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Fuel cells for distributed power: benefits, barriers and perspectives

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2. Fuel cells for distributed power: benefits, barriers and perspectives – Executive Summary

Fuel cells are often portrayed as the answer to the world's pressing need for clean, efficient power. They are also seen as a key component in a future »hydrogen economy« that will substantially reduce or eliminate pollutant and greenhouse gas emissions associated with current power generation and transport. However, questions about the technology still remain: to what degree are the expectations surrounding fuel cells realistic and can they deliver what they promise?

The following report summary, which focuses on stationary fuel cells, addresses these questions. Stationary fuel cells are the type of fuel cells used in buildings or power generation parks. They will most likely enter the market before automotive fuel cells for technical and cost reasons.

What are fuel cells?

A fuel cell combines hydrogen with oxygen (from air) in a chemical reaction, producing water, electricity and heat. Fuel cells do not "burn" the fuel, the conversion takes place electrochemically without combustion. Fuelled with pure hydrogen, they produce zero emissions of pollutant and greenhouse gases at the location of the power plant. Where hydrocarbon fuels such as natural gas are used a "fuel reformer" (or "fuel processor") is required to extract the hydrogen. In this case the production of hydrogen is connected to greenhouse gas emissions and - very low - emissions of pollutants. However, the production and supply of the fuel also causes emissions. Therefore the future role of fuel cells and their environmental benefits have to be assessed through life-cycle and energy systems analyses.

Where does the fuel come from?

Hydrogen, the most common chemical element, is not naturally available in useful quantities in its pure form. The process of separating hydrogen from chemical compounds like water, natural gas and other carriers always requires energy. The method used to produce this energy determines the environmental impact and economic prospects of power generation in fuel cells.

The cleanest and most environmentally friendly way to produce hydrogen is through renewable energy. Electricity from wind and solar power can be used to produce hydrogen by electrolysis as one component of the ultimate long-term vision of a fully renewable based energy system. Unfortunately the conversion of renewable electricity into hydrogen and then back into electricity is associated with significant energy losses and additional costs.

For stationary fuel cell applications, this solar hydrogen path makes sense only with a high share of renewables in the electricity generation system, because in these systems, a storage medium for electricity generated from intermittent renewable sources such as wind or solar power is required. In large electricity

grids, stationary fuel cells run with solar hydrogen are thus a longterm option whereas island and remote applications could offer an early niche market.

Fuel cells can also operate on biomass-derived fuels. In bio fuel applications, all combined heat and power (CHP) technologies have very low greenhouse gas (GHG) emissions. The advantage that fuel cells deliver in this application is the more efficient use of limited – and often costly – biomass resources. Due to the high capital cost and the technically challenging integration of still premature components like gasification, gas processing and fuel cells, bio-based fuel cells are a long-term option for 2020 and beyond. Biogas produced from manure or sewage gas could, however, provide an attractive early market.

Fossil fuels and nuclear power can also be used to produce hydrogen. However, fossil fuels generate greenhouse gas emissions and nuclear power causes many problems such as waste disposal and safety risks. Due to extremely high capital cost, low electrical efficiencies and prevailing technical problems, the use of coal gas in fuel cells with subsequent CO₂ storage is not seen as a successful climate strategy for the next decades. In addition, carbon disposal remains an open issue, as the safe storage of CO₂ cannot be guaranteed presently.

The cleanest conventional hydrocarbon fuel to be used in fuel cells is natural gas. It has the lowest greenhouse gas emissions per energy unit of all fossil fuels. While natural gas based CHP is not considered a sustainable energy source as such, it does represent an efficient way of economising the inevitable fossil energy input during a transition period to a renewable energy supply system. Moreover, natural gas can bridge the gap between our fossil system and a future system because it offers the possibility to gradually switch to renewably produced hydrogen (or biogas/synthesis gas). This can then be fed into the pipeline distribution system and ultimately replace natural gas as a fuel. Therefore this report focuses on the environmental benefits of natural gas powered fuel cells in comparison with conventional technologies.

Can fuel cells help to reduce CO₂ and pollutant emissions?

Fuel cells will enter the market too late to make a significant contribution to the Kyoto commitments for 2008/2012. In the mid-to-long-term, however, stationary fuel cells have a high potential for environmentally friendly energy conversion: they offer high electrical efficiencies and extremely low (fuel: hydrocarbon) or even zero (fuel: hydrogen) pollutant emissions. The potentially high electrical efficiency of fuel cell power plants is one of the major advantages of these systems. For each power range, fuel cells will offer higher efficiencies than the conventional competitors.

For instance, compared to separate electricity production in central power stations with a coal biased electricity mix (such as the German electricity mix) or even compared to a lignite power plant, GHG reductions above 50% can be achieved with fuel cells powered by natural gas. In a life cycle assessment, each kWh of electricity produced by a fuel cell will reduce the related CO₂ emissions by at least 40% compared to the existing fossil power generation in the current 15

countries of the European Union (EU-15) and 20 to 30% compared to modern separate production (modern gas plants and boilers). However, compared to competing CHP technologies such as Stirling and reciprocating engines or gas turbines, only low GHG reductions, if any, can be achieved. This is mainly due to lower thermal efficiencies of fuel cells and it underlines the necessity to optimise their total/thermal efficiency. Fuel cells powered by renewable hydrogen will reduce emissions almost 100% compared to fossil options.

In order to estimate the total potential emission reductions achievable in the EU-15 until 2020 this report adopts a market introduction scenario of the United Nations Environment Programme (UNEP). The UNEP projections envisage some 27 GW of installed fuel cell capacity in OECD Europe for the year 2020, which represents an optimistic starting point for the analysis.

Under the assumption that fuel cells displace the average EU electricity and heat mix (excluding nuclear and hydropower), the estimated GHG reduction amounts to 55.4 Mt/a CO₂ equivalents, which equals 1.3 % of the European GHG emissions in 1990, or 22.3 Mt/a CO₂ eq., if the electricity mix includes nuclear and hydropower.

These reductions are the result of four separate mechanisms: the reduction due to a fuel shift (oil and coal to gas), an efficiency increase from average to advanced power plants and heating systems, an efficiency increase from separate to combined production, and an efficiency increase from modern CHP to fuel cells. The first three would also be realised based on conventional CHP so that only the last effect can be fully attributed to fuel cell technology. If one considers the coming need to replace power generation capacity in Europe, a comparison of fuel cells to modern separate production (i.e. a natural gas combined cycle plant and a gas condensing boiler) is required. In this comparison a GHG reduction of 14 Mt/a CO₂ eq. would be achieved.

Under the assumption that CHP is developing quickly we must also compare fuel cells with competing CHP technologies, e.g. the reciprocating engine in district heating CHP or the gas turbine in industrial CHP applications. In this instance, and using the UNEP scenario assumption, a GHG reduction in the order of 5 Mt/a CO₂ eq. would be achieved.

In addition to climate change mitigation, fuel cells offer great advantages with respect to environmental impacts that are caused by criteria pollutants, such as acidification (mainly caused by NO_x and SO₂), eutrophication, summer smog or carcinogenic substances. Compared to these impacts, fuel cell power plants yield reductions of pollutants ranging from 40% (summer smog) to almost 90% (eutrophication) depending on the baseline technologies. The EU 15's emissions situation differs from the EU accession countries. Because pollutant emission levels are much higher in central and eastern Europe, the introduction of fuel cells would lower emission levels significantly.

What are other benefits?

Fuel cells offer several technical advantages, such as modularity, good partial load characteristics, dynamic response or high heat levels which are favourable for industrial and cooling applications. In addition, advantages that are common to all cogeneration technologies, such as reduced transmission losses, reduction of required grid capacity, etc. can be made accessible. Moreover, fuel cells might open up a completely new market segment: that of domestic CHP (MicroCHP) with small-scale systems below 10 kW, which would provide heat and power for single and multi-family houses. Considering the large replacement market for gas heating boilers, a mass market for MicroCHP can be expected. In fact, most major European heating systems manufacturers are currently active in developing domestic combined heat and power systems.

The key to the market success of fuel cell heating systems as seen as providing a “one-stop solution” complete energy service package to the customer. In line with this emerging market for new energy services (micro-contracting), fuel cells offer new business opportunities, e.g. for utilities that aim to provide a broad range of supply services (multi-utility approach). In this context, fuel cells provide gas utilities with an opportunity to increase sales and compensate for a decreasing need for space heating – and thus domestic gas demand.

New applications might arise from grid-related operation of fuel cells that build on the dynamic performance of electricity generation. Sophisticated concepts such as the “virtual power plant” aim at the interconnection of a large number of fuel cells via communication technologies. This would enable central control and management of the decentralised generating units, e.g. for the purpose of load levelling of intermittent power production. However, considerable technological obstacles need to be overcome.

What are the barriers to a broad market introduction of fuel cells?

As fuel cells have to succeed in an already competitive market, cost is seen as the major market entry barrier. Stationary fuel cells are still between 2.5 to 20 times more expensive than competing technologies, with the balance of plant (periphery) being responsible for a large share of total capital cost. The challenge for fuel cell development is to reconcile the often conflicting requirements of cost reduction and performance improvement. For this reason, there is still considerable uncertainty with respect to the size and time scale of the market entry of stationary fuel cells. Today’s investments in CHP should not be postponed, however, in order to wait for fuel cells. Conventional technologies should instead be used to establish CHP infrastructures that can be updated later with second generation fuel cell systems.

Traditional players in the heat market such as installation contractors play a decisive role in the dissemination of new heating technologies. They will need to be fully prepared in time through information dissemination and professional training in order for them to play an active role in the promotion of fuel cells CHP systems.

Certain barriers that may hinder a wide spread utilisation of stationary fuel cells apply to all CHP applications and are not specific to fuel cells. Among these, easy grid connection is a key to market success of fuel cells. Today, however, current distribution grids are not designed for large-scale integration of distributed power generators. All of the envisaged problems can be solved from a technical point of view but institutional arrangements for a fair and discrimination-free allocation of costs for upgrading, investment and management of grids are still lacking.

In this context, the interconnection of mid to small scale CHP plants to the grid is often hindered by restrictive conditions and complicated procedures. Problems arise with regard to connection charges, determination of the point of connection, safety and liability issues. Most importantly, a standardised technical interface needs to be established as do non-discriminatory rules for the allocation of connection costs that take into account possible positive effects of distributed generation on grid investments and transmission and distribution losses.

Regulatory regimes, however, still do not provide sufficient incentives for grid operators to connect distributed generation plants, and conditions differ between member states, regions and utilities. Often, connection charges lack transparency and appear to exceed factual costs of the grid operator. Moreover, the administrative handling of CHP projects is delayed due to low priority for the utility.

For this reason, the introduction of distributed generation is strongly linked with the controversial debate on the unbundling of power generation and network operation and the regulation of systems operators in order to assure a neutral stance towards independent CHP plants.

Closely related to the aspect of interconnection, new traders for renewable and CHP electricity can suffer from non-transparent and excessively high connection fees and costs for stand-by and back-up power. Whereas grid use fees are of less relevance for a single project under a priority dispatch scheme, the marketing of "green power" is strongly affected. This limits the possibility to sell CHP electricity at premium prices to specific market segments.

How to overcome the barriers?

There is still uncertainty surrounding the long-term development of the energy policy framework. This hinders strategic investments into distributed generation. For this reason, long-term target setting by the EU and member states in terms of distributed generation integration would increase the reliability of market projections and investor confidence.

In parallel to the technical progress, therefore, a co-evolution of socio-economic and institutional prerequisites has to take place to pave the way for a smooth market introduction.

Especially during the first phases of market introduction, additional incentives will be needed to close the cost gap with competing technology. Energy policy can

provide direct incentives for early adopters, e.g. as investment subsidies, grants, tax deduction, etc.; stabilise market prospects for distributed power generation by enhancing market entries and competition together with a removal of barriers; and create general incentives for efficient and environmentally benign use of energy, e.g. energy and/or GHG taxes, emissions trading, air quality standards, noise pollution regulation, etc.

Conclusion

Fuel cells are a potentially important option among others that may contribute to increased economic efficiency and environmental performance of Europe's energy system. It is therefore critical that fuel cell policies be integrated into an overall guiding strategy for the sustainable development of European energy systems which aims for efficient use of energy and the expansion of renewable energy sources.

The transition from a fossil based system and its fully developed infrastructure to a "renewable hydrogen system" as an ultimate goal will take a long time. During the transition, research and development as well as deployment in niche markets and lead applications can pave the road.

It is important to make clear that these demonstration projects do not substitute, but supplement the development of rational use of energy and renewable energy carriers. The political and economic decisions for tomorrow's power generation must support the full range of climate friendly and sustainable technologies in order to surmount the "fossil fuel age". With natural gas as a bridging fuel, fuel cells will help to realise the renewable energy economy and a carbon free power sector.

3 Introduction

One hundred years ago, the electro-chemist Wilhelm Ostwald presented his vision of the 20th century as the century of electrochemical, combustion free energy conversion. In the age of coal, his credo 'no smoke, no soot' seemed unrealistic. However, 70 years before Ostwald's statement the British amateur chemist William Grove and the German Christian Friedrich Schönbein – the latter known for discovering ozone – had already invented the fuel cell, a device converting the energy of a fuel into electricity without any open flame. One century later, we are much closer to Ostwald's vision. Innovative energy converting technologies with higher efficiencies and lower environmental impacts will generally play a key role in developing sustainability strategies for national and European energy systems.

3.1 Fuel cells as a disruptive technology?

In the past years, fuel cells have been considered frequently as an attractive energy converter. Fuel cells are an energy system with a high potential for environmentally-friendly energy conversion. Fuel cells convert the chemical energy of a fuel and oxygen continuously and electrochemically into electrical energy (for details on the function of fuel cells see (Pehnt 2002) and Appendix A). The "secret" of fuel cells is the electrolyte that separates the two reactants, H₂ and O₂, to avoid an uncontrolled explosive reaction. Basically, the fuel cell consists of a sandwich of layers which are placed around this central electrolyte: the anode at which the fuel is oxidised, the cathode at which the oxygen is reduced, and bipolar plates which feed the gases, collect the electrons, and conduct the reaction heat. Fuel cell stacks consist of many single cells connected in series.

High potential for environmentally friendly conversion

Fuel cells can be categorised according to the electrolyte material and, correspondingly, the required operating temperatures into low, medium and high-temperature applications (see Table 1 and Appendix A). Although the higher operating temperatures of MCFC and SOFC result in decreasing thermodynamic efficiencies, the better kinetics as well as the option to use the high temperature exhaust gas (e.g. in gas turbines) more than offset this efficiency reduction. In addition, high temperature fuel cells offer the advantage of internal reforming, i.e. the heat produced in the electrochemical reaction is simultaneously used for reforming natural gas or other fuels into hydrogen inside the stack, thus decreasing the required cooling effort while efficiently using the heat. Also, high-temperature fuel cells have lower purity requirements of the fuel. Whereas AFCs are sensitive to CO₂ and PEFC to CO impurities, CO₂ acts in high-temperature fuel cells as inert gas only, and CO can even be used as a fuel.

Types of fuel cells

Table 1: Types of fuel cells and main characteristics

	AFC	PEFC	DMFC	PAFC	MCFC	SOFC
Electrolyte	KOH	Proton conducting membrane	Proton conducting membrane	Phosphoric acid	Carbonate melt	Y stabilised ZrO ₂
Temperature	60 - 90 °C	60 - 90 °C	80 - 130 °C	200 °C	650 °C	800 - 1000 °C
Ion	OH ⁻	H ⁺	H ⁺	H ⁺	CO ₃ ²⁻	O ²⁻
? _{System, el} (%) (natural gas)		30* - 42		38 - 42	50 - 55, w/ ST > 55	30* - 55, w/ GT > 60
? _{System, el} (%) (hydrogen)		38* - 50		47 - 50	n. a.	n. a.
Favoured application	Space, military, portable	Mobile, portable, CHP	Mobile, portable	CHP	CHP, CC	CHP, CC
Power range (kW _{el})		2 - 200		50 - 10,000	200 - 100,000	2 - 100,000
Status	First commercial production	Prototypes, first commercial production	Research	Small series production (200 kW _{el})	Demonstration	Demonstration

ST: Steam turbine; GT: Gas turbine; CHP: Combined Heat and Power Production; AFC: Alkaline Electrolyte Fuel Cell; PEFC: Polymer Electrolyte Membrane Fuel Cell; DMFC: Direct Methanol Fuel Cell; PAFC: Phosphoric Acid Fuel Cell; MCFC: Molten Carbonate Fuel Cell; SOFC: Solid Oxide Fuel Cell n. a. not available * for MicroCHP

Fuel cells can be used in stationary and mobile applications. Depending on the type of fuel cells, stationary applications include small residential, medium sized cogeneration or large power plant applications. In the mobile sector, particularly low-temperature fuel cells, can be used for heavy-duty and passenger vehicles, for trains, boats or auxiliary power units for air planes. Mobile applications also include portable low power systems for various uses (Pehnt 2002).

Applications

From an environmental point of view, the high efficiency can lead to a significant reduction of fossil fuel use and of greenhouse gas (GHG) emissions. In addition, the electrochemical nature of the reaction, the low temperature of the reforming reaction and the necessity to remove impurities in the fuel (such as sulfur) result in extremely low local emissions – an important feature especially in densely populated and highly polluted areas. In vehicle applications, particularly at low speed, reductions in noise emissions are to be expected.

At the same time, however, the conventional technologies have been constantly optimised, creating a strong competition and lowering the margin for potential benefits of fuel cells. Consequently, the public perception of fuel cells differs. This can be shown quite plainly with two quotations from the 24/2/2003 VDEW-Fuel cell Newsletter. It quotes Johannes van Bergen, president of the German „Bundesverband Kraft-Wärme-Kopplung“ (German Cogeneration Association):

Diverging public perception of fuel cells

„Die Brennstoffzelle im Haushalt braucht noch zehn bis 15 Jahre, wenn sie überhaupt kommt. Die Euphorie, die hier mitunter herrscht, ist durch nichts gerechtfertigt. Was soll an der Brennstoffzelle besser sein als an den heutigen BHKW?“ (The fuel cell in domestic

applications will need some 10 to 15 years if it comes at all. The euphoria is not justified at all. Which aspects of fuel cells shall be better and in today's reciprocal engines?"

In the same newsletter, Dietmar Kuhnt, CEO of the RWE AG is quoted saying:

"Fuel Cell Technology is predestined to make a major contribution to distributed power and heat production for generations to come. In Germany a market potential of up to 65 TWh annually is achievable by 2015. This is almost the yearly power consumption of Belgium."

3.2 Structure of this study

In this short study, we will collect and bring forward arguments, potential advantages and barriers of stationary fuel cell applications. The study was commissioned by the World Wide Fund for Nature and Fuel Cell Europe.

In chapter 4, we will analyse potential advantages of fuel cells in stationary applications, in chapter 5 the barriers hampering the implementation of fuel cell power plants. Chapter 6 will try to synthesize the information from the preceding chapters, deriving strategic elements and giving hints to a possible future market development of fuel cells.

It has to be noted that due to the limited time budget, some aspects can only be touched and not worked out in a detailed manner. Particularly, due to the complexity of the CHP debate today and the discussion on the European Directive, only advantages and barriers that are specific to fuel cells, and not to CHP as a whole, will be analysed.

4 Potential advantages of stationary fuel cells

Advantages of stationary fuel cells can be determined on various levels (Figure 1), from environmental and technical advantages to energy economic aspects. In the following sections, main potential advantages of fuel cells will be outlined and investigated with respect to correctness, feasibility, and implications.

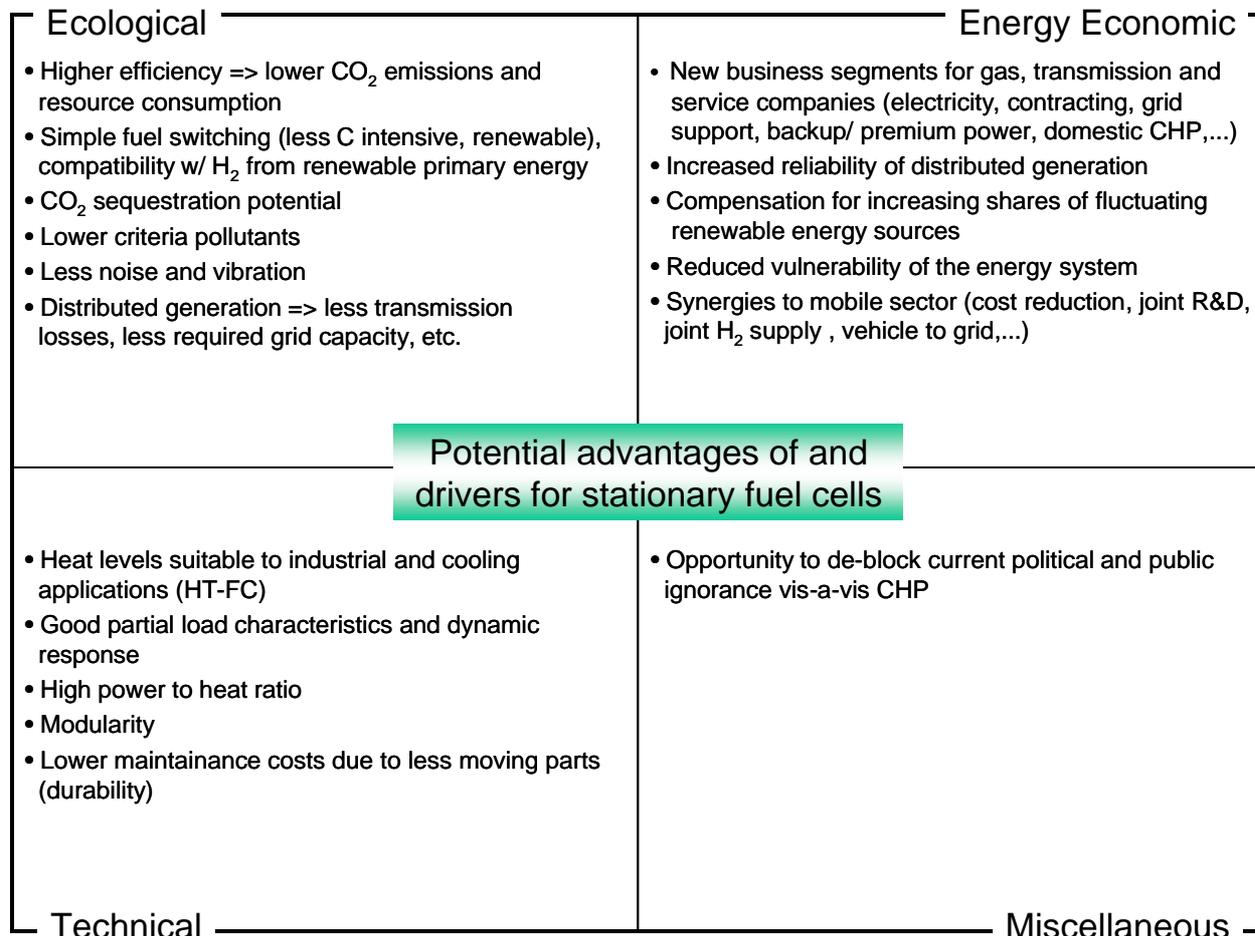


Figure 1 Potential advantages of fuel cells in stationary applications

4.1 The *efficiency advantage*: Reduction of climate gas emissions and primary energy demand through high electrical efficiency

The potentially high electrical efficiency of fuel cell power plants is one of the major advantages of these systems. For each power range, fuel cells will offer higher efficiencies than the conventional competitors (Figure 2). It has to be mentioned that for fuel cells, these numbers present target values whereas the demonstration plants do not yet reach these numbers. For conventional systems, future optimisation potentials are also included in Figure 2 as the upper boundaries of the boxes.

Fuel cells offer high electrical efficiencies

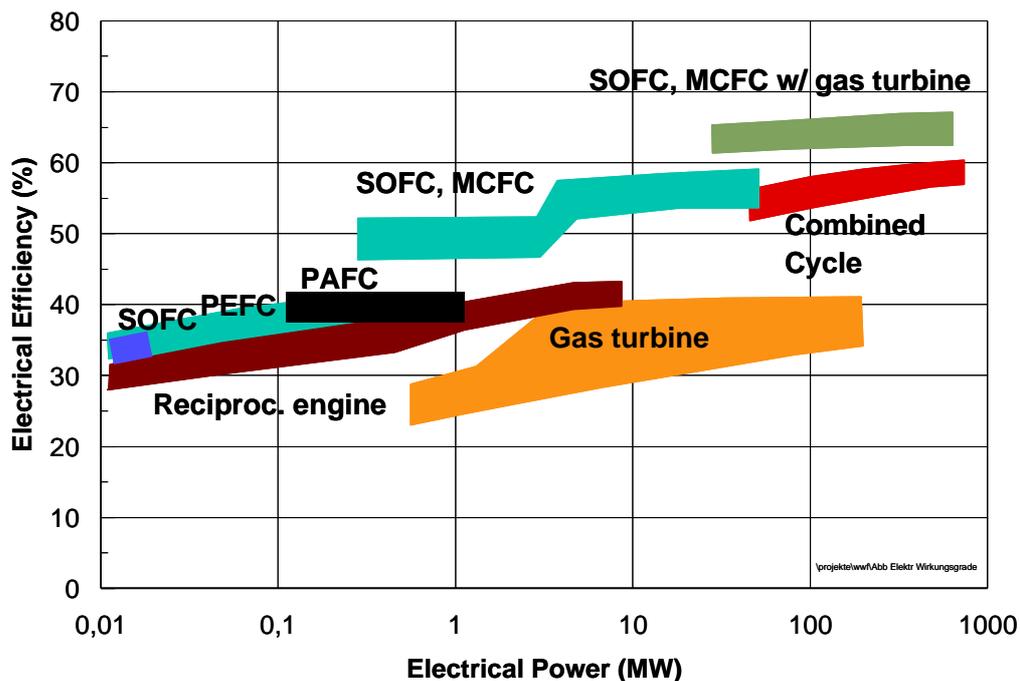


Figure 2 Electrical efficiencies of various future stationary fuel cell systems and their competitors

Referring to natural gas as the dominant fuel cell fuel in a short and midterm perspective, PEFC in the low power range will reach electrical efficiencies in the order of 28 to 33 %, in the long-term possibly up to 36 % for domestic systems and 40 % in the 200 kW_{el} range. The latter value has not been achieved in pilot plants so far but is projected for future systems.¹ In a large number of demonstration projects, 40 % have already been demonstrated with PAFCs. In some systems, especially of the early generations, however, degradation effects lower the "lifetime efficiency" substantially.

High-temperature fuel cells offer efficiencies of 50 % when used in lower power regimes. 47 % have already been demonstrated in the Netherlands SOFC demonstration system as well as in the Bielefeld (Germany) MCFC. In future, coupling fuel cells with gas turbines (SOFC) to use the exhaust heat promises efficiencies of up to 60 % at the beginning of the operation in cogeneration applications, with an average efficiency of 57 % over the lifetime; MCFC can be coupled with steam turbines, with slightly lower electrical efficiencies. In the very long-term, applying fuel cells for separate electricity generation (no cogeneration) in larger systems might lead to efficiencies even above 65 % (for instance by using fuel cells plus combined cycle, or by using cascades of fuel cells).

¹ The first European 250 kW_{el} Ballard CHP plant in Berlin achieves electrical efficiencies of 34 % and total efficiencies of 70 % (Pokojski 2001). This data is also consistent with the recent EnBW Ballard/Alstom Mingolsheim power plant.

Table 2 Efficiencies, life-cycle CO₂ equivalent emissions and climate gas reduction potential of various CHP technologies compared to central electricity production (fuel: natural gas (except for mixes)). Efficiencies based on lower heating value. Efficiency assumptions for electrical power plants are in line with the EU directive on the promotion of cogeneration (COM(2002) 415 final). LCA data based on (Pehnt 2002) and (Pehnt 2003).

Technology (fossil fuels except for mixes)		η_{el}	η_{th}	Electricity	Heat	Life cycle CO ₂ equiv.	Heat credit	Life Cycle CO ₂ equiv.	% CO ₂ eq. reduction (heat credit: gas boiler)				
									compared to				
Status 2010 (modern technology)		incl. degradation				gas boiler		w/ heat credit		Comp. techn.	Comb. Cycle	Fossil Mix EU	Lignite
Yearly averaged efficiencies		%	%	kWh	kWh	g/(heat and electricity)	g	g/kWh _{el}					
Heat production	Gas condensing boiler		99	-	1,0	273	-	-					
	Gas average boiler		85	-	1,0	315	-	-					
	Gas industrial boiler		90	-	1,0	292	-	-					
	Oil average Europe		85	-	1,0	360	-	-					
	Coal average Europe		65	-	1,0	670	-	-					
	Wood average Europe		65	-	1,0	30	-	-					
	Mix of European heating systems			-	1,0	342	-	-					
MicroCHP (1-5 kW_{el})	PEFC (eta = 80 %)	28	52	1	1,9	920	507	413	-3%	9%	41%	59%	
	PEFC (eta = 90 %)	32	58	1	1,8	806	495	311	23%	31%	55%	69%	
	SOFC (eta = 80%)	28	52	1	1,9	935	507	428	-7%	6%	38%	58%	
	SOFC (eta = 90 %)	32	58	1	1,8	820	495	325	19%	28%	53%	68%	
	<i>Stirling (competing techn.)</i>	24	68	1	2,8	1175	773	402		11%	42%	60%	
CHP (200-300 kW_{el})	PEFC	41	39	1	1,0	631	260	371	0%	18%	47%	63%	
	MCFC	50	35	1	0,7	529	191	338	9%	26%	51%	67%	
	SOFC	50	35	1	0,7	521	191	330	11%	27%	53%	67%	
	<i>Reciproc. Engine (compet. techn.)</i>	32	60	1	1,9	882	512	370		18%	47%	63%	
Industr. CHP (1-3 MW_{el})	MCFC w/ steam turbine	55	25	1	0,5	481	133	348	6%	23%	50%	65%	
	SOFC w/ GT	57	23	1	0,4	445	118	327	12%	28%	53%	68%	
	<i>Gas turbine (competing techn.)</i>	39	36	1	0,9	641	269	372		18%	46%	63%	
Central electricity	Gas Comb. Cycle (600 MW)	55	-	1	-	454	-	454					
	New Lignite Power Plant	42	-	1	-	1010	-	1010					
	Electricity Mix Germany (2010)			1	-	617	-	617					
	Electricity Mix fossil EU*			1	-	695	-	695					
	Electricity Mix EU 15*			1	-	457	-	457					

Sources: Pehnt 2002 and Ifeu 2003. Oil, wood and coal heating: Gemis 2002. European heating mix: Save 2002 (61 % gas, 32 % oil, 6 % coal, 1 % wood). All emissions based on LCA (incl. fuel and system production).

Electricity Mix Germany 2010 according to the scenario of the Enquete commission "Nachhaltige Energieversorgung". Considered climate gases: CO₂, CH₄, N₂O. * only available for 2000.

Reading example: Compared to the Stirling engine (which is the directly competing technology to fuel cells in the field of microCHP), a 1 kW_{el} SOFC with 90 % total efficiency saves 19 % greenhouse gas emissions.

However, conventional systems are constantly optimised, too. In the US advanced turbine programme, for instance, gas turbines in the MW range have reached electrical efficiencies of above 40 %. Also, combined cycle plants will achieve average efficiencies of 58-60 %, with 65 % (without degradation) being forecasted by some researchers. That means that the competition is getting tougher.

Conventional competitors are also constantly optimised.

It is worth mentioning, however, that even in the 3-10 MW power regime, the efficiencies of fuel cell systems would exceed those of large combined cycle power plants in the 100 MW range.

Fuel cells achieve similar electrical efficiencies as CC at much smaller size.

The thermal efficiency of the plants is, of course, a function of the temperature of the heat medium. If only steam is needed as in many industrial applications, it will be lower than for a low-temperature district or house heating system. Also, the thermal efficiency is a function of the load. Generally, current target values for most fuel cell systems are approximately 80 % total efficiency.

When power plant technologies are compared to each other, not only the environmental impacts of their operation should be included, but also the impacts associated with fuel supply and production of the plants. The following comparison is based on such a "Life Cycle" approach (see Appendix B).

In Figure 3, the **resulting climate gases** of different fuel cell cogeneration (CHP) systems including all life cycle stages (for a description of the life cycle approach please see *Appendix B*) are compared to CHP competitors as well as central electricity production are represented based on natural gas as a fuel.²

Why do we only evaluate GHG reduction for natural gas in this chapter and not for renewable fuels? For renewable fuels, the GHG emissions are very low anyway. That means that any technology, regardless whether this is a fuel cell, a gas or steam turbine, a reciprocating or Stirling engine, has very low GHG emissions (depending only on origin and processing of the renewable fuel). As pointed out in chapter 4.2, the advantage of fuel cells with bio- or solar fuels is the more efficient use of the limited (and often costly) resource "renewable fuel".

² On a life-cycle basis, production of the infrastructure, i. e. the production of the fuel cell power plant, is of almost no significance for the CO₂ equivalent emissions and contributes less than 20 % to other impacts, such as the life-cycle acidification (that means less than 20 % of the acidifying emissions (SO₂, NO_x, etc.) are caused by the production of the system (Pehnt 2002)).

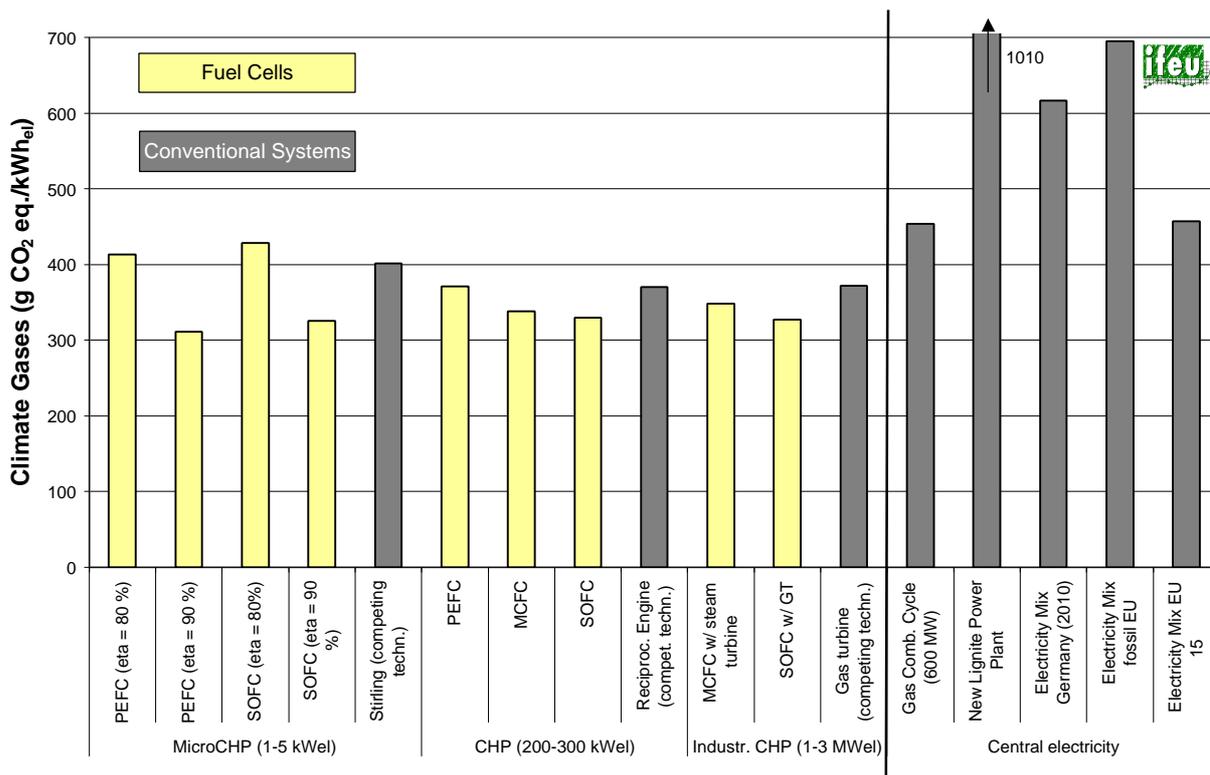


Figure 3 Greenhouse gas emissions from various CHP and central electricity production technologies (for CHP, the co-product heat is credited with a gas condensing boiler („avoided burden“) including supply of the fuel, production of the system and avoided grid losses (Pehnt 2002; Pehnt 2003) (see also Table 2).

The GHG reduction potential (Table 2; right columns) depends strongly on the electrical efficiency, the thermal efficiency and the “baseline system” to which the fuel cell is compared. So far, there is still uncertainty about the total efficiency to be achieved by fuel cell systems, particularly in the domestic applications.

Compared to the **separate production** with a natural gas combined cycle plant and a natural gas condensing boiler, reductions are in the order of 20 to 30 %.³ Similar reduction potentials occur compared to the EU 15 electricity mix because it consists of a mixture of other hydrocarbon based energy carriers such as coal with almost CO₂ free production paths (hydro and nuclear). There is still some uncertainty about the achievable total average yearly efficiency. Estimates for domestic systems range between 80 and 90 % whereas today, the systems are far from this value. For larger systems, typical target values are 80 %. In principal, however, one could imagine that this efficiency could be further increased.

When taking the lower bound of 80 % total efficiency only, the achievable reduction for domestic systems does not seem too high. However, one can also reverse the argument: Based on natural gas as a fuel, domestic systems might

GHG reduction depends strongly on efficiencies and baseline.

Compared to modern separate production GHG reductions around 20 and 30 %

Small domestic systems achieve comparable GHG emission levels to large centralized power plants.

³ As long as we compare systems with the same fuel (e. g. all based on natural gas), a reduction of 10 % of the greenhouse gases is also equivalent to a reduction of 10 % primary energy demand. Only when we compare to other fuels, e. g. coal, we have to consider that the different fuels have different carbon intensities and thus, different CO₂ emissions per energy unit.

reach the same CO₂ emissions as a modern gas combined cycle plant, even though the systems are a factor 100.000 smaller, thus offering other benefits and opening the market of MicroCHP (see chapter 4.9.2).

Compared to the **conventional competitors** (e. g. Stirling engines in domestic applications, engine CHP, gas turbine) there are, however, smaller GHG reductions in the order of 10 % (20 % for high efficiency domestic CHP), if any. This is particularly due to the lower total efficiency of the fuel cell systems compared to engine CHP for example. To successfully compete with the conventional systems, future work should therefore also focus on increasing thermal efficiencies by using the reformer exhaust heat and other heat sources. In industrial applications, GHG reductions are in the order of 6 to 12 %.

Compared to competing technologies only low GHG reductions, if any, can be achieved due to lower thermal efficiencies

Moreover, it has to be taken into account that conventional heating systems become increasingly efficient, too. The development of natural gas condensing boilers has significantly enhanced the efficiency; and recently, oil condensing boilers have been improved so that also on the heat side, competition is increasing.

The reduction effects become larger when other fuels enter the comparison. For instance compared to the **separate production with more coal** dominated electricity mixes, such as the German electricity mix, or even compared to a lignite power plant, GHG reductions above 50 % can be achieved. Also, a number of diesel oil fuelled boilers exist in Europe. In these cases it has to be noted that the GHG reduction is to a great part due to a fuel switch from more C containing fuels to natural gas.

If not only the electricity production, but also the **heat production is based on** other fuels than natural gas (i. e. **oil, coal** based space heating) (not shown in Table 2) the GHG reduction of the fuel cell systems becomes even larger. However, under these conditions the competing technologies (reciprocating engines, Stirling engines, gas turbines), which generally produce more heat than the fuel cell, achieve even higher greenhouse gas reductions than the fuel cell itself because they displace even more oil and coal heating systems.

It can be concluded that independently of the conversion technology, CHP proves to be superior to pure electricity production due to the use of the exhaust heat. Combined heat and power production should therefore generally be promoted. In addition, not only the electrical, but the total efficiency needs to be optimised. On the other hand, the development of high-efficiency centralised electricity production and an increasing share of renewable electricity production decrease the gap between cogeneration and non-cogeneration plants.

All CHP systems show reduced CO₂ emissions compared to separate production and should therefore be promoted.

It has to be mentioned that all these comparisons are based on the future performance of fuel cell and conventional systems. In the process of fuel cell development, two goals will have to be attained simultaneously: cost reduction and performance improvement. Unfortunately, in many cases cost reduction means a trade-off for performance. This underlines that the targets set in the comparison are ambitious.

Trade-off between cost reduction and efficiency increase

At the same time, however, the ecological assessment has to account for changes of the reference system. Most important, the specific CO₂ emissions of the public grid will decrease significantly once a large-scale integration of renewable energies will take place. Accordingly, the emission reduction benefit of CHP such as gas-based fuel cells will be depreciated. From an ecological point of view, therefore, other advantages such as the use of renewable energy carriers for fuel cells or the possibility to provide back-up of intermittent power production will steadily gain importance (see chapter 4.2).

With decreasing C intensity of the public grid, relative advantages of fuel cells decrease

4.2 Fuel switching: Using renewable primary energy carriers for fuel cells

For several reasons, it is essential that our fossil-based energy systems integrate the further use of renewable energy carriers. Firstly, and most importantly, the climate gas emissions associated with the combustion limit the amount of fossil energy carriers that can be used in the future. In addition, the limited reserves, particularly of crude oil, but also of natural gas, make a shift in fuel supply inevitable. Furthermore, Europe is becoming increasingly dependent on energy imports particularly from politically instable countries. Due to the high GHG emissions and other environmental issues associated with coal as an energy carrier, coal does not offer an easy solution to the resource issue.

Principally, every fuel containing hydrogen can be used to run fuel cells. Beside fossil energy carriers such as natural gas, crude oil, or coal, *renewable primary energy carriers* such as organic residues (which, for instance, can be turned into biogas using anaerobic digestion and subsequently be used in a high-temperature fuel cell), wood and other lignin sources (which can be gasified), energy crops such as sugar cane or rapeseed (which can be converted into ethanol or RME and subsequently be reformed in the fuel cell), or, via water electrolysis, also renewable electricity (Figure 4).⁴ This greatly enhances the fuel flexibility.

Fuel cells offer great fuel flexibility.

Not only renewable energy carriers can be used for hydrogen production, but also nuclear power (either via electricity/electrolysis or via thermochemical cycles using the high-temperature heat). Due to the risks and waste disposal issues associated with the nuclear power cycle – the discussion of which is outside the scope of this study – this hydrogen production path is not regarded by the authors to be a sustainable option.

⁴ For a recent review of biomass options for fuel cells, see (Abe, Chaytors et al. 2002).

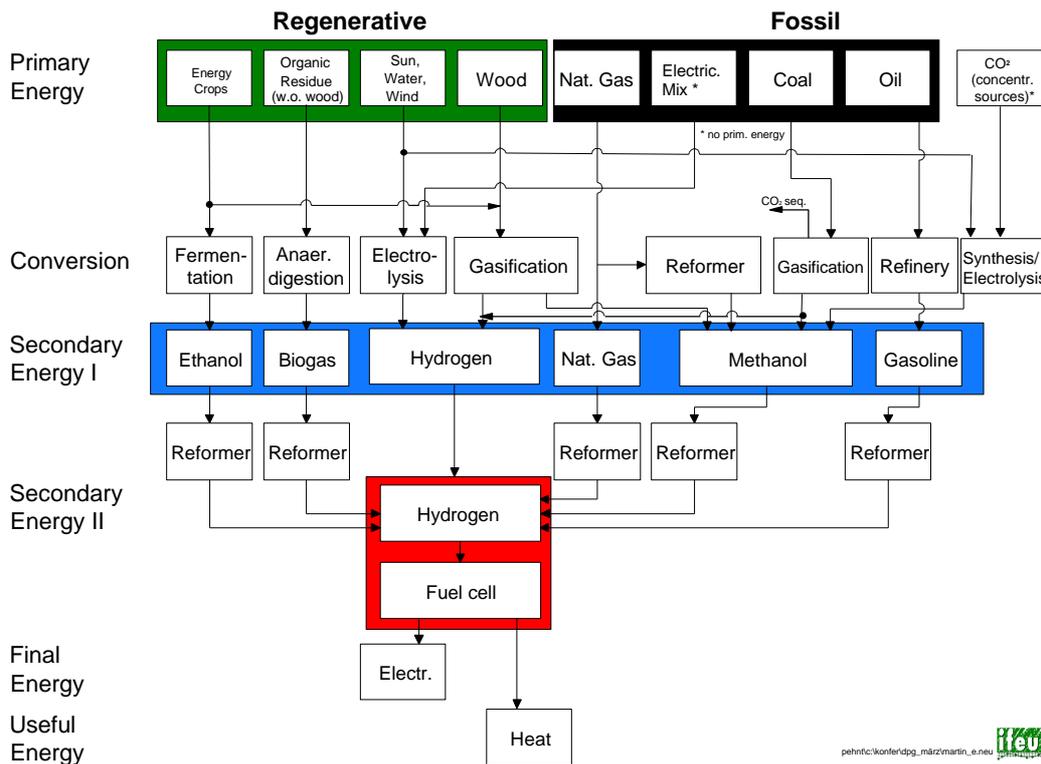


Figure 4 Selected fuels for the fuel cell

However, these fuels can also be used in conventional power conversion systems, such as reciprocating engines, gas and steam turbines. The following subchapters investigate which specific advantages fuel cells run with renewable H₂ (or H₂ rich gases) might offer.

4.2.1 Bio-based fuels

Fuel cells using **bio-based fuels** have the following specific characteristics:

- From an ecological point of view, the use of **bio fuels** in fuel cells combines the low direct emissions⁵ (see chapter 4.3) with extremely low resource consumption and greenhouse gas emissions (see the example in Figure 5). It can be seen that the primary energy demand and the GHG emissions can be drastically reduced by both the fuel cell and the gas turbine.
- However, no pronounced GHG reductions per kWh_{el} can be achieved with fuel cells compared to the conventional competitors, because both operate essentially GHG free. The efficiency advantage of fuel cells shows here not in GHG reduction, but in a more efficient use of the usually limited biomass potentials and thus lower fuel costs.

FC: Combination of low GHG and resource use with low pollutant emissions

No further GHG reduction per kWh_{el}, but more efficient use of limited resources and lower fuel costs.

⁵ unlike some other technologies based on combustion, such as the reciprocating engine, especially when it cannot be operated with a three-way catalyst which is the case with some problem gases.

In addition, high power-to-heat ratios as offered by fuel cells are economically and ecologically advantageous if the external heat demand is limited as is often the case in biogas plants.

High power-to-heat ratio advantageous

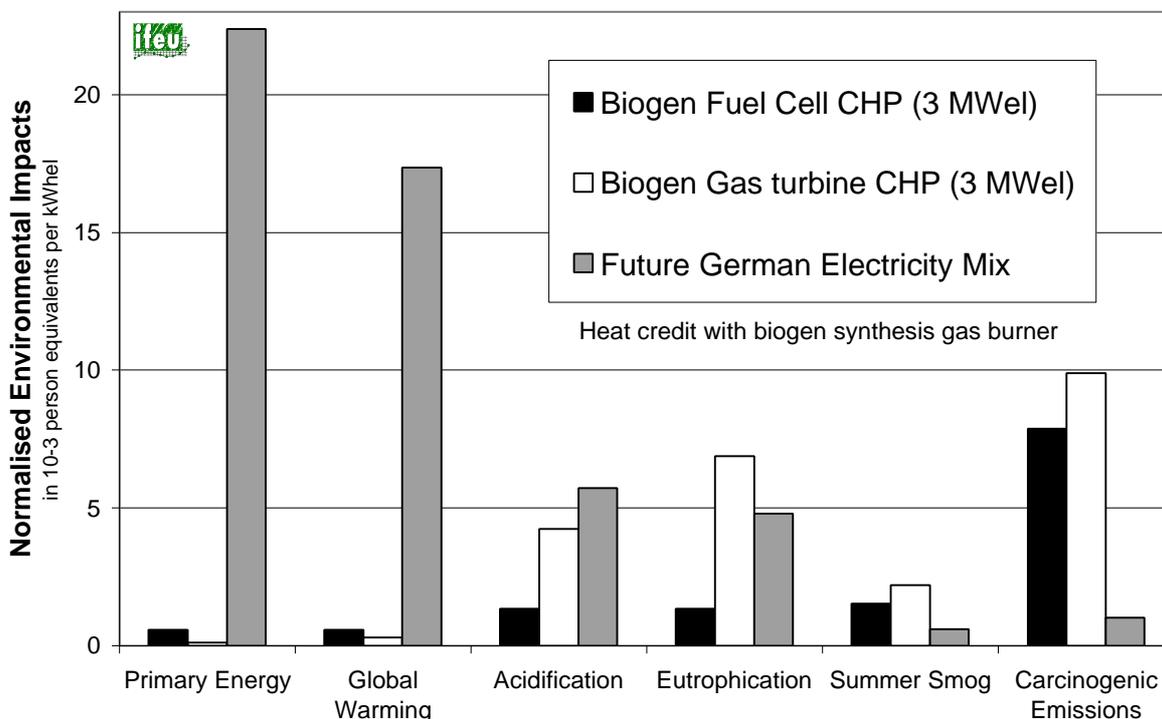


Figure 5 Normalised results of LCAs of different electricity generating systems converting synthesis gas from gasified wood in a high-temperature fuel cell and a gas turbine compared to the 2010 German electricity mix (functional unit: 1 kWh_{el}). If heat is co-produced it is credited with a modern gas burner using the same synthesis gas (“avoided burden”). To be able to present the data in one diagram, all data is normalised to “person equivalents” by dividing the impacts by the average daily per capita impact in Germany.⁶ (Pehnt 2002)

Unfortunately, severe **barriers** on a technical and economic side are opposed to these advantages:

- Coupling fuel cells with bio-based fuels require the combination of three innovative processes: the production of a hydrogen-rich gas, for example via gasification, which is, even for conventional technologies, a complex process realised only in a small number of pilot plants; the processing of this gas, especially the removal of contaminants (S, F, Cl, Silicates,...) to a yet unknown purity of the gas; and the fuel cell itself. Even though the technical challenges are not insurmountable, they require considerable further research.
- Consequently, the high costs of fuel cells, of fuel conversion and processing and, in many applications, of fuel supply add up to a severe cost barrier for midterm application of this path.

Threefold innovation

High cost intensity

Fuel cells with bio-based fuels are a long-term option with biogas being a market opener.

⁶ 10*10⁻³ person equivalents equal 4.93 MJ primary energy (non-renewable); 361 g CO₂ eq.; 1.46 g SO₂ eq.; 0.153 g PO₄³⁻ eq.; 0.625 g NMHC; 2.54 e-6 g*URF carcinogenic emissions.

On a time-scale, therefore, this option is characterised as a long-term option for 2020 and beyond, with certain niche applications (biogas from landfill, agricultural residues, sewage gas) being possible market openers.

4.2.2 Renewable electricity: Fuel cells in a “Hydrogen Economy”

Another possible renewable energy source for hydrogen is the production of hydrogen with renewable electricity, such as wind power, solar thermal power plants, hydroelectric and geothermal power etc. This significantly increases the number of primary energy carriers. Some of these electricity sources, such as off-shore wind parks and import of solar thermal power plant electricity are characterised by huge potentials. Particularly, the development of solar thermal power plants, for instance in the Mediterranean area, offers almost unlimited resources. (Nitsch and Trieb 2000) quantify, for instance, the potential for solar import to Germany from North Africa to 1'360'000 TWh/a (German electricity demand: 550 TWh/a).

However, particularly for stationary fuel cell applications, there must be good reasons for the intermediate production of hydrogen, because the conversion of renewable electricity into hydrogen and back into electricity is associated with significant losses and additional costs. There are mainly two reasons for the deployment of hydrogen in the stationary sector:

Hydrogen for energy transport, for example from solar thermal power plants in African countries to Europe. However, for distances of that order, the transport via high voltage direct current lines is generally cheaper (Dreier and Wagner 2001; Nitsch 2002). Only for larger distances or for mobile applications, where the conversion to a storable fuel is needed anyway, the conversion to hydrogen seems to be appropriate. Under these conditions, stationary applications may benefit from existing hydrogen supply.

Storage of intermittent sources, load levelling: when renewable energy sources with a fluctuating generation gain importance, such as wind or solar power, there will be rising demand for a storage or load levelling device.

- In island applications, where no supporting grid is available, hydrogen electrolysis coupled with a fuel cell will be an attractive option.
- In grid applications, several investigations with time-resolved supply and demand simulation have proven (Langniß, Nitsch et al. 1997; Quaschnig 1999; Nitsch and Trieb 2000) that only for high shares of renewables to total electricity supply (> 30 %) hydrogen as a storage medium might be required. This is because the fluctuating characteristics of certain renewables are to a certain degree already averaged due to the large area distribution of renewables, due to the use of non-fluctuating renewables (biomass, geothermal), due to electricity import (to average out

Hydrogen/FC systems attractive in off-grid applications

In electricity grids, FC systems based on renewable hydrogen will not be required before 2030.

daily (east-west import) or yearly (south-north import) fluctuations), due to load management and dynamic variable power plants.

As even the ambitious solar scenarios forecast such high shares of renewables in electricity grids only after 2030, fuel cell systems based on renewably produced hydrogen will, from an energy economic point of view, not be required before 2030 and, in larger unit numbers, before 2050.

On the other hand, the transition from a fossil based system and its fully developed infrastructure to a “solar hydrogen system” as an ultimate goal takes a long time. Thus, research and development as well as deployment in niche markets and lead applications already today can pave the road. It is then important to make clear that these demonstration projects do not substitute, but supplement the development of rational use of energy and renewable energy carriers.

Hydrogen/fuel cell demonstration projects already today can supplement (not substitute!) efforts towards efficient and renewable energy supply and thus pave the road for long-term developments.

4.2.3 The transition to higher shares of renewables

For the determination of a possible fuel switch to renewable energies based on fuel cells, another aspect has to be taken into account: To which degree can this transition take place continuously, i. e. without the need for high infrastructure investments at discrete points in time?

In the conventional *electricity* sector, due to the possibility of an incremental feeding-in of renewable electricity, a step-by-step increase in the share of renewable primary energy carriers is unproblematic. For some renewable *heat* technologies, higher investments are required, either in the distribution of energy carriers (e. g. wood pellets) or in the set-up of district heating systems (e. g. biomass fuelled CHP or geothermal systems). In the *transport* sector, there are some opportunities for a gradual transition (e. g. E5, i.e. gasoline with 5 % bioethanol) or for fuels that only require minor modifications (e. g. bio diesel and the set-up of bio diesel distribution/modification of vehicles). If large shares of renewable energy in the transport sector are desired, however, a transition to solar hydrogen with the concomitant installation of a different fuel supply system is necessary.

With respect to fuel cells and relevant fuels, it is possible to gradually switch from natural gas to renewably produced hydrogen (or biogas/synthesis gas) which can be fed into the pipeline distribution system and ultimately replace natural gas as a fuel. Biogas applications can be “greened” by feeding-in of biogas or processed synthesis gas into the natural gas distribution system as long as minimum quality standards are guaranteed.⁷ Therefore, natural gas can bridge the gap between our fossil system and a more renewable based system based on hydrogen.

Gradual feed-in of gaseous bio fuels into the natural gas pipeline

⁷ For technological approaches and difficulties of H₂ pipeline transport, see (Winter and Nitsch 1989).

The principal transition characteristics, thus, do not differ fundamentally from competing technologies⁸ which could, in principal, also run with the mixture of natural gas and bio fuels (see, for instance, the projects of the Stadtwerke Schwäbisch Hall to run reciprocating engines with synthesis gas from wood and natural gas (<http://www.stadtwerke-hall.de>)). For fuel cell systems that are not connected to the natural gas grid, solid biomass has to be transported to the fuel cell system and gasified on-site, similarly to biomass CHP in steam turbines or reciprocating engines.

Transition characteristics similar to conventional CHP

4.3 Low criteria pollutant emissions

In addition to high electrical efficiencies, the low pollutant emissions of fuel cell power plants are a major advantage. In hydrogen operation these are zero. When reforming natural gas or methanol they are extremely low due to the comparatively low temperatures involved and the requirement to clean up impurities such as sulphur and CO. However, for a complete assessment of environmental impacts, the entire life-cycle should be considered (see Appendix B).

Fuel cells couple the advantages of reduced energy consumption common to CHP with low direct emissions.

Figure 6 shows that fuel cells offer great advantages with respect to environmental impacts that are caused by criteria pollutants, such as acidification (mainly caused by NO_x and SO₂), eutrophication, summer smog or carcinogenic substances. In these impact categories, fuel cell power plants allow reductions ranging from 40 % (Summer smog) to 88 % (Eutrophication). Unlike engine CHP plants which emit pollutants, fuel cells couple the advantages of reduced energy consumption with low direct emissions.

The upstream emissions (fuel supply and system production) limit the achievable reduction.

For example, an investigated high-temperature fuel cell produces 70 % less acidification on a life-cycle basis than a low-NO_x gas turbine and 30 % less than a modern natural gas combined cycle plant. In the case of the fuel cell, the acidifying emissions stem almost exclusively from the energy chain and the production of the system. For gas turbines, in contrast, the direct NO_x emissions account for more than 50 % of total acidification.

⁸ The difference is, however, as pointed out in chapter 4.2.1, the higher harvesting efficiency of the fuel cell and, thus, the reduced requirement of (expensive and limited) renewable fuels.

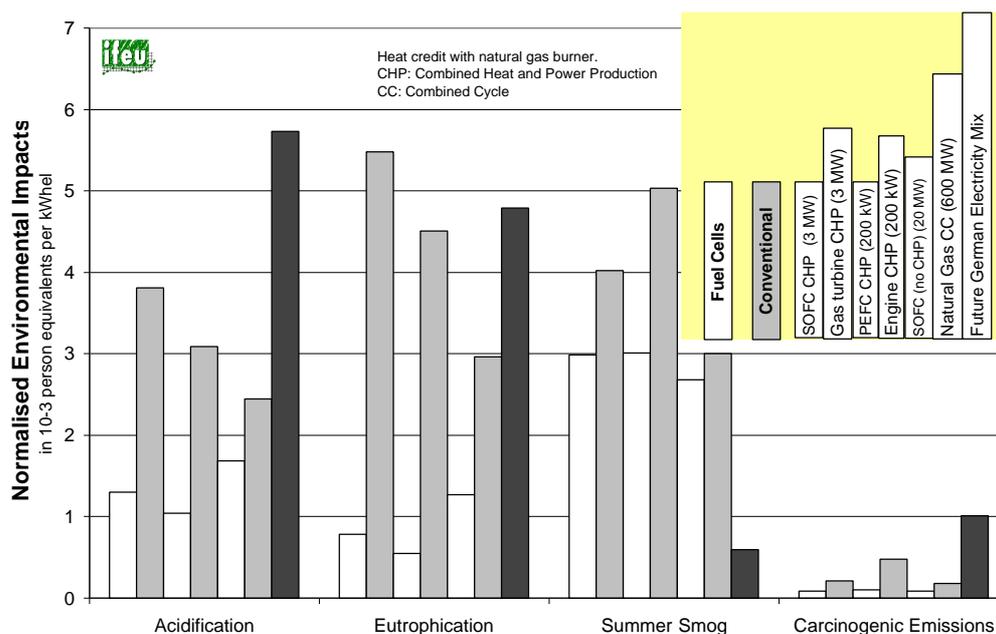


Figure 6 Normalised results of LCAs of different electricity generating systems (non-renewable fuels) for various impact categories (functional unit: 1 kWh_{el}). If heat is co-produced it is credited with a modern natural gas burner (“avoided burden”). All data is normalized to person equivalents by dividing the impacts by the average daily per capita impact in Germany (see Figure 5). Data taken from (Pehnt 2002).

The *relevance of pollutant emission reduction* not only depends on the *environmental significance* of the pollutants, but also on the *specific contribution* of electricity production/energy conversion to total European emissions. For instance, only 19 % of European NO_x emissions stem from the sector „energy industries“ with the dominant part emitted by transport (<http://themes.eea.eu.int>).

For SO₂, “energy industries” contribute nearly two thirds of total emissions. Here, however, a significant reduction has already taken place (1998 30 % of 1980 emissions, with further achievements in the past 5 years). Thus, the absolute emission levels are much lower than some time ago.

Beyond EU 15, however, the emission situation is different. In central and Eastern European countries, for instance, pollutant emission levels are much higher. Here, fuel cells would bring down emission levels instantaneously. However, in these countries, capital cost is an even more critical issue than in EU 15 countries.

4.4 Noise, vibration, space

Since fuel cells contain only few rotating parts, *noise* emissions and *vibration* are low. The phosphoric acid units, for instance, have noise rates of 66 dB(A) at 10 m distance. Also, the 11 MW units that run on higher pressure and have larger compressors are rated at <65 dB(A) at 30 ft from the site fence.

The noise is produced especially by the balance-of-plant components, particularly the compressor. It can be attenuated with appropriate noise

protection devices. In the case of a hospital installation of the mtu hot-module, for instance, the compressors were protected with noise insulation.

In domestic applications, where conventional small reciprocating engines are too noisy for individual buildings; fuel cells could offer significant advantages.

Sometimes, the *compactness* of fuel cells is mentioned as an advantage. Due to the pilot plant character of the systems realised today, it is difficult to derive the future space requirements. For Phosphoric Acid Fuel Cells, for instance, the required volume of the PC-25C could be halved compared to the PC-25A. Today, the PC-25C requires $83 \text{ m}^2/\text{MW}_{\text{el}}$, comparable to the Alstom Ballard system ($79 \text{ m}^2/\text{MW}_{\text{el}}$). Other pilot plants which were not optimised with respect to space, are in the range between 290 (100 kW_{el} SOFC Westervoort) and 450 (11 MW_{el} system in Japan) $\text{m}^2/\text{MW}_{\text{el}}$. The Hot Module will require $90 \text{ m}^2/\text{MW}_{\text{el}}$, the Siemens Westinghouse system approx. $170 \text{ m}^2/\text{MW}_{\text{el}}$. Further improvements can be achieved by higher power densities and better system integration.

For comparison, a typical 3 MW_{el} gas turbine system requires $15 \text{ m}^2/\text{MW}_{\text{el}}$, a natural gas combined cycle plant 65 (200 MW_{el}) to 30 (600 MW_{el}) $\text{m}^2/\text{MW}_{\text{el}}$ (IKARUS 1994; DLR, Dienhart et al. 1999), and a reciprocating engine between 8 and $34 \text{ m}^2/\text{MW}_{\text{el}}$ for 3 to 0.28 MW_{el} systems, including heat integration.

The compactness of a system might be a special issue in the case of domestic systems; today's systems, with weights at around 450 kg for 1 kW_{el} (Sulzer HEXIS), are extremely difficult to install by local craftsmen. Therefore, considerable development in this area is required. Further, in many countries houses have no basement. Thus, wall mounting the systems is required.

Mass and volume might be particularly critical for domestic CHP.

4.5 Heat levels suitable for industrial and cooling applications

Due to the high operating temperatures of MCFC and SOFC they are suited for different kinds of CHP applications, from house and district heating applications (90-120 °C) to cooling applications to industrial process heat supply up to 400 °C. Of the conventional CHP technologies, the gas turbine has a similar flexibility, whereas reciprocating engines typically produce heat up to 90 °C (only in special applications flue gas and cooling water heat are used separately with the possibility of higher temperatures).

High-temperature FC offer similar features with respect to industrial applications as gas turbines.

If one analyses the amount of industrial heat demand as a function of temperature (Figure 7), only 35 % of the total demand lies below 500 °C and is therefore suitable for CHP. In the temperature range between 500 °C and 800°C the heat demand is rather low. Only above 800 °C, a considerable amount of heat is consumed primarily for anorganic processes. These are no suitable applications for CHP. Therefore, the – compared to the gas turbine potentially higher – temperature of the SOFC flue gas does not result in considerably increased industrial applications. Rather, gas turbine and high-temperature fuel cells can, in terms of temperature, equally well serve the industrial process heat.

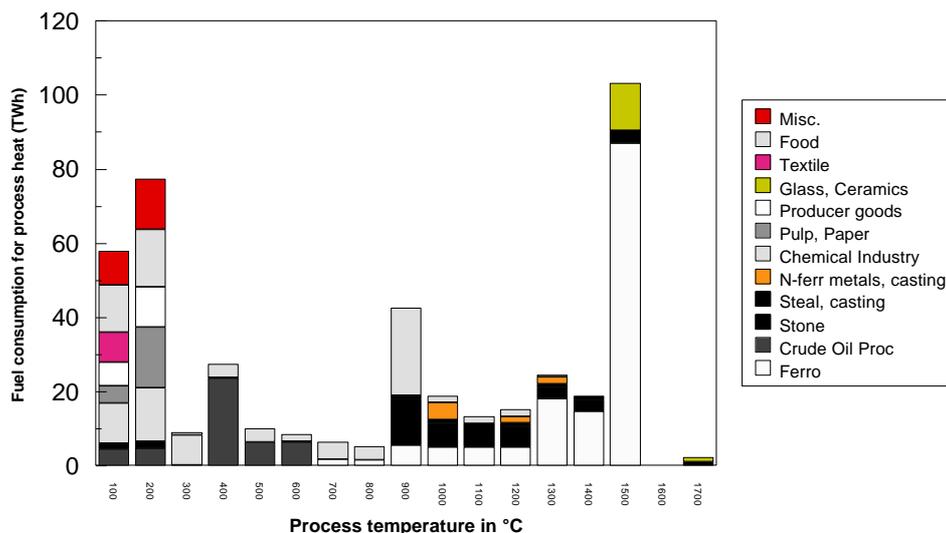


Figure 7 Fuel consumption as a function of process temperature according to (Hofer 1995), cited after (DLR, Dienhart et al. 1999)

As another interesting application, the demand for cold (air-conditioning, refrigeration, and freezing) has increased in the past years, with further growth expected in the coming years. The use of absorption chillers is also attractive because absorption chillers work with heat as energy source whereas conventional compression chillers need electricity. For providing the heat to absorption chillers, high-temperature fuel cells are more appropriate than reciprocating engines. This is due to the fact that for cooling energy at 6 °C via an absorption chiller, a temperature of the heat source between 60 and 90 °C is sufficient, but for temperatures below 0 °C, an absorption cooling device requires 120 to 180 °C (DLR, Dienhart et al. 1999). These higher temperatures would require to use the heat from the exhaust gas heat exchanger only (not from the cooling water circulation) which cannot provide such high flow rates.

For cooling applications, particularly below 6 °C, HT-FC are more appropriate than reciprocating engines.

4.6 Dynamic load response

In certain applications, for instance for grid conducted operation of fuel cells, where the load is determined by the load of the grid and a dynamic response is desired to supply regulating energy, the dynamic response particularly of low-temperature fuel cells will be of advantage. Thus, the electricity supplied can potentially be of higher economic value when together with suitable communication devices, a second-by-second response is possible. However, the dynamic response is much less pronounced for high-temperature fuel cells and yet has to be demonstrated. Here, thermal cycles and the heat capacity of the system may limit the response rate and the minimum allowable partial load.

Low-temperature fuel cells have the potential for high dynamics and may reach similar dynamics micro-turbines exhibit today.

4.7 High power to heat ratio

For certain applications it is desirable to have CHP systems with a high power to heat ratio (i. e. the ratio of the electrical and the thermal efficiency). Here, fuel cells offer power-to-heat ratios > 1 (except for domestic systems) which might be advantageous.

In some applications, for instance, the co-product heat cannot be used but must be cooled away, thus reducing the total efficiency considerably. One example are certain biogas plants, where the heat is used for the anaerobic process and for heating the premises, but often considerable amounts of excess heat cannot be used due to the large distance to settlements (Pehnt 2002). Here, fuel cells promise a better use of biomass resources.

In some industrial applications requiring high amounts of electricity, high power-to-heat ratios are economically advantageous. For instance, this is the case in metal processing/ electroplating companies and electrolytic production of aluminium, chromium or magnesium (DLR, Dienhart et al. 1999).

4.8 Synergies to mobile sector

As there is still substantial R&D effort required to bring down fuel cell capital costs to allowable levels (see chapter 5.1), every approach to reduce cost is welcome. One possibility is to exploit synergies between mobile and stationary applications which could occur on several levels:

- joint purchasing: companies could get better purchasing conditions when buying materials or components in larger amounts;
- joint R&D, for instance developing membrane electrode assemblies with reduced catalyst loadings for both applications;
- joint use of identical components and processing steps, thus allowing higher unit numbers and lower costs (example: marketing a vehicle stack also for premium power applications); particularly important in the initial phase where for vehicle applications, systems are still too expensive, and where stationary applications could offer an early market;
- joint build-up of a H₂ infrastructure; in a long-term perspective, stationary fuel cell systems with integrated reformers could supply hydrogen to the first pilot vehicles thus eliminating the need for an extra H₂ filling station (see Plug Power & Honda);
- and, in the very long-term, the vehicle to grid (V2G) approach, where fuel cell vehicles are connected to the electricity (and potentially heat distribution) grid to supply, for instance, peak load, spinning reserves or regulating energy (Kempton, Tomic et al. 2001).

Synergies on different levels

Stationary applications require 10-fold higher life-time and better efficiencies than mobile applications.

When assessing these synergies, one has to keep in mind that in stationary and mobile applications, totally different specifications have to be fulfilled. In vehicles, a stack life-time of 4000 h may be sufficient, whereas in stationary applications,

the life-time typically has to be an order of magnitude higher. This reduces the joint R&D possibilities and the feasibility of the V2G approach. On the other side, the major part of the R&D efforts of the companies (from which also stationary systems will benefit) is motivated by the strict cost targets of mobile applications.

Thus, some car manufacturers, such as Toshiba IFC, announced to start mass production of 5 kW_{el} PEM fuel cells for residential applications (press release 3/2/2003).

For others, the stationary application offers an early market. General Motors for instance develops a 70 kW stationary system based on the vehicle stack for premium power use. In the premium power sector, lower life-times and efficiencies and higher capital costs are not so relevant and reliability is the key issue.

Stationary applications with reduced performance requirements as early market

These intermediate products help the mobile applications because the high R&D costs can be lessened to a certain degree. However, stationary fuel cells, particularly larger systems (> 200 kW_{el}), will not to the same extent profit from these synergies because for them, less overlapping applications exist, whereas for small scale domestic systems one could imagine such cheap capital costs due to developments in the mobile sector that replacing a stack would be no barrier for the economics of that system.

Additionally, such synergies between the mobile and the stationary sector are not specific to the fuel cell business segment. For instance, General Motors also develops a micro-turbine jointly for stationary and vehicle applications in a series electric hybrid. Another example for such synergies are reciprocating engines used in CHP which are mainly based on vehicle combustion engines and can, therefore, profit from developments made for the vehicle market. Nevertheless, despite these synergies, these technologies have to fight for their economic survival.

Synergies also for conventional technologies

4.9 New business segments for IPP, small scale CHP, gas suppliers and energy services

4.9.1 Premium power

Many businesses — especially the growing number dependent on microprocessors — need high-quality, reliable electricity to keep manufacturing processes going, or to provide services such as financial transactions. Power quality therefore is an important concern for today's power grid and the loads that it serves.

Traditionally, electric utilities have assured reliable service to what is called "four nines", that is, power will be available 99.99% of the time. But high-tech industries like internet server farms and computerized banking systems demand

Increasing demand for "premium power"

much higher reliability, in the range of “nine nines” (available 99.9999999% of the time) (Mansoor, Keebler et al. 2000).

Creating this level of reliability can potentially be achieved using traditional grid technologies — for example, by supplying multiple power feeders to the system and providing a backup line from a hydropower station — but the cost is high, and the reliability is generally guaranteed at the expense of service to other customers. Yet a typical computer system annually experiences around 300 power disturbances outside the manufacturer’s voltage tolerance limits.

However, even momentary power disturbances can cost some businesses millions of dollars (Table 3). According to DOE's Office of Distributed Energy Resources, power fluctuations and outages cost U.S. business about \$50 billion a year (DER 2003).

Premium power user	Typical cost for 1-hour interruption
Cellular communication	\$41,000
Telephone ticket sales	\$72,000
Air reservation system	\$90,000
Semiconductor manufacturer	\$2,000,000
Credit card operation	\$2,580,000
Brokerage firm	\$6,480,000

Table 3 Examples for hourly costs of power outage in the US (Source: http://www.gm.com/automotive/innovations/Fuelcell/fuel_cell_cost.html)

Depending on the specific technologies, site conditions, and potential interaction with the existing electric power system, various distributed energy resources (DER) including fuel cells represent a way to address the emerging need for high power quality. Some energy consumers have already responded by installing their own distributed energy systems. The First National Bank of Omaha, for example, uses fuel cells to run its credit card processing centres, thereby saving up to \$6 million per hour of power outages (DPP 2003). More elaborated concepts are power parks (also called “premium power parks”) that include on-site power sources to increase reliability in combination with uninterruptible power supplies, such as battery banks, ultracapacitors, or flywheels.

Due to the few moving parts and the reliable mechanisms underlying the fuel cell, it is often regarded as a highly reliable systems. The operating experience gained so far underlines that as long as “teething troubles” of new technologies will be overcome this could turn out to be a valuable advantage of fuel cells. For example, PAFC have demonstrated 98+% uptime when run on clean fuels and suitable care. When operated with premium service, between 96.8 and 99.4 % were achieved (Lovins, Lehmann et al. 2002). Based on PAFC technology, 99.9999 % reliable systems are offered by some companies (e. g. SurePower). However, so far, with the exception of some PAFC systems, “the long-term

Fuel cells are one option for power quality solutions

performance and reliability of certain fuel cell systems has not been significantly demonstrated to the market” (NFCRC 2003).

4.9.2 Domestic CHP as new market opportunity

In addition to the market segments mentioned above, fuel cells, possibly in combination with Stirling engines, might open up a completely new market segment: that of domestic CHP (MicroCHP). The mass market for MicroCHP will be for the replacement of gas heating boilers (Harrison and Redford 2001). Because of the vivid development of small fuel cell heating systems, the development of domestic systems is well on the way. Experience with first activities of some energy suppliers (e. g. EWE and EnBW in Germany) where the companies were overrun by people interested in such systems show that fuel cells enjoy a high confidence of end-users who would have no objection to install these systems in their houses (Ballhausen 2002).

The domestic sector micro cogeneration could, if the right market and economic factors support this segment, represent a considerable market. The FutureCogen project estimated that under optimistic assumptions, by 2020 up to 50 GW_{el} in EU15 could be installed in this sector (Future_Cogen 2001). Micromap calculates different scenarios, with up to 12 million MicroCHP systems delivered in Europe by 2020 in the optimistic and 5 million in the Business as Usual scenario (MicroMap 2002). United Kingdom, Germany and Netherlands are seen as initial markets for MicroCHP. In addition, some 700.000 units could be installed in Central and Eastern European countries.

One of the key factors for economic viability is the electricity price (see chapter 5.1) which enters the calculation because either domestic electricity consumption is displaced – and thus associated costs eliminated – or because electricity is fed into the electricity grid with a corresponding feed-in tariff. Due to the high capital costs of any MicroCHP system, related connection issues, and the more complicated installation process, these systems are likely to be marketed by Energy Service Companies (ESCOs).

In this market for MicroCHP, Stirling engines will be close competitors. In spite of a lower electrical efficiency, Stirling engines offer high total efficiencies as well as flexibility with respect to fuel contamination because they rely on external combustion.

4.9.3 New energy services for the household customers

It is commonly expected that the market introduction of fuel cells in the household sector will depend on a supply push. The manufacturers and other involved parties have to take a pro-active role in order to increase the attractiveness of the new solution. For this reason, the key to the market success of fuel cell heating systems is commonly seen in “one-stop solutions”, providing a complete service package to the customer (Figure 8). It is foreseen that manufacturers, licensed

Fuel cells might open the completely new market of domestic CHP

Stirling engines main competitors

Energy service packages seen as key to market success

installation contractors and/or utilities will take care of installation, operation and maintenance of the device and will coordinate the integration of the CHP into the public grid. Obviously, the widespread dissemination of such energy services will represent the precondition for realizing the concept of a virtual power plant/virtual utility.

In line with this emerging market for new energy services (micro-contracting) fuel cells offer new business opportunities, e. g. for utilities that aim at providing a broad range of supply services (multi-utility approach).

The starting conditions for such service offers are quite favourable since heat related energy services have already been introduced to the market so that necessary competence and experience is available. Compared with other approaches of third-party financing and performance contracting schemes, heat services which demonstrate the highest growth rates and most favourable market prospects might push the introduction of fuel cells.

In the commercial and industrial sector a comparable chance can be seen for energy service companies (ESCOs), which evaluate energy use, recommend energy management strategies, and provide related services, including a variety of supply-side and demand-side options — see new opportunities for selling, financing, and managing distributed generation and load reduction technologies and approaches.

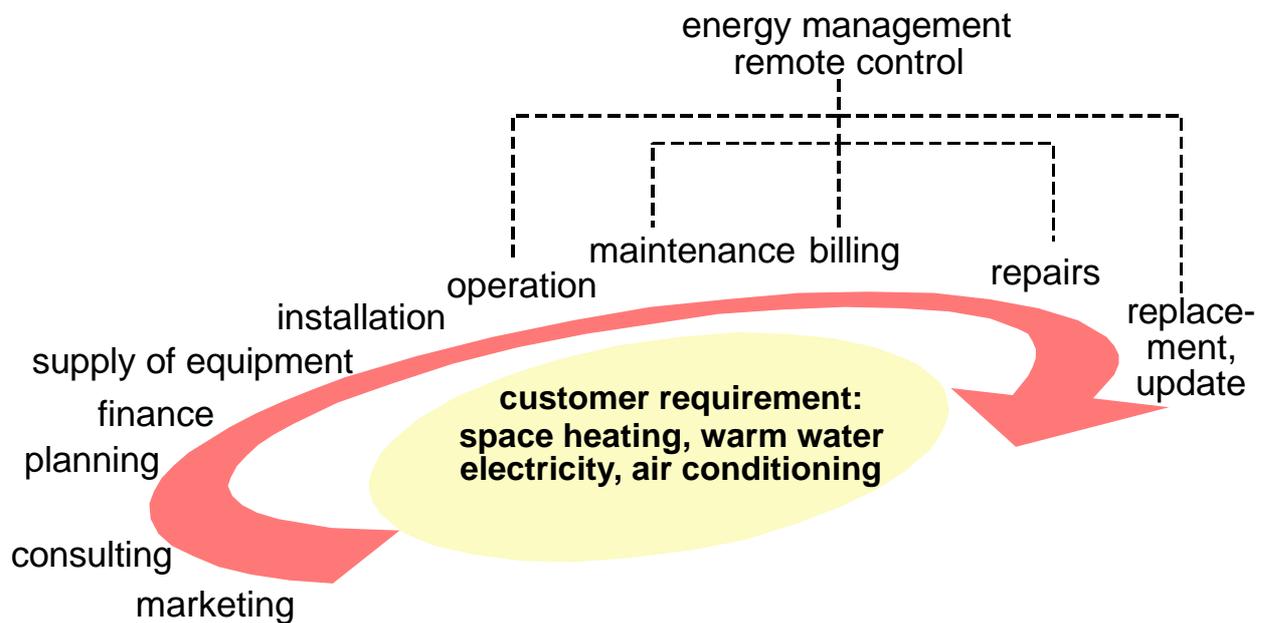


Figure 8 Energy services bundled to “one-stop-solutions”

4.9.4 Market opportunities for gas utilities

The gas utility sector envisages ambivalent mid-long-term market prospects. Whereas in many sectors such as power generation, gas demand is rising, in other segments such as new urban settlements, space heat demand – and correspondingly gas demand – is decreasing. Energy saving standards and

Domestic gas demand decreases – fuel cells offer new market shares for gas utilities

innovative constructions allow to squeeze the specific energy consumption below 50 kWh/m²*a and even much less. Among gas utilities this is often considered to be the critical threshold to profitably operate a gas grid. As a result in certain regions, such as in development areas in rural regions, gas supply companies decide not to invest in a gas distribution system.

In a longer perspective (see chapter 6), significant shares of the domestic heat market risk to get lost for the gas industry so that natural gas based CHP via fuel cells offer a new option to promote gas use. In addition to innovative gas appliances such as gas fired tumble dryers, etc. gas demand is increased significantly by fuel cells due to the simultaneous production of heat and electricity.

4.9.5 New options for supply of backup power

Fuel cell CHP systems that follow the heat demand of end-users will generate a rather stochastic electricity production. However, fuel cells can be used as well as a means to manage the end-users' electric load curve, especially when several units are interlinked through information technologies and centrally controlled. Appropriate timing of operation can contribute to peak load shaving, compensation of seasonal load asymmetries and provide the option to balance the increasing share of intermittent generation from renewable energy sources.

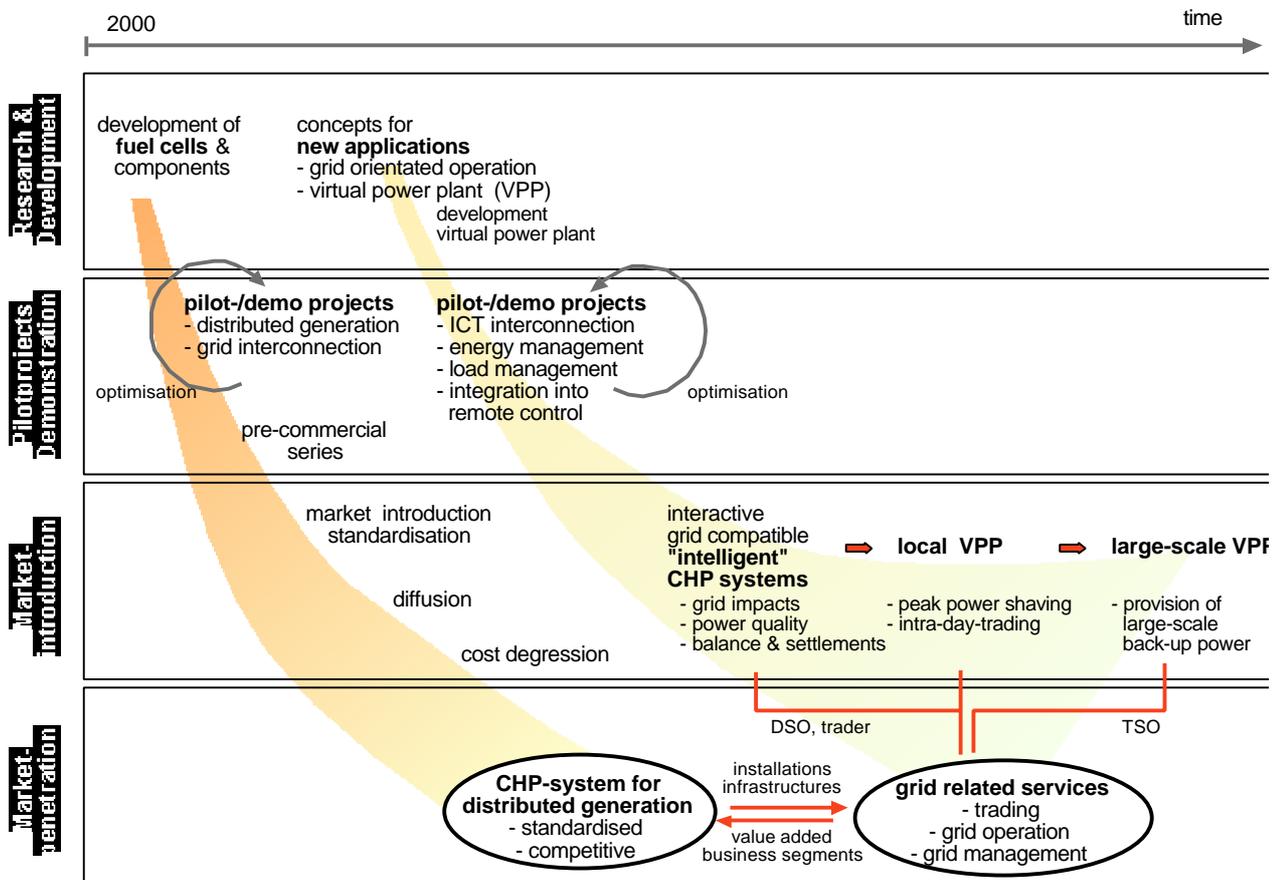
Grid-related operation strategies of fuel cells, therefore, are of special interest for systems operators and distribution utilities. They are obliged to purchase expensive back-up power from reserve capacity in order to balance the differences between load prognosis and factual demand. In this context, the load management of fuel cells creates specific added value that adds to the profitability of installations. New opportunities emerge with regard to

- a fixed electricity generation according to pre-negotiated load profiles, i. e. an exclusion of stochastic feed-in;
- provision of back-up power from spinning or supplemental reserves that can be used to balance excess demand and peak loads;
- regular selling of electricity in liberalised energy markets on the basis of flexibly negotiated supply contracts , e.g. on the energy spot market.

In order to benefit from these options, however, remarkable progress in grid related RTD is required. In addition to the ongoing technology development of stationary fuel cells, an additional line of innovation has to be opened up (Figure 9). Technical solutions for grid interconnection, communication and control as well as the necessary regulatory and institutional arrangements have to be achieved. It can be expected that grid related solutions and products will enter the market with a certain delay compared to the single stationary fuel cell application. Due to the fact that not only fuel cells, but other kinds of conversion technologies such as reciprocating engines are suited for the purpose of backup supply, these available options can already be used to develop the field (see for

New value added through grid-related operation of fuel cells

instance the Stadtwerke Unna project that aims at creating a network of remote controlled reciprocating engines and micro-turbines (www.sw-unna.de)).



VPP - virtual power plant
 CHP - combined heat & power generation
 DSO/TSO - distribution/transport system operator

Figure 9 A new technology field is required to generate innovative business opportunities for fuel cell operators in the field of grid support services

Moreover, it has to be kept in mind that due to the relatively small size of domestic fuel cells an aggregation of units appears to be inevitable. Commercially attractive capacities will hardly be realised without a pooling and central control of a larger number of applications. A widespread deployment of fully integrated distributed power generation from fuel cells and other technologies enables advanced operating concepts such as the self-healing grid, micro-grids and the virtual utility (CEIDS 2002). These concepts hold the potential for providing the high reliability, quality, security and availability of electrical service required by society.

Triggered by recent advances in IT-technology, *virtuality* is a new concept for energy industry in which transactions between buyers and sellers of electricity would be handled in a non-traditional manner⁹. For example, an operator of a

⁹ Apart from new arrangements on the supply side, new modes of bundling of demand such as bulk purchase through a *virtual consumer/buyer* can be possible.

virtual power plant could own several distributed energy resource (DER) units such as stationary fuel cells and remotely dispatch energy and capacity in accordance with contractual agreements made with the buyers of its services. This operator would act as a *virtual utility* as long he is able to remotely monitor and control the fuel cell units and the consumer's energy management system as well as to respond to external signals, e.g. price signals from buyers in the spot market. In a more general case, the virtual operator may also own other types of equipment that enable it to provide other types of services like improved power quality or load management. Most or all functions necessary for the operation of the virtual utility, such as maintenance, billing, and information technology system, could be outsourced. In fact, the distributed generation units and other equipment used to provide services could be owned by other entities and managed by the virtual operator. Collectively, the changes will mandate the overall physical infrastructure of the distribution system to evolve into something that is capable of supporting the business arrangements of the virtual utility. Figure 10 shows a schematic of the virtual utility.

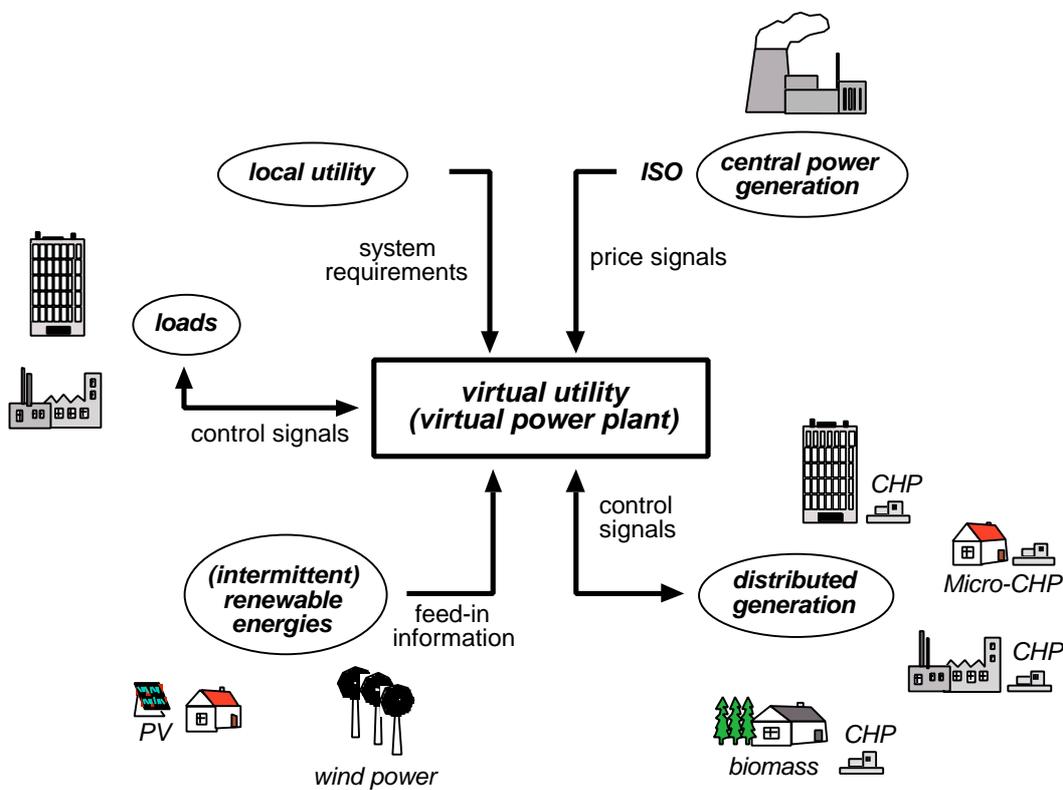


Figure 10 Schematic of the virtual utility

4.10 Possibility of 'simpler' CO₂ storage

When a complete fuel switch to renewable fuels is not possible under certain conditions, one alternative is to reduce the impacts of the fossil fuel conversion. Of particular interest in this context is coal that has large reserves especially in some countries with high increases in electricity demand (e. g. China). It has been discussed for some time that the capture and subsequent storage of the

CO₂ which is produced when the coal is combusted would offer a new option to produce electricity with climate-compatible coal plants (see, for instance, (IPCC 2002)). Beside the necessity to dispose of the CO₂, e. g. by storage in oil fields, caverns or aquifers, carbonation via magnesium hydride, etc., it is also necessary to capture the CO₂. There are two basic options: capture from the atmosphere, or direct absorption of the CO₂ in the power plants. For the latter, a number of investigations have been carried out with the goal to optimise the power conversion processes (high CO₂ content in the flue gas) such that minimum efforts have to be taken to remove the CO₂. One option was to develop IGCC power plants which include a coal gasification and allow the capture of the CO₂ in the synthesis gas prior to combustion.

In the debate on CO₂ storage, the fuel cell enters the stage primarily due to two reasons:

In the **mobile sector**, the many decentralised CO₂ emission sources in the vehicles make a CO₂ capture very difficult. The centralised hydrogen (H₂) production for hydrogen vehicles would allow an easier capture of the CO₂ at the H₂ plant. This enables to tap the CO₂ reduction potential of the mobile sector.

In the **stationary sector**, fuel cells might, due to the separate flows of anode and cathode, in principal offer good conditions for a rather high CO₂ concentration in the flue gas. In the recent DoE FutureGen initiative, for instance, production of a hydrogen rich synthesis gas from coal with subsequent CO₂ capture and electricity production in a fuel cell is planned (DoE 2003). Siemens Westinghouse carried out a study to find out specific technological set-ups (using a part of the fuel cell stack as an "oxygen pump" to avoid diluting the flue gas) to have only CO₂ (and H₂O which can easily be removed) in the flue gas (Hassmann 1999). The study concluded that this set-up is principally possible, with many materials science issues to be addressed. One particular application of that design is the use on oil platforms where the CO₂ can be pumped into the reservoir, thus enhancing the oil yield of the deposit (enhanced oil recovery).

Even though, from a technical point of view, the combination of coal gasification, fuel cells and CO₂ storage seems attractive, a number of severe short-comings prohibit the realisation of such plants as a near or midterm option:

- **Technical feasibility.** For each of the process steps, i. e. coal gasification, decarbonisation of the flue gas, fuel cell, and CO₂ storage, severe technical problems have to be solved. This is particularly true for the storage (for instance storage quality, impacts of an increased pressure in geological formations, etc.), but also for, for instance, fuel cells, where additional technical adaptations to the CO₂ capture process are required.
- **Low efficiencies.** A recent study (Köhler, Krammer et al. 2003) could not confirm the high efficiencies of the fuel cell/carbon capture system from the large Zero Emission Coal project, but rather forecasted an electrical efficiency (LHV) below 40 % (*without* considering CO₂ storage). This is less than in IGCC projects. The efforts for CO₂ transport and storage further reduce this efficiency.

In mobile applications, hydrogen offers the possibility to centrally capture the CO₂.

In stationary applications, Fuel cells might, in the very long-term, allow a better capture of CO₂ from the flue gas. Due to high capital cost, low electrical efficiencies and prevailing technical problems, and open questions regarding safety and CO₂ leakage, the use of coal gas in fuel cells with subsequent CO₂ storage is not seen as a successful climate strategy for the next 50 years.

- **Cost.** Furthermore, the costs of carbon capture and storage (see for instance (Enquete 2002)) in general and particularly of fuel cell/carbon capture systems (Köhler, Krammer et al. 2003) are significantly higher than competitive processes even if the target costs for fuel cells are used for the calculation. Additionally, the use of renewable energy carriers sets a benchmark for CO₂ reduction costs. (Köhler, Krammer et al. 2003) therefore draws the conclusion that „due to technical barriers, lacking feasibility and high capital costs the realisation of this process is not foreseeable.“
- **Risk and environmental aspects.** Some severe environmental and safety aspects concerning CO₂ capture and storage remain unresolved and need significant further consideration. Depending on the various capture and storage options, these include, for instance, continuous leakage rates (depending upon the cap rock integrity and the security of the well capping methods), the risk of sudden CO₂ releases, waste, groundwater issues, ecosystem compatibility, etc. (see for instance (Enquete 2002; Johnston and Santillo 2002)).

Our conclusion is that coal fuel cell plants combined with CO₂ storage will not contribute significantly to GHG abatement in the next 50 years.

4.11 Opportunity to de-block current ignorance vis-à-vis CHP

As we have seen, fuel cell heating systems offer a wide range of interesting implementation cases and some exciting prospects for the future. In any case, they represent an innovation to the traditional market for heating systems. Moreover, due to the innovative character they represent an opportunity to de-block the still prevailing ignorance vis-à-vis CHP solutions.

As opposed to areas like consumer electronics, average end-users are barely interested in the technical aspects of their heating system and only little knowledge about efficiency, emissions, etc. can be found. Today, the heating system is a black box without any further appeal; it is hidden in the cellar. Accordingly, the specific value added and the environmental benefits of CHP solutions – especially from a system’s perspective – will hardly motivate customers to make extra efforts or to take technical risks during the market introduction phase. Even CHP solutions that are widely available and market proven still suffer from marketing problems although they demonstrate technical reliability, convincing performance and a competitive price.

In this situation, all solutions on the CHP market can benefit from the current high-tech image of fuel cells as a clean technology. Fuel cells might become as “sexy” as PV panels and can open the eye for the hidden potential of combined generation. This effect should be deliberately exploited for social marketing not only of fuel cells but of the important role of CHP in general.

**"Sexy" image of FC
opens the eye for
CHP benefits**

However, one could also reverse the argument: once the fuel cell euphoria diminishes, the ignorance regarding the heating system or the electricity supply might dominate the consumer’s perspective; consequently, only the economic

attractiveness of the systems would prevail the purchase decision. Only extensive marketing and educational efforts could then consolidate the image of fuel cells.

4.12 Further advantages common to all distributed generation technologies

There are further advantages of fuel cell systems that are common to all distributed generation technologies. These will only be mentioned briefly here.

4.12.1 Reduced transmission/distribution losses and less required grid capacity

Depending on the load of a grid, its capacity, the weather conditions etc., a considerable amount of energy might be lost because of transmission and distribution of electricity. Whereas in many countries, these losses are in the range of 5 to 8 %, under certain conditions (high load, low voltage, weak grid, etc.) they might be as high as 15 %. Even in Europe, estimated average losses vary between 3.7 % (Finland) and 9.9 % (Ireland) (Ofgem 2003). DG technologies, and fuel cells as well, are considered to reduce these losses due to feed in of electricity, thus reducing the currents in the cables (for further information on this issue, consult (Dunn 2000; Lovins, Lehmann et al. 2002)).

4.12.2 Reduced vulnerability of the energy system

A reliable and safe supply of electricity is the indispensable foundation of western economies and the emerging digital society. For instance, EPRI estimates indicate that the proportion of U.S. electricity requiring highly reliable, digital quality power will grow from 0.6% of current consumption to nearly 10% by 2020, and that the proportion of enhanced reliability will grow from about 8-10% to nearly 60% (CEIDS 2002) (see also chapter 4.9.1). In this context the development of a robust and “self-healing” transmission and distribution system – capable of automatically anticipating and responding to disturbances, while continually optimising its own performance – will be critical for meeting the future electricity needs of industry and the knowledge society.

In combination with new information and communication technologies, sophisticated sensors, and operation and management practices, distributed power generation by fuel cells can make a contribution to the avoidance of widespread network failure due to cascading and interactive effects – threats include intentional disturbances by terrorists, natural disasters, and material failures. Decentralised power generation will thus complement efforts to increase grid security in response to the threat of terrorism.

4.12.3 Modularity of the system

CHP systems in general, and particularly fuel cells, can be installed in a modular way. Thus, instead of installing large-scale power plants with a sudden high increase in installed capacity, a step-wise build-up of capacity can be realised. Under certain circumstances, this may be of economic advantage (caused by reduced forecasting risks, reduced financial risks and reduced risk of technological or regulatory obsolescence, see (Lovins, Lehmann et al. 2002)). Another advantage of this modularity is the possibility to pre-install the fuel cell system in containers, thus lowering the time to install the system. In addition, for example in the case of stack manufacturing, economies of mass can be realised due to higher possible unit numbers. On the other hand, certain components, for instance the reformer, show increasing specific costs with decreasing size (economy of scale) that offsets this trend.

**Economic benefits
through modular
investments**

5 Barriers, challenges and open questions

In analogy to the discussion of the advantages and drivers for fuel cells above, in the following sections, main barriers and open questions regarding stationary fuel cells (Figure 11) will be outlined and investigated.

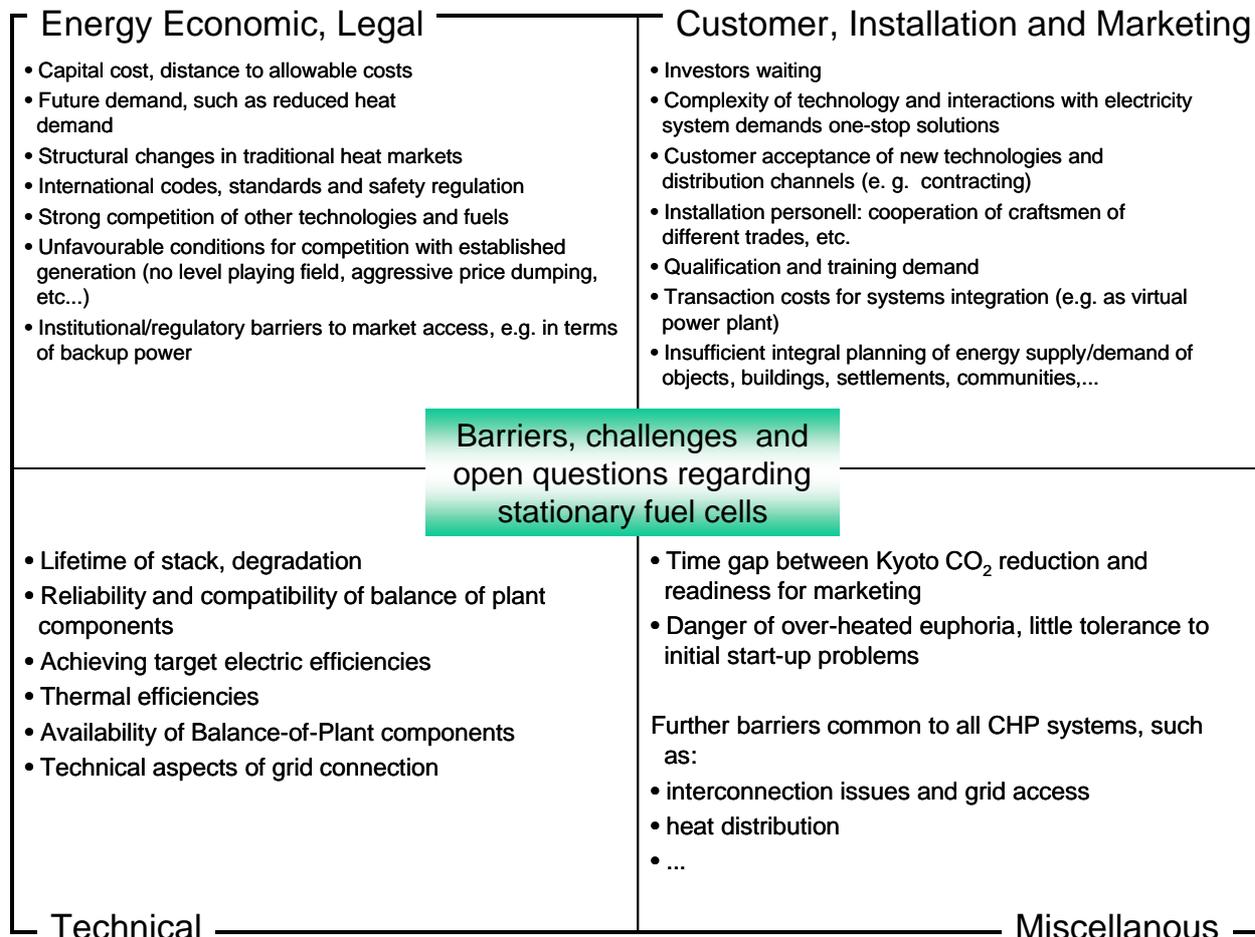


Figure 11 Potential barriers and open questions regarding fuel cells in stationary applications

5.1 Cost

The main challenge for fuel cells is to achieve the competitive cost goals. In stationary applications, cost targets are not quite as strict as in mobile applications where system costs in the order of 50 to 100 €/kW have to be met. However, the two applications cannot directly be compared to each other. Stationary applications have to fulfil higher standards because in typical applications, tenfold higher stack lifetimes are demanded, and the high electric efficiencies of the competing technologies will require operating the systems at much lower current densities than in mobile applications (where the efficiency is

considerably higher) thus leading to an enhanced requirement of active fuel cell area (= cost).

5.1.1 Cost targets

The target costs of fuel cells, i. e. the allowable costs at which fuel cells will become competitive, are determined by the market segment, by the costs of the competing technologies and by the energy economic developments, e.g. in terms of energy taxation. Due to the higher efficiency of the fuel cell system, fuel costs are lower and the maintenance costs are typically assumed to be lower than, for example, in gas turbine applications. This leads to higher allowable capital costs for the fuel cell system. In several studies, the allowable capital costs per kW_{el} are specified to be around 20 to 30 % above the competing technologies (see, for instance, (DLR, Dienhart et al. 1999)). This represents a comparatively low increment which partially results from the required replacement of the stack.

Typically, in smaller systems the allowable cost difference increases because of the higher efficiency advantage of fuel cell systems. Furthermore, in domestic applications, the high household electricity costs increase the economic competitiveness of fuel cells so that in this application, the allowable costs of can amount to up to 2'000 €/kW (Table 4).

Factors strongly influencing the allowable costs are:

- the future electricity costs (when the costs are compared to the separate production of electricity and heat) and the feed-in tariffs for self-produced electricity from CHP
- the ratio of electricity replacing own demand compared to the electricity fed into the grid; due to different economics – replaced own demand is usually more attractive (unless there is no significant financial support by the government) than feed-in because the compensation by the net operator is lower than the cost of electricity supply – this can lead to substantially different economic situations
- the cost of natural gas
- the cost of the conventional heat production to which the fuel cell system is compared to
- the operational mode (heat conducted, electricity conducted, grid orientated, or combinations)
- the lifetime of the system (costs for stack replacement)
- the load factor of the system
- via the parameters mentioned above, certain demand patterns of the objects, such as ratio of electricity to heat demand, baseload demand, etc. determine the allowable costs.

Table 4 Allowable capital cost ((DLR, Ifeu et al. 2003), (DLR, Dienhart et al. 1999) (industrial CHP))

Market segment	Allowable capital cost (€/kW _{el}) compared to	
	separate production*	reciprocating engine/gas turbine
Domestic (2kW _{el})	2000	
10 "passive houses" (2kW _{el})	2500-4000	
small multifamily residence	2200	2000
small district heating	800-1800 **	n. a.
Industrial CHP	n. a.	1070

* (condensing boiler and electricity mix) ** depending on the share of own consumption/grid feed-in



To bring down investment costs of fuel cell systems, various measures have to be taken:

- Improving fuel cell stack design (increased power densities, particularly for high-temperature fuel cell systems; altered structures such as thin electrolytes, anode-supported systems, adopted SOFC tubes, etc.);
- Reducing degradation and increasing tolerance towards gas contaminants, thus reducing gas cleanup efforts;
- Using lower cost materials (e. g. conventional steel for the mtu hot module vessel, cheaper separator plates, etc.);
- Minimizing temperature constraints (e. g. lowering SOFC operating temperature to use lower cost materials and sealings, or enhancing PEFC temperature to reduce gas cleanup requirements);
- Using reliable and standardised fuel processing and other balance-of-plant components (power electronics, etc.);
- Learning effects due to higher unit numbers. For that purpose, high-volume production in the order of hundreds of Megawatts are required;
- Streamlining manufacturing processes.

It has to be underlined that there is a certain trade-off between cost reduction and high performance so that achieving cost and performance goals simultaneously seems to be the major challenge for research and development.

To try a first quantification of possible learning effects, one can use the concept of learning curves which show the dependence of unit costs on the cumulative production. From a range of products, learning factors were derived which describe the percentage the cost is reduced to when the cumulative production of a product is doubled. For many products, learning factors between 0.7 (very high

learning effects) to 0.9 (especially in later phases of market development) were derived.

Figure 13 shows the possible development of future cost of a generic fuel cell¹⁰ when a learning factor of 0.8 and a market entry cost of 15.000 €/kW at 20 MW cumulative production is assumed. The resulting initial - rather steep – cost reduction will bring fuel cells rather early into the cost sector of 3000 €/kW, where certain applications are economically attractive already under today's conditions. At a level above 10'000 MW cumulative production, the threshold of 2'000 €/kW is reached. According to some scenarios, such as the UNEP scenario (see chapter 6.1), this will be the case even before 2010.

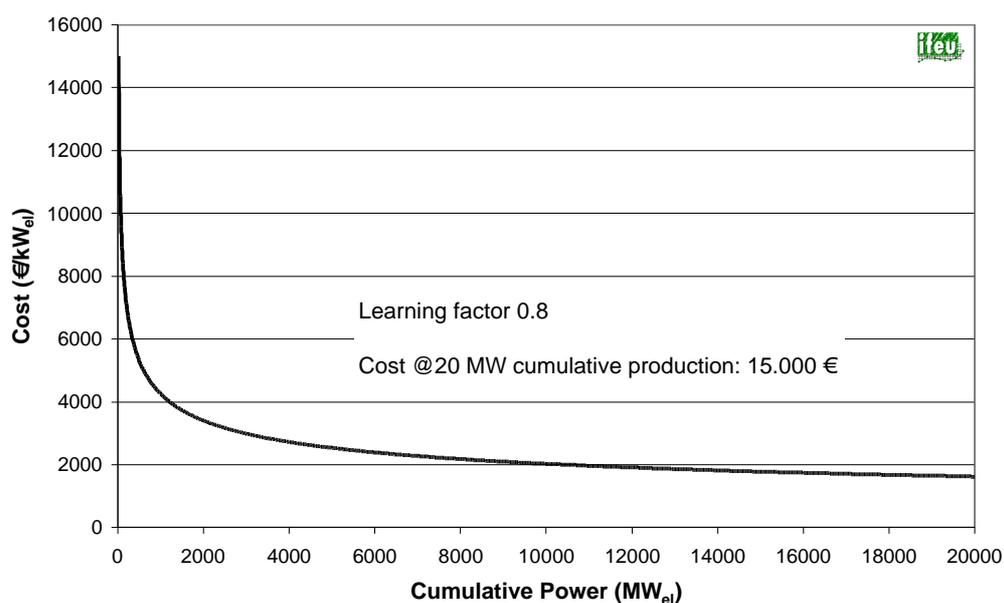


Figure 12 Possible development of future production cost of fuel cells assuming a learning factor of 0.8 and a „generic fuel cell development“(DLR, Ifeu et al. 2003)

5.1.2 Where are we now?

When we compare the current state of costs with the allowable costs we have to acknowledge that, in the past years, most manufacturers have already undergone a significant learning curve. Taking the manufacturing of a 4.6 kW_{el} Vaillant system as an example, Vaillant has achieved a reduction to 41 % of the initial value of 110'000 € in January 2001 (Figure 13).

¹⁰ Here, as a first order approximation, no distinction between fuel cell technologies is made.

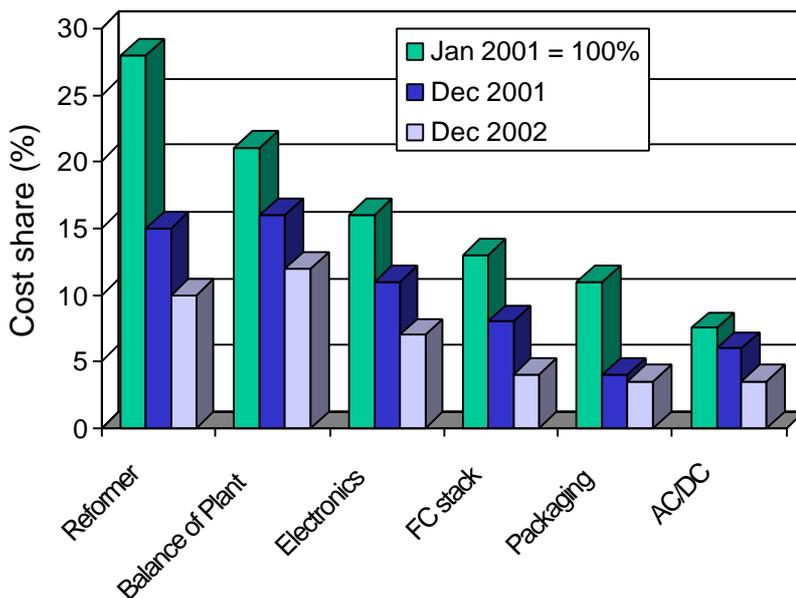


Figure 13 Cost reduction of fuel cells: the example of a Vaillant PEFC system (Klinder 2003)

Interestingly, it is not only the cost for the fuel cell stack, which in many cases causes less than one third of the total capital cost (this is true for large SOFC and MCFC systems as well as for domestic energy systems (Teagan, Thijssen et al. 2000; Vaillant 2003)). Rather, a large portion of the cost is caused by the reformer and other balance of plant components.

Balance of Plant is responsible for a large share of total capital cost.

Also, not in every field the cost of all fuel cell systems goes down. Whereas, for instance, the UTC prognosis for 1998 was 280'000 € for the PAFC system, the actual cost amounted to 690'000 € and further increased to 1'060'000 € (5'300 €/kW_{el}) due to reduced subsidies and the changing dollar rate. This was the main reason why UTC announced withdrawal from the PAFC business.

If one looks at the current cost situation of different systems, smaller systems for domestic applications cost between 10'000 and 50'000 €/kW_{el}, larger systems between 5'500 (UTC PC25C) and 18'000 € (Siemens 250 kW system), with the mtu hot module in between (10'000 €/kW).

This means that today's systems are, depending on the application, manufacturer and technology, a factor 2.5 (PAFC) to 20 too expensive — or roughly spoken one order of magnitude too expensive.

Fuel cells are a factor 2.5 to 20 too expensive.

5.2 Decreasing future heat demand in households and buildings

Space heating and warm water together represent approx. 80 % of end-energy-use of households (without transport). Considering the usually poor energetic quality of the existing building stock, significant energy saving potentials can be found (e.g. the Enquete commission of the German Bundestag estimates the

potential to be 30 % until 2020 and 70 % until 2050 compared to the year 2000 (Enquete 2002, p.312). With regard to new buildings, various concepts for ultra-efficient houses are available and practically proved such as passive houses, solar architecture, zero-energy houses, etc. Almost in every country considerable efforts are made to promote these innovations. On the European level, the directive on the energy performance of buildings (2002/91/EC) provides an additional impetus to advance in this field.

Future space heat demand will go down significantly.

For these reasons it can be expected that even in a business-as-usual case the heat demand will be reduced significantly whereas more ambitious climate policies may trigger further achievements. In the German case, for example, a recent scenario analysis identified for the year 2050 (1990 base year) a range of reductions between –18% (trend case) down to –60% in the case of a sustainable policy strategy heading for a 80 % CO₂ reduction within this time span (Fischedick, Nitsch et al. 2002).

As a direct effect of a decreasing demand for space heating, however, the relatively constant consumption of warm water gains importance. Warm water demand represents a base load for fuel cells even in summer time, so that the annual heat demand profile will show less seasonal disbalances. In this regard it will be easier to dimension the CHP units with a reasonable load factor.

Constant warm water demand smoothes the demand profile.

5.3 Structural changes in traditional heat markets

It has been mentioned already that technical reliability, convincing performance and a competitive price will be mandatory preconditions for a broader market introduction of fuel cells. A competitive price alone, however, will hardly be sufficient for success in traditional markets for space heating. As seen in the recent history of introducing condensing boilers, the conservative attitude of buyers and installation contractors can hinder the penetration of innovative technologies. This is even more true if the new option represents a highly complex solution.

The conservative attitude of market players can suppress innovation.

In this regard a fuel cell is not only a substitute for traditional heating equipment but represents a remarkable shift of paradigms in the field of domestic energy supply (Figure 14). Compared to the conventional situation of separate supply of electricity and heat, fuel cells

- introduce an innovative, unknown technology which demands new qualifications in terms of installation, operation and maintenance by the contractors involved,
- might make the private home owner become an independent power producer, and
- turn the family home's cellar into a knot of a decentralised power generation network (see the virtual power plant above).

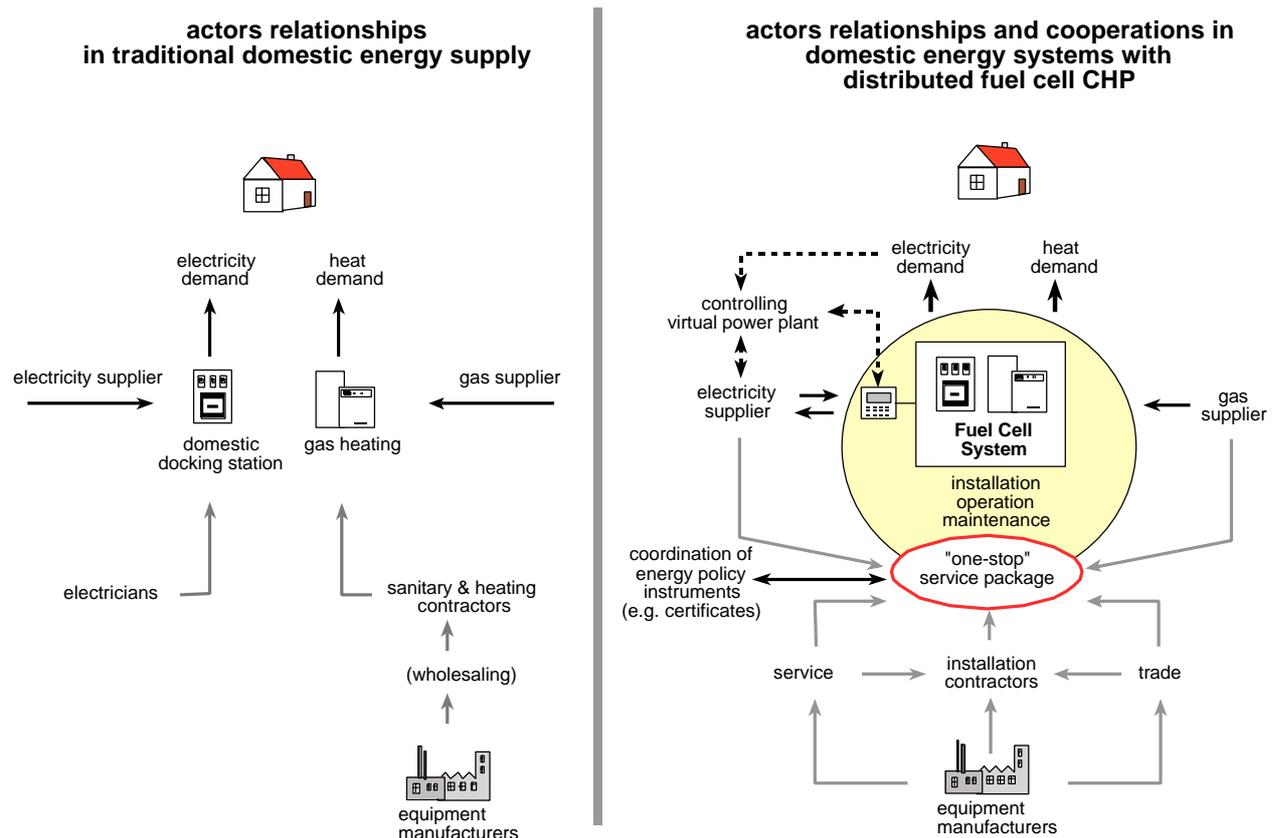


Figure 14 Shift of market structures in the field of domestic energy supply induced by fuel cells

It is obvious that such a far reaching shift of market structures will affect the relations between the various actors. Roles and responsibilities are likely to change and the different market players involved have to be motivated to promote the new fuel cell solution:

- Utilities** can engage in fuel cell related energy services in order to consolidate market shares vis-à-vis the emerging competition of independent producers and energy service companies (ESCOs). Multi-year contracts with private house-owners will strengthen customer relationships and will hinder a shift of suppliers. Fuel cells can help to broaden the business activities in the area of heat supply and local/district heating systems and specific synergies can be realised by multi-utilities that are already engaged in the electricity and gas market. Especially on the local and regional level, a central load management via remote control offers new options for (distribution) grid operators and the optimisation of wholesale electricity purchase. In order to benefit from these chances, however, utilities need to build up new competences and a business philosophy that may differ drastically from the traditional corporate identity. Another major problem results from the fact that from a utility perspective, fuel cells do not substitute electricity at high retail prices but at marginal costs of own generation/ wholesale purchase plus specific boni according to avoided grid costs. Depending on the individual situation, therefore, the possible economic benefits of utilities may erode.

- Different to the electricity sector the **heat market** is much more heterogeneous. Besides private house owners, the sector of commercial housing industries and flat-letting business plays an important role (1998 in Germany some 60 % of households). In this group, large house building companies as well as a large number of private landlords can be found that have to be motivated to invest in fuel cell heating systems. The ambivalent experiences made with other energy saving measures indicate that the market introduction of fuel cells will be affected by manifold – sometimes country specific – obstacles such as insufficient information and missing technical competence, capital constraints and institutional and legal barriers. The latter often reinforce the well-known investor-user dilemma, i.e. the situation where the house owner/lessor has to pay for the up-front investment without a chance for compensation (e.g. through higher rents) whereas the tenant takes the benefit from lower energy costs.
- **Craftsmen and installation contractors** traditionally have a strong influence on the investment decisions of private house owners. They represent a strategic bottleneck for the marketing of the new heating technology so that special emphasis has to be put on a mobilisation of this target group. Moreover, the necessity to design “one-stop solutions” concerning the installation, operation and maintenance of fuel cell home systems induces new qualification requirements for craftsmen and contractors who are traditionally divided into electricians, plumbers, etc. A fuel cell heating system combines various technical aspects and, therefore, demands an interdisciplinary qualification that is not yet part of the traditional structures of professional education and training. Comparable to the IT business, totally new professions emerge in the field of new energies. The energy agency of North Rhine-Westphalia, for example, has recently established the new qualification of a “solarteur”, providing a specific training for solar energy systems. Moreover, extensive service packages have to be offered, partially in partnership with the utilities. Especially in countries with rigid structures for professional education and training such as Germany, initiatives have to be brought onto the way early enough in order to timely adapt curricula, training institutions, certificates and so on. At the same time, however, it has to be taken care that the mobilisation of professionals occurs in line with the availability of units on the market because otherwise the impetus risks to die away before market introduction really takes off.

5.4 Growing ecological competition from renewable energy sources

In order to outperform alternative options in terms of GHG emissions, fossil based CHP systems like gas-fired fuel cells need to take out the best value out of the fossil fuel input, i.e. to exceed specific benchmarks for electric efficiencies. These benchmarks can be derived as a function of the technical characteristics and the specific GHG emissions of the competing technologies (see chapter 4.1).

Considering the fact that the GHG emissions of the public grid are likely to decrease within the next two to three decades, the generic advantage of CHP will be steadily depreciated. In Germany, for instance, public power generation today incorporates specific GHG emissions of some 680 g CO₂ eq./kWh (trend estimation 617 g CO₂ eq./kWh in 2010) so that fuel cells with electric efficiencies of 20-35 % (and 40 % thermal efficiency) are able to beat electrical heat pumps or condensing boilers in combination with the public grid. In the mid/long-term, however, a large scale integration of renewable electricity, e. g. from off-shore wind generation, solar energy imports, biomass, etc. will significantly squeeze the GHG impacts from electricity production. It is evident that under these changing conditions natural gas-based fuel cell will not remain a golden solution *per se*. In order to maintain ecological comparative advantages, the systems efficiency needs to be augmented, renewable energy carriers have to be used and new applications in relation to RES such as back-up power for wind parks have to be realised.

5.5 International Codes and Standards, safety regulation

As any other energy technology, stationary fuel cells have to meet the highest standards with regard to safety, pollution prevention, health, etc. Moreover, products designed for the segment of private end-users must be suitable for mass-markets, i.e. purchase has to exclude any extra efforts for certification and permitting, and products need to be standardised with regard to all existing fittings and infrastructures and easy to handle ("fool-proof"). For these reasons, the issue of codes and standards gains special importance during the pre-commercial stages of RTD. Some relevant aspects are:

- Basically, stationary fuel cells are composed of gas technology components that are subject of existing standards and codes. To a large extent, established rules and procedures, e.g. concerning piping and fittings, can be applied. Nevertheless, international code and standardisation processes usually follow a slow pace and are characterised by manifold struggles for interests, influence and technical dominance. As in the case of any other innovation there is a trade-off between an early standardisation that would trigger mass-markets and the need for technical flexibility and the fight for the best solution.
- For field trial projects, the smooth handling of larger numbers of pre-commercial units require a CE-certificate that imposes significant costs to the manufactures in order to avoid an even much more expensive unit-by-unit certification. Accordingly, larger sets of up to 50 similar units are certified in order to share these costs. However, once practical experiences demand a modification of single components, construction principles, etc. these changes cannot be realised within the set but must be part of a new CE-certification. Improvements, therefore, can only be incorporated within the next generation of field test units – an obstacle to continuous modification and improvement of the technology.

Products designed for the segment of private end-users must be standardised for mass-markets - and no extra efforts for certification and permitting.

- Another issue concerns the internal processing of hydrogen, especially in the case of PEMFC. Pointing at the safety concerns with regard to hydrogen some stakeholders aim at establishing related codes and regulations, e.g. in terms of mandatory H₂ sensors in private households in order to prevent accidents. On the contrary, other stakeholders argue that the fuel cell process should be considered as a natural gas device, regardless of any intermediate product. In practice, the difference would be a costly requirement for the sensor installation at any installation site in combination with regular testing and calibration that would impose an additional cost disadvantage in competitive markets.

5.6 Investors waiting

In many applications, fuel cell systems compete with well established options such as internal combustion engines or alternative technologies such as micro-turbines or Stirling engines. Considering the still existing cost gap and the remaining technical questions unsolved, the market success of fuel cells cannot yet be guaranteed. From an investors perspective it appears to be wise to wait for the one technology gaining dominance in order to benefit from mass production cost decrease, more suppliers and higher competition, standardisation, lower operation and maintenance (O&M) costs, etc. As a result, market may be hindered by a wide-spread reluctance and “stand-by attitude” that might retain needed capital.

**Unclear time-scale
may contribute to
reluctance and
postponing of
investments**

Moreover, reluctance can be found among other players, too. A recent investigation of participants of a workshop series in Germany sheds light on the fact that a majority of companies and institutions from all backgrounds does not yet follow a systematic approach to become familiar with the new technology. Information campaigns, promotion and market transformation activities will be necessary in order to alleviate these barriers to a rapid diffusion of the fuel cell technology.

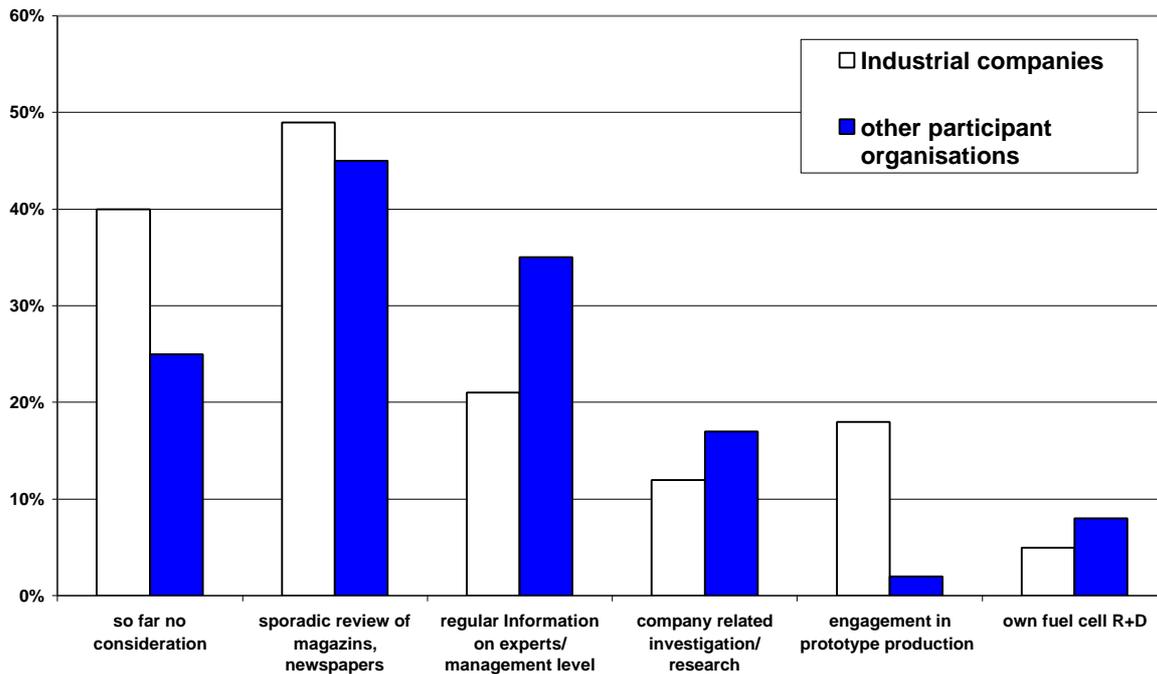


Figure 15 Attitudes of companies towards fuel cells (non-representative survey among workshop participants (FHG-ISI 2003))

Most important, however, it has to be clearly stated, that profitable investment decisions into existing CHP or high-efficient heating technology should not be withdrawn in order to wait for the fuel cell. Looking at the time scale it can be expected that a broad market introduction cannot be achieved before the end of this decade. Accordingly, investments of today have 10-15 years time to refinance capital costs – and then can be replaced by second generation fuel cells. In this context, fuel cells on the one side and reciprocating engines, Stirling engines or micro turbines on the other side are not competitors but the latter can serve to prepare the infrastructure for the new option fuel cell.

Investment in CHP should not be postponed in order to wait for fuel cells

5.7 Technical challenges

Technical challenges also hamper an early market introduction of fuel cells. It is beyond the scope of this short study to review in detail the technical challenges of the various fuel cell types. Generally, challenges include reaching the targeted performance characteristics, increasing the lifetime of the stack, reducing the degradation of the system and enhancing the reliability of the balance of plant components.

Technical challenges include reaching performance targets while reducing costs, increasing longevity, enhancing reliability of balance of plant.

At this point of development, the technical targets, especially with respect to efficiencies, have not yet been reached. For instance, SOFC in domestic applications are today below 70 % total efficiencies with >80 % targeted for future

applications. Domestic PEFC systems are in the range of 22, 23 % electrical efficiencies and thus have to increase their efficiencies by 10 %-pt. Larger-scale PEFC power plants have been operating around 34 % (target: 40 %) and then have suffered from degradation. Also high-temperature fuel cells have to undergo further advancements, with MCFC hitting 47 % electric efficiency at the beginning of the operation (target: 50 % for systems without and 55 % for systems with steam turbine averaged over life-time) and SOFC reaching 46 % in the 100 kW application (Krumbeck, Huster et al. 2003). The integration of fuel cells and gas or steam turbines to hybrid systems has only been realised in one single SOFC system so far.

The long lifetimes required for fuel cell stacks still pose a significant challenge to fuel cell developers. So far, the pilot systems are still undergoing significant degradation. In addition, there is a trade-off between less expensive production methods suitable for large-scale production volumes and longevity. This can be seen in the latest generation of Sulzer HEXIS systems. Due to new production equipment, partly of one of the component suppliers, the lower degradation and higher life-times of the system generation before could not be reproduced.

It is not only the stack as the various pilot plant failure reports display, but rather the balance of plant components that often lead to the shut-down of a power plant. Thus, the interplay between fuel cell systems and the conventional periphery are still subject of intense research.

Whereas all these technical aspects are not expected to be fundamental knock-out criteria for fuel cell market introduction, they do determine a lower time limit before which a market introduction in larger numbers is not feasible.

5.8 Availability of Balance-of-Plant (periphery) components

In some cases, not only the reliability, but more fundamentally the availability of balance of plant components (that means the periphery of the plant, e. g. the gas processing, air compressor, AC/DC converter, etc.) is in question. There are, in particular, two key components that are difficult to obtain and to match with the specific demands of a fuel cell:

- small natural gas reformers; reformers have, initially, been developed for industrial process dimensions. Downsizing reformers while maintaining good dynamics and a proper thermal management is not simple. Whereas in the UTC PC25 systems, a number of reformers have been employed, smaller reformers are still difficult to obtain.
- micro turbines for hybrid power plants. For hybrid fuel cell power plants, i. e. a high-temperature fuel cell linked to a micro-turbine which uses the exhaust heat from the fuel cell plant, small turbines with specific characteristics are required. A planned 1 MW_{el} SOFC pilot plant in Marbach, Germany had to be cancelled because no appropriate gas turbine was available.

Certain BoP components, e. g. gas reformers and micro turbines, have to be adapted to FC use.

Again, for an optimised total system, further development and thus time is required.

5.9 Technical aspects of grid connection

Together with other technologies for distributed generation (DG), stationary fuel cells represent a “disruptive technology” that could fundamentally change the designs and business models of power delivery systems. To do so, however, fuel cells must be properly integrated into the distribution system so that it enhances system value for all stakeholders. First concept studies are currently underway but it has to be recognised that still significant technical, organisational and regulatory obstacles have to be removed (e. g. www.dispower.org, www.sustelnet.net). Problems include:

- Lack of open monitoring, communications and control protocols and standards that will allow operators to remotely dispatch DG.
- Need for advanced concepts for redesigning existing distribution systems so that utilities, fuel cell owners, energy consumers and society can take full advantage of the opportunities made available by the widespread deployment of fuel cells and other DG technologies.

Particular problems results from the prospect that a large number of generation units of 1-5 kW will be operated in parallel to the distribution grid. Up to now the low voltage grids have not been designed for a broad integration of distributed generation (DG) and beyond a certain threshold critical impacts on grid operation can be expected if no modifications and measures for grid adaption take place (EPRI 2000). In order to avoid limitations and bottlenecks for market growth, these critical impacts have to be investigated in detail and the envisaged technical and institutional solutions have to be explored and implemented early enough.

Restrictions with network connection and parallel plant operation can occur especially with regard to the given rated power of network equipment, with the compliance of steady-state voltage rules and with the reliability of system protection (Ramesohl 2003). Other network criteria appear not to impose substantial barriers to grid interconnection of fuel cells (Table 5).

In most cases, the technical solutions are already available today but any upgrading of grid infrastructures induces significant investment costs to grid operators. Institutional and regulatory arrangements have to be made in order to guarantee a fair and discrimination-free allocation of these costs. It can be expected that the issue of grid access and grid management will become a key problem for a large scale diffusion of stationary fuel cells and other distributed generation technologies.

Easy grid connection is a key to market success of FC

Current distribution grids are not designed for large scale integration of FC

Technical solutions are envisaged – cost allocation is the problem

Table 5 Evaluation summary of relevant connection criteria and impacts on electricity net operation by stationary fuel cells

Criteria	Problem	Degree of restriction	Relevant mode of operation controlled by		Technical solvability
			heat	electricity	
equipment	overload	XX	XX		N
steady state voltage	bad supply quality (grid)	XXX	XX		FC/N
short circuit current	overload	–			FC/N
fast voltage fluctuations	bad supply quality (customer)	(X)	(X)	XX	FC/N
long term flicker	bad supply quality (customer)	–		XX	FC
harmonics	grid losses, overload	–			FC
asymmetrical currents	inhomogeneous load of outer conductor	–			FC/N
audio frequency control	malfunctions of accessory installations	–			FC
system protection	malfunctions of plant and network protection	XX			FC/N

Remarks:

(X) = possibly critical; XX = critical; XXX = very critical; - not relevant

FC/N= measurements at fuel cell plants resp. network

grey shaded = criteria with special network-wide relevance

5.10 Time gap between Kyoto and readiness for marketing

During the last years, fuel cells have shown a remarkable career as a hot topic for the public opinion. Both politics as well as industry have been pushing the issue with strong efforts. In the media there is a tendency to appraise fuel cells as the salvation technology of the 21st century. Although this high level of public attention helps to generate the needed resources for R&D, at the same time it risks to degenerate to overheated euphoria. Once the over-optimistic projections cannot not be realised – and announced deadlines for market introduction tend to be regularly delayed both in the stationary and mobile sector – euphoria may turn into frustration. Especially when early products suffer from unacceptable teething problems customers may withdraw from the fuel cell technology. The resulting scepticism can last for decades such as in the case of electrical heat pumps where the topic was “burned” for nearly twenty years after an unsuccessful market introduction in the early 80’s. In this regard, special attention and care has to be spend to a sound preparation and a sustainable launch of the fuel cell technology.

Fuel cells will enter the market too late to make a contribution to Kyoto commitments

From a political perspective, an additional risk can be seen in the fact, that most probably fuel cells will gain relevance on mass markets only after the Kyoto deadline of 2008/2012. Therefore, both energy policy and industry have to avoid unjustified expectations that cannot be met because fuel cells will hardly make any significant contribution to meet the obligations under the Kyoto protocol. In parallel to the ongoing fuel cell development for the post-Kyoto period, the broad range of short-term options such as energy efficiency, other CHP, renewable energy sources etc. needs to be pursued.

5.11 Further barriers common to all CHP systems

A certain class of barriers that may hinder a wide spread utilisation of stationary fuel cells are not typical to the fuel cell technology itself but relate to CHP applications in general. Some of them are even generic to all sources of distributed generation (DG) including renewable energy sources (RES). An overview of various implementation stages of DG projects and related barriers in liberalised energy markets is shown in Figure 16. In the following, the major obstacles are briefly sketched, a more detailed assessment can be found in the DECENT study for the European markets (Uyterlinde, Sambeek et al. 2002) and in a NREL study for the US (NREL 2000).

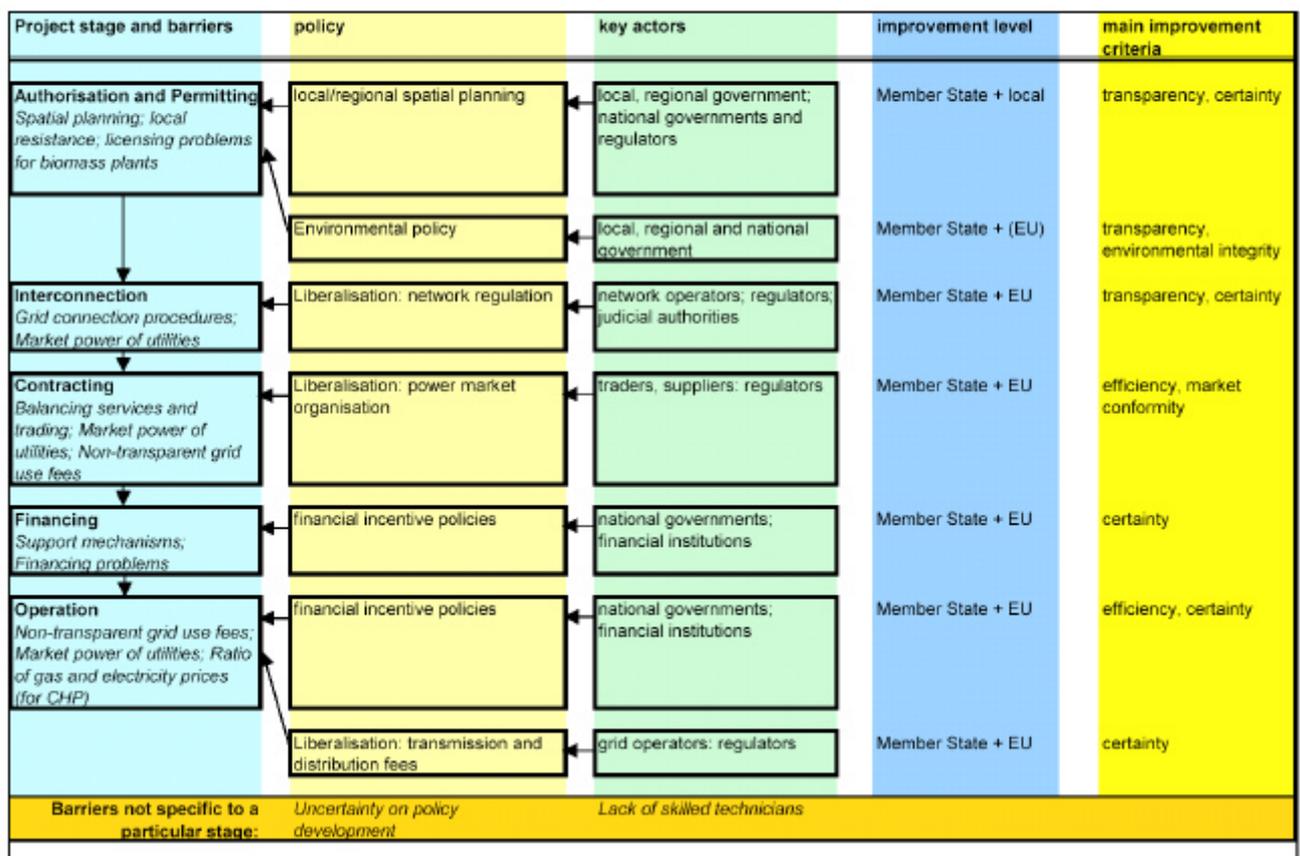


Figure 16 Actor-phase diagram for distributed generation in liberalised markets (Uyterlinde, Sambeek et al. 2002)

5.11.1 Grid connection and systems integration barriers

The interconnection of mid-small scale CHP plants to the grid is still hindered by restrictive conditions and procedures for grid connection. Problems arise with regard to connection charges, determination of the point of connection, safety and liability issues. Most important it is needed to establish a standardized technical interface and non-discriminatory rules for the allocation of connection costs that take into account possible positive effects of DG on grid investments and transmission and distribution losses.

The grid inter-connection of mid-small scale CHP plants is still hindered by restrictive conditions and procedures

However, regulatory regimes often do not provide sufficient incentives for grid operators to connect DG plants and conditions differ between member states, regions and utilities. Often, connection charges lack transparency and appear to exceed factual costs of the grid operator. Moreover, the administrative handling of CHP projects is delayed due to low priority for the utility.

For this reason, the introduction of DG is strongly linked with the controversial debate on the unbundling of power generation and network operation and the regulation of systems operators in order to assure a neutral stance towards independent CHP plants.

5.11.2 Market access and contracting

In order to be able to fully commercialise the CHP electricity production, CHP plants have to be integrated into the balance and settlement systems of the power market. At the moment, however, technical requirements and rules for market access such as the UK New Electricity Trading Arrangement (NETA) limit the opportunities for CHP operators to participate in the market. According to the UK regulator OFGEM, the restrictive impact of NETA has significantly reduced the activities of smaller generators (OFGEM 2001). In addition, resulting high transaction costs represent another hurdle for market access of small-mid-scale CHP plants.

At least for the beginning of market introduction, problems related to the balance and settlement systems can be alleviated through the instrument of priority dispatch that assures an exemption from balancing responsibilities. In the long-run, however, increasing shares of distributed generation will induce growing technical and economic effects on the systems. It is evident that new institutional and regulatory arrangements have to be found in order to handle a changing electricity market.

5.11.3 Financing and price structures in liberalised markets

Already mentioned, CHP plants provide various benefits to the energy system and to society that are not yet fully reflected in market prices. More over, present electricity markets lack a level playing field and there is evidence from countless cases that CHP projects could not compete with specific utility offers based on depreciated power plants running near marginal fuel costs.

For these reasons, CHP projects often can not achieve profitability within existing market transactions but have to be compensated for the social benefits they deliver. Accordingly, the energy policy goal of increasing the share of CHP has to be backed by support schemes that mitigate current price distortions and balance the asymmetric power of utilities, e.g. through feed-in tariffs, priority dispatch, etc. (Hewett 2001; Strachan and Dowlatabadi 2002)

Closely related to the aspect of interconnection, new traders for RES and CHP electricity can suffer from intransparent and excessively high grid use fees and the costs for stand-by and back-up power. Whereas grid use fees are of less relevance for a single project under a priority dispatch scheme, the marketing of “green power” is strongly affected. This limits the possibility to sell CHP electricity at premium prices to specific market segments.

5.11.4 Integration and coordination of the regulatory framework

The distributed generation projects are subject of many different regulations on the European, national and even regional level (Figure 17). Due to the multi-dimensional interactions, frictions and even contradictions can be found especially with regard to the market regulation and the energy taxation framework on the one side and CHP promotion policies on the other side. This situation induces administrative efforts and transaction costs to the market players that delay the project implementation and may even deteriorate profitability. Moreover, there is still uncertainty concerning the long-term development of the energy policy framework that hinders strategic investments into DG. For this reason, long-term target setting by the EU and the member states in terms of DG integration would increase the reliability of market projections.

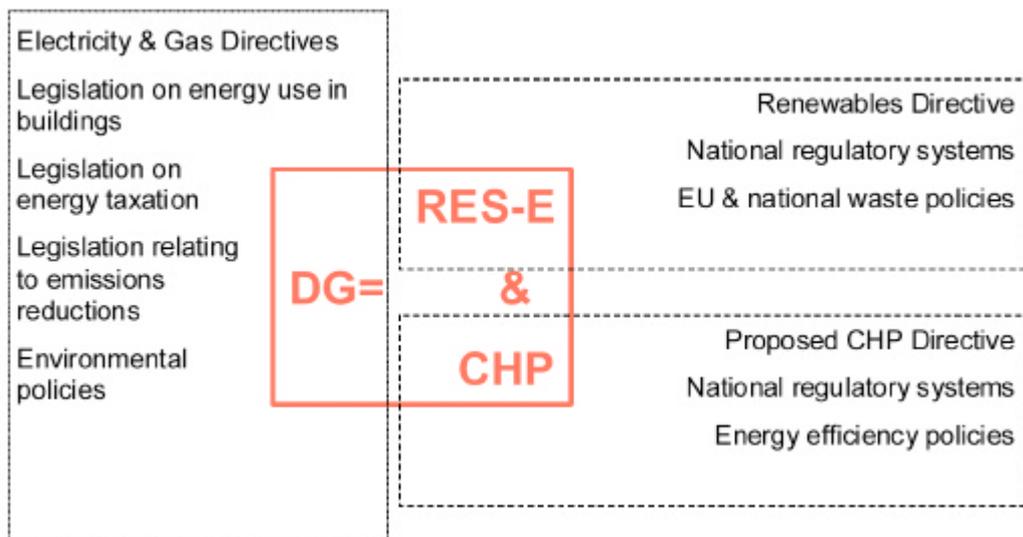


Figure 17 The regulatory environment of DG in Europe (Uyterlinde, Sambeek et al. 2002)

5.11.5 Dependency on natural gas as the major energy carrier

It has been argued in chapter 4.2, that in the long-term, a switch from fossil to renewable fuels is required for several reasons. In the midterm, however, *natural gas* will be the fuel of choice for the fuel cell as well as for most other CHP technologies. An increasing dependency on natural gas would mean a dependency particularly on Norwegian and, in the midterm, Russian/North African countries. Even though for natural gas, the risk of cartels is more limited than for crude oil, political disruption is possible.

In this regard natural gas based CHP is not a sustainable energy source *per se* but it represents an efficient way to economise the inevitable fossil energy input during a transition period on the way to a renewable energy supply system.

Gradual switch from natural gas to renewables.

6 Market perspectives and strategic implications

In the following chapter, we will synthesize a picture of future market perspectives based on the results of chapters 4 and 5. Toward this end, we will compile existing market surveys and their results (chapter 6.1). Then we will, based on one selected scenario, estimate a potential contribution of fuel cell expansion to GHG emission reduction (chapter 6.2). Finally, we will resume the boundary conditions (chapter 6.3) and the resulting required policy incentives for a successful development of fuel cells in stationary applications (chapter 6.4).

6.1 Market surveys

Today it is estimated that a cumulative number of around 600 fuel cell systems $> 10 \text{ kW}_{\text{el}}$ and above 1000 small fuel cell systems ($< 10 \text{ kW}_{\text{el}}$) have been operated so far (Cropper and Jollie 2002). Predictions on future market shares of stationary fuel cells vary considerably and have been adjusted frequently in the past years. The market size is determined by many different factors, including suitable heating loads, extensive natural gas distribution networks, tightening climate change commitments, necessity of grid reinforcement, suitable energy market conditions, etc. and thus depend heavily on the regional situation.

Market size determined by many exogenous factors

For instance, in Central and Eastern Europe, the share of district heating in heat supply systems is high. There, 40 % of the population are connected to such district heating networks (Future_Cogen 2001) which are in many cases overdue to modernisation. Fuel cells would enter these markets via substitution. However, total energy demand in these countries has also fallen with economic recession. In some countries, the installed heat generation capacities exceed heat load requirements by some 50 %. For fuel cells to achieve considerable market shares in these areas, modernising the heat grids and connecting new consumers is essential – challenge to the new EU member states (Future_Cogen 2001).

If one looks into the literature of stationary fuel cell market surveys, many references predict an increase in decentralised energy supply regardless of the conversion technology, with fuel cells being one technology option.

- **Allied Business Intelligence** studies see a worldwide increase of decentralised electricity supply from now 20'000 MW to 280'000-350'000 MW in 2011. After 2006, mainly fuel cells shall contribute to this trend.
- The German energy company **RWE** predicts that by the year 2015, 30 % of the German electricity demand could be supplied by distributed power, one third of which by fuel cells. For Germany, RWE determines a potential of 400'000 heating systems/a, from which 20 to 70 % could be fuel cell systems, corresponding to 1'000 to 5'000 MW_{el} (3 to 15 TWh_{el}). In commercial and industrial applications, a CHP potential of 100 and 250 TWh_{el} , respectively, is forecasted, with a possible fuel cell share of 10-50 % (2-10 GW_{el} ; 10-50 TWh_{el} /a). In total, RWE sees a fuel cell potential of 3 to 15 GW_{el} and 13-65

TWh_{el}/a in Germany (Dinter and Halupka 2001). However, even within the RWE company, this optimistic forecast is disputed.

- Another optimistic statement, however with a significantly stretched time scale, is given by the energy company **E.ON**. According to them, fuel cells could, by the year 2010, produce 3 % of the German electricity demand. In a trend scenario, E.on assumes 3 GW installed electric capacity by 2025, and even 7.8 GW in a more optimistic scenario (Henken-Mellies and Schiebelsberger 2002).
- The consultancy Trend:research sees a market of between 0.75 and – in the “euphoric” scenario – 7 GW for German systems below 300 kW_{el} (trend:research 2002).
- As for the **timing of market entry**, RWE plans market introduction for commercial and industrial systems by 2005, for domestic systems by 2007 with “considerable market shares “ by 2010. **Production** of fuel cells in smaller unit numbers of most companies are announced for the second half of this decade.

As for **domestic (MicroCHP) applications** of fuel cells, factors like the rate of refurbishment and replacement of the existing building stock as well as the development of new building umbers are of strong influence (Pehnt 2003):

MicroCHP

- For European MicroCHP, (< 10 kW_{el} including reciprocating engines and Stirling machines), **Frost&Sullivan** forecast an installed total capacity of 3'500 MW in 2010 (VDI 2001), corresponding to an increase in sales volume from 20 Mio. Euro in 2000 (2000 systems) to 2 Bill. Euro (500'000 systems) in 2010. The share of fuel cells is estimated to be 62 % of the systems. In other Frost & Sullivan estimates, a sales volume of 3.2 Bill. Euro in 2011 (400.000 systems/a) is forecasted (BZM 2002). The market entry is anticipated in niche markets such as premium power supply.
- **Bokämper** determines a possible market potential of 110'000 domestic systems by 2010 (mainly SOFC) (Bokämper 2002).
- Depending on the incentives given to producers and operators, **Krammer** models that by 2010, 55 to 180'000 systems and by 2025, 1.75 (“trend”) to 5 millionen (“BZ plus”) domestic systems could be installed in Germany (Krammer 2001) corresponding to up to 500.000 systems/a. Particularly after 2010, when the 1990ies generation of gas boilers which had been installed in many east German households has to be replaced, a market increase is expected by Krammer. For the American market, Krammer expects a significantly higher potential of 440'000 2.5 kW units until 2005, however mainly dominated by systems for electricity production only (e. g. backup power).
- **Sulzer Hexis** predicts a demand of 230'000/a heating systems for new building/modernisation of one family homes and 130'000/a apartment houses. Assuming 70 % natural gas availability, this corresponds to a theoretic potential of 550'000 systems/a. For the Sulzer Hexis system, Sulzer

derives for 2010 100'000-120'000 units/a. For OECD countries, the 5-10 fold volume is expected (Raak 2001; Raak and Riggenbach 2001).

- **Vaillant** plans to start a small series production of their domestic fuel cell system by the middle of the decade. It is interesting to compare this forecast to earlier forecasts from 2001 where for the year 2003, several thousands of fuel cell systems should have been produced already. According to that forecast, 100'000 systems in Germany and 250'000 in Europe were expected for 2010. Estimates of EFC/HGC are in a similar magnitude (150-200'000 units/a) (Oertel and Fleischer 2001).
- Other studies, such as **MicroMap** (MicroMap 2002), see a large potential for MicroCHP, however evaluate the competitiveness of fuel cells lower. MicroMap concludes that Stirling engines have the highest potential in the domestic energy supply.

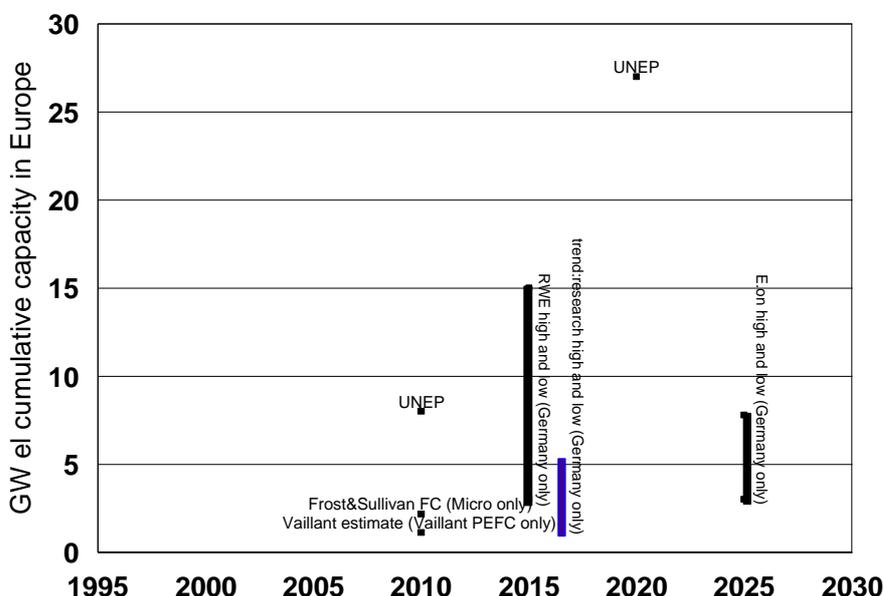


Figure 18 Forecasts for future cumulative fuel cell capacity in Europe and Germany according to some estimates

It is difficult to assess the above estimates because in most instances, the underlying assumptions are not fully transparent. The uncertainty with respect to size and time scale of market introduction can be seen in Figure 18 where cumulative fuel cell capacities in Europe and Germany according to some forecasts are shown. Most of these market forecasts have, however, a positive market sentiment in common.

Considerable uncertainty with respect to size and time scale

When determining production numbers and cumulative production, it has to be kept in mind that the fuel cell market is global.

Markets are global

- According to Fuel Cell Europe, in Japan very high unit numbers are planned which are in the order of 1.2 Mill CHP systems with 1 kW_{el} und 230'000 4 kW_{el}.
- On a global scale, **UNEP** has made projections of future fuel cell distributed generation (UNEP 2002). They forecast that by 2020, 95 GW

of cumulative capacity could be installed, more than half of the total distributed generation capacity (Figure 19). Only 15 GW of these would be installed in North America and 27 GW in OECD Europe. Split up by power range, almost 30 % of the 95 GW would be below 100 kW_{el}, and 47 % over 1 MW_{el}.

- The World Alliance for Decentralized Energy (**Wade**) developed a number of scenarios for global DG development; in the most optimistic scenario, fuel cells achieve some 150 GW installed capacity worldwide in the year 2020 (www.localpower.org).
- The International Energy Agency **IEA** assumes that some 6 % of 2030 OECD power consumption could be produced with fuel cells using natural gas as a fuel (cited after (EU 2003)).

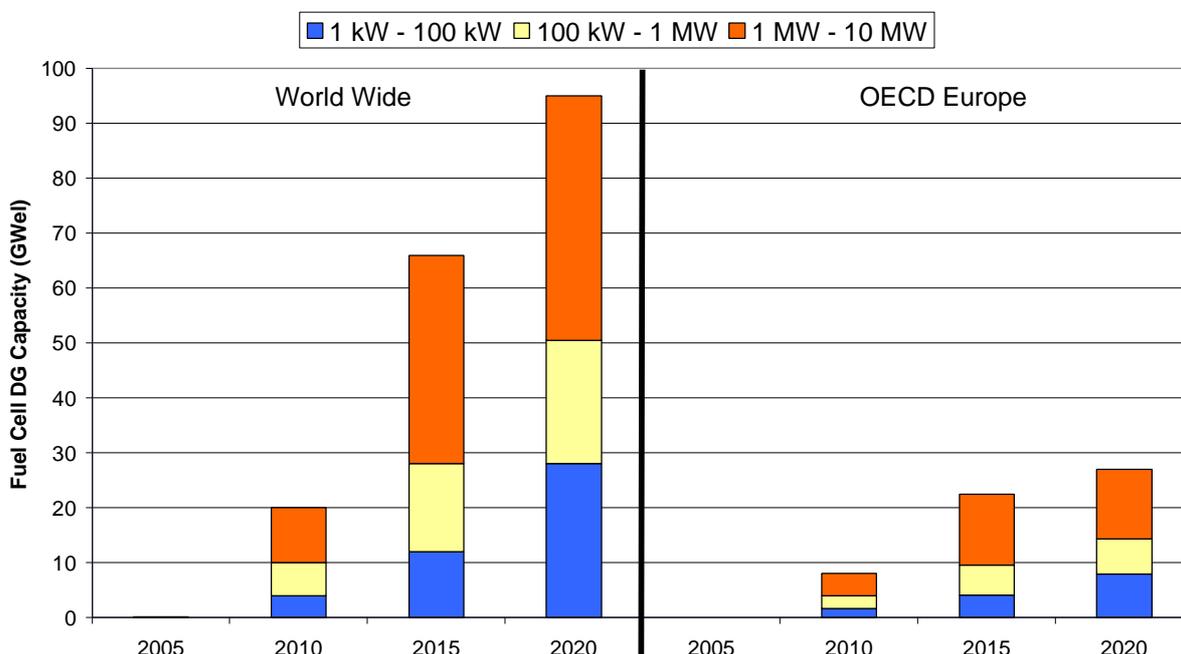


Figure 19 Estimated growth in fuel cell distributed growth capacity to 2020 by capacity range according to (UNEP 2002).

6.2 Example: The UNEP scenario and its consequences

To exemplify the consequences of a widespread fuel cell introduction, we will use the UNEP scenario assumptions and calculate the GHG emission reduction associated with that scenario. **It is important to note that – as in every scenario – there is room for debate and discussion on the specific assumptions made. However, the scenario shall not be taken as a realistic future development path, but rather an analytical tool to simulate the impacts of „What-if“ considerations.**

6.2.1 How likely is the UNEP scenario?

To get a feeling on how ambitious the UNEP scenario is let us first compare the resulting European fuel cell capacity addition with scenarios made for CHP development in another project, the „Future Cogen“ project (Future_Cogen 2001). Based on a market assessment in various countries this project tried to derive market potentials of cogeneration under different conditions. Drawing from experiences learnt in countries with high degrees of CHP, with early liberalisation and wide-spread district heating systems, the Future Cogen project investigated a number of scenarios with differently favourable conditions for CHP. The CHP capacity development according to the four scenarios is shown in Figure 20.

According to the „Future Cogen“ project, considerable CHP development only takes place in two of these scenarios (Future_Cogen 2001):

- “Heightened Environmental Awareness Scenario” assuming more demanding targets with strong EU-level policy, internalisation of external benefits of CHP (carbon tax, faster technological developments); in this scenario, CHP electricity production increases almost by a factor 2 from 1998 to 2020.
- the “Post Kyoto Scenario”, where the benefits of CHP are fully internalised, micro generation becomes economically and technically feasible, energy policies focussed on decentralised energy supply; in this “best case” scenario, CHP electricity production increases almost by a factor 3 from 1998 to 2020.

The UNEP assumptions of fuel cell capacity addition are also shown in Figure 20. As it can be seen, the capacity addition expected by UNEP is rather ambitious. If we assume the Heightened Environmental Awareness Scenario (which is closer to the general UNEP assumptions), more than half of the UNEP 2000-2020 capacity addition would have to be realised with fuel cells. Compared to our remarks in chapters 4 and 5, we expect fuel cell development to occur later and with lower capacities than the UNEP scenario so that some features of the UNEP scenario can be questioned. Nonetheless, we will use this scenario as a heuristic starting point for the following first estimation of possible GHG abatement impacts. The exercise, thereby, relies on UNEP's best case expectation that **a principally positive attitude towards CHP exists and that high shares of the envisaged CHP capacity increase will be realised with fuel cells.**

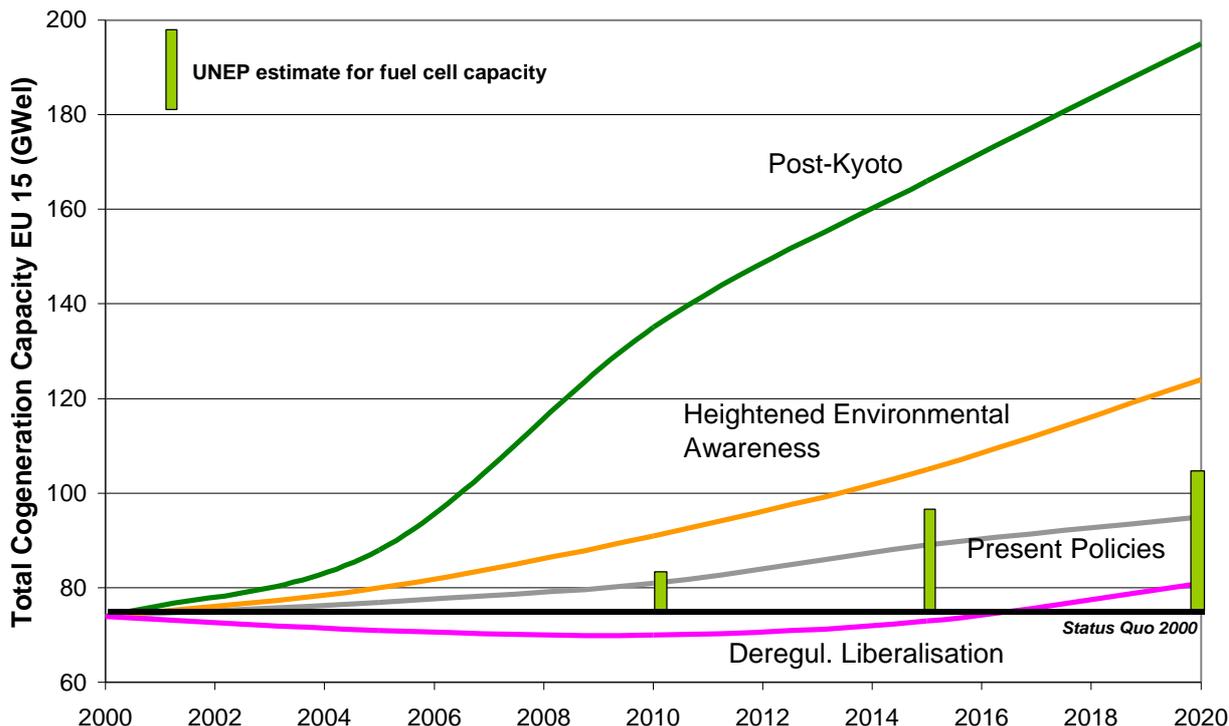


Figure 20 Development of *total* European cogeneration capacity according to the four Future Cogen scenarios (Future_Cogen 2001) and possible capacity addition of *fuel cells* (green boxes) in (UNEP 2002)

6.2.2 GHG reduction in the UNEP scenario

To determine a possible contribution of this fuel cell capacity additionally installed to GHG abatement we take the specific reduction numbers derived in Table 2 (page 16) and the UNEP capacity estimates and then calculate the GHG emissions. We base our calculation on the following additional assumptions:

- natural gas as main fuel for fuel cells¹¹;
- full load hours of 5000 h/a.

For these kinds of calculations, the reference system (“baseline”) is of highest importance. These baseline emissions depend on the perspective of the decision-maker:

The baseline emissions depend on the perspective

If the question is: (1) “What is the additional contribution of fuel cells to GHG reduction if we assume that CHP will be realised anyway?” we have to compare to the competing technologies, e. g. the reciprocating engine in district heating CHP or the gas turbine in industrial CHP.

¹¹ We assume this because up to 2020, biomass-based fuel cell systems will just about enter technical maturity and economic feasibility (see chapter 4.2). Thus, only after 2020 bio-fuel cells will contribute significantly to the European electricity production.

If the question is: (2) “Should future power plant capacity additions be based on fuel cells or modern separate power production?” we have to compare to marginal power and heating systems, e. g. natural gas CC and a gas condensing boiler.

If the question is: (3) “What is the overall effect of fuel cell introduction in the European Union?” we assume that fuel cells displace the average (fossil) EU electricity and heat and thus compare to the EU electricity mix¹² and a mix of heating systems.

Here, we report all these baseline options. The resulting GHG reductions are shown in Table 6.

(ad 1) If we assume a dynamic development of CHP is happening anyway and we are interested in the *additional* contribution of fuel cells to climate protection, taking the UNEP scenario as a foundation, the resulting GHG reduction is in the order of 5 Mt/a which corresponds to 0.1 % of the European GHG emissions in 1990.

(ad 2) If we want to compare fuel cells to modern separate production, i. e. a natural gas CC plant and a gas condensing boiler, the comparison to these marginal technologies leads to GHG reductions of 14 Mt/a.

(ad 3) If we want to know the effect of fuel cells displacing existing power plants and the average heating system in the EU, we compare it to the EU electricity mix and a mix of heating systems (coal, oil, gas, wood; calculated using the fuel distribution of dwellings and block systems in major EU countries (Save 2002).

(3a) If we assume that mainly the fossil power plants are displaced, the GHG reduction amounts to 55.4 Mt/a, which equals 1.3 % of the European GHG emissions in 1990.

(3b) If we compare to the European electricity mix *including* nuclear and hydropower the emission reduction amounts to 22.3 Mt/a.

Concerning the third case, we have to take into account that this reduction effect is the result of four separate mechanisms: the reduction due to a fuel shift (oil and coal to gas), an efficiency increase from average to marginal (that means here: modern) power plants and heating systems, an efficiency increase from separate to combined production, and an efficiency increase from modern CHP to fuel cells. The first three would also be realised based on conventional CHP so that only the last effect as specified in question (1) can be fully ascribed to the fuel cell technology.

GHG emission reduction varies between 5 Mt/a (baseline: competing technologies) and 55 Mt/a (baseline: fossil EU electricity and heat production)

¹² It can then be argued whether nuclear and regenerative energy should be included in this mix. It is unlikely that fuel cells will replace e. g. hydropower. Likewise, phase-out of nuclear energy is an “anyway” option in some countries (meaning that the introduction of fuel cells does not change this decision); also, environmental impacts of nuclear power generation is not mirrored in the GHG number. It is common, therefore, to take the fossil electricity mix as a baseline system. However, in Table 6, we include both figures.

Table 6 Life-cycle Greenhouse gas reduction of stationary fuel cell systems in 2020 in the EU based on natural gas (for the underlying data, see Table 2) in the two optimistic CHP scenarios (Pehnt 2003)

No.	Question	Compare to	Resulting GHG reduction (Mt/a)	% of EU GHG emissions 1990
1	CHP will come anyway. What is the additional contribution of fuel cells?	Competing technology	4.6	0.1
2	Should future power plant capacity additions be based on fuel cells or modern separate power production?	Gas combined cycle + gas condensing boiler	14.0	0.3
3a	What is the overall effect of fuel cell introduction in the European Union?	Fossil EU electricity mix and EU heat mix	55.4	1.3
3b	What is the overall effect of fuel cell introduction in the European Union?	EU electricity mix (including hydro and nuclear) and EU heat mix	22.3	0.5
<i>For comparison:</i>				
EU GHG emissions 1990 (Mt/a)			4334	

6.3 Long-term market prospects and future challenges

If optimistic scenarios such as the UNEP analysis are realised, the foreseen commercialisation of stationary fuel cells will demand significant public and private investments that have to be backed by reliable long-term perspectives of the technology. Apart from the manifold short-term market studies, therefore, a sound mid-to-long-term assessment has to take place, investigating the future market prospects for the time after 2020 that will most probably be characterised by changing frame conditions.

Chapters 4 and 5 have shown that many aspects determine the development and volume of stationary fuel cell markets. To summarise them, we will distinguish the general future framework (“context”), techno-economic aspects and the socio-economic and institutional prerequisites for working fuel cell markets.

6.3.1 General framework conditions

Although fuel cells in general offer a convincing growth perspective, a closer look, e. g. to the field of household energy supply, reveals some open questions and uncertainties. Due to interdependencies between competing technologies and trends (Figure 21), currently seen comparative advantages of fuel cells might lose relevance if in the future frame conditions will change. On the other hand, new opportunities may emerge that call for adaptation of products and applications. Major aspects include:

- Even in the reference case, the future role of CHP in the segment of new buildings will erode because ultra-efficient building concepts (e. g. “passive

house”) together with renewable energy supply options such as solar-thermal heating gain increasing importance, so that the demand for conventional space heating and warm water will drop dramatically.

- It can be expected that increased energy saving efforts will effect the heat demand of the existing building stock, too, so that the size of the future heat market in general is likely to decrease.
- Increasingly efficient and clean conventional technologies put fuel cells under cost and performance pressure. The relative ecological performance of fuel cell CHP will be affected by a changing environment, e.g. in terms of decreasing specific GHG emissions of the public power generation that will build more and more on renewables.

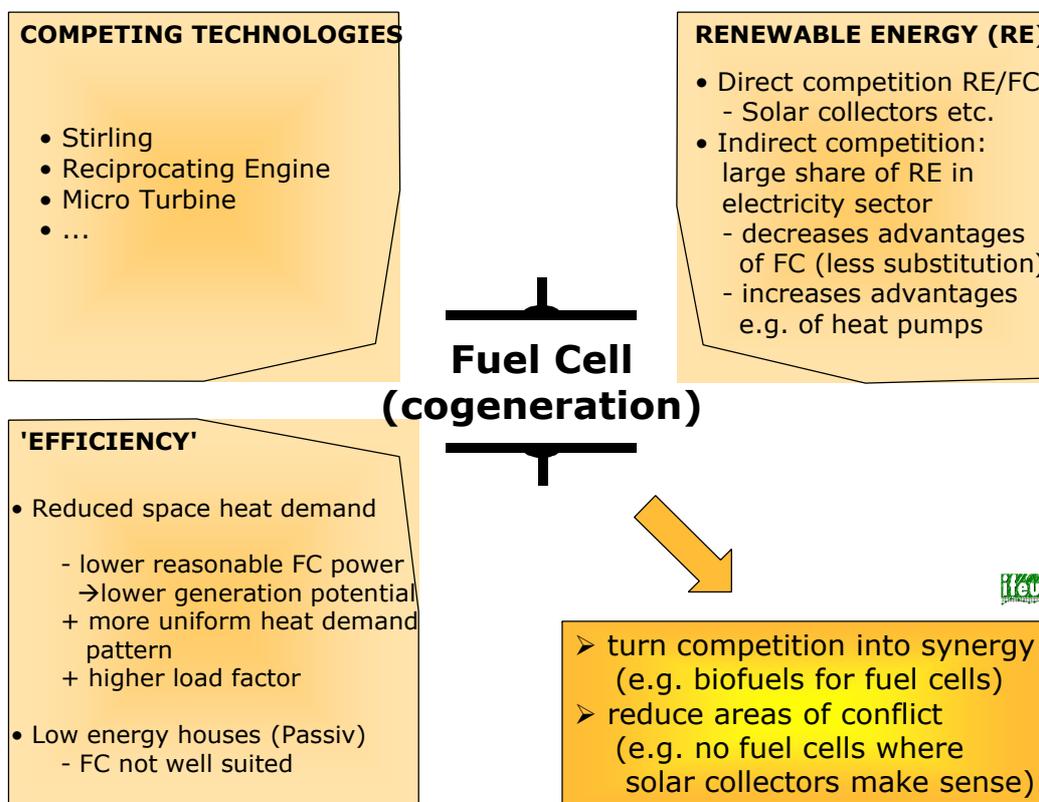


Figure 21 Potential areas of conflict for fuel cells

- On the other side, fuel cells benefit from a European policy framework which, principally, supports CHP. As a non-binding target, the European Commission suggested to double the electricity production from cogeneration systems from 9 to 18 % by 2010 (COM(97)514 final).
- The power plant replacement, which allows new technologies to enter the stage, is determined by the vintage pattern of the existing European power park, by political decisions (e.g. phase-out of nuclear power plants in several EU member states), and other aspects. In Germany, for instance, depending on the mortality line of the power plants (200'-300'000 full-load hours), 50 % of today's existing capacity will be decommissioned by the year 2010 or 2020, respectively (Markewitz, Nollen et al. 2002).

- A likely increase in electricity and gas costs will make efficient technologies and electricity feed-in more attractive; higher gas costs, however, shift the economic advantages towards renewable energy carriers.
- At the same time, however, new business opportunities and markets may emerge (chapter 4.9), e. g. in terms of grid-oriented strategies in decentralised energy systems or the use of biogen fuels. In addition, small fuel cells might open up a completely new market, that of domestic CHP with MicroCHP systems.

Taking the interdependencies between all these aspects into account, a mid-/long-term projection of market perspectives is not trivial at all. A sound foundation for strategic planning is still missing, and it would require comprehensive energy systems analyses and technology assessments that go beyond the current state of research.

6.3.2 Techno-economic factors

On the techno-economic side, the time-scale is determined by

- the availability of reliable technologies, including degradation and balance-of-plant components and achieving performance targets;
- a significant decrease in capital costs;
- the availability of equipment to operate fuel cells on biomass-derived fuels;
- a competition between the different types of fuel cells, reducing the respective market volumes and thus, to a certain degree, the possibility to get down the learning curve;
- the availability of technical solutions for grid connection of fuel cells;
- emerging opportunities for plant management and control through new ICT solutions;
- in the long term, the possible necessity to use hydrogen as an intermediate storage system for renewable energy sources.

6.3.3 Socio-economic and institutional prerequisites for functioning fuel cell markets

It is evident, that in general a technologically reliable and economically attractive option will hardly succeed on the market if other obstacles prevent a diffusion of the technology. In parallel to the technical progress, therefore, a co-evolution of socio-economic and institutional prerequisites has to take place to pave the way for a smooth market introduction. As discussed in chapter 5, these prerequisites for working fuel cell markets include

- cost-efficient and consumer friendly standardisation;

- timely qualification of installation contractors and other market actors involved;
- information and promotion activities that enable the end-user to take investment decisions in a new technology area;
- a further dissemination of integral planning techniques for buildings that – from the very beginning – combine efficiency aspects with regard to the building shell, the HVAC technologies and the energy supply solution within a holistic optimisation;
- smooth and non-discriminating grid interconnection of fuel cells and other distributed generation technologies;
- a fair grid access and a level playing field for market entry of fuel cell generation capacity;
- development of appropriate rules and balance and settlement systems for integrating smaller scale power generation into the energy markets, e.g. in terms of back up power.

6.3.4 Conclusion: future market prospects result from various interdependencies

Summing up, it can be concluded that the future market prospects of stationary fuel cells can not be described in a mono-causal manner. On the contrary, a great variety of enhancing or hindering factors together with various mandatory preconditions will most likely interact. Drawn on a time-scale – which is for indicative purposes only and does not claim to show exact time-resolved developments! – the possible paths might look like Figure 1.

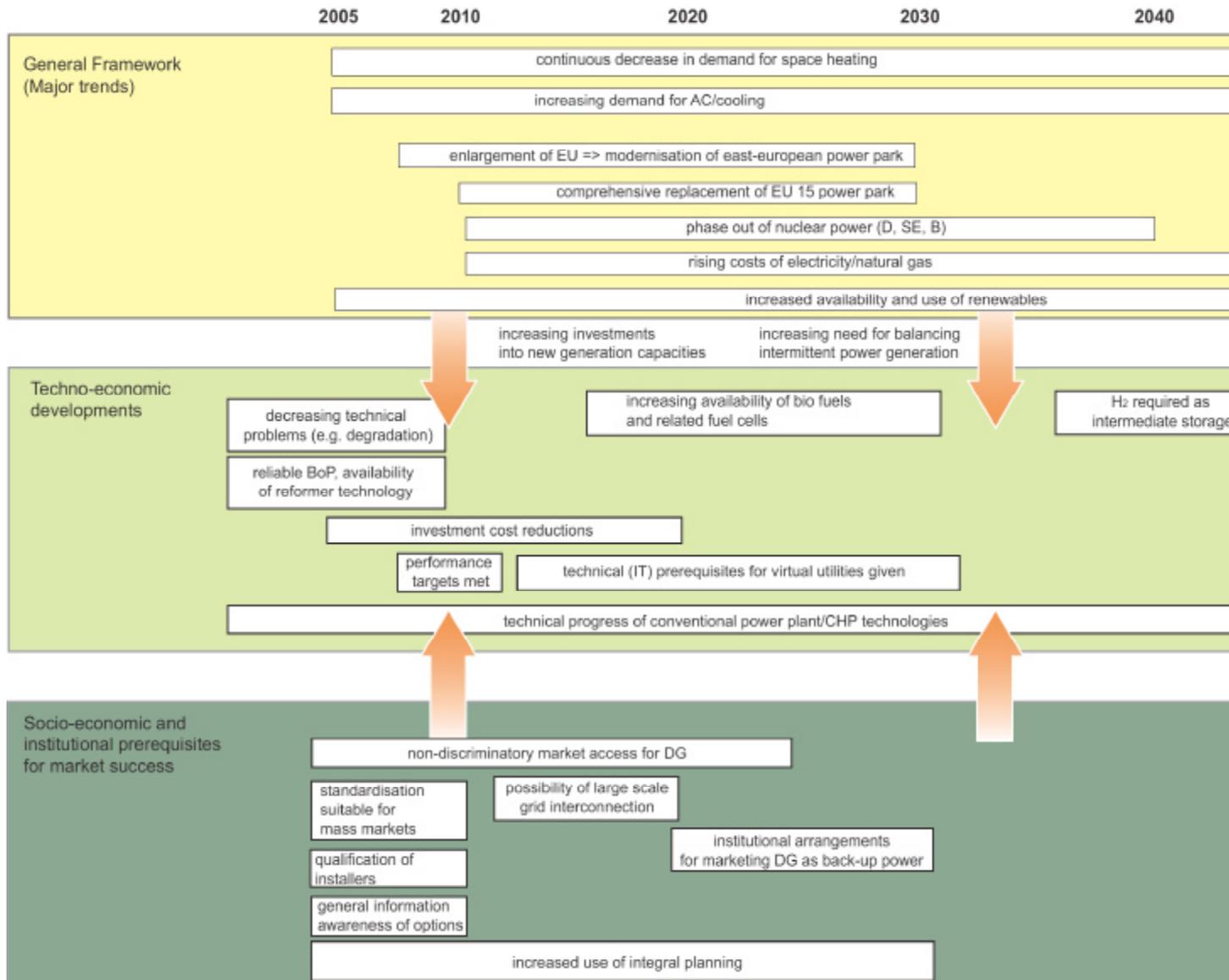


Figure 22 Exemplary illustration of the interaction between the various determining factors that trigger market penetration of fuel cells

6.4 Incentives and Policy Framework

From a policy-making perspective, the interplay between the various dimensions illustrated above offers multiple starting points for policy action. Looking at the time scale one may be tempted to come to the conclusion that the market entry of fuel cells is probably still years away from now so that particular engagement is not yet required. However, when taking a closer look this stance risks to give away the promising potential of the fuel cell technology. Already for today, two core areas of activity can be identified:

- In order to maintain technical progress and to achieve the projected performance targets, quite substantial RTD efforts still have to be undertaken. As discussed above, a multitude of open questions call for better, more reliable and – most important – much cheaper solutions. Here the ongoing research on the national and European level, i.e. within the FP 6, needs to be maintained and streamlined. Compared to the main competitors United States and Japan, Europe appears to be behind in terms of research and demonstration activities. Fuel Cell Europe estimates that, compared to the US (280 million €/a with more funding recently announced) and Japan (240 million €/a), Europe's expenditures amount to 60 million €/a including national support (FCEu 2003). However, taking into account the need to maintain or even to strengthen the efforts in other areas of strategic importance such as energy efficiency or renewable energy carriers, too, the scope for additional funding is limited. For this reason, special attention has to be given to international cooperation and a strategic prioritisation of activities.
- At the same time, however, the future progress will strongly depend on private engagement from industry that, in turn, depends on a reliable market perspective - especially with regard to the prospects of distributed generation in the European energy system. As mentioned several times before, in this context fuel cells are confronted with the same obstacles like any other small-to-mid scale CHP technology. In order to allow for a commercialisation of stationary fuel cells, a general advancement concerning grid interconnection and market integration of distributed power generation is required. Positive as well as negative examples from the various member states underline the paramount importance of the regulatory and institutional framework for the penetration of CHP technologies.

R&D efforts must be increased

International cooperation and research prioritisation

A long-term perspective for CHP in general is crucial for stationary FC development

In these two core areas, energy policy can already today prepare the ground for the envisaged market introduction of fuel cells. Once the market entry took place, further incentives of a more specific character can be provided. Given the fact, that first series will be introduced within this decade, even for this 1st generation still some advances have to be made in order to refine the technology and to exploit the cost-cutting potential of mass production. It is evident that at the very beginning, the technology will still be quite expensive. Apart from distinguished niche markets with premium price levels (e. g. military applications, premium power, off-grid), therefore, additional incentives will be required to trigger the

larger demand volumes and to accelerate diffusion and the underlying mass production.

In a stylised manner, these interactions are illustrated in Figure 23. It is distinguished between the Research and technology development (RTD) phase, the market introduction phase and the market penetration phase. Moreover, the allowable cost of the competing option and the investment costs for fuel cells are indicated, the latter being characterised by the decrease of production costs due to mass production (often referred to as experience or learning curves, see (IEA 2000))¹³.

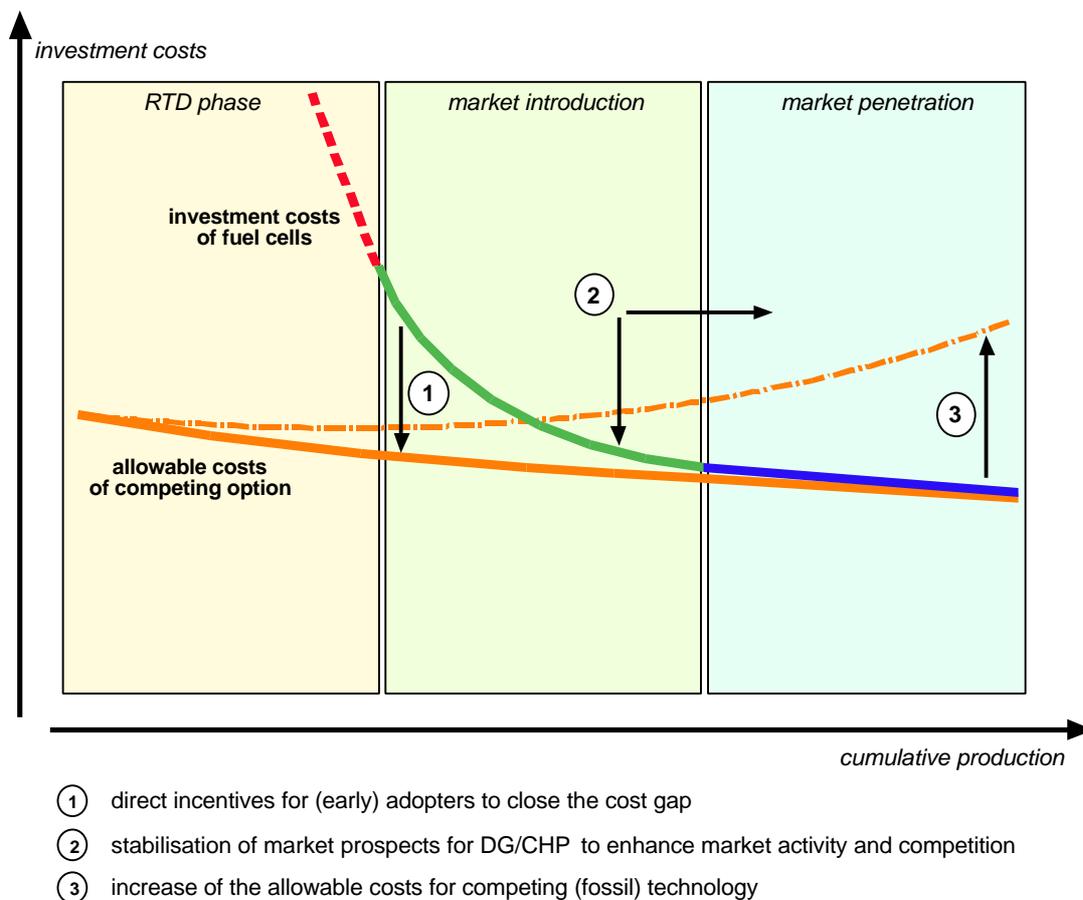


Figure 23 Stylised illustration of the different stages of market introduction and the related options for policy support

Figure 23 illustrates the fact that – especially at the beginning – additional incentives are needed to close the cost gap compared to the allowable costs of the competing technology. In this regard, energy policy can build on three major strategies that should be combined:

1. **providing direct incentives for early adopters**, e.g. as investment subsidies, grants, tax deduction, etc.

¹³ When discussing cost trajectories it has to be taken into account that in order to allow for a re-financing of RTD investments and further improvements, in an early stage market prices are likely to be higher than the real

2. **stabilising market prospects for DG power generation** by enhancing market entries and competition together with a removal of barriers, e. g. concerning grid interconnection, grid access, access to electricity markets (priority dispatch, feed-in tariffs), etc.
3. **increasing the allowable costs for the competing (fossil) options** by creating general incentives for an efficient and environmentally benign use of energy, e.g. energy and/or GHG taxes, emissions trading, air quality standards, noise pollution regulation, etc.

A detailed policy analysis and evaluation of the different instruments and strategies is beyond the scope of this study. It can be concluded, however, that various measures need to be bundled in a policy mix in order to provide sufficient incentives, to remove all relevant barriers and to achieve synergies between instruments. Moreover, fuel cell policies must not stand alone but have to be integrated into an overall guiding strategy for a sustainable development of European energy systems that builds on the two core pillars of a much more efficient use of energy and the expansion of renewable energy sources.

In this context, the fuel cell policy mix needs to develop over time by adapting the intervention mechanisms to shifting priorities, modifying (degressive) rates of financial support, reacting to technical progress, etc. More research is needed to investigate the untapped possibilities and the practical details of policy design and implementation in this field.

Fuel cell policies have to be integrated into an overall guiding strategy for a sustainable development of European energy systems that builds on the much more efficient use of energy and the expansion of renewable energy sources.

production costs whereas in a later stage profit margins typically diminish due to increased competition and saturation effects.

7 Stationary fuel cells: trying to summarise a complex topic

Within this report, many technical, economic, ecological and political aspects have been discussed, and a multitude of interdependencies and open issues could be identified. Obviously the topic is quite complex so that the results can hardly be condensed to a single message. For this reason, we will not come to a final conclusion but use this last section to summarize key findings in the following – still comprehensive – list of statements. More detailed information and the underlying arguments can be found in the respective chapters.

Environmental and technical aspects

- (1) Stationary fuel cells have a high potential for environmentally friendly conversion: they offer high electrical efficiencies and extremely low (fuel: hydrocarbon) or even zero (fuel: hydrogen) direct pollutant emissions.
- (2) Life Cycle Assessments support the emission reductions. The production of the fuel cell systems is generally of low environmental significance. However, the upstream emissions of the fuel supply (e. g. natural gas extraction and distribution) limit the achievable emission reduction.
- (3) Fuel cells will enter the market too late to make a contribution to the Kyoto commitments for 2008/2012.
- (4) Whereas fuel cells offer significant potentials with respect to environmentally benign energy conversion, they should be closely interlinked with efficient energy use on all levels of the conversion chain and with renewable energy carriers. As any other CHP option, fuel cells should not compete with, but rather supplement the development of renewable and efficient energy systems.
- (5) Conventional “competitors”, such as reciprocating or Stirling engines and gas turbines on the electricity side and condensing boilers on the heat side are constantly optimised as well, creating a strong environmental competition. Moreover, these technologies are much more cost competitive today than fuel cells.
- (6) Stationary fuel cells will shift the power range of electricity production to smaller capacities: they achieve electrical efficiencies similar to combined cycle plants at much smaller size. This might open new markets (see below).
- (7) Further advantages common to all CHP systems might be made accessible through fuel cells, such as reduced transmission/distribution losses, reduced vulnerability of the energy system, or economic benefits through modular investments.
- (8) The specific greenhouse gas (GHG) emission reduction (per kWh_{el}) depends strongly on plant efficiencies and baselines. Compared to modern gas power plants and boilers, GHG reductions between around 20 and 30

% can be achieved. Compared to competing CHP technologies, only low GHG reductions, if any, can be achieved. This is mainly due to lower thermal efficiencies of fuel cells. That underlines the necessity to also optimise the total/thermal efficiency of fuel cells. Compared to coal power plants, however, the GHG reduction effect is over 50 %.

- (9) The total GHG reduction due to the deployment of fuel cells in Europe depends on the baseline and the assumed fuel cell capacity. Using the UNEP estimate with 27 GW installed fuel cell capacity in 2020, the market introduction of fuel cells would yield GHG reductions between 5 Mt/a (baseline: competing technologies) and 55 Mt/a (baseline: fossil EU electricity and average heat production); this would represent 0.1 and 1.3 % of the European greenhouse gas emissions in 1990, respectively. It has to be kept in mind that the latter number combine the effect of fuel shift, CHP introduction *and* specific fuel cell efficiency advantages.
- (10) All CHP systems show reduced GHG emissions compared to separate production and should therefore be promoted.
- (11) With decreasing carbon intensity of the public grid (more renewable electricity, more gas, more efficient power plants) and of heat production, the relative GHG advantages of fuel cells based on natural gas decrease and make other technologies based on electricity from the public grid, for instance electric heat pumps, more attractive in relative terms.
- (12) Fuel cells can also be operated on renewable fuels. They offer great fuel flexibility, for instance the use of bio-fuels and hydrogen produced from renewable energy sources.
- (13) Unlike some other biomass energy converters, fuel cells that run on bio fuels combine climate friendly fuels with low pollutant emissions. In bio fuel applications, the advantage of fuel cells is less a reduction of specific GHG emissions (per kWh_{el}) (because all biomass technology options have very low GHG emissions). The particular benefit from fuel cells is the possibility for a more efficient use of limited – and often costly – biomass resources.
- (14) However, due to the high capital cost and the technically challenging components gasification, gas processing and fuel cells and their combination, fuel cells based on bio fuels are a long-term option with biogas being a market opener.
- (15) The use of renewable hydrogen produced from renewable electricity is attractive in off-grid applications. In electricity grids, however, hydrogen/FC system will not be required before 2030, i.e. only when significantly higher shares of renewable energy carriers contribute to electricity production. Before that date, load management, flexible backup plants and averaging a variety of renewable sources is sufficient for load levelling purposes.
- (16) The use of coal gas in fuel cells with subsequent CO₂ storage is not seen as a successful climate strategy for the next 50 years. These systems exhibit extremely high capital cost, low electrical efficiencies and many technical and materials science problems. In addition, CO₂ storage

potentials remain an open question, both from an environmental as well as a social point of view.

Economic and market aspects

- (17) As fuel cells have to succeed on a functioning and fully developed market, cost is seen as the major market entry barrier. Today, stationary fuel cells are a factor 2.5 to 20 too expensive, with the balance of plant (periphery) being responsible for a large share of total capital cost.
- (18) Allowable capital costs in stationary applications vary between 800 €/kW_{el} and – in some niche applications – above 2000 €/kW_{el}, with future electricity costs and the share of own consumption in total electricity production being important parameters.
- (19) The timing of fuel cell market entry will, beside the cost, be determined by technical challenges that include reaching performance targets, increasing longevity, enhancing reliability of balance of plant, and adapting balance of plant components, e.g. gas reformers and micro turbines, to fuel cell systems.
- (20) There is a trade-off between cost reduction and performance of the fuel cell that will require careful balancing between the search for low cost components/materials etc. and the aim at maximising efficiencies.
- (21) With decreasing space heat – and thus domestic gas – demand, fuel cells offer new market shares for gas utilities especially in development or rural areas.
- (22) Fuel cells might open some entirely new markets for CHP such as domestic (Micro-) CHP with small-scale systems below 10 kW providing heat and power for one family and multi-residence houses.
- (23) Success of fuel cells in the domestic sector will depend on a supply push, requiring pro-active manufacturers and other parties involved. For this reason, the key to the market success of fuel cell heating systems is seen in “one-stop solutions”, providing a complete service package to the customer. In line with this emerging market for new energy services (micro-contracting) fuel cells offer new business opportunities, e. g. for utilities that aim at providing a broad range of supply services (multi-utility approach).
- (24) Traditional players in the heat market such as installation contractors play a decisive role for the dissemination of new heating technologies. These actors need to be prepared in time through information, education and professional training activities in order to promote fuel cells.
- (25) New value added might arise from grid-related operation of fuel cells. Sophisticated concepts such as the virtual power plant aim at a ICT interconnection of a large number of fuel cells in order to realise a central control and management of the decentralised capacities. However, considerable technological obstacles need to be overcome.

- (26) The "sexy" image of fuel cells might open the eye for general benefits of CHP.
- (27) There is still considerable uncertainty with respect to size and time scale of the market entry of stationary fuel cells that may contribute to reluctance and postponing of investments. However, investment in available CHP technologies should not be postponed to wait for fuel cells.
- (28) Easy grid connection is a key to market success of fuel cells. Current distribution grids are not designed for large scale integration of fuel cells. From a technical point of view, however, envisaged problems can be solved. More critical, institutional arrangements for a fair and discrimination-free allocation of costs for upgrading, investment and management of grids are still missing.
- (29) In order to enhance the market for distributed generation from fuel cells and other CHP technologies, prevailing barriers with regard to grid access, balance and settlement, trading, conditions for back-up power, etc., need to be removed.

Policy aspects

- (30) Fuel cells are only one option among others that may contribute to increasing economic efficiency and environmental performance of the energy system in Europe. Hence, fuel cell policies must not stand alone but have to be integrated into an overall guiding strategy for a sustainable development of European energy systems that builds on the core pillars of a much more efficient use of energy and the expansion of renewable energy sources.
- (31) In order to maintain technical progress and to achieve the projected performance targets, quite substantial RTD efforts still have to be undertaken. The ongoing research on the national and European level, i.e. within the FP 6, needs to be maintained and streamlined. Looking at the immense budget dedicated by the main competitors United States and Japan special attention has to be given to international cooperation and a strategic prioritisation of RTD activities – especially when taking into account limited financial resources and the prevailing need to maintain or even to strengthen the efforts in other areas of strategic importance such as energy efficiency or renewable energy sources.
- (32) The required private engagement from industry depends on a reliable market perspective - especially with regard to the prospects of distributed generation in the European energy system. In order to allow for a commercialisation of stationary fuel cells a general advancement concerning grid interconnection and market integration of distributed power generation is required. The regulatory and institutional framework is of paramount importance for the penetration of CHP technologies.

- (33) Especially during the first phases of market introduction, additional incentives will be needed to close the cost gap compared to the allowable costs of the competing technology. In this regard, energy policy can provide direct incentives for early adopters, e.g. as investment subsidies, grants, tax deduction, etc.; stabilise market prospects for DG power generation by enhancing market entries and competition together with a removal of barriers; and increase the allowable costs for the competing (fossil) option by creating general incentives for an efficient and environmentally benign use of energy, e.g. energy and/or GHG taxes, emissions trading, air quality standards, noise pollution regulation, etc.
- (34) Lessons from the market introduction of other technologies suggest that the various measures need to be bundled in a policy mix in order to provide sufficient incentives, to remove all relevant barriers and to achieve synergies between instruments.
- (35) The fuel cell policy-mix needs to develop over time by adapting the intervention mechanisms to shifting priorities, modifying (degressive) rates of financial support, reacting to technical progress, etc.
- (36) More research is needed to investigate the untapped possibilities and the practical details of policy design and implementation in this field.

8 Abbreviations

CC	Combined Cycle
CHP	Combined Heat and Power Production
eq.	Equivalents
FC	Fuel Cell
GHG	Greenhouse gas emissions
GT	Gas turbine
GW	Gigawatt
GWP	Global warming potential
HT	High temperature
HVAC	Heating, Ventilation, Air Conditioning and Refrigeration
ICE	Internal combustion engine
ICT	Information and communication technologies
Ifeu	Institute für Energie- und Umweltforschung Heidelberg
IGCC	Integrated Gasification Has Combined Cycle
kW	Kilowatt
kWh	Kilowatthour
MJ	Megajoule
O&M	Operation and maintenance
RES	Renewable energy resources
RTD	Research and technological development
ST	Steam turbine
WI	Wuppertal Institute for Climate Environment Energy

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Appendix A: Fuel Cells: A short introduction

(based on (Pehnt 2003))

A fuel cell converts the chemical energy of a fuel and oxygen continuously into electrical energy. Typically, the fuel is hydrogen. Thus, the energy incorporated in the reaction of hydrogen and oxygen to water will be transformed into electrical energy.

However, the change of enthalpy of formation DH which is released in the reaction



and which characterises this “energy of the reaction” can only partially be transformed into electrical energy. The maximum possible electrical energy can be obtained in the reversible oxidation of H_2 and is given by the change of Gibbs free energy of formation DG . For this reaction under standard conditions ($p = 1$ bar and $T = 298,15$ K), DG amounts to -237 kJ/mol. According to the Gibbs function, the difference of DH and DG is given by TDS (T operating temperature of the fuel cell, DS change of entropy in the reaction). Therefore, the maximum thermodynamic efficiency (“ideal efficiency”) is given by

$$h_{\text{thermo}} = \frac{\Delta G}{\Delta H} = 1 - T \cdot \frac{\Delta S}{\Delta H}.$$

That means that with increasing temperature, h_{thermo} decreases. DG determines the open circuit voltage of a fuel cell

$$E_0 = - \frac{\Delta G}{n_e \cdot F}$$

(F Faraday constant 96.485 As/mol, n_e number of electrons). Under standard conditions E_0 is 1,229 V.

The "secret" of fuel cells is the electrolyte which separates the two reactants, H_2 and O_2 , to avoid an uncontrolled explosive reaction. Basically, the fuel cell consists of a sandwich of layers which are placed around this central electrolyte: the anode at which the fuel is oxidized, the cathode at which the oxygen is reduced, and bipolar plates which feed the gases, collect the electrons, and conduct the reaction heat (Figure 24). To achieve higher powers of fuel cells, a number of single cells are connected in series. This is called a fuel cell stack.

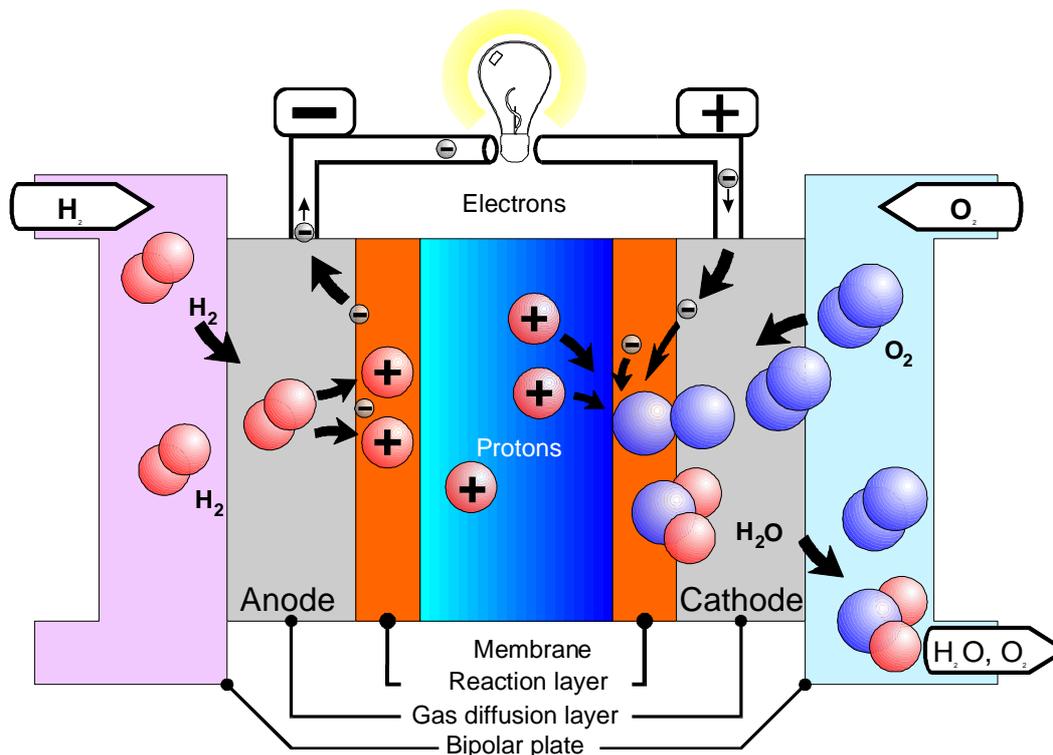


Figure 24 Basic construction of a fuel cell: example Polymer Electrolyte Fuel Cell

The theoretically possible open circuit voltage is, unfortunately, reduced by a number of over-voltages. In areas of low current densities, activation losses are relevant which are caused by the slowness of the reactions on the surface of the electrodes. In the region of medium current density, Ohmic losses reduce the cell voltage, and at high current densities mass transport effects lower the voltage. An example of a resulting cell/stack efficiency (which is proportional to the voltage) versus the current density of the fuel cell is shown in Figure 25.

The **system efficiency** is the efficiency of energy conversion of a total system, consisting of the stack as well as all other components which are necessary for the function of the system. For instance, the fuel has to be processed, cleaned and reformed (that means that the fuel, for instance natural gas, is transformed into hydrogen), fuel and air (which supplies the oxygen) have to be compressed, and control and AC/DC inverter need energy as well. These additional consumers influence the efficiency curve especially in regions of low current densities (Figure 25) and lead to the system efficiency.

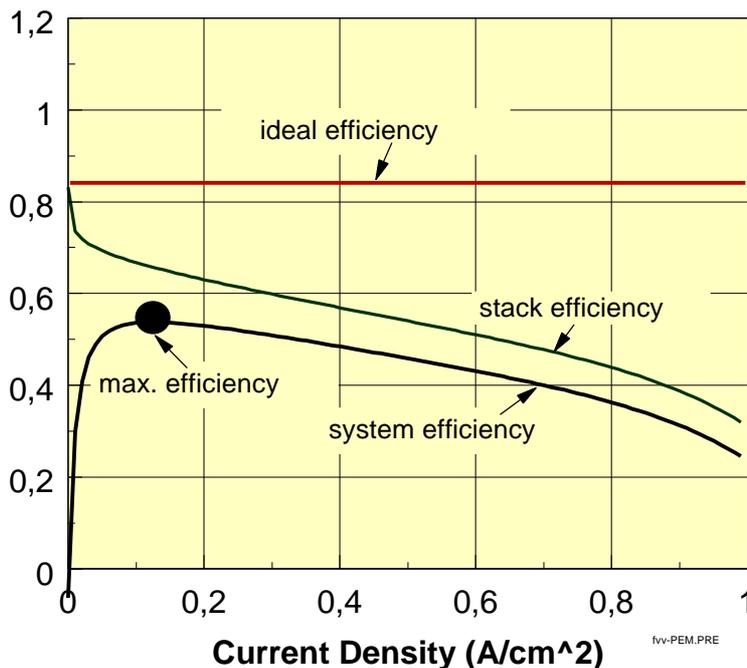


Figure 25 Schematic of the theoretical efficiency, the stack and the system efficiency as a function of the current density (example: PEFC)

Fuel cells can be categorised according to the electrolyte material which separates fuel and air, and, correspondingly, the required operating temperatures into low, medium and high-temperatures. Although the higher operating temperatures of MCFC and SOFC result in decreasing thermodynamic efficiencies (see Gibbs-Helmholtz relation above), the better kinetics as well as the option to use the high temperature exhaust gas (e. g. in turbines) more than offset this efficiency reduction. In addition, the high temperature fuel cells offer the advantage of internal reforming, i. e. the heat produced in the electrochemical reaction is simultaneously used for reforming natural gas or other fuels into hydrogen, thus decreasing the required cooling effort while efficiently using the heat. Also, high-temperature fuel cells have lower purity requirements of the fuel. Whereas AFCs are sensitive to CO₂ and PEFC to CO impurities, CO₂ in high-temperature fuel cells acts as inert gas only, and CO can even be used as a fuel.

Types of fuel cells

Information box: Fuel cell types in detail

The Alkaline Fuel Cell (AFC)

Alkaline fuel cells use KOH as electrolyte. The charge transfer in the electrolyte is based on OH⁻ ions. At the anode, these ions react with hydrogen.



At the cathode, new OH⁻ are formed:

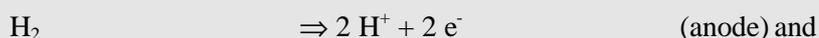


AFC operate at temperatures around 80 °C and have high efficiencies because the oxygen reduction in alkaline electrolytes happens fast. One problem of the AFC is that the electrolyte reacts with the CO₂ which is present in the feeding air

and forms carbonates. These clog the electrodes. Due to the advances of PEFC technology in recent years, the AFC has been neglected a little bit in the past.

The Polymer Electrolyte Membrane Fuel Cell (PEMFC), also called Proton Exchange Fuel Cell (PEFC)

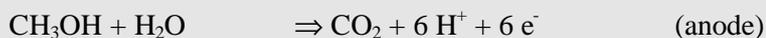
In the PEFC, the electrolyte consists of a proton conducting membrane. This membrane is similar to PTFE, also known as Teflon. However, the material was prepared to conduct protons (H^+ particles). So unlike in the AFC, in the PEFC the protons are the transferred ions. The overall reaction of hydrogen and oxygen to water therefore divides into the following reactions:



The PEFC operates at low temperatures around 80 °C to avoid melting of the membrane. Therefore it requires a catalyst to promote the reactions. Typically, platinum group metals are used for this purpose. As they are very sensitive towards carbon monoxide or sulphur contaminations in the feed gas, the gas must be cleaned properly.

The Direct Methanol Fuel Cell (DMFC)

The DMFC is a sister of the PEFC. It is structured similarly. However, not hydrogen, but methanol is oxidized directly:



So far, some problems have to be overcome. High amounts of catalysts must be applied, and the cross-over of methanol through the membrane is another challenge for materials scientists.

The Phosphoric Acid Fuel Cell (PAFC)

The PAFC applies phosphoric acids instead of the membrane as electrolyte. It is fixed in a matrix. Due to the acid conditions in the cell, again the protons are transferred through the electrolyte. The partial reactions are thus identical to the PEFC. The PAFC operates at 200 °C and is therefore less sensitive to carbon monoxide than the PEFC. The PAFC is the only fuel cell type that has been produced commercially in larger numbers for stationary applications.

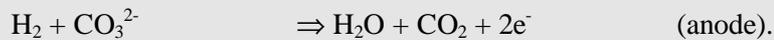
The Molten Carbonate Fuel Cell (MCFC)

In the MCFC, carbonates (Li_2CO_3 , K_2CO_3) are used as electrolyte. It is operated at 650 °C. The electrodes consist of nickel materials.

In the MCFC, carbonate ions which are produced at the cathode are conducted through the electrolyte:



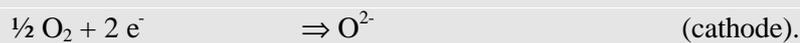
At the anode, the H_2 reduces these ions to CO_2 :



To supply the CO_2 required at the cathode, the CO_2 from the anode off gas is fed back. One potential problem of MCFC yet to solve are the corrosive electrolyte materials. In addition, the electrodes degrade because the nickel from the electrodes enters the melt and causes short circuits.

The Solid Oxide Fuel Cell (SOFC)

The SOFC is operating at the highest temperatures of all fuel cell types. At above $750\text{ }^\circ\text{C}$, the electrolyte, a ceramic made of zirconia doped with yttrium, conducts oxygen ions:



In both MCFC and SOFC, gases containing CH_4 and CO can be used directly as a fuel. In the low and medium temperature fuel cells, a **reformer** converts natural gas or other hydrogen containing gases into hydrogen.

Appendix B: The Life Cycle Assessment Approach

The appropriate instrument to investigate environmental impacts of new products and services is the life-cycle assessment (LCA). The two key elements of LCA are

- the assessment of the total life-cycle ("cradle-to-grave approach"), involving the exploration, processing and distribution of materials and fuels, the production and operation of the investigated objects and their disposal/recycling; and
- the assessment of different environmental impacts to resources, human health and ecosystems.

According to international ISO standards, the LCA consists of four steps (Figure 26): the *Goal and Scope Definition* in which the investigated product, the data sources and system boundaries are described and the functional unit - i.e. the reference of all related in- and outputs - is defined. The *Inventory Analysis* "involves data collection and calculation procedure to quantify relevant inputs and outputs" (ISO_14040 1997). The potential impacts of the in- and outputs of the Inventory Analysis are then determined by the *Impact Assessment* which categorises and aggregates the in- and outputs from or to the biosphere. For that purpose, impact categories, such as the global warming, eutrophication, acidification, summer smog, etc., are defined and characterisation factors calculated which determine the contribution of different substances to that particular impact category (e.g. CO₂, CH₄ or N₂O to global warming). In the fourth step, the *Interpretation*, the findings from the inventory analysis and the impact assessment are combined to give recommendations or draw conclusions.

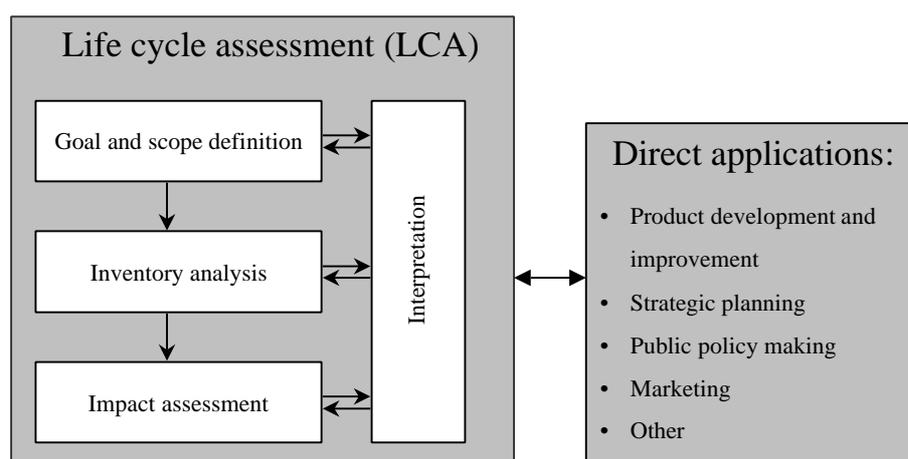


Figure 26 Life-Cycle Assessment according to (ISO_14040 1997)

A typical life-cycle of fuel cells is shown in Figure 27. The life-cycle data in this study is based on the investigations carried out in (Pehnt 2002).

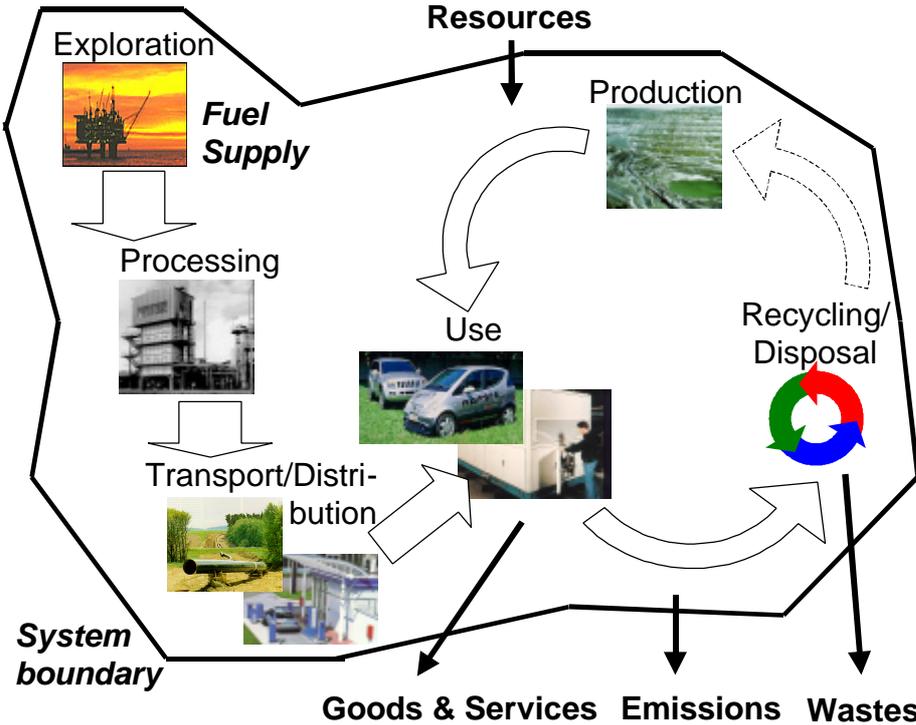


Figure 27 The life cycle of fuel cells