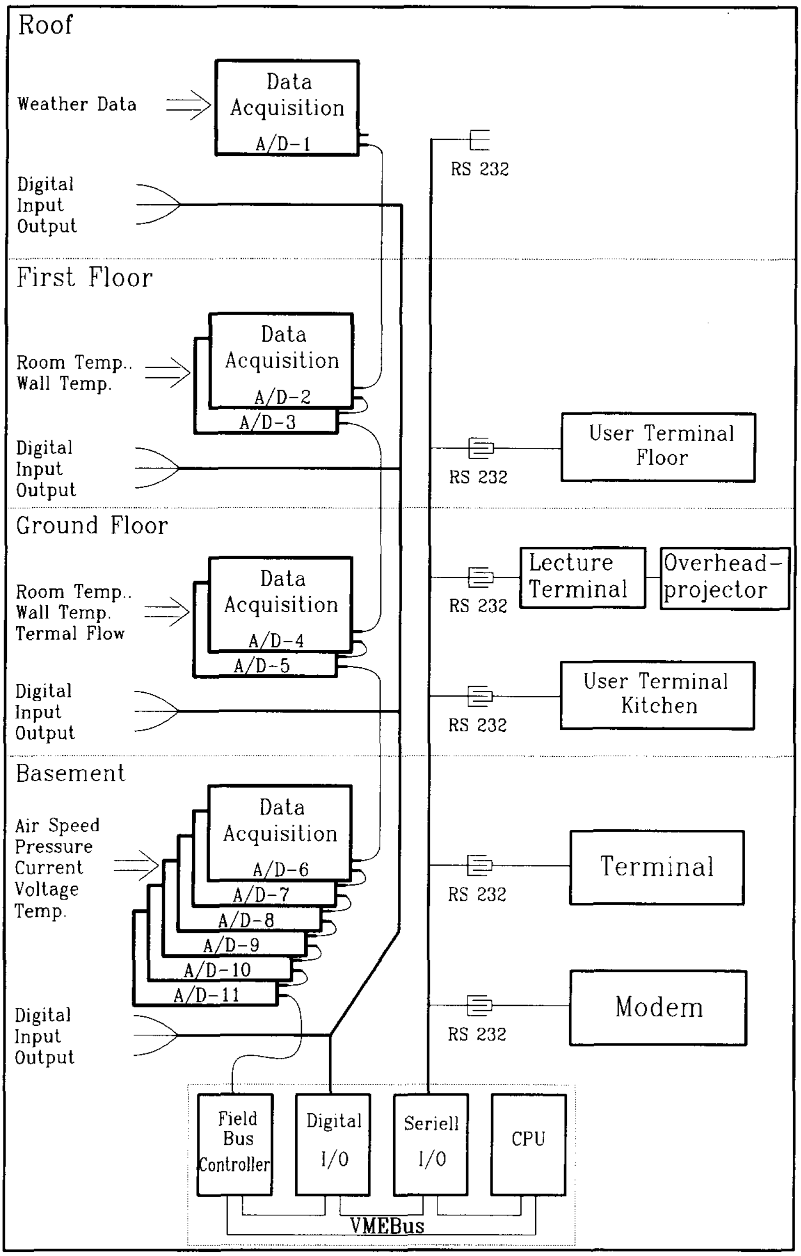

Fig. 15. Control and data acquisition system.

for running purely electrical household appliances. The relevant parameters of the electrical system covering this energy demand are given in Table 7. The size of each component and the orientation and inclination of the PV generator are optimized using the computer simulation.

A computer operated control and data acquisition system is needed to regulate and measure the whole energy system (Fig. 15). Each system has its own CPU so that the control can operate independently of the data acquisition, but the two CPUs can exchange data via a serial interface. An independent battery supplies the power. As almost all control systems and components, e.g. solenoid switches, are available in 24 DC versions, 24 V DC was chosen as the voltage level for the control system. The control and data acquisition system, including two LCD control monitors, has a power consumption of only 80 W, but this results in an energy consumption of 700 kWh/a for continuous operation. This is the same energy requirement as for the whole household, and must also be supplied by the photovoltaic generator. By using self-regulating system components the extent of the automatisation should be kept as small as possible.

HYDROGEN SYSTEM

Hydrogen is a convenient energy carrier, comparable to natural gas. In contrast to batteries, any required storage capacity may be attained without com-

Table 6. Electrical consumption of the household appliances in the SSSH; the German average in 1988 is given for comparison

	SSSH (kWh/year)	German average (kWh/year)
Lighting	88	380
Refrigerator	110	530
Freezer	110	780
Washing machine	146	380
Dishwasher	62	380
TV	28	220
Small appliances	157	600
Total	701	3270

Values listed for the SSSH and the German average are for a four-person household.

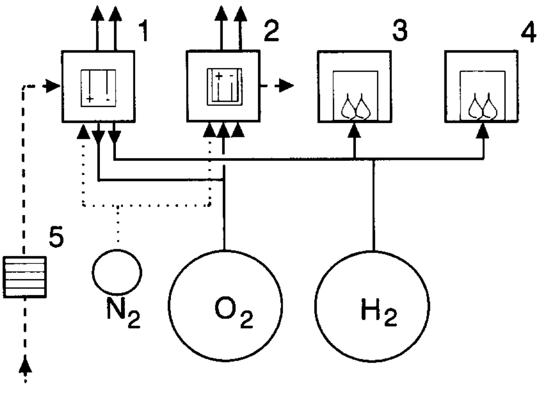

Fig. 16. Diagram of the hydrogen system. 1: electrolyser, 2: fuel cell, 3: catalytic burner in the ventilation system, 4: catalytic stove, 5: water treatment.

mensurate increase in system cost. The concept of a hydrogen system in the low power range with the components is shown in Fig. 16 [13]. To implement this system, the following tasks had to be fulfilled:

- adaptation of commercial devices to the special requirements of the SSSH;
- set-up of a complete, automatic control system according to the safety regulations;
- minimization of the energy demand of the peripheral gas and water management systems.

Depending on the consumption behaviour of the occupants, an overall system efficiency of 65–70% will be reached. The electrolyser has an efficiency of 75%. The consumption of electricity in winter via the fuel cell leads to efficiencies of approximately 42%. The power and storage capacity data resulting from the computer simulation are given in Table 8.

Instead of a commercial alkaline electrolyser a construction with a polymer membrane as the solid electrolyte is used. This type of electrolyser has been developed in the Institute since 1990. Tests have shown encouraging results. The cell stack of the electrolyser consists of 29 cells. The power density is very high, the safety standard is good. The electrolyser operates at a pressure of 30 bar. The long term stability of the performance will be shown in the application. Special adaptations have been made to minimize energy for operation: all valves are pneumatic and no pressure pump is needed for the water supply. An optimal operating point of the electrolyser is at a rated power input of 2 kW. The control system is programmed to operate the electrolyser at the optimal operating point whenever possible. The maximum power is over 5 kW.

Table 7. Parameters of the electrical system

PV Generator	
Monocrystalline silicon solar cells	
84 SM 50 modules, 3.5 modules in series	
Module area	36 m^2
Solar cell area	30 m^2
Power	4.2 kW (peak)
Orientation	South
Inclination	40°
Lead acid battery	
48 batteries, each battery	2 V, 200 Ah
24 in series	48 V
Capacity	19.2 kWh
Lead acid battery for the control system	
11 batteries, each battery	2 V, 75 Ah
11 in series	22 V
Capacity	1.65 kWh
Inverter	
Power	3 kW (peak)

In the case of the fuel cell, only alkaline technology has been available up to now. Recently, the first membrane fuel cells were delivered for testing purposes to the Institute. The performance was not as good as expected, so a commercial alkaline fuel cell was also bought and tested. This fuel cell also revealed some problems: electrolyte creepage and difficulties in the start procedure. Two non-commercial fuel cells were purchased in 1991. One of these cells will be used in the SSSH.

The cooking stove in the SSSH is operated by catalytic combustion of hydrogen with air. The burners of a normal cooking stove will be replaced by burners with porous metallic cylinders. During operation various regions are formed in the cylinders in which hydrogen and oxygen are mixed. The mixing is caused by gas diffusion. The catalytic material in the cylinders allows relatively low temperatures of about 600°C, so the formation of nitric oxides is avoided.

Table 8. Parameters of the hydrogen system

Electrolyser	
Power	2 kW
Fuel cell	
Power	0.5 kW (peak)
Catalytic stove	
Power	2.6/1.7/1.7/1.0 kW (peak)
Hydrogen storage	
Volume	15 m^3
Pressure	30 bar
Oxygen storage	
Volume	7.5 m^3
Pressure	30 bar

ECOLOGY

Although energy is one of the most severe ecological problems today, this will change when more renewable energy sources contribute to cover our energy demand. Considerations of energy pay-back time or—in a wider sense—ecological pay-back time, questions of material recycling, pollution during production, environmental compatibility etc. will influence our lives. The SSSH embodies these ideas in many respects. Concrete and sand-lime blocks are construction materials with a low energy demand for production. Aluminum frames for the TI facade have been chosen despite the energy consumed in production, because a wooden frame would cause high irradiation losses due to the increased frame size. Rain water is collected to be used for the washing machine and the toilets. Except for the electric wiring, no resins containing fluorine are used. The opaque insulation of the north facade is made from recycled waste paper. Foam glass is used for the insulation from the ground.

The energy pay-back time of the self-sufficient solar house is one of the ecological aspects that has been examined in detail. A literature study has shown that the main uncertainties arise in the values for the energy expenditure for production of many components. Electricity was converted in primary energy by multiplication with a factor of 3.

We calculated a primary energy equivalent for the SSSH of approxemately 600 MWh. This is shown in Fig. 17 for different building components. The building's construction, the PV modules and the storage tanks dominate the primary energy equivalent. For the building's construction, the cellar and the ceilings made of reinforced concrete need a lot of production energy. For the TI wall, the aluminum framework is decisive. We assumed an aluminum recycling share of 50%. The PV modules are calculated with a primary energy consumption of 2000 kWh/m^2 module area. A conventional low energy building needs between 150 and 250 MWh primary energy equivalent for construction. Such a house consumes primary energy equivalents per year of assumed 20–40 MWh for heating, domestic hot water and electricity. Therefore, the SSSH will recover the expended energy within 10–20 years. Thereafter this house will provide its services with no adverse influence on the environment. With an assumed building life time of 80 years, the SSSH will save the environment from many tons of pollution.

FINANCIAL SUPPORT AND COST

The project is planned to have a duration of 6 years. The scientific part including planning, simulation, measurements and evaluation is supported by the Federal Ministry for Research and Technology with a total of 5.8 million DM, most of this money being for personnel. The State of Baden-Württemberg has been supporting the development of the H_2/O_2 storage system with 4 million DM. The building lot was supplied by the city of Freiburg at advantageous conditions. The Fraunhofer Society, finally, met the cost for the building's construction. The total cost for the building amounts to 1.6 million DM, of which 0.7 million DM are for all the technical components, electrolyser prototypes, fuel cell and solar collector included. The data acquisition and the control units are more sophisticated than usual. Also the circular shape of the SSSH has turned out to be more expensive than expected. Altogether there is a large cost saving potential for a second generation SSSH.

SUMMARY

The Self-Sufficient Solar House has been built to demonstrate the technical potential of solar energy to replace depletable energy carriers in dwellings. Under the climatic conditions of central Europe, the heating demand dominates the energy consumption. On the other hand, the monthly solar radiation totals are up to a factor of 6 lower during months in the heating season. To store solar energy from summer to winter is one solution which has been applied in several projects. The system efficiencies are low, mainly due to the losses of the storage devices. In the SSSH only solar systems with the highest efficiencies are applied, so it is possible to utilize low solar insolation during winter:

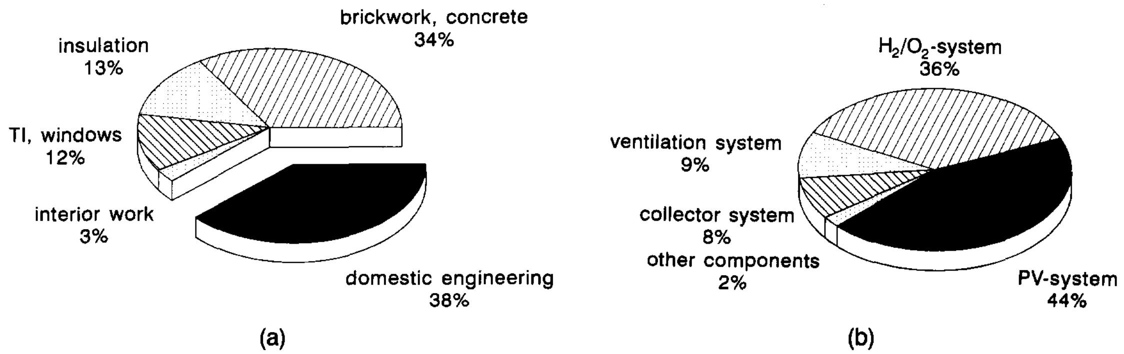

Fig. 17. Energy expenditure for the construction of the SSSH: (a) total building (593 MWh) and (b) domestic engineering (227 MWh).

	Conversion efficiency
Heat recovery in the ventilation system	80%
TI wall	50%
Bifacial illuminated thermal collector	50%
PV array	10%
Electrolyser	75%
Fuel cell	55%
Inverter	87%

Besides the demonstration of the technical potential of solar energy, the project stimulated the scientists responsible to adopt new approaches. Under the constraints of self-sufficiency, it was necessary to optimize the total energy management of the building. On the basis of very good thermal energy conservation measures, it is shown that a dwelling can be heated exclusively by solar energy. In order to satisfy the high quality energy demand by solar energy, it is imperative to use only highly efficient appliances. The fans and pumps are just as important as the household appliances. In addition more than 120 sensors, the data acquisition systems and the control systems in the SSSH are supplied by solar-generated energy. Many new solutions have been needed to achieve an extremely low demand for electricity.

The SSSH is monitored over a period of 3 years. The measurements will be used for the validation of the computer simulations. The operation of the systems is observed and improvements will be made. Immediately after completion the building has been occupied by a family. Besides the physically measurable parameters the inhabitants assess their subjective impressions.

As a demonstration project, the technology of the SSSH is accessible to the public. A wide range from applicable solar technologies to scientific research prototypes can be viewed. The SSSH also shows that solar self-sufficiency can be achieved with pleasing architecture. High thermal comfort is taken for granted in the SSSH.

Acknowledgments—The presented project is the work of many colleagues in our Institute. It is a pleasure to express gratitude and appreciation to all of them for their efforts. The architectural work was done by Planerwerkstatt Hölken & Berghoff, Vörstetten. We thank them for very fruitful cooperation.

The project is supported by the German Ministry for Research and Technology, the State of Baden-Württemberg and the City of Freiburg.

Of great importance are the companies which are involved in the project. We thank the companies AEG Haushaltsgeräte, Deutsche Pittsburgh Corning, Gebr. Schneider Fensterfabrik, Held Fensterwerk, flor design, Kalksandsteinkontor Südwest, Kalksandsteinwerke Birkenmeier, Menerga Apparatebau, Ökologische Bautechnik Hirschhagen, Okalux Kapillarglas, Rud. Otto Meyer, SE-System, Siemens Solar, Solar & Environmental Technologies, Vereinigte Glaswerke and Wiesner & Hager for their financial contribution.

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