Journal of Power Sources, 37 (1992) 271–277

Hydrogen and fuel cells – the clean energy system

B. Rohland
Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW), Pfaffenwaldring 38-40, 7000 Stuttgart 80 (FRG)

J. Nitsch
DLR Stuttgart, Studiengruppe Energiesysteme, Pfaffenwaldring 38-40, 7000 Stuttgart 80 (FRG)

H. Wendt
Technische Hochschule Darmstadt, Petersenstrasse 20, 6100 Darmstadt (FRG)

Abstract

Hydrogen will play an important role in a future energy economy mainly as a storage and transportation medium for renewable energy sources. To illustrate this possible strategy, first a scenario for the FRG is presented as an example, where renewable energies are used in an extensive but technologically achievable way. Renewable shares of 13% (2005), 36% (2025) and 69% (2050) on the total energy demand will lead to hydrogen shares of 11% in 2025 and 34% in 2050. An essential part of such a strategy is the very efficient conversion of hydrogen into useful energies like electricity and heat mainly by fuel cells in the co-generation mode. Fuel cells offer considerably higher conversion efficiencies with respect to electricity and also allow the use of waste heat at different temperature levels. Whereas low- and medium-temperature fuel cells will have advantages if pure hydrogen is used, high-temperature fuel cells offer the possibility to perform a mixed biogas–hydrogen conversion with a high energy yield. Both systems will be discussed and achievable efficiencies and costs are presented in a future energy scenario.

Introduction

Today's energy supply has a considerable impact on the environment. It is clear that our present world energy system cannot be sustained indefinitely. Whether due to limitations in the availability of fossil fuels or due to limitations in the ability of the environment to absorb byproducts of our present energy system, mankind is approaching the day when the present energy system will be unacceptable. It must be the responsibility of governments to assure that appropriate alternatives are available and instituted before a crisis is reached.

Initiated by the Toronto Conference of Climate in 1988, the German Government formulated in 1989 a resolution to reduce the CO_2 emission by 25% by 2005 in the FRG [1, 2]. The path to achieve this goal is given in Figs. 1 and 2. It can be recognized, that the main potential for reducing CO_2 emission is the lower energy use, caused by better heat insulation of our buildings, the compensation of fossil fuels by solar energy and measures for saving all kinds of energy. But this potential is limited. As the human population of Earth continues to expand and as the expectations of that population for material goods and for services increase, the consumption of energy in its various forms continues to grow.

0378-7753/92/$5.00

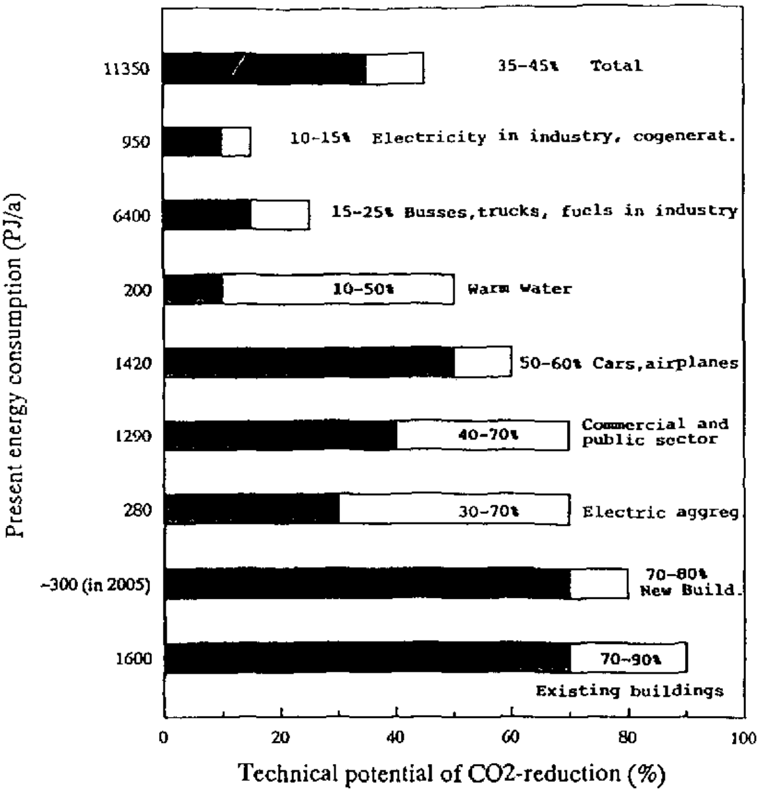

Fig. 1. Technical potentials of efficient energy use in Germany related to corresponding energy consumption, without former GDR; from German Parliament [2].

Approaches to a clean energy system

The ultimate solution to these problems is an energy system in which the harvesting of energy, its transportation and ultimate use cause negligible environmental damage. At the same time energy must be available in quantities and forms which allow for the maintenance of the economic well being of our people and the political and economic security of our nations.

Hydrogen, produced from all kinds of renewable energy sources, is the only energy carrier which can be produced and used with negligible environmental damage. Its production from energy and water and its reconversion in a fuel cell to water and energy is a cycle which can be repeated indefinitely without the production of environmentally damaging byproducts.

Hydrogen production technologies have been and are being developed and commercialized. Hydrogen is routinely produced in large quantities by steam reforming of methane and other light hydrocarbons in natural gas. Hydrogen is also produced commercially by the electrolysis of water. Several technologies are available for this purpose or will be developed. Electrolysis is an efficient process, with energy efficiencies of commercial units in the range of 85%, and developmental units of hot steam electrolysis by solid oxide cells of 90% [3]. Costs of LH_2 from electrolysis compared to fossil fuels and fossil LH_2 are listed in Table 1. Fossil LH_2 will still have 50% of

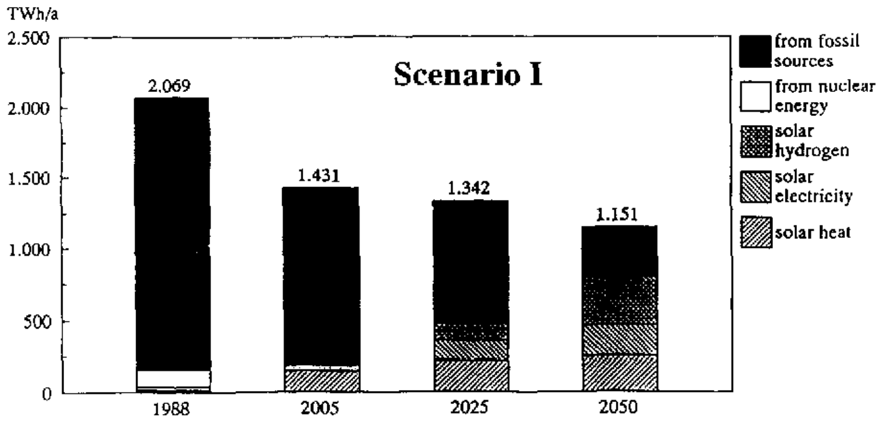

Fig. 2. Share of individual primary energy sources in meeting final energy needs, differentiating for the renewables direct thermal utilization, direct use of solar electricity and the use of solar hydrogen. Source: ref. 1.

TABLE 1

Costs and contents of thermal energies for selected energy carriers

	kW h_{th}/l	DM/kW h_{th}	DM/l gasoline-equivalent	
			1988	2005
Heavy fuel oil	11.7[a]	0.034	0.31	0.31
Diesel oil	10.0	0.109	1.00	1.0
Gasoline	9.1	0.132	1.20	1.2
Natural gas	10.2[a]	0.035	0.32	0.32
Fossil-LH_2	2.64	0.15–0.17	1.35	1.24
Bio-LH_2	2.64	0.27	2.48	2.0
Hydro-LH_2	2.64	0.30	2.73	2.5
Wind-LH_2	2.64	0.59	5.36	5.0
Solarthermic-LH_2	2.64	0.79	7.17	5.0
Photovoltaic-LH_2	2.64	2.80	25.48	5.6[b]

[a]kW h_{th}/kg
[b]Cost-degression according to Nitsch [4].

the hydro-hydrogen costs [5] in 2005, if cost progression of the fossil fuels does not occur. The cost composition of LH_2 from Canadian hydropower is shown in Fig. 3; costs of liquifying are calculated to 11 DPf/kW h.

Of course electrolysis can be linked to such renewable energy sources as solar-, wind- and hydropower. For this linkage fuel cells are the key components in a clean energy system, as can be seen in Fig. 4.

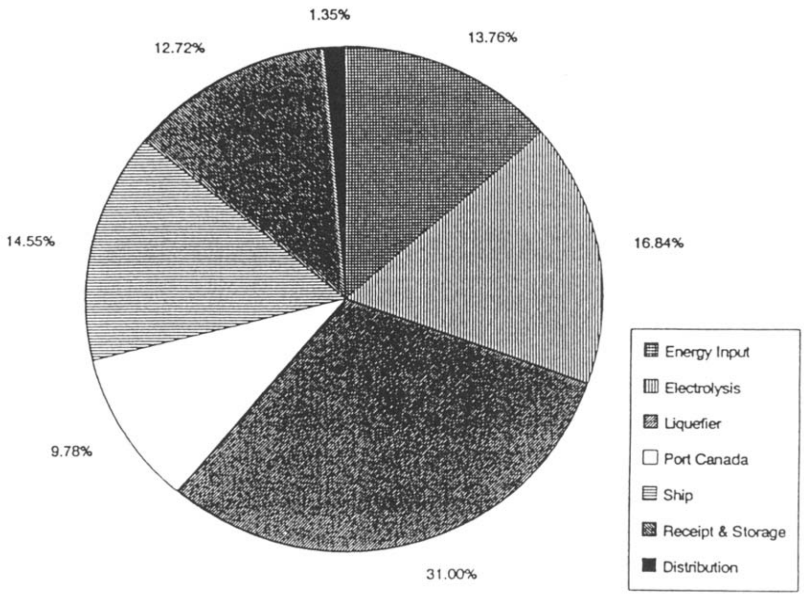

Fig. 3. Cost composition of Canadian LH_2.

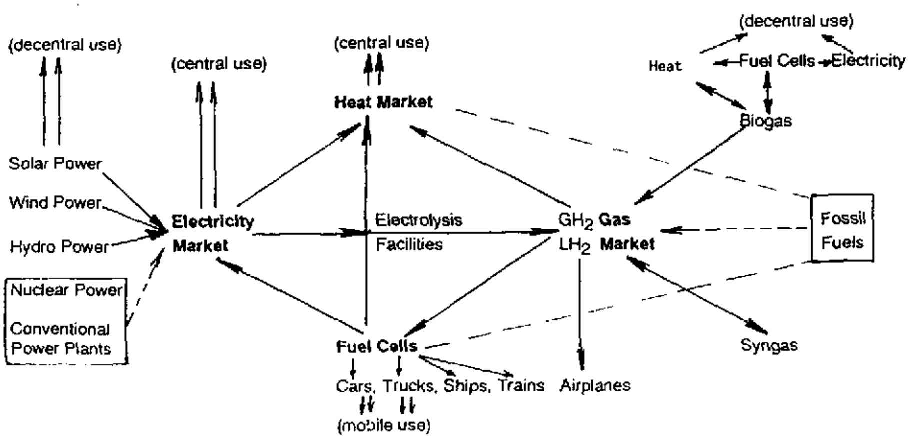

Fig. 4. Schedule of the future clean energy system.

Together with the electrolysis facilities, fuel cells can complete the future energy market, which consists of the market for liquid and gaseous hydrogen, the electricity market and the heat market. Such a system allows energy conversion from the gas market to the electricity and the heat market by use of fuel cells and the reverse by use of electrolysis facilities. Because hydrogen is a medium which can be stored by liquifying, this energy system is very flexible. The main input to this system in the future comes from renewable energies – solar power, wind power, hydropower and biogas. During the transition period, fossil fuels and nuclear power will play an important role, until renewables become established.

Benefits of fuel cells in a clean energy system

From Fig. 4 it can be seen that fuel cells have three inherent benefits:

(1) In combination with water electrolysis facilities, fuel cells are the best option for the integration of renewable energies into the future energy market. They give the possibility of reducing the share of fossil fuels and nuclear power successively in a market-like way, because they also burn hydrocarbons with high efficiency. Whether the integration gives central or decentral use of solar power or biogas is a question of the local energy use situation. In the case of biogas conversion by fuel cells a decentral use can be effective. As can be seen in Fig. 5, the process heat of 100 to 500 kW units of HTFC, e.g. SOFC, can be used effectively in the external steam reforming process of biogas or for flash pyrolysis of biomass [6].

(2) If hydrogen is used as a fuel, fuel cells produce only electric power, usable heat and pure water. The answer to the question – why do SOFCs give negligible NO_x at working temperatures of 1000 °C – is the low air speed in the channels of the FC cathode and the method of activation of oxygen during reaction to oxygen ions. This reaction takes place on the surface of the perovskite cathode and gives no oxygen radicals because the effect of the Co ion orbitals results in increasing O–O bond distance and so ionic oxygen species are rapidly produced, giving no reaction with nitrogen. This is also important for direct catalytic burning of hydrogen by air for production of heat.

(3) Fuel cells have the highest efficiency of conversion of gas energy into electricity (see Table 2). It is particularly true in the case of small units, which can power vehicles in an effective way. The efficiency of fuel cell units in the 10–100 kW range is two times higher than the efficiency of conventional heat engines. This fact is very important if expensive fuels such as liquid hydrogen are to be used for cars. As seen in Table 2, the practical efficiency (which is the product of theoretical multiplied by voltage efficiency at 75% of the maximum power output of the cell) is excellent for the H_2-fueled PEMFC and AFC. For the HTFC the efficiency has about the same value, if methane is converted to hydrogen by internal steam reforming. For conversion of pure hydrogen without the use of process heat for steam reforming the HTFC achieves no more than 50% of the practical efficiency. They must be coupled to a heat user as in Fig. 4, or to an endothermic process used in the metals or ceramic industry. Otherwise the process heat can be used by a secondary steam turbine, although this increases the investment costs.

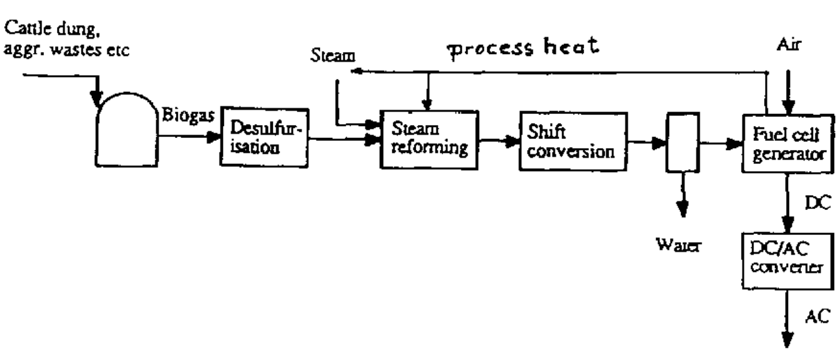

Fig. 5. Fuel cell electricity from biomass fuels.

TABLE 2

Basic data of fuel cells

FC type[a]	Range of temperature (cell) (°C)	Fuel gas (primary)	Oxidant	System components	Electrical efficiencies (%)			Remarks
					Cell		System[b]	
					theor.	pract.		
Alkaline AFC	60–90	pure H_2	pure O_2	cell, water removal unit, (inverter)	83	60		CO_2 sensitive
Membrane PEMFC	*c.* 80	H_2 C(CO) < 300 ppm	O_2, air	cell, water removal, (inverter)	83	60		CO sensitive
Phosphoric acid PAFC	160–220	methane, natural gas, H_2 C(CO) < 1%	O_2, air	reformer, cell, inverter, heat exchange system	80	55	40	CO sensitive
Molten carbonate MCFC	660	methane, natural gas, coal gas, H_2	O_2, air	coal gasifier or reformer; cell, inverter and GuD-unit (bottoming cycle)	78	55–65 47–50 (H_2)	48–55[c] *c.* 60[d]	CO_2 must be recycled internal reforming
Solid oxide SOFC	800–1000	methane, natural gas, coal gas, H_2	O_2, air		73	60–65 44–47 (H_2)	55–60[d]	internal reforming

[a]The cells are named for the type of electrolyte; alkaline: 30 wt.% KOH, membrane: proton conducting ion exchange membrane (e.g. Nafion or Dow membrane), phosphoric acid: 103% H_3PO_4, molten carbonate: molten Li_2CO_3/K_2CO_3 eutectic, solid oxide: stabilized ZrO_2.

[b]Basis: methane, 80% utilization of fuel gas in the cell; oxidant: air (with coal gas, the system efficiency decreases by 8–10%), reference: heating value.

[c]External reforming.

[d]Internal reforming, 70% efficiency is possible on improvement of cell.

Conclusions

The development of fuel cells and the development of hydrogen technology can promote one another. An example is the Hysolar building in Stuttgart (Fig. 6) and its enlargement in combination with a fuel cell power plant by Solar-Wasserstoff-Bayern. This means that liquid hydrogen will be more attractive when fuel cells become available devices, because its effective conversion into electricity becomes much easier. Then it will not be recommendable to burn the expensive LH_2 in a heat engine with an efficiency of lower than 20%.

Fig. 6. Hysolar building in Stuttgart, FRG.

References

1 *Bedingungen und Folgen von Aufbaustrategien für eine solare Wasserstoffwirtschaft,* Untersuchung für die Enquete-Kommission des Deutschen Bundestages 'Technikfolgen-Abschätzung und Bewertung', Ottobrunn, FRG, 1990.

2 *Technikfolgen-Abschätzung und Bewertung,* Bericht der Enquete-Kommission des Deutschen Bundestages, Bonn, FRG, 1987.

3 W. Dönitz, E. Erdle and R. Schamm, SOFC technology — status of development in Germany, *Proc. CEC-Italian Fuel Cell Workshop, Taormina, Italy, 1987.*

4 J. Nitsch, *On the Way to a Solar Energy Economy,* Internal Study, DLR, Stuttgart, FRG, 1991.

5 D. Klyuskens, O. Ullmann and R. Wurster, *EQHHPP, Phase 2, Executives Summary,* Draft Version, Munich, FRG, 1991.

6 H. Wendt, V. Plzak and B. Rohland, Conversion of biogas, biomass obtained gases in SOFC, *Proc. 2nd Int. Symp. on SOFC, Athens, Greece, 1991.*