Available online at www.sciencedirect.com
SCIENCE DIRECT®
Solar Energy 75 (2003) 469–478
SOLAR ENERGY
www.elsevier.com/locate/solener

Ten years of operational experience with a hydrogen-based renewable energy supply system

P.C. Ghosh *, B. Emonts, H. Janßen, J. Mergel, D. Stolten

Institute for Materials and Processes in Energy Systems (IWV-3), Forschungszentrum Jülich GmbH (FZJ), 52425 Jülich, Germany

Received 31 July 2003; accepted 2 September 2003

Abstract

The PHOEBUS demonstration plant supplied energy to part of the Central Library in Forschungszentrum Jülich, Germany, for 10 years. The technical feasibility of a self-sufficient energy supply system based on photovoltaic, battery and hydrogen storage was demonstrated. The overall efficiency based on the annual energy balance excluding the photovoltaic efficiency varied from 51% to 64%. The battery bank was able to supply energy to the load for three days in the absence of solar radiation. Around 50–52% of the demands were delivered by the battery. In addition, another 20–25% of the demand was supplied by the fuel cell, which indicates that the energy should be stored in a long-term storage system. Thus, the highest level of energetic reliability can be achieved with relatively low battery capacity and hydrogen storage.

1. Introduction

The rapid growth of global climate change along with the fear of an energy supply shortage is creating great interest in the potential benefits of sustainable energy. The natural concentration of CO_2 has increased from 280 to 370 ppm in the industrial era (Conte et al., 2001). To reduce the rate of increase of CO_2 concentration, a shift of the fuels used towards a lower content of carbon is necessary. Hydrogen produced by renewable energy sources can be considered as the zero emission fuel.

Efforts have been carried out to produce hydrogen from photovoltaic on a small scale (Vanhanen et al., 1997; Kauranen et al., 1994; Galli and Stefanoni, 1997) as well as on an industrial scale (Szyszka, 1994, 1998) in different institutes and the hydrogen produced is utilised for stationary and also mobile applications (Hollmuller et al., 2000).

At Forschungszentrum Jülich, Germany a demonstration plant, PHOEBUS (PHOtovoltaik, Elektrolyseur, Brennstoffzelle Und Systemtechnik) was installed in which hydrogen was produced from photovoltaic (Meurer, 1999; Barthels et al., 1998). The produced hydrogen was stored for considerable periods to accommodate the seasonal variations in the solar radiation. In the PHOEBUS plant, hydrogen storage was used in parallel with relatively low battery capacity to achieve the highest level of reliability. In this paper, the operational experience with the PHOEBUS plant is discussed.

2. System description

The schematic diagram of the PHOEBUS plant is shown in Fig. 1. The main components used in the system are discussed below.

2.1. Photovoltaic array

The photovoltaic array was mounted on top of the Central Library (shown in Fig. 2) in four different orientations to reduce the mismatch between the load demand and the photovoltaic output in the morning and afternoon. It minimised the use of the accumulator in

* Corresponding author. Tel.: +49-2461-614013; fax: +49-2461-616695.
E-mail address: p.c.ghosh@fz-juelich.de (P.C. Ghosh).

0038-092X/$ - see front matter
doi:10.1016/j.solener.2003.09.006

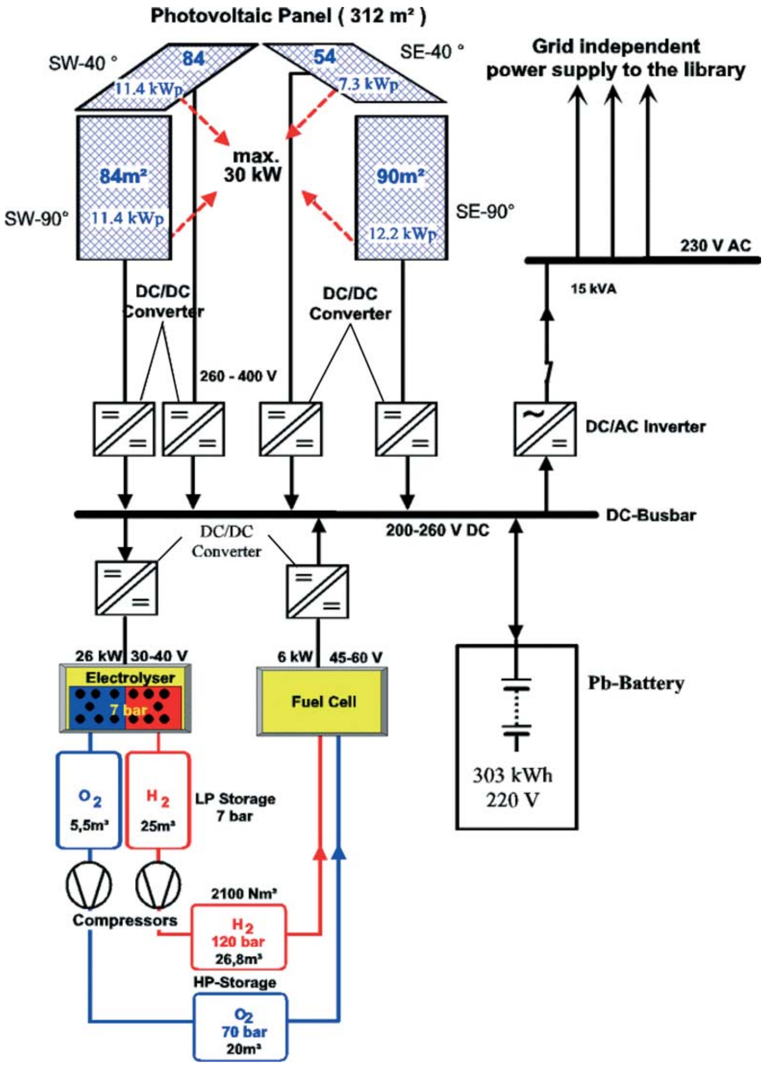

Fig. 1. Schematic diagram of the PHOEBUS plant.

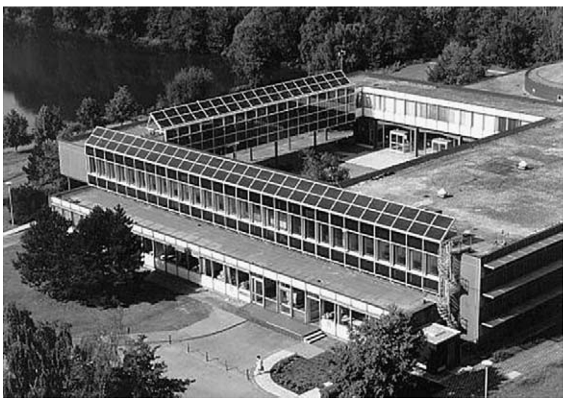

Fig. 2. Photovoltaic arrays on top of the library building in four different orientations.

the system. Two arrays out of four were integrated on the south-east and south-west walls of the library building. In total 312 m^2 (Groehn and Barthels, 1998) of photovoltaic array was installed with a peak-power output of 43 kW$_p$. The details of the different arrays are given in Table 1. Due to the deviation in the orientations of the photovoltaic arrays from the optimum direction (south) the input solar radiation was reduced by 5% but maximum accumulator charging current decreased by 9% (Groehn and Barthels, 1998) which increased the lifetime of the accumulator. Each array was connected to the dc-busbar through a dc–dc converter and MPP (maximum power point) controller. In each photovoltaic array, a total of 600 solar cells were connected in series to achieve a 220 V dc-busbar. The high voltage was selected to reduce the ohmic losses in the cables because

Table 1
Details of the photovoltaic arrays in the PHOEBUS plant

Array	Direction	Inclination angle (°)	No. of modules per array	No. of cells per module	Total area (m^2)
PV1	South-west	40	56	150	84
PV2	South-west	90	56	150	84
PV3	South-east	40	36	150	54
PV4	South-east	90	36	150	54
			36	100	36

the power-conditioning unit was situated around 200 m away from the photovoltaic arrays.

2.2. Battery

The battery bank consisted of 110 lead-acid cells in series to provide the dc-busbar voltage of around 220 V. The battery bank used in the PHOEBUS plant is shown in Fig. 3. The capacity of each of the cells was 1380 A h and, in total, the battery bank capacity was 303 kW h (at 10 A), which could fulfil the energy demand for three days. An aqueous electrolyte and electrode grids with copper are utilised in this type of cells. The gas produced in the battery was vented through the vent caps.

2.3. Electrolyser

The electrolyser used in the plant was developed at Forschungszentrum Jülich and is shown in Fig. 4. Due to the varying nature of the photovoltaic output, it was designed to operate between the power ranges 5–26 kW. The details of the electrolyser are given in Table 2. The oxygen content in the hydrogen produced was lowered from 400 ppm to less than 1 ppm by using a downstream gas treatment system. The electrolyser operated without any major problems for 10 years.

Fig. 3. Battery bank in the system; 110 cells of capacity 1380 A h are connected in series.

Fig. 4. Low-pressure (~7 bar) electrolyser of 26 kW capacity.

Table 2
Details of the electrolyser used in the plant

Anode	Ni/Co_3O_4/Fe on perforated Ni-plate
Cathode	C–Pt on perforated Ni-plate
Diaphragms	Ni-mesh supported NiO
Design	Zero spacing
Number of cells	21
Connection	Series
Electrode area	0.25 m^2
Max. current density	3000 A/m^2
Max. block voltage	35–37 V
Max. operating pressure	7 bar
Max. operational temperature	80 °C
Max. power	26 kW
Min. power	5 kW
Electrolyte	KOH (40 wt.%)

2.4. Fuel cell

In the first phase of operation, an alkaline fuel cell (Siemens BZA 4-2 type) was introduced into the system.

The maximum power output of the fuel cell was 6.5 kW achieved by of 60 cells in series. The technical specifications are given in Table 3. During operation, it was found that the alkaline fuel cell was not reliable, which is undesirable for an autonomous energy supply system. Afterwards an effort was made to develop a 5 kW PEM (polymer electrolyte membrane) fuel cell. However, the targeted power level was not achieved. Finally, at the end of 1999 a PEM fuel cell (shown in Fig. 5) was introduced, which functioned in the system until the end of the operations of the PHOEBUS without any problem. The PEM fuel cell consisted of 33 cells in series with active electrode area 1163 cm^2. However, due to the limitation of the step-up converter in the system it was operated at a lower power level though the fuel cell had the ability to supply higher power. The technical details of the PEM fuel cell are given in Table 4. Due to the unreliable operation of the alkaline fuel cell a fuel cell simulator was introduced to supply energy to the load without any interruptions. The fuel cell simulator was nothing but an energy supply system directly from the grid.

Table 3
Technical details of the alkaline fuel cell

Type	Alkaline
Nominal voltage	48 V
Nominal current	135 A
Rated power	6.5 kW
Open circuit voltage	60 V
Operating pressure	2–3 bar
Start-up time	15–20 min
Operating temperature	90 °C
Electrolyte	KOH (30 wt.%)
Diaphragm	Asbestos fabric
Active electrode area	0.034 m^2
Current density	400 mA/cm^2

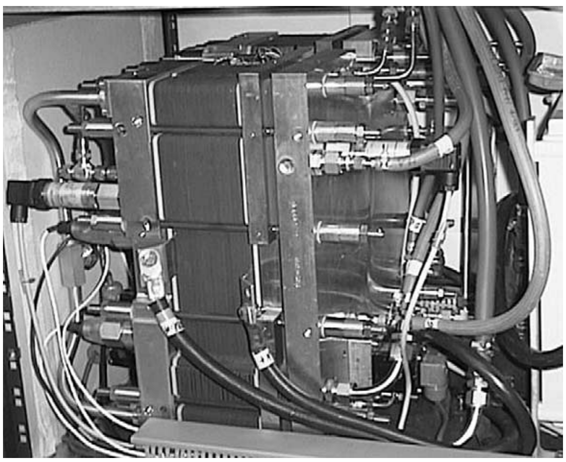

Fig. 5. The PEM fuel cell stack used in the system.

Table 4
Technical details of the PEM fuel cell

Type	PEM
Rated power	5.6 kW
Open circuit voltage	35 V
Operating pressure	2–2.3 bar
Start-up time	Instant
Operating temperature	80 °C
Active electrode area	1167 cm^2
Max. current	200 A

2.5. Tank

In the PHOEBUS plant, tanks were used to store the hydrogen and oxygen produced by the electrolyser for long-term use. Hydrogen has a very low energy density under normal conditions and requires considerable tank volume. To reduce the tank volume, hydrogen and oxygen gases were stored at high pressure. A maximum pressure of 7 bar could be achieved by the electrolyser. The produced gases were stored at first in the buffer tanks and finally the gases were compressed and stored in the high-pressure tanks.

2.5.1. Hydrogen tanks

A 25 m^3 hydrogen buffer tank was used in the system. The maximum pressure of hydrogen in the buffer tank was 7 bar. The volume of the high-pressure hydrogen tank was 26.8 m^3 and maximum pressure was 120 bar.

2.5.2. Oxygen tanks

The volume of the oxygen buffer tank was 5.5 m^3 and the maximum attainable pressure was 7 bar. The volume of the high-pressure oxygen tank was 20 m^3 and the pressure was 70 bar.

2.6. Others

Besides the above-mentioned components, there were other important components in the plant, which are discussed in the following sections.

2.6.1. Compressor

The compressor was used in the system to compress hydrogen and oxygen gases to increase the energy density. It reduced the volume of the tank required for gas storage. At the beginning of PHOEBUS operation, pneumatic piston compressors were used. The compressors were driven by the compressed air of the institute, which is used for different purposes. The advantage of the pneumatic piston compressors is that they are not expensive. However, these compressors are not energy-efficient and more than 100% of the stored energy (Janßen et al., 2001a,b) was required to compress the gases. Thus, the pneumatic compressor for hydrogen was replaced by a metal membrane compressor, which needs only about 9% of the total stored energy for compression.

2.6.2. DC–DC converter

In the PHOEBUS plant, different components operated at different voltage levels. Thus, dc–dc converters coupled these components with the dc-busbar. The battery bank was directly coupled to the dc-busbar and the dc-busbar voltage varied from 200–260 V depending on the charging or discharging of the battery bank. The photovoltaic arrays operated between 260 and 400 V. Thus, the photovoltaic arrays were coupled with the dc-busbar by dc–dc converter. The electrolyser operating voltage was between 30 and 40 V and a step-down converter was used to couple the electrolyser with dc-busbar. A step-up dc–dc converter was introduced between the fuel cell and the dc-busbar because the fuel cell operated between 45 and 60 V.

2.6.3. DC–AC inverter

To serve the AC demand of the consumer, the direct current in the plant was inverted to alternating current by an inverter. The capacity of the inverter was 15 kV A and the output voltage was 230 V AC.

2.6.4. Energy management

There were three different ways to supply energy from the photovoltaic arrays to the consumer. Energy management is nothing but a logical algorithm, which determined the flow of the energy from the photovoltaic to the consumer in the plant to make the system energy efficient. The state of charge (SOC) of the battery played the key role for the energy management in the system. The SOC of the battery was not measured continuously but at time intervals when the battery discharging current was at its minimum level. The dynamic SOC was calculated based on the charging, discharging current and gassing current (Saupe, 1993) in the system. In the entire range of the state of charge of the battery, four critical points were considered, which divided the entire range into the following five different stages as shown in Fig. 6:

- Battery in normal mode
- Electrolyser in normal mode
- Electrolyser in protection mode
- Fuel cell in normal mode
- Fuel cell in protection mode

Of the above-mentioned four critical points, two points were on the upper side of the SOC and the other two points were on the lower side of the SOC. At these points, the transition from one operational mode to another operational mode took place. To provide operational stability to the system at every transition point, a hysteresis band was considered.

2.6.4.1. Normal battery operation. In the region between B′ (20%) and C (80%) during the charging mode and between C′ (75%) and B (17%) during the discharging mode in Fig. 6, the battery operated in the normal mode. In this mode of operation, the battery was normally charged when there was surplus energy in the system after fulfilling the load requirements and discharged when there was a deficit of energy in the system. The electrolyser and the fuel cell were not connected to the dc-busbar during normal battery operation.

2.6.4.2. Electrolyser in normal mode. When SOC reached point C in Fig. 6, the electrolyser was connected to the dc-busbar together with the battery in order to protect the battery from overcharging. Under such conditions, the excess energy after fulfilling the demand of the load is converted into hydrogen by the electrolyser. As a result, the battery discharged if the total demand of the load and the electrolyser was higher than the energy produced by the photovoltaic. Accordingly, the battery was discharged below C. Still the electrolyser operated until SOC reached point C′. In this mode, the electrolyser operated at the rated power. CC′ was the hysteresis

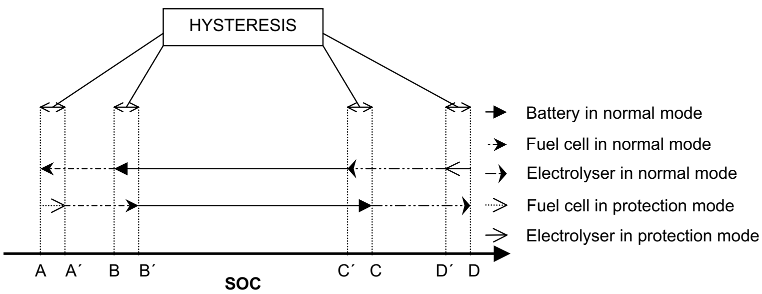

Fig. 6. SOC-dependent five-step energy management.

bandwidth for normal operation of the electrolyser. When the SOC reached C′, the electrolyser was switched off.

2.6.4.3. Electrolyser in protection mode. In spite of the electrolyser operation in the normal mode, the battery was charged if the total energy supply from the photovoltaic was higher than the sum of the energy demand from the electrolyser and the load. In that case, when SOC reached point D (95%) in Fig. 6, the electrolyser was operated at the nominal power, which was sufficient to consume the surplus energy in the system and the battery was discharged. When the electrolyser operated in the protection mode, the battery was always discharged. The electrolyser operated in the protection mode until SOC reached point D′ (85%) as shown in Fig. 6. Thereafter the electrolyser again operated in the normal mode.

2.6.4.4. Fuel cell in normal mode. When the SOC reached point B in Fig. 6, the fuel cell was switched on to protect the battery from deep discharging. In this mode of operation, the fuel cell operated at the rated power. In such a situation, the fuel cell and the battery were connected together with dc-busbar. If there was any excess energy after fulfilling the load demand, it was stored in the battery and charged the battery. When the battery was charged to point B′ then fuel cell was switched off.

2.6.4.5. Fuel cell in protection mode. If the load demand during fuel cell operation in the normal mode was higher than the total sum of the power output from the photovoltaic and fuel cell, the battery was discharged further. In order to boost the battery the fuel cell was operated at maximum power when the battery reached point A (5%) in Fig. 6. The fuel cell operation changed from the protection mode to the normal fuel cell mode when the SOC was increased to A′ (15%). AA′ was the hysteresis bandwidth for the fuel cell operation in the protection mode.

2.7. Load

The energy was supplied to some of the offices in the Central Library, Forschungszentrum Jülich. The weekly load profile is shown in Fig. 7. It is clear from the figure that it is a typical office load profile, which shows five peaks per week on five working days. The annual energy demand in different years and peak power demand is shown in Fig. 8.

3. Operational result

Though the system was put into operation in 1994, the different components in the system were not in regular operation due to various technical problems in the initial phase of the operation. Thus, the result from 1994 to 1996 is not considered for analysis in this paper. The experimental data from 1997 to 2001 are taken into consideration for the present analysis.

The photovoltaic arrays were located on the top and the facade of the library building. The arrays on the facade received less solar radiation. As a result, the outputs of the arrays were also reduced. The annual average losses of radiation in the different years due to the non-optimal inclination of the arrays on the facade with respect to the roof (inclination angle 40°) are given in Table 5. The arrays on the facade facing south-west received around 37–40% less solar radiation with respect to the arrays with an inclination angle of 40°. In the case of the arrays facing south-east the loss varied from 26% to 32%.

The average efficiencies of the photovoltaic arrays were found to be around 10%. The arrays PV2 and PV3

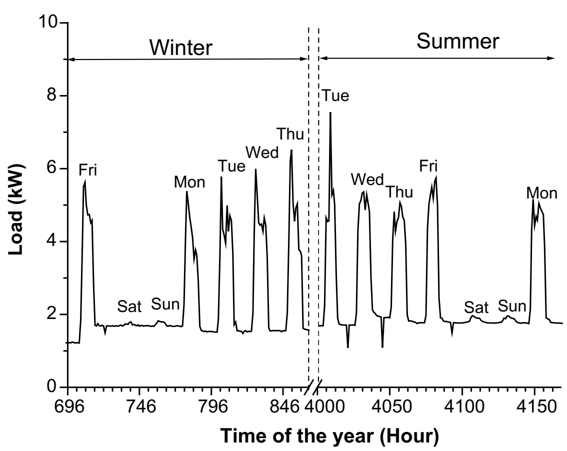

Fig. 7. Weekly load profile in winter and summer.

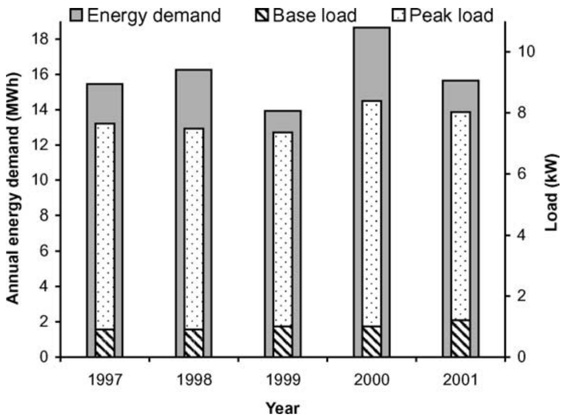

Fig. 8. Annual energy demand, base load and the peak load in different years.

Table 5
Comparison of the solar radiation on the plane with inclination angles of 90° and 40°

Year	Loss of radiation due to non-optimum vertical PV orientation	
	SW (%)	SE (%)
1997	36.7	27.9
1998	39.8	30.5
1999	39.5	31.9
2000	39.6	26.0
2001	40.4	31.6
2002	37.0	26.4

showed better performance with respect to the arrays PV1 and PV4, as shown in Fig. 9.

Besides the individual efficiencies of the arrays, the overall efficiencies are shown in Fig. 10 for different years. In Fig. 10, in addition to the photovoltaic efficiency, the efficiencies of the other main components in the system are also plotted. As the operation of the fuel cell was not regular in the system, it was not possible to calculate the efficiency of the fuel cell. Thus, the efficiency of the fuel cell is assumed to be 50% for the present calculations. The electrolyser showed efficiency of more than 80% after 10 years of operations. The battery efficiency varied between 91% and 95%. The annual charging and discharging energy of the battery measured at the dc-busbar is shown in Fig. 11. The total stored energy in the battery bank at the end of the year 2001 was found to be 91,342 kW h, which leads the full effective cycle (FEC) of the battery equal to 301. At the end of the systems operation (March, 2002), damages were found at some positive poles of the battery due to the growth of the poles. The total stored energy in the whole battery bank at the end was found to be 94,457 kW h, which leads the FEC of the battery equal to 312 (Bringmann et al., 2002). This lifetime is too low for

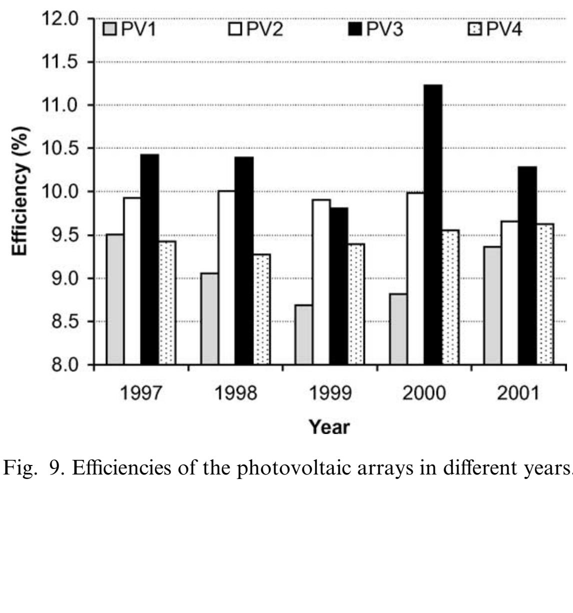

Fig. 9. Efficiencies of the photovoltaic arrays in different years.

stationary application, which is normally expected to be around 535 FEC (Ashari and Nayar, 1999).

In the PHOEBUS plant, there were three different paths for energy flow directly from the photovoltaic to the load, through the battery and through the electrolyser–fuel cell. The contribution of the different paths to the load is given in Fig. 12. The absolute values of the energies given in Fig. 12 are calculated at the output of the inverter. Thus, the efficiency of the inverter is also included in the absolute values. Due to that, the values of the energies contributed by the battery in Fig. 11 differ from the values in Fig. 12. The energy flow through the battery refers to the energy required in the system for short-term storage and the flow through the electrolyser–fuel cell refers to the energy required for long-term storage in the system. It was found that around 20–30% of the total demand was fulfilled by the photovoltaic array directly. Another 50–52% of the demand was fulfilled by the battery and the rest of the demand, which was around 20–25%, was fulfilled by the long-term storage. Thus, the energetic reliability could reach a maximum of 80% without long-term storage in the system. In addition to that, lots of energy would have been wasted during the good solar season, which was utilised in the electrolyser in PHOEBUS plant to provide a more energetic reliable system. The efficiencies of the different paths from the photovoltaic output to the load are shown in Fig. 13. The efficiency of the whole system varied from 51% to 64% excluding the energy coming from the fuel cell simulator. The long-term storage loop had very low efficiency. However, there was not such a great influence on the overall efficiency because the overall efficiency of the system depends not only on the efficiency of the different paths but also on the amount of energy flowing through the path.

Though the PHOEBUS plant was made to fulfil the whole energy demand of the library from the photovoltaic array, this was not always possible due to various technical problems. In addition to that, there was not sufficient energy stored in the long-term storage every year as shown in Fig. 14. Except for 1997, every year there was a deficit of hydrogen, which was made up by the fuel cell simulator. In 1997, the annual solar radiation on the photovoltaic arrays was higher than other years by 10–15%.

4. Lesson learned

The PHOEBUS plant was installed to demonstrate long-term storage using an electrolyser and fuel cell, which increases the energetic reliability of the system. There are some remote applications like telecommunications or medical applications where highly reliable system is required. To achieve the highest level of reliability a very big battery bank capacity is introduced

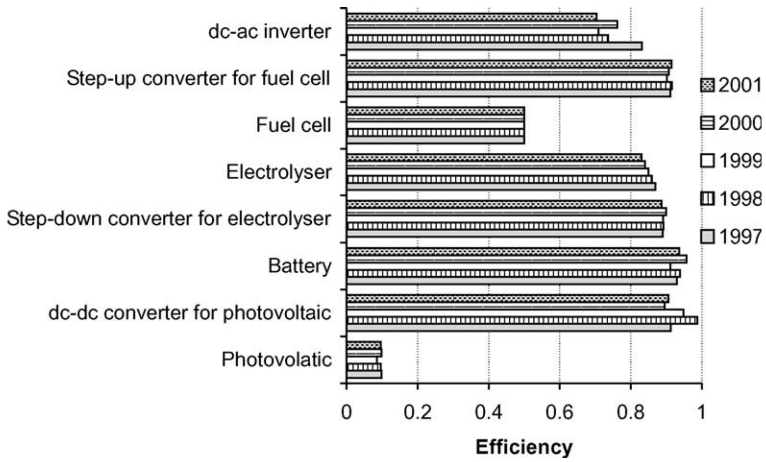

Fig. 10. Efficiencies of the different main components in the system in different years.

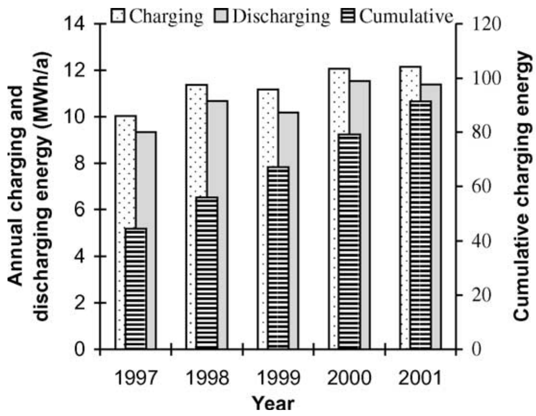

Fig. 11. Annual stored energy in the battery and cumulative energy stored in the battery.

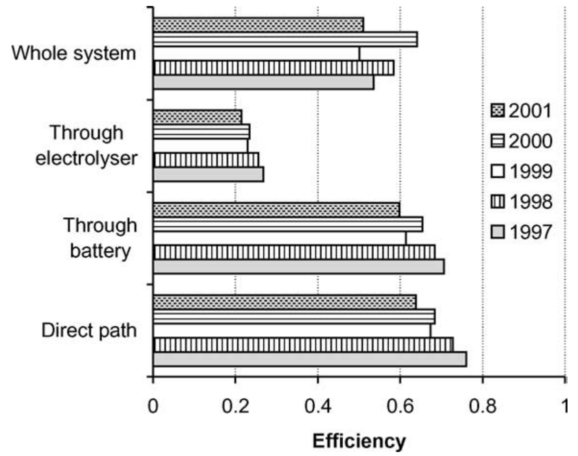

Fig. 13. Efficiencies of the different energy flow paths in the system and the whole system.

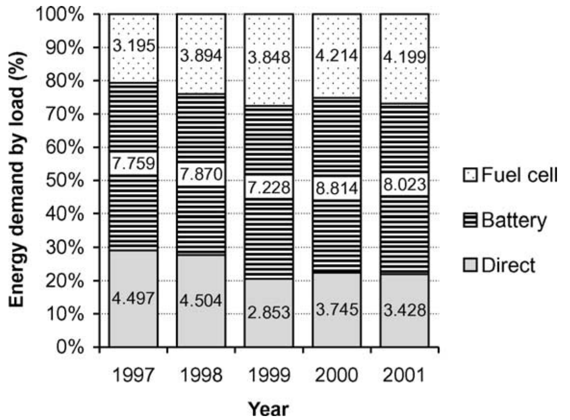

Fig. 12. Contribution of the different energy paths to the energy demand.

into the system, which is not cost effective or eco-friendly. Besides that, a huge amount of energy is wasted in the system during the good period of the year. The PHOEBUS plant shows the possibility of storing excess energy in the good season for long-term use.

The dc–dc converter between the photovoltaic and the dc-busbar was omitted for nine months in 1997. Because of that, the photovoltaic output was reduced by 3%. At the same time, the loss in the dc–dc converter, which was around 10%, was also reduced and the overall efficiency of the system was gained.

In the PHOEBUS plant, oxygen was also stored in the system and utilised in the fuel cell, which increased the investment cost of the system for long-term storage. It is possible to operate the fuel cell with air, which eliminates the oxygen loop in the long-term storage path and reduces the investment cost significantly.

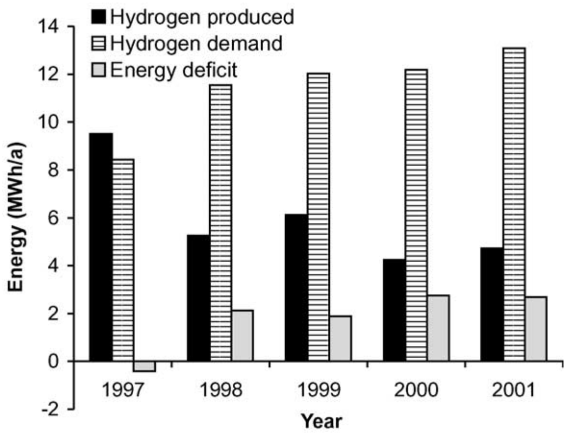

Fig. 14. Annual production of hydrogen by electrolyser, annual hydrogen demand by the fuel cell and energy deficit in different years.

The water produced by the fuel cell was not stored. Thus electrolyser water was wasted at the fuel cell end. To provide an autonomous renewable energy supply system the water produced by the fuel cell should be stored and circulated through the electrolyser.

The energy required to compress hydrogen and oxygen by air-driven pneumatic compressors was more than 100% of the total energy stored. Thus, the pneumatic compressor was replaced by the metal membrane compressor and the energy demand for the compression of the hydrogen gas was reduced to 9% (Janßen et al., 2001a). It was also learned that it is possible to eliminate the compressor in the system by producing hydrogen at high pressure (~200 bar) in the electrolyser. It makes the system simple and the energy consumption for compression can be reduced to 3%.

In the PHOEBUS plant, the electrolyser size was taken to be the same as the photovoltaic size. It is also possible to produce sufficient hydrogen for long-term storage with a small electrolyser size (Ghosh, 2003) without sacrificing the energetic reliability of the system. As a result of that the investment cost of the electrolyser will drop resulting in low investment cost for long-term storage.

Due to the small electrolyser size, it will not be always possible to operate the electrolyser in the protection mode. Thus, the five-step energy management should be modified for small electrolyser size.

5. Conclusions

The experimental results of the PHOEBUS plant show that it is possible to achieve a highly energetically reliable system with very low battery capacity. The battery is used only for short-term energy storage. The contribution from the long-term storage depends on the renewable energy scenario at the site of the application. The contribution of the long-term storage system rises with increases in the seasonal variation of the solar radiation. The seasonal variation of the solar radiation increases with the increase in latitude. The orientation is also very important for the photovoltaic system. It was found from the results that the system could produce sufficient energy to fulfil the long-term deficit. The deficit was found to be in the range of 10–14%. The power output of the array, PV2 could be increased by ~36% and the power output of the array, PV4, could be increased by ~30% by merely modifying the inclination angle from 90° to 40°. This would have been sufficient to produce enough energy to balance the long-term energy deficit from 1998 to 2001.

References

Ashari, M., Nayar, C.V., 1999. An optimum dispatch strategy using set points for a photovoltaic (PV)–diesel–battery hybrid power system. Solar Energy 66, 1–9.

Barthels, H. et al., 1998. Phoebus-Jülich: An autonomous energy supply system comprising photovoltaics, electrolytic hydrogen, fuel cell. International Journal of Hydrogen Energy 23, 295–301.

Bringmann, J.C., et al., 2002. Nine years of operating experience with a lead-acid battery in the self-sufficient PV_Hydrogen Plant PHOEBUS Jülich. In: 8th Ulm Electrochemical Talks, June 20–21, 2002, Neu-Ulm, Germany.

Conte, M. et al., 2001. Hydrogen economy for sustainable development: state-of-the-art and technological perspectives. Journal of Power Sources 100, 171–187.

Galli, S., Stefanoni, M., 1997. Development of solar-hydrogen cycle in Italy. International Journal of Hydrogen Energy 22, 453–458.

Ghosh, P.C., 2003. Cost optimisation of a self-sufficient hydrogen based energy supply system. Ph.D. thesis. Forschungszentrum Jülich, Zentralbibliothek Berichte des Forschungszentrums Jülich, JUEL-4049, Aachen Techn, Hochschule.

Groehn, H.-G., Barthels, H., 1998. 43 kW PV at facades and roofs of a public building—peculiarities in design and operation, thermohydraulic description of the PV modules. In: 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, 6–10 July, Vienna.

Hollmuller, P. et al., 2000. Evaluation of a 5 kW_p photovoltaic hydrogen production and storage installation for a residential home in Switzerland. International Journal of Hydrogen Energy 25, 97–109.

Janßen, H., et al., 2001a. High pressure electrolysis: the key technology for efficient H_2 production HYPOTHESYS IV hydrogen power—theoretical and engineering solutions. In: International Symposium, Stralsund, Germany, vol. 1, pp. 172–177.

Janßen, H., et al., 2001b. PHOEBUS hydrogen makes solar electricity always available, HYPOTHESYS IV hydrogen power—theoretical and engineering solutions. In: International Symposium, Stralsund, Germany, vol. 1, pp. 93–99.

Kauranen, P.S. et al., 1994. Development of a self-sufficient solar-hydrogen energy system. International Journal of Hydrogen Energy 19, 99–106.

Meurer, C., 1999. PHOEBUS—an autonomous supply system with renewable energy: six years of operational experience and advanced concepts. Solar Energy 67, 131–138.

Saupe, G., 1993. Photovoltaische stormversorgungsanlagen mit bleibatteriespeichern—analyse der grundprobleme, verbesserung der anlagetechnik, entwicklung eines simulationsmodells für die batterie. Ph.D. thesis. University of Stuttgart, Germany.

Szyszka, A., 1998. Ten years of solar hydrogen demonstration project at Neunburg Vorm Wald, Germany. International Journal of Hydrogen Energy 23, 849–860.

Szyszka, A., 1994. Neunburg Vorm Wald-Test centre for solar hydrogen technology. International Journal of Hydrogen Energy 19, 823–841.

Vanhanen, J.P. et al., 1997. Operating experience of a phosphoric acid fuel cell in a solar hydrogen energy system. International Journal of Hydrogen Energy 22, 707–713.