Very Long Term Energy-Environment Model (VLEEM)

Monograph on Fuel Cells

for stationary application

prepared for VLEEM

K.U. Birnbaum

Forschungszentrum Jülich GmbH

Systemforschung und Technologische Entwicklung (STE)

The role of the fuel cell

In most industrialised countries area-wide energy supply structures were built up, which ensured a high measure of supply security and which have transnational linkages. Due to technical developments and possibilities power stations with capacities within the GW-range were developed and installed, to deliver the predominant proportion of the power input to the grid.

The liberalisation of the electricity and gas market in the European Union causes extensive consequences for the existing structure of the energy market. Important and central elements of the reorientation respectively the market-opening are:

- separation between production and distribution,
- free access of energy producers to the distributed network and
- free selection of the power supplier for all customers.

An important aim of the liberalisation is larger competition among the producers, which should lead to sinking electricity prices. In the Federal Republic of Germany that was achieved at first, the electricity tariffs fell, whereby the reduction for the consumer group "households" was quite small.

The new competition, which started with unequal suppositions for the different European generators, became problematic for some of the small ones in Germany. Due to the missing sale warranty for electricity, smaller enterprises came into economic difficulties, because their maintenance, fuel costs or also capital costs were too high to be competitive to others. The German power suppliers are sure that the high quality (frequency stability) and reliability level of the power supply cannot be preserved at sinking prices. That leads to the question whether all consumers or applications need that high electricity quality. Some suppliers do develop concepts, to install measurements to ensure a high electricity quality at the consumer if it is needed. That electricity will be more expensive than the normal one.

The change, in which the electricity supply industry is, also gets stimulation from another corner. It is the concern about the finiteness of fossil resources as well as the concern about a further increase of climatic relevant pollutants, which favour on the one hand the development of concepts, to achieve a more efficient energy use on the basis of conventional primary energy carriers, and on the other hand the transition to "new" sources of energy and the increased use of renewable energy sources.

An important item of these conceptions are techniques for combined heat and power production. They can be operated with "cleaner" fossil fuels (natural gas) or also with regenerative sources of energy, the degree of fuel utilisation is higher than with the separate production of electricity and heat, whereby it is however presupposed that the produced heat can also be used and is not transferred to the environment due to a lack of demand.

From the circumstances that there are only a few industrial sectors with a continuous, high demand for heat (e.g. refinery or chemical industry) and usually no district heating networks or customers of really large amount of heat, the combined heat and power plants have normally less capacity than the typical central power stations.

The change of the structure of the energy supply system, at least the electricity supply, touches thereby also the area "centralised or decentralised (local) system". By the term "decentralised" smaller systems are understood, which are attached to distribution networks, but which are usually not integrated into power station operational planning, i.e. they are not used for the reliability of the public electricity supply.

It is expected that the fuel cells fulfil a majority of that which is demanded from the future energy production techniques, e.g. higher efficiency, less environmental impacts, high performance and so on.

Principles

In a conventional power generation process, see fig. 1, you have several conversion steps: first the chemical bounded energy is converted to heat energy by burning. The heat generates steam in a water/steam cycle. The steam, which is standing at pressure, is relaxed over a turbine and thereby carries out rotation work, it shifts the turbine into a rotary motion and with it a generator too. That generator generates electricity. Each process step has it's own efficiency losses, whereby the highest losses happen with the steam.

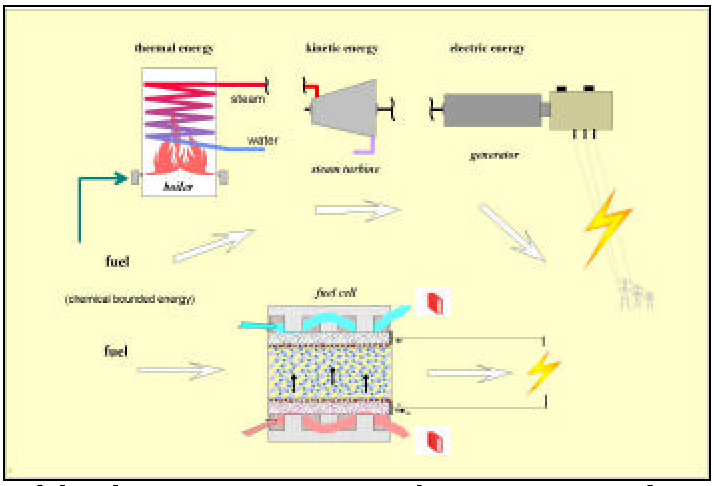

figure 1: principles of the electricity generation with water/steam cycle and with the fuel cell

The fuel cell process does not make that detour, it converts the chemical energy of the fuel directly to electricity. Electrons are devided from the fuel by eletrochemical reactions. They are transmitted via an external line from the one electrode to the other and can do electric work, if an electric consumer is present. Heat descends from the chemical reaction heat.

Because of the direct generation, the electric efficiency of the fuel cell process has theoretically a very high potential, as the Carnot-limits don't be valid. Its energetic conversion rate is given by the relation[1]:

$$\eta^{BZ} = \frac{\text{Produced Energy}}{\Delta H} x 100 (\%)$$

The value ÄH represents the corresponding enthalpy change of the combustion reaction. In contrast to normal thermal combustion, however, in which the total reaction enthalpy ÄH is converted into heat, in a fuel cell only the energetic fraction ÄG (free reaction enthalpy) is directly converted into electricity, i.e. the maximum theoretical efficiency ç$^{BZ}_{max}$ is given by the formula:

$$\eta^{BZ}_{max} = \frac{\Delta G_T}{\Delta H^0} \times 100 \ (\%)$$

where ÄG$_T$ is the value of the free reaction enthalpy at the cell operating temperature T_C and ÄH^0 the standard value of the reaction enthalpy.

The thermodynamic relations indicate the maximum possible energy which a fuel cell can supply, it is more a theoretical value. In real operation, however, energetic losses occur which may have to do with the kinetics of the electrode reactions, the structure of the cell and/or with the process flow.

[1] http://www.fuel-cell.de/allgemeines/prinzipien/index-e.html

The main differences between the several fuel cell types and their characteristics are pointed out with figure 2. The heart of the fuel cell is the Anode-Electrolyte-Cathode unit, where the chemical reactions are running.

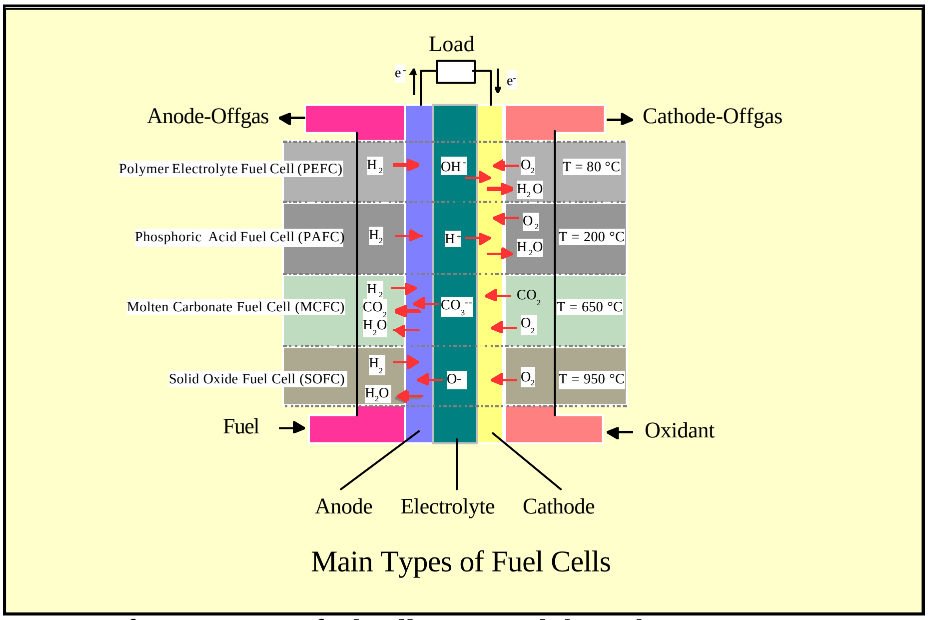

figure 2: main fuel cell types and their characteristics

The art of the electrolyte is one distinctive feature. You can differ the fluid ones and the solid ones whereas there are for each group two subgroups.

The one representative of the group with a solid electrolyte is the Polymer Electrolyte Membrane Fuel Cell, called PEFC or PEM. It uses as electrolyte a thin polymer foil. The other one is the Solid Oxide Fuel Cell (SOFC) which has a solid oxide-ceramic as electrolyte.
The two other types are equipped with a fluid electrolyte, for the Phosphoric Acid Fuel Cell (PAFC) it is phosphoric acid and for the Molten Carbonate Fuel Cell (MCFC) it is a carbonate-mixture of lithium and potassium, which melts at around 500°C.

A second criteria is the operating temperature of the different types. They are divided in the category low temperature fuel cells and high temperature fuel cells. The two first types in figure 2, the PEFC and the PAFC, operate at around 80°C resp. at 200°C and are associated with the low temperature ones. The MCFC and the SOFC do operate at a temperature level of more than 600°C and are so called high temperature fuel cells.

From figure 2 one can see, that hydrogen is a main component of the chemical reactions. Therefore hydrogen is so to say the fuel you need to operate a fuel cell and it has to be reformed from the energy carriers, which can be used with a fuel cell, as coal gas, natural gas, bio gas, waste gas, landfill gas or fluids as methanol and other. The requirements concerning the pureness of the fuel-gas or the hydrogen depend on the special thermodynamic and kinetic conditions of the cell type, on the sensitivity of the applied catalytic material and from the operation temperature. The coherence between these coefficients is demonstrated in figure 3. Additional the allowable sulphur and carbon-monoxide contents in the fuel are included in the figure. The requirements are very high for the low temperature fuel cell and they decline for the MCFC with its high operating temperature as well as for the SOFC. All types are damageable by sulphur and some are tolerant with carbon-monoxide.

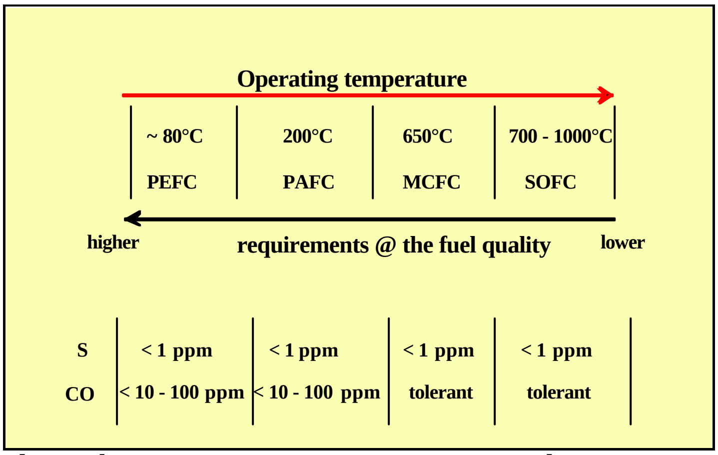

figure 3: relation between pureness requirements and operating temperature

Components of a fuel cell system

Fuel cells are built up very modular, so that the manufacturer can vary the unit-capacity by reducing or multiplying the cells and the stacks (a couple of cells are gathered in a stack). It is ensured, that the high efficiency is maintained whether the fuel cell has a small capacity or a big one, more decisive is the adjustment of the whole other system aggregates. For a PEFC-system figure 4 gives a rough survey of the main groups as the fuel-/air-system, the auxiliary components, stack elements

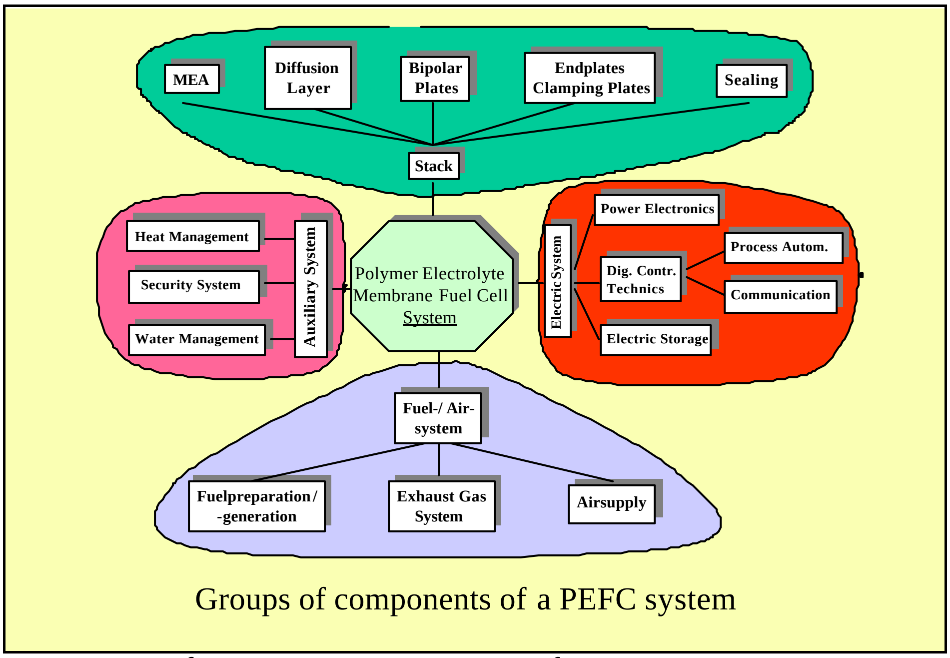

figure 4: main components of a PEFC-system

and the electric system, which enables the operator to feed the electricity into the network. It seems that especially the small heat exchange systems are not yet optimised so that research and development activities are necessary.

The heart of the fuel cell is the stack with the components electrolyte/electrodes assembly (at the PEFC called Membrane Electrode Assembly) with the diffusion layer, the bipolar plates, the clamping plates and the sealing, which is one of the most important aspects for the SOFC as the different materials have different coefficients of expansion. That can lead to destruction of the sealing.

Even for those fuel cells which have a liquid electrolyte as the PAFC with phosphoric acid and the MCFC with molten carbonate the sealing is a very important component, which has to remain intact, as the phosphoric acid and the carbonate are very aggressive.

The second important field is the fuel-/airsystem. Fuel cells need hydrogen which must be reformed from other fuels. The reforming process is well practised for industrial processes with high flow rates, which lead to great production capacities. Looking to households or cars, we do find plant capacities of less than 10 kW_{th} or up to 100 or 200 kW_{el} when apartment houses are regarded. Passenger cars of the compact class have drive power up to 60 kW, that means 60 kW_{el}. Instead of a flow rate of thousands of m^3 per hour there are flow rates of only some ten m^3 and the reformer has to be very small, as all components have to be very small, if they shall be installed in a passenger car. Their output will not be higher even if they are foreseen for a household. A difference is to be seen in the fact, that the flow rate will pulse when installed in a car. In general the dimension and the light weight are a problem. This can be seen from the strategy of Daimler Chrysler. Instead of realising the fuel cell passenger car, they try to realise the mobile application via busses and vans. One of the main reasons for that strategy seems to be the problem which they have with reducing the dimension and the weight.

The auxiliary system is the third component group. For the PEFC the correct water management (humidification) decides on ”to be” or not ”to be”. If the membrane will fall dry, its function will stop. If it becomes too wet, the same effect will happen.

The forth component package is the electric system with the power electronic, the digital process control technique and at least the power inverter. That is a large field for research and development, as it seems, that the actual state is not able to transmit the theoretical advantages of the fuel cell to the practical use.

But nevertheless, using components and aggregates, which are optimised and synchronised on each other, the system efficiency of a fuel cell will be better than of conventional systems as it is a special attribute of them, that the electrical efficiency is not bounded to a certain/optimal performance size as it happens often with other techniques, as shown with the overview in figure 5.

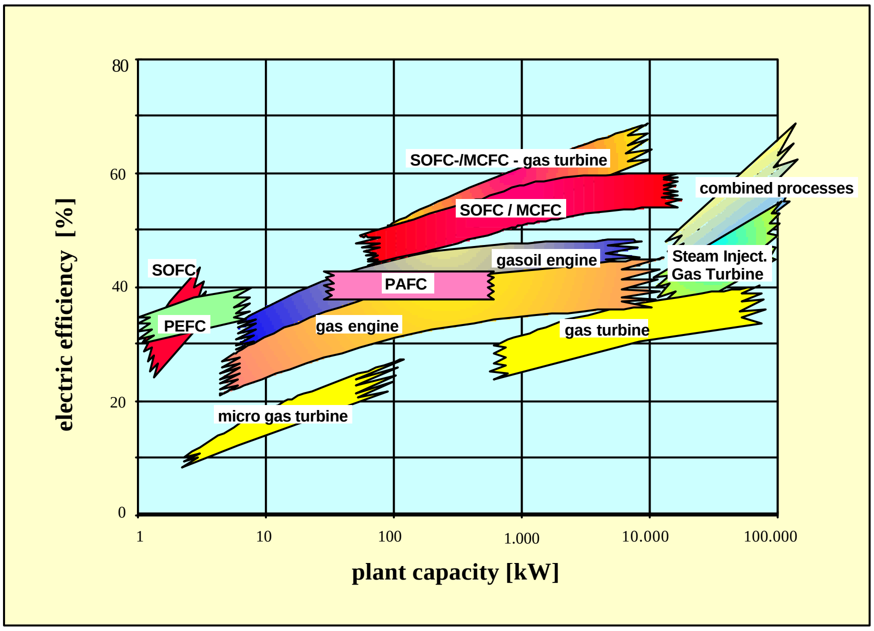

figure 5: relation between plant capacity and electric efficiency

The ranges of the fuel cell values have to do on one hand with the early stadium of development and on the other hand with the expectation, that a couple of aggregates will become better, as far as the fuel cells will find its market and will be manufactured in mass production.

Stationary applications

Due to its positively regarded characteristics the fuel cell is already deemed to be a key technique for the local (decentralised) generation of electricity up to a capacity range of 10 MW. They will compete with other established techniques and they will complete the broad field of energy production techniques for that range as:

- internal combustion engines,
- gas turbines,
- micro gas turbines as well as,
- solar and wind-powered devices.

With the today's status of development three capacity categories appear conceivable for fuel cell stationary application, whereas the chances for realisation differ a little:

- 1 – 10 kW_{el}
  PEFC: because of the low operating temperature it can be manufactured from relatively simple and low cost materials; it has great advantage to use a solid electrolyte material (synthetic foil).
  SOFC: the high operating temperature makes the fuel cell insensible against impurities.
- 200 kW_{el} and larger
  PAFC: it is ready for commercialisation, but it has less perspectives for upgrading the efficiency or for reducing the investment costs (less developing perspectives)
  MCFC: the temperature level of the discharged heat is suitable also for operation of heat networks and steam sterilisation, which is used in hospitals
- 1 MW_{el} and more
  SOFC and/or **SOFC-GT** (combined with gas turbine), very high electrical efficiencies, high temperature level of the heat

Figure 6 summarises once more the competitors and the expected differences with regard to the important parameter "electrical efficiency".

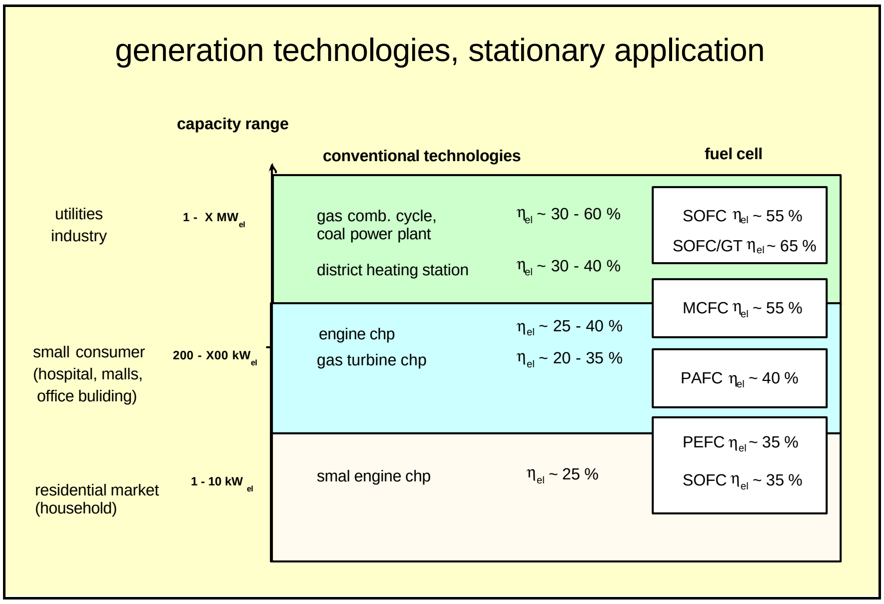

figure 6: discussed capacity ranges and fields of application for fuel cell systems

In Germany the residential market is a most important final energy consumer, with a share of ~ 30%[2]. Around 75% of the final energy is used for room heating in the houses[3]. The contribution of this sector to the total carbon dioxide emission has a range of around 13%[4] and can be seen as an additional motivation for the search for new and better solutions. The fuel cell is handled as one of such better solutions and R&D activities did already start.

The heating system manufacturers Vaillant, Buderus, Viessmann or Bosch-Junkers are developing house fuel cell systems on the basis of the PEFC technology. (Also companies as Siemens, ABB and even EdF invest in research and developing in that field, as they see it as an attractive tomorrow's market.) From their opinion, the low operating temperature of only 80 °C enables for example the use of simple and cheep materials, so that the price for such a system will become competitive and acceptable by the end-user. Supposition for the PEFC is the availability of hydrogen, which is generated on site from natural gas, which is common in many German households, or which is generated in a central plant and distributed with a hydrogen network.

The Swiss company Sulzer-Hexis develops a fuel cell house energy system on the basis of the SOFC concept. They do represent the opinion that the SOFC-characteristic will alleviate the system-change, as there is no need for a complicated fuel preparation system as the SOFC can be operated with natural gas.

Table 1 gives an overview of some German/European fuel cell house energy concepts which are under construction/development and tested with first demonstration programs.

	PEFC	PEFC	PEFC	SOFC
european developer	Vaillant	HGC	Buderus	Sulzer-Hexis
capacity	1 - 4,6 kW_{el} / 1 - 7 kW_{th} (plus an auxiliary unit for 28 kW_{th})	3 kW_{el} / 8 kW_{th} (increase of current production on 5 kW_{el} for short time by battery)	4,5 kW_{el} / 6,5 kW_{th}	1 kW_{el} / 2,5 kW_{th}
status	laboraty tests: since 2000	fieldtest: since 1999	planning state	fieldtest: since 1998
first market segment	residential sector (multi-family dwelling)	residential sector (multi-family dwelling)	residential sector (multi-family dwelling)	residential sector (one family house)
comments	cooperator: **Plug Power** (USA), has experience with serial production of house energy systems	cooperator: **Dais-Analytic** (USA)	cooperator: **UTC Fuel Cells** (USA)	Planar system; cost reduction potential by synergetic effects or Know How exchange

table 1: concepts of fuel cell systems for the residential market in Germany

There cannot be any doubt, that the fuel cell systems will not be able to supply by its own the heat and/or electricity demand of a today's houses. The required heat capacity for room and water heating depends on the square meter of the flat or the house but it starts at around 10 kW_{th}. The connected load of the electric appliances in a German household reaches quickly 20 to 40 kW and figure 7 shows the load curve of a free standing house where two adults and two children are living. The electrical load curve was calculated with a time interval of 10 seconds, whereas the heat demand curve was calculated with an interval of 20 minutes. The electric load shows a very high fluctuation with very short intervals.

[2] Arbeitsgemeinschaft Energiebilanzen
[3] Geiger, Wittke, BWK Bd54 (2002) Nr. 1/2
[4] Daten zur Umwelt 2000, Umweltbundesamt

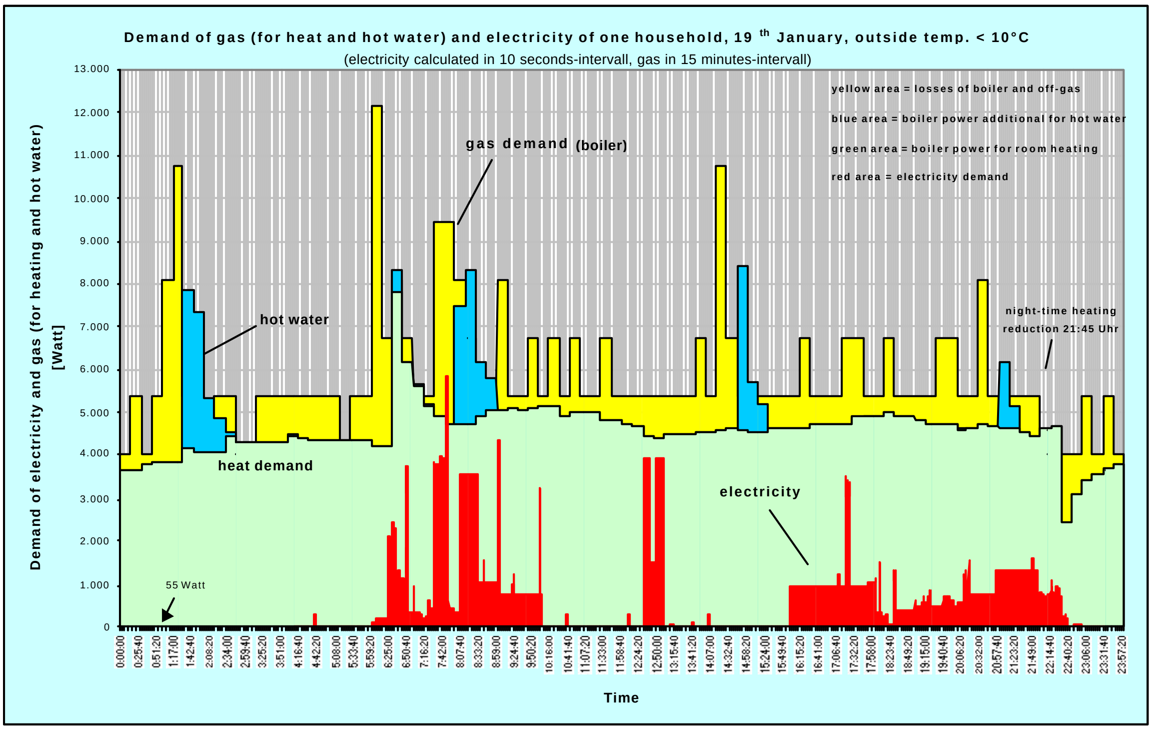

figure 7: load curves of a free standing one family house, built in 1990

Regarding such curves, there is less doubt, that a fuel cell system will not be able to supply the house demand by it self. It can only be operated in such a house-type as a system which works together with the electricity network. In that case it can be imagined, that the electricity from the fuel cell is feeded in the network whereas the heat is used for the house-demand. A storage and a peak boiler would ensure the heat supply.

One can imagine, that the situation will change with the new low energy house concepts. These types will have a better insulation, an optimised construction avoiding cold-bridges and air leakages to get by with 70 kWh/m²a. Figure 8 shows the development of the specific heat demand in new residential buildings, due to the legal regulations. The today's standard (since 2002)

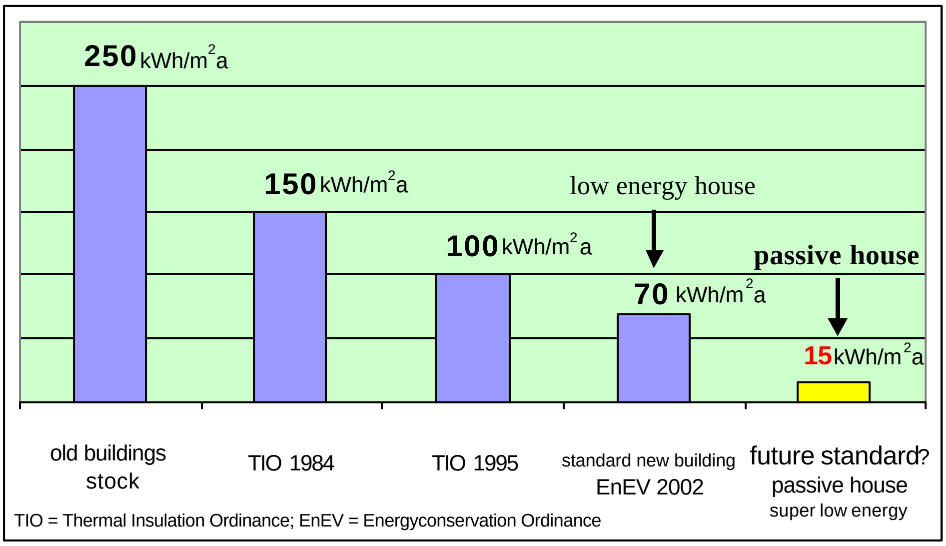

figure 8: development of the specific heat demand due to the Thermal Insulation Ordinances

is not more than 70 kWh/m²a for the so called low energy house. The ongoing development will lead to the passive house, which will have a more efficient conception with a regulated ventilation,

a heat-recovery system and other energy saving components so that the heat demand can be reduced to a minimum. Passive house means also new high efficient electrical devices, to reduce the electricity demand too.
In such future house configuration the use of small fuel cell systems can be imagined. It can be assumed, that fuel cell systems will not be installed in old buildings as the operating conditions will not be good enough. The conditions will change, if multi-family houses or residential settlements are regarded. In that case, the electricity demand will have a more balanced curve progression so that the combined heat and power production of the fuel cell can be better used. That requires larger capacities and leads towards further energy consumer sectors as trade, commerce and services as mentioned with figure 6. Even if a 200 kW PAFC system is available, there are less units in commercial application, so that one can say, that that system has not yet proved itself. A 300 kW-MCFC-concept of MTU is tested in several application as in a central heating station, in a hospital and an energy supply system for tele-communication, but up today it is still demonstration under real condition and not application as a market competitor.

The situation in the market segment industrial use and power plant is comparable, as there is less experience. Well known in Europe is a 300 kW SOFC-system, manufactured by Siemens-Westinghouse and tested in the Netherlands for a couple of years as a combined heat and power plant. Actual the Siemens Power Generation Group (PG) is to build for the very first time a close-to-series fuel-cell power plant in Europe[5]. Under contract to Stadtwerke Hannover AG and E.ON Energie AG a standardised SOFC plant with a maximum electrical capacity of 250 kilowatts is to be built in Hanover on the site of a power plant by 2003. The high-temperature fuel-cell power plant valued at around EUR 5 million, which PG will be supplying on a turnkey basis, will in normal operating mode feed 225 kilowatts of electrical energy into the grid operated by Stadtwerke Hanover. Simultaneously some 160 kilowatts of heat will be generated for the district heating network.

Economical aspects

That last paragraph gives a hint at the biggest barrier for the commercialisation of fuel cells. Beside technical difficulties (as reducing dimensions or/and weight) there are economic aspects which do not look really good. The costs of the most advanced demonstration projects in Europe are still well above commercial targets. Publications on investment cost of fuel cells present a confused picture as the range is extremely wide. Figure 9[6] shows a summary of estimated cost data for several fuel

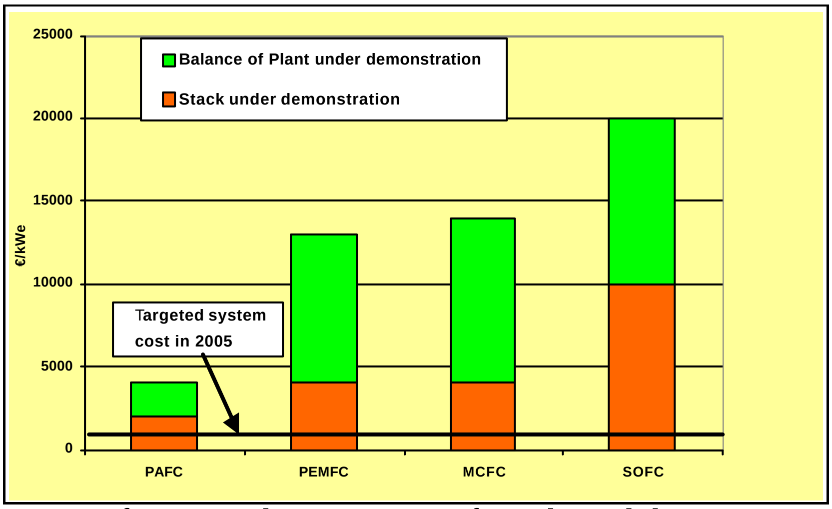

figure 9: specific cost under construction for industrial demonstration units

[5] http://www.pg.siemens.de/en/press/pg200202014/index.cfm, February 26, 2002
[6] Fuel Cells Powering the Future – Sustainable Power for the European Union, EC EUR nr 19367, 2000

cell demonstration units. Even if that reflects only an early stage of development, the distance between reality and target is not short, so that it seems to be hard to reach the target cost which can be handled as “allowable cost” as they are derived from the investment for the competitive generation techniques, see figure 10.

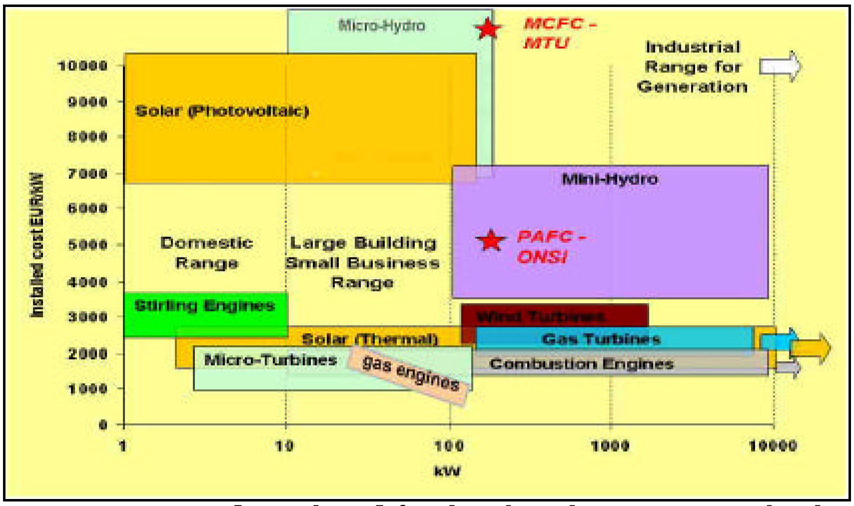

figure 10: investment [Euro/kW_{el}] for distributed generation technologies[7]

The US-Energy Information Administration in Washington don’t see that values within the next two centuries. In a contribution[8] for the Annual Energy Outlook 2000 the authors did assume a reduction from 3,625 US-$/kW in the period 2000 – 2004 to 1,725 US-$/kW in the period 2015 - 2020, table 2.

Installed Cost and Electrical Conversion Efficiency for Distributed Generation Technologies by Year of Introduction, 2000-2020

Technology	2000-2004 Cost (1998 Dollars per Kilowatt)	2000-2004 Efficiency (Percent)	2005-2009 Cost (1998 Dollars per Kilowatt)	2005-2009 Efficiency (Percent)	2010-2014 Cost (1998 Dollars per Kilowatt)	2010-2014 Efficiency (Percent)	2015-2020 Cost (1998 Dollars per Kilowatt)	2015-2020 Efficiency (Percent)
PV	5,529	14	4,158	16	3,178	18	2,426	20
Fuel Cell	3,625	40	3	40	2,425	40	1,725	40
Gas Turbine	900	29	900	29	900	29	900	29
Gas Engine	900	35	900	35	900	35	900	35
Gas Microturbine	800	27	700	27	700	27	700	27
Conventional Oil	500	33	500	33	500	33	500	33

Note: Fuel cells are not yet available in sizes and configurations appropriate for the residential sector. The first marketed units are expected around 2003.

Sources: **Solar PV:** U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, and Electric Power Research Institute, *Renewable Energy Technology Characterizations* , EPRI-TR-109496 (Washington, DC, December 1997). **Technologies other than Fuel Cells and Solar PV:** Electric Power Research Institute, *Quantifying the Market for Distributed Resource Technologies* , EPRI-TR-111962 (Palo Alto, CA, December 1998). **Fuel Cells:** Energy Information Administration, *Technology Forecast Updates—Residential and Commercial Building Technologies—Advanced Adoption Case* (Arthur D. Little, Inc., September 1998).

table 2: installed cost and electrical conversion efficiency for distributed generation technologies by year of introduction, 2000-2020

Nevertheless all developers publish, that the costs will fall extremely towards an economical price, as far as the stadium of prototypes will be passed. They argue their expectations in reference to so

[7] IEA Advanced Fuel Cells, Annex XII

[8] Modeling Distributed Electricity Generation in the NEMS Buildings Models, http://eia.doe.gov/oiaf/analysispaper/electricity_generation.html

called learning curves, which are taken from other but comparable technical areas (as chemical applications or engine development and others) and which show cost degradation over a couple of years due to better knowledge, better manufacturing processes and other effects. An additional argument for the expected cost reduction is the subject “mass production“, but several producers chain their expectation with the condition, that series production must be 100 000 units per year.

General remarks and virtual power plant

Coming back to the possible application area of the fuel cell systems, you can expect some differences between the use in the sector household and the use in the industrial sector, where the units, so it is to assume, will be dimensioned for the needs of the company, that means, heat and power will be used within the companies process chain.

That will differ from the situation in the sector household, where fuel cell heat and power will on one hand not suffer to supply the demand and on the other hand can’t be consumed by the household so that heat must be stored and electricity must be feeded into the public grid.

Fuel cell lobbyists do imagine, that many small fuel cells an other decentralised technologies as wind power and photovoltaics can be combined into so called “virtual power plants”, which can substitute central power plants.

At the moment it is hard to imagine, that such a substitution can happen in Europe without restrictive regulations. To understand that, it is necessary to look at the structure of the European electricity network and it organisation/operation, figure 11.

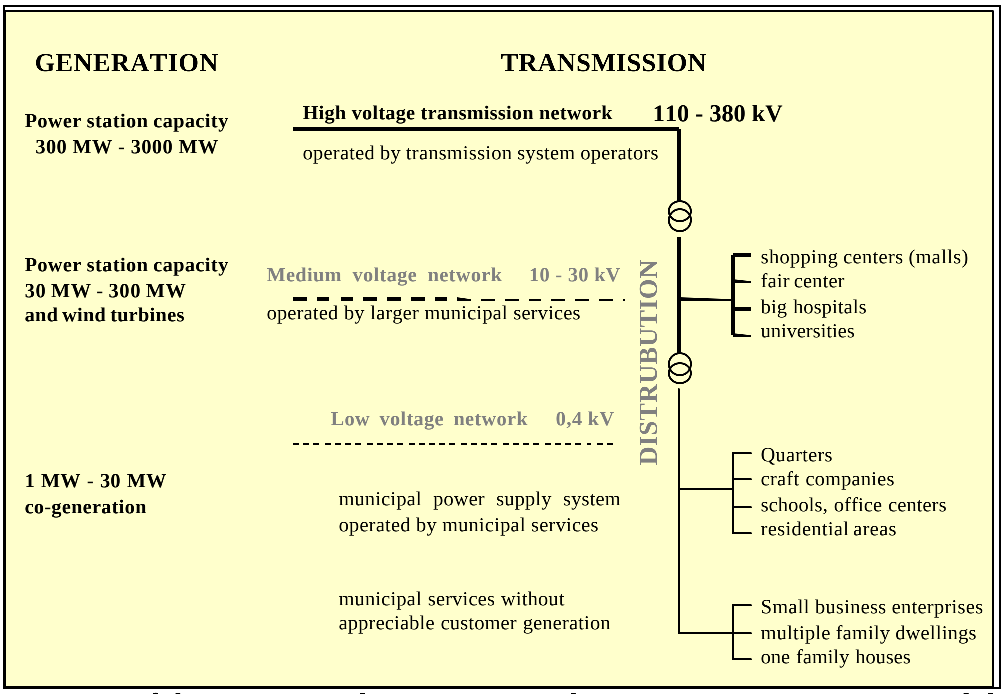

figure 11: structure of the European electricity network, generation, transmission and distribution

Main elements of the today’s electricity supply system/network are big power plants in the capacity range up to some GW. They feed into the grid at a voltage level of 110 – 380 kV (to reduce the transmission losses to a minimum). With the national “GridCode” as part of the common rules of the "Union for the Co-ordination of Transmission of Electricity" (UCTE) it is regulated, that power plants have to hold reserve generating capacity to be able to cover the outages of generation capacities or other disturbances affecting generation. That reserve capacity must be made available within seconds, which is enabled by the rotary masses of the power plant generators.

The first step of the "distribution grid" is the medium voltage network, which operates at a 10 – 30 kV level. Smaller power plants and especially wind turbines feed into this network, whereby wind turbines are not able to hold reserve capacity. That must be done by conventional systems.
The second step of the distribution level is the low voltage network at 0,4 kV or less by which small consumer, households and other are supplied. Photovoltaics, which are installed at house roofs do feed into that level and the fuel cell house station would also feed into that network.
If large capacities would be installed, capacities which are not able to make available calculable reserve energy or which are incalculable as they are not controlled by a central operator, the today's supply standards couldn't be hold any longer.

Therefore it must be considered which technical solutions must/could be developed, to put the fuel cell by technical measures in a position to fulfil the conditions which are necessary to ensure

- as well the short-term reliability of the electricity network with regard to load, frequency control, stability, etc as
- the medium-term adequacy between generation and load

Alternative it is to think about formalities/rules which ensure a central supervision of the fuel cells, so that that they can be operated with regard to the demand in terms of a new sustainable energy supply structure.

Conclusion

The development state of the fuel cell technology doesn't yet allow a reliable forecast when or if this technique will be competitive with conventional ones which make progress too with regard to efficiency or emission-reduction.

The reflections lead to the result, that the research and development programs have to concentrate to following points to bring the fuel cell technology successful into a future market:

- finding of manufacturing processes which need less energy, which are simpler
- finding of simpler and cheaper materials, which can be used for fuel cells
- developing of process-techniques for the fuel cell periphery, which reduce the dimensions and weight
- developing of strategies to implement hydrogen as a new fuel, as the availability of hydrogen can be able to solve a couple problems of the today's energy system
- developing strategies to enable also poor economies to use such new systems

Literature

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/2/ Arbeitsgemeinschaft Energiebilanzen; http://www.ag-energiebilanzen.de

/3/ Geiger, Wittke, BWK Bd54 (2002) Nr. 1/2

/4/ Daten zur Umwelt 2000, Umweltbundesamt; http://www.umweltbundesamt.org/cgi-bin/byteserver.pl/dzu-e/data2000.pdf

/5/ Siemens AG, February 26, 2002; http://www.pg.siemens.de/en/press/pg200202014/index.cfm

/6/ Fuel Cells Powering the Future – Sustainable Power for the European Union, EC EUR nr 19367, 2000, http://www.cordis.lu/eesd/src/ev290500.htm

/7/ IEA Advanced Fuel Cells, Annex XII

/8/ Modeling Distributed Electricity Generation in the NEMS Buildings Models, http://eia.doe.gov/oiaf/analysispaper/electricity_generation.html

Several presentations and reports of K.U. Birnbaum for the VLEEM-meetings