Discussion Paper 4

Micro CHP – a sustainable innovation?

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Berlin/Heidelberg, June 2004

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Abstract

The introduction of micro CHP – that is, the simultaneous production of heat and power in an individual building based on small energy conversion units (e. g. Stirling or reciprocating engine, fuel cells) – is of increasing interest: Large-scale introduction of micro CHP would radically change the electricity system. This paper investigates the driving forces behind and barriers to micro CHP market diffusion in an interdisciplinary perspective.

Life Cycle Assessments prove that micro CHP systems are superior in reducing GHG emissions and resource demand compared to average energy supply, and even efficient and state-of-the art separate production of electricity in power plants and heat in condensing boilers. Micro CHP might help to increase the security of electricity grids and create opportunities for new and smaller market players, and might in this way pave the way to an electricity supply system with less market concentration. However, under current conditions, micro CHP also has disadvantages, such as more difficult integration of renewable energy carriers and competition to (ecologically and economically attractive) district heating. Furthermore, whether micro CHP is economically viable depends significantly on plant type and on the specific conditions of the facility as well as on political support schemes implemented in the respective countries. At the same time, micro CHP could, if supported by favourable economic and policy conditions, represent a considerable market segment, promoting downstream innovations such as “virtual power plants”, enhanced consumer awareness and new household energy management systems.

A specific strategic approach is necessary to adequately embed the new technology and investment and operation practices in the expectations, skills, routines and living conditions of the parties involved with the technology.

Key words: Micro CHP, micro-cogeneration, fuel cell, Stirling engine, reciprocating engine

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* This paper reports the interim results of a case study performed within the interdisciplinary research project „Transformation and Innovation in Power Systems“ (see www.tips-project.de for more information), funded by the German Ministry for Education and Research (BMBF) under its Socio-Ecological Research Framework. An earlier version of this paper was presented at the Symposium Erfolgreiche Energieinnovationsprozesse, TU Graz, in February 2004. The present version has been submitted to Energy Policy in June 2004.

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1 Introduction

The electricity system in Germany and Europe is currently undergoing a process of transformation. Market deregulation has led to mergers and acquisitions in the electricity sector, but has also forced companies to seek out new business areas. Environmental regulations, like the Kyoto process and the European Emissions Trading Scheme, are exposing the sector to external pressure. New technologies, such as renewable energy technologies, combined heat and power (CHP) or "clean coal" technologies, are emerging. In Germany, the nuclear phase-out and the decommissioning of outdated coal plants will lead to a need for replacement of at least 40,000 MW_{el} of generation capacity by 2020 (Umweltbundesamt, 2003). The need for replacement is an extremely important driving force for transformation, making conventional and new technologies compete for a role in the future energy supply. Recent worldwide experiences with blackouts have once more put security of supply on the agenda.

One possible development path is decentralization of the electricity system. Distributed power generation in small, decentralized units could help to reduce emissions, save grid capacity and provide opportunities for renewable energy. It could be a constituent part of a more sustainable energy future. Broad implementation of distributed generation, however, would imply thorough structural change and require a surge in innovation.

In a current project, the interdisciplinary research group TIPS (Transformation and Innovation in Power Systems, www.tips-project.de) investigates a section of this potential innovation cluster: small combined heat and power plants (micro CHP) and the conditions for their diffusion. The goal is to identify possible levers and steering mechanisms to shape a process of innovation – and thereby, transformation – in a more sustainable direction. This paper presents selected results of this project case study (for a full account of micro CHP development opportunities see Pehnt et al., 2005).

2 What is micro CHP?

Micro CHP (combined heat and power production) is the simultaneous production of heat and power in a single building (Harrison and Redford, 2001) based on small energy conversion units.[1] The heat produced is used for space and water heating and possibly for cooling, the electricity is used within the building or fed into the grid. Micro CHP is one of several options for micro-generation, the generation of electricity in individual homes, which is regarded as a potentially disruptive innovation in the energy sector (Dunn, 2000; Watson, in press).

A number of different conversion technologies have been developed for the application in the domestic sector. These include reciprocating engines, Stirling engines, low- and high-temperature fuel cells, micro gas turbines and various other technologies, such as organic Rankine cycle machines, modified steam engines, thermo photovoltaics, thermoelectric devices, etc. (for a review of the technologies, see Pehnt et al., 2005).

In addition to these technological innovations, the successful implementation of micro CHP requires further changes, such as new user routines and an improved institutional setting. For micro CHP to work, that is, to be implemented and be effective in fulfilling its purpose, all these changes need to happen simultaneously. From an integrated and interdisciplinary perspective we therefore see micro CHP as an innovation that comprises complementary novelties in a number of components of the socio-technical configuration that makes micro CHP work (**Figure 1**).

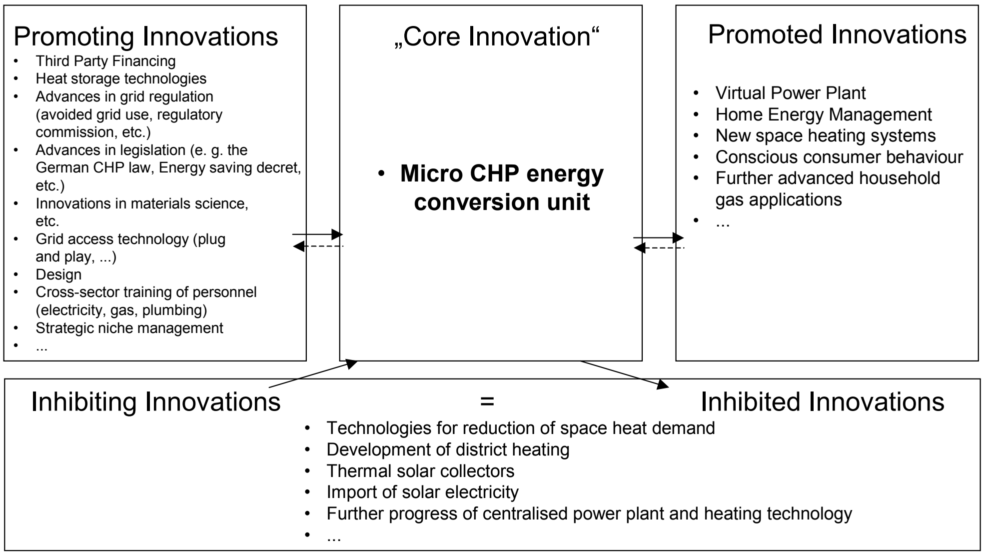

Figure 1: Innovation cluster for micro CHP

Consequently, we envisage the "innovation micro CHP" as an innovative *cluster*, consisting of the "core innovation", which is influenced by a set of other social and technological developments that may support or inhibit it ("promoting innovations" and "inhibiting innovations"). For instance, the development of advanced grid-access technologies would simplify the micro CHP installation process (promoting innovation). On the other hand, broad diffusion of thermal solar collectors makes the use of micro CHP economically less attractive (inhibiting innovation).

In turn, the core innovation itself influences other technologies or developments, promoting or inhibiting them ("promoted innovations" and "inhibited innovations"). For instance, micro CHP might induce further developments with respect to control and information/communication technologies (virtual power plant or home load management). In many cases, inhibiting and inhibited innovations are identical (for example, the successful market penetration of district heating may inhibit the development of micro CHP, and vice versa) and depend on whether the core innovation comes first, or turns out to be more successful.

Depending on the technology used, micro CHP plants are at different stages of development and introduction. In **Table 1**, different conversion technologies are compared on the basis of selected criteria. Whereas reciprocating engines are commercially available and produced in large numbers, they suffer from higher exhaust emissions compared to the competing micro CHP systems (see section 3.1).

Conversion technology	Electrical efficiency	Total efficiency	Noise level	Pollutant emissions	Fuel flexibility	Market availability	Economic viability
Reciprocating engine	20-25	> 85	Medium	Rather high, depending on catalyst/engine technology and maintenance	Medium	Commercially available	Given for applications w/ high operational hours and own electricity demand
Stirling engine	10-24 [a)]	> 85	Low	Very low to medium [b)]	High	Near to market	
Fuel cell	28-35	80-85	Low	Zero (H_2) to almost zero (hydrocarbons)	Medium	Pilot plants, R&D	High cost reduction necessary

[a)] depending on the Stirling concept [b)] depending on the burner type .

Table 1: Characteristics of micro CHP technologies

Due to the fact that fuel combustion is carried out in a separate burner, *Stirling engines* offer lower emissions as well as high fuel flexibility, allowing, in particular, for the use of biofuels and solar irradiation. Stirling engines have the potential to achieve high total efficiency with moderate electrical efficiency. So far, efficiency rates of 20 % have been achieved[2], with a predicted increase to more than 24 % in larger systems. Smaller Stirling engines have a lower electrical efficiency and are primarily designed to be compatible with detached houses.

Fuel cells are still in the R & D phase, with a number of pilot plants currently being tested (Pehnt and Ramesohl, 2003). They offer the potential benefit of the highest electrical efficiency and almost zero local emissions. Referring to natural gas as the dominant fuel in a short- and medium-term perspective, low-temperature fuel cells (PEMFC) in the low power range will achieve electrical efficiency of the order of 28 to 33 %, in the long-term possibly up to 36 % for domestic systems. In the last decade, there have been considerable efforts to further develop this technology. However, it is so far unclear whether fuel cell systems can achieve the total efficiency that is promised by competing technologies. Also, the high capital cost of early product generations remains a major challenge.

In the following, we investigate the ecological and environmental performance of micro CHP compared to several competing options. Toward this end, we define reference systems that do not necessarily represent a particular system of one manufacturer, but rather a generic system based on data from various manufacturers (**Table 2**).

		Micro CHP										Larger CHP	
		Reciprocating engines					Stirling engines			Fuel cells *		Recipr. Engine	Comb. Cycle w/CHP
Reference number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
		1kW	3-6 kW (λ=1)	3-6 kW lean (HighNOX)	3-6 kW lean (HighNOX cond)	3-6 kW lean (LowNOX)	0,8 kW	3 kW	9,5 kW	PEMFC	SOFC	50 kW	
Capacity (Default)													
Electric	kW_{el}	1.0	4.7	5.5	5.5	5.0	0.8	3.0	9.5	4.7	1.0	50.0	
Thermal	kW	3.25	12.5	13.9	14.9	12.6	6.0	15.0	28.5	12.5	2.7	98	
Efficiency (Default)													
Electric	-	20%	25%	25%	25%	25%	10%	15%	24%	32%	32%	30%	45%
Total	-	85%	88%	88%	93%	88%	85%	90%	96%	85%	85% *	85% **	84% **
Efficiency (min)*													
Electric	-		25%	25%	25%	25%	10%	15%	22%	28%	28%	28%	45%
Total	-		84%	84%	88%	84%	80%	85%	88%	80%	80% *	82% **	77% **
Efficiency (max)*													
Electric	-		25%	25%	25%	25%	12%	19%	24%	32%	32%	33%	49%
Total	-		95%	95%	99%	95%	90%	94%	98%	90%	90% *	87% **	84% **
NO_x emission													
Default	mg/Nm^3		125	300	300	135	70	15	15	3	3	125	95
Bandwidth	mg/Nm^3		50-400	70-400	70-400	60-200	-	15-80	15-80	-	-	50-400	n. a.
Investment costs (module + installation)	EUR/kW_{el}	5,148	3,389	2,928	3,139	3,208	3,662	4,689	3,004				
Operation and maintenance costs	$Cent/kWh_{el}$	3.5	3.0	2.6	2.6	2.6	2.0	1.5	1.5				
Economic Lifetime		80,000 hours or 15 years, whatever is lower											
All efficiencies are seasonal efficiencies. * plus hot stand-by loss ** includ. distribution losses													

Table 2: Economic and environmental parameters of micro CHP technologies. Sources: Manufacturers' information, own estimates based on operational experience with many installed systems as well as bibliographical review (ZSW, 2000; ASUE, 2003; ASUE/ Energiereferat der Stadt Frankfurt/Main, 2001). Cost estimates in 2000 prices.

It should be noted that some cost estimates or parameters are associated with significant uncertainties. Therefore, the results of the analysis can only be indicative, but they provide an initial assessment of economic opportunities for different micro CHP technologies. Due to the high capital cost of fuel cells and high uncertainty with respect to the achievable target cost (Krewitt et al., 2004), we did not include fuel cells in the economic comparison at this point.

3 Is micro CHP a sustainable innovation?

In this section, we briefly discuss micro CHP systems in the light of some selected, particularly important aspects of sustainability that, in our opinion, are important for sustainable development of the energy system (for sustainability criteria see also HGF (2001) and Enquete (2002)).

3.1 Resource and climate protection

Results of the **environmental Life Cycle Assessment** at a technology level (**Figure 2**) show that micro CHP systems are superior, so far as the reduction of GHG emissions is concerned, not only to average electricity supply mixes, but also to efficient and state-of-the art separate production of electricity in power plants and heat in condensing boilers (η = 0.97).[3] This, despite strong dependence on the electrical and thermal efficiency of micro CHP technologies and the "reference systems" to which the micro CHP system is compared. That means that at an electrical capacity up to 500,000 times smaller than that of large gas combined-cycle power plants, lower GHG emission levels can be achieved, assuming that state of the art gas condensing boilers are substituted. Even larger reduction effects could be achieved if heating systems based on more carbon-intensive fuels, such as diesel oil, were displaced.

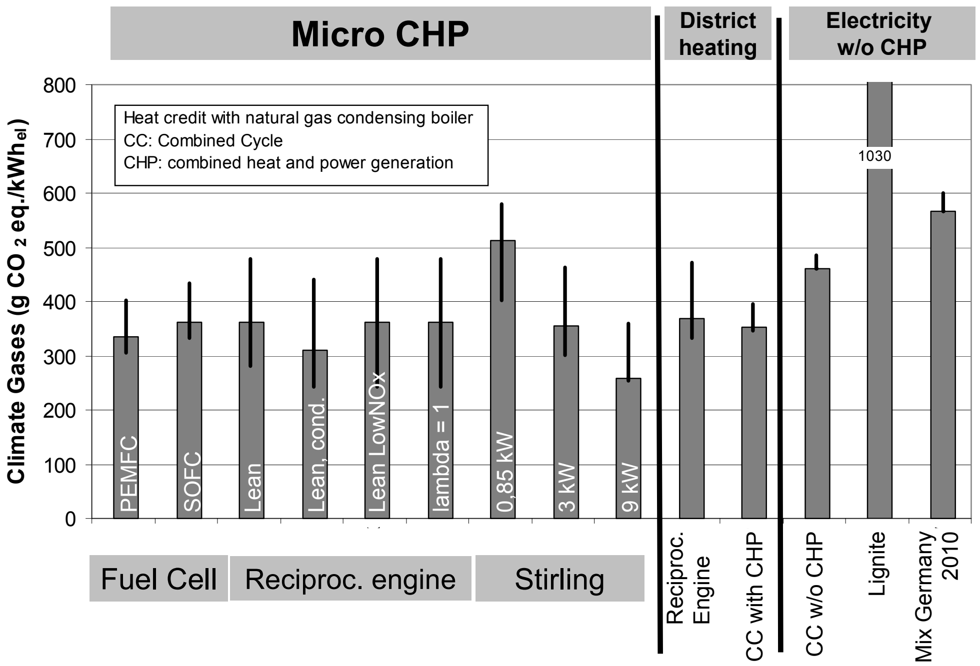

Figure 2: Life cycle GHG emissions (fuel supply, operation and system manufacture) of various micro CHP technologies compared to district CHP and conventional electricity production. Functional Unit: 1 kWh electricity at low voltage level. CHP co-product heat is considered by applying a heat credit ("avoided burden"), assuming that a gas condensing boiler is substituted. District CHP with small reciprocating engine (50 kW_{el}) and large gas combined cycle plant. For the detailed input data see (Pehnt et al., 2005). The *error bars* represent the bandwidth of achievable efficiencies/emission factors depending on the specific application and technical system and on the data uncertainty range.

The GHG advantages of micro CHP plants are comparable to district heating with CHP. When, due to unfavourable heat integration, the systems only achieve the lower end of assumed total efficiency, however, they come rather close to central production in modern combined cycle plants without CHP.

The performance of micro CHP technologies with respect to climate and resource protection depends mainly on the total conversion efficiency that can be achieved. Under the assumption that gas-condensing boilers are the competing heat-supply technology, all technologies (fuel cells, reciprocating and Stirling engines) are within a very narrow range, with the exception of the Stirling engine with lower electrical and total efficiency. The high electrical efficiency of the large Stirling engine leads to the lowest GHG emissions, while fuel cells reach almost the same GHG emission level when they achieve a total conversion efficiency of 90 %. For reciprocating engines, the values for methane emissions due to unburned natural gas vary considerably. Therefore, the error bar for this technology is larger. Further research is needed in this area.

It is important to note that not only electrical efficiency determines the environmental performance, but also total efficiency (including the thermal output of the system). However, the more complex thermal management and the more diffused heat sources inside the fuel cell system make it more difficult to harvest the heat co-produced in the system than, for instance, in a Stirling or reciprocating engine (Krewitt et al., 2004).

The emission-reduction and resource-protection potential of micro CHP could partially be offset by a "**rebound effect**", implying that energy savings achieved by a more efficient technology are at least partly compensated, and sometimes overcompensated, by an increase in energy demand. One potential rebound effect may result from the German Energy Savings Decree (Energieeinsparverordnung, EnEV). The decree sets a maximum level for the overall energy demand in new buildings. Building owners who install a micro CHP plant are permitted to apply less stringent heat insulation measures. However, a poorer insulation of buildings has very long-term implications on energy demand, while a micro CHP plant, that has achieved its technical lifetime, may be replaced by a conventional boiler, increasing the energy demand of the building.

A second potentiaol rebound effect could result from behavioural change. A direct analysis of such behavioural change has not yet been carried out for micro CHP. However, from the analysis of energy efficiency and renewable energy technologies it can be gathered that a rebound effect may occur, which potentially foils energy savings through micro CHP. This depends, among other things, on the relevance of ecological norms to the user, on behavioural consciousness, on the degree to which micro CHP possession is perceived as ecologically relevant, and on knowledge of its effects. In the initial market introduction phase, micro CHP is targeted at homeowners, who, in Germany, form a relatively wealthy section of the population. It is safe to assume that the comfort levels of their dwellings are already high. Research on the rebound effect suggests that in such cases a significant increase in energy consumption is improbable (Genennig and Hoffmann, 1996; Haas et al., 1999; Henderson et al., 2003). On the contrary, a positive effect of feedback and increased involvement with energy topics is possible, both with respect to total consumption and adaptation of time-related consumption patterns, which opens up interesting possibilities for load management. This effect depends greatly on the specific form, timing and detail of feedback, and on the presence of other incentives, such as price incentives, importance of independence and ecological motives. It seems advisable to provide information both on electricity production and consumption patterns in the individual dwelling to allow users to compare and match them.

3.2 Environmental and health compatibility

Environmental impacts other than those related to climate and resource protection relate more specifically to technology. Whereas for fuel cells and Stirling engines (as long as these use innovative flameless burner technologies) emissions of air pollutants are extremely low, reciprocating engines emit more significant amounts of NO_x, CO and hydrocarbons. Furthermore, the emission factors of reciprocating engines depend heavily on operation characteristics (lean operation or λ=1; partial load or full load, etc.) and on the maintenance of the systems (catalyst exchange, engine characteristics, etc.). Thus, larger bandwidths characterise this system (Pehnt et al., 2005).

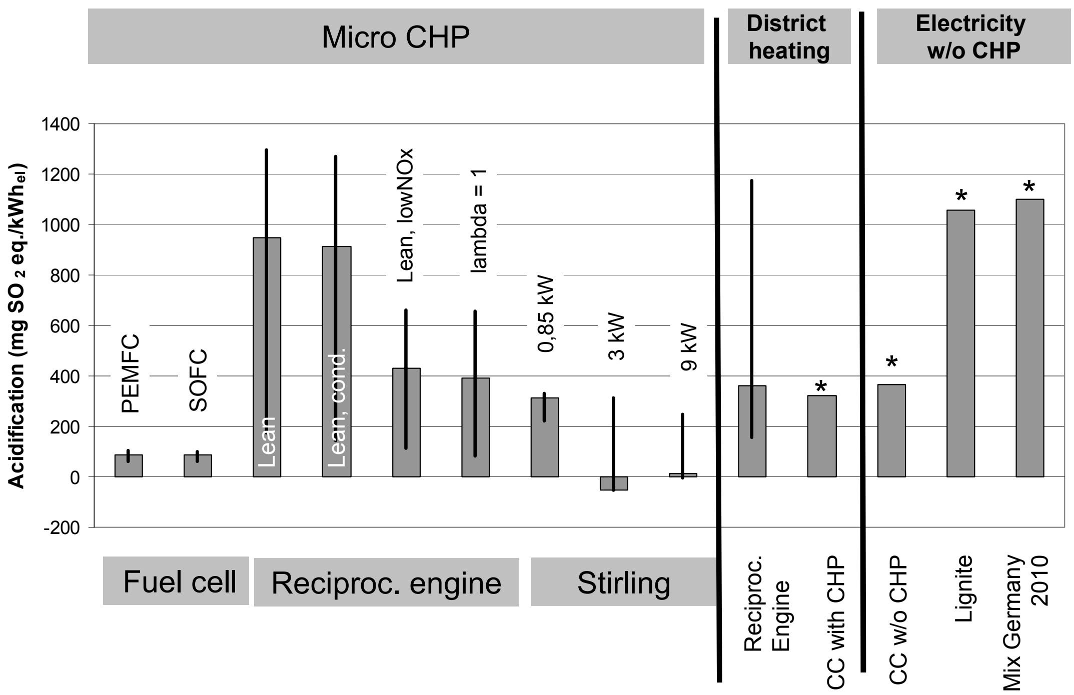

Figure 3: Life cycle (fuel supply, operation and system manufacture) acidifying emissions (NO_x, SO_2, NH_3) of various micro CHP technologies compared to district CHP and conventional electricity production. Explanations see Figure 2. - * No bandwidth data available.

As a consequence, acidifying emissions of small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants (**Figure 3**), due to more efficient emission control in large power plants.

The significance of pollutant emission reductions not only depends on the absolute environmental impact of the pollutants, but also on the specific contribution to total European emissions, including from other sectors. For instance, only 19 % of European NO_x emissions stem from the “energy industry“ sector while the dominant part is emitted by the transport sector. Generally, differences in acidification or eutrophication of electricity generation systems are therefore considered to be of lower overall significance than GHG emission reduction.

In addition to the emission side, further analysis of the immission situation of a residential area supplied by reciprocating engines was carried out (Pehnt et al., 2005), on the assumption of multi-family housing, with one-third equipped with micro CHP, 300 mg NO_x/Nm^3. The analysis shows that for selected, rather unfavourable meteorological conditions, but for a flat topology and urban housing structure, the additional immission of NO_x due to the engines is below the value of relevance according to German legislation, and does not create severe additional environmental impacts (Pehnt et al. 2005).

4.3 Flexibility, adaptability and competing supply options

The ability to adapt to different contingent developments and transformation is an important criterion for the assessment of any innovation, since “a sustainable society must allow and sustain change“ (Bossel, 1999)). With regard to micro CHP, therefore, the question arises whether widespread introduction would lead to inflexibility, making a later change of course difficult. In particular, it is necessary to investigate whether a broad diffusion of micro CHP might hinder the establishment of other ecologically, economically or socially favourable supply options.

Inflexibility or path dependencies may emerge from technical, infrastructural or economic factors, or from certain actor constellations. They might occur both on the heat and, to a lesser extent, on the electricity side of a CHP plant. Regarding heat generation, micro CHP plants provide an alternative to conventional boilers, solar collectors and district heating.

Up to now, micro CHP systems have mainly relied on natural gas, although other fossil fuels, and to a limited extent renewable energy carriers, can be used in most technologies. Micro CHP systems operated on fossil and exhaustible fuels may compete with renewable energy supply and thus impair the diffusion of, for example, solar collectors or biomass boilers. However, although micro CHP and solar collectors require different integration in the respective building, a building previously equipped with a micro CHP plant may in the future also be provided with a solar collector. The situation can be further improved by developing renewable-fuel-based technologies for operating micro CHP systems, particularly Stirling engines.

District heating systems achieve similar or even higher CO_2 reductions than micro CHP and are in many cases economically superior (section 4.1). Furthermore, it is much easier to integrate renewable energy sources into larger-scale CHP systems than into micro CHP. In district heating, different heat suppliers – such as large solar thermal collectors, biomass boilers, geothermal heat, CHP plants and conventional boilers – can be connected to the grid. District heating is of particular importance in cases where a certain minimum size is required for a particular supply technology, as is it the case for combustion of straw or gasification of wood, long-term heat storage, geothermal energy etc. However, despite these advantages with respect to integrating renewable energy fuels, district heating systems suffer from other substantial barriers such as low acceptability (because the heating system cannot be controlled by the house owner or tenant), lack of cost transparency (particularly in the initial phase of system development, including price escalation clauses), a long implementation process, heat losses depending on the number of connections per kilometre, and more difficult realization in old building stock (Nast, 2003).

With respect to *grid development*, a broad diffusion of micro CHP systems would probably restrict the penetration of district heating grids. If, for example, during the development of new residential areas, it were decided, due to the availability and attractiveness of micro CHP, to establish a gas instead of a district-heating grid, it would be very unlikely that an additional grid system would be installed in the future. Therefore, micro CHP can create local path dependencies that hinder the development of an ecologically and economically benign competing heat supply system. Taking into account that currently, and in the near future, micro CHP plants are most likely to be fuelled with natural gas, micro CHP systems should not be promoted in areas where district heating systems are available or feasible, or where other local and attractive options for the use of renewable energy exist.

Regarding *electricity generation*, electricity purchased from the public grid and, thus, power generation in more centralized plants provide the alternative to micro CHP plants. If, in contrast, micro CHP plants gain a considerable market share, grid operators may be able to reduce transmission and distribution capacity. For example, they might choose smaller size cables or transformers when there is need of replacement. This, however, would imply a long-term decision that might hamper the future switch to renewable generation patterns such as, for example, large solar imports from the Mediterranean or offshore wind production.

Altogether, the small system size and short lead-time allow flexible and immediate installation and thus better adaptation to unforeseen future developments in the electricity sector. The adaptability of the energy system is not irreversibly or significantly impaired. However, the penetration of micro

CHP should not be spurred in areas where other supply options, such as district heating or the use of renewable sources, are more appropriate from a sustainability perspective.

3.3 Impacts on the electricity system and security of electricity supply

During recent years, security of electricity supply has become an increasingly important issue. Several blackouts in the United States and in Europe have demonstrated that uninterrupted electricity supply is not guaranteed in liberalized markets. At the same time, costs of electricity interruptions are increasing significantly in the emerging digital economy. As a result, there is a growing demand for highly reliable electricity, sometimes referred to as premium power. On-site production with CHP systems could help to achieve highly reliable electricity supply.

Another important challenge is the rapidly increasing share of wind power in Germany. In Western Denmark the potential power overflow due to wind and CHP power is expected to amount to 2,900 MW by 2005, whereas peak demand in Western Denmark is only about 3,650 MW (Hilger 2002; Jensen 2002; Varming, Nielson 2004). In Northern Germany, the construction of offshore wind power plants may also lead to local power overflows.

As a result of these challenges, security of energy supply is also back on the political agenda. In 2001, the European Commission presented a Green Paper on security of energy supply (European Commission 2001). Recently, in December 2003, the European Commission proposed a new legislative package to promote investment in the European energy sector, to both strengthen competition and help prevent the reoccurrence of the blackouts that took place in summer 2003. Part of the proposal focuses on energy demand management and the increase of energy efficiency.

In recent discussions on security of energy supply, distributed generation plays an important role. Distributed generation, and in particular combined heat and power plants, are regarded as a way forward to mitigate the risks of energy supply security (Casten 2003).

In contrast to large centralized power plants, micro CHP plants have the important advantage that they are located directly at the consumer site. This has beneficial effects on the system, as currents in transformers as well as transmission and distribution lines are lowered. As a consequence, transmission and distribution losses are avoided and upgrading of the transmission or distribution system might be deferred or suspended. In this way, micro CHP plants could help Distribution Network Operators to overcome local bottlenecks in the distribution system, saving costs for expensive upgrades (IEA 2002). With respect to their site and their size, micro CHP plants are also advantageous compared with other distributed power technologies such as wind power plants, which are mostly installed in remote areas, potentially involving reinforcement of transmission and distribution systems.

In the existing power system, central steam power plants have the responsibility to provide ancillary services required to operate the electricity system and to maintain a high power quality. These ancillary services comprise reserve power control, voltage and reactive power control as well as certain fault behaviour requirements. The need for these ancillary services will increase in the future, mainly due to the increasing share of more unpredictable wind power generation. This has technical and institutional implications. To maintain high power quality and system reliability in an electricity system with a large share of distributed generation, distributed power plants should be designed to provide some of these ancillary services.

For micro CHP plants, heat demand is the most limiting factor in providing power control services. In winter, large heat demand involves continuous power generation by micro CHP plants. In spring and autumn, micro CHP plants are typically operated for a couple of hours per day. In summer, overall power generation is restricted by hot water demand, limiting power generation to approximately one hour per day.

Power generation can be decoupled from heat demand to a certain extent by means of hot water storage tanks. Appropriately operated and controlled, hot water storage tanks enable micro CHP plants to increase or decrease their power generation for a limited time span. This allows a shift in power generation towards the peak hours in the system, if corresponding economic incentives are provided. This is particularly useful in summer, when the power generation potential of micro CHP plants is most limited. As feed-in tariffs for electricity are significantly lower than electricity purchase prices, micro CHP plant operators already have certain incentives to optimize the time match between CHP operation and on-site electricity demand.

Reciprocating and Stirling engines can generally be started quickly and power output varied instantly. Hence, they can principally be used for power control services. The ability of fuel cells to change power output is still subject to research.

To provide ancillary power control services, micro CHP plants need to have information on actual control requirements. For this purpose, many micro CHP plants could be interconnected to a virtual power plant. The virtual power plant operator could provide ancillary power control services by controlling the power output of all connected units. This could principally include primary and secondary power control as well as minutes reserve.

With increasing market penetration of micro CHP systems, interaction of micro CHP systems with the electricity network can occur. The maximum micro CHP connection capacity of the distribution grid is difficult to quantify and depends, amongst other things, on the grid topology and the share of fluctuating electricity. The most critical limitation is in many cases the voltage variation due to electricity feed-in. Micro CHP not only poses problems for D&T infrastructure, but can also offer advantages to the grid such as congestion relief. It is important to note that many of these impacts are interpreted against the background of our current network, dominated by a one-directional system layout and large-scale block-type power stations. With a future power system moving more into the direction of bi-directional electricity and distributed generation, both the backup generation structure and the T&D system have to adapt to this development

In summary, compared to large steam and hydro power plants, the provision of ancillary power control services by micro CHP plants is more complicated but possible. For this purpose, the most important challenge is the interconnection of many micro CHP plants to virtual power plants. Micro CHP plants may also be able to reduce network operation costs, especially if their operation is controlled within virtual power plants.

4 Barriers to and conditions for micro CHP introduction in Germany

In spite of the sustainability potential identified above, the global development of micro CHP is rather disappointing. In Germany, for instance, only around 1,414 new systems (< 50 kW_{el}) per year have been registered, with a total power of merely 10.8 MW_{el} (Golbach, 2003).[4]

In contrast, studies such as MicroMap (2002) see a large potential for micro CHP. They develop scenarios according to which in 2020 in Europe some 5 to – in the optimistic scenario – 12 million micro CHP systems could be delivered, with the United Kingdom, Germany and the Netherlands as initial markets. MicroMap concludes that Stirling engines have the highest potential in domestic energy supply. The FutureCogen project estimated that under optimistic assumptions up to 50 GW_{el} could be installed in the EU15 (Future_Cogen, 2001).

The mass market for micro CHP will be for the replacement of gas heating boilers (Harrison and Redford, 2001). For Germany, RWE forecasts up to 400,000 micro CHP heating systems per year in 2015 (Dinter and Halupka, 2001). In a model analysis of fuel-cell micro CHP, Krammer calculates a maximum market volume of 120,000 systems/a in the trend and up to 300,000 systems/a in the optimistic scenario (Krammer, 2001).

This large gap between expectations and reality make it important to identify the barriers that are responsible for this discrepancy. Toward this end, the following chapters investigate the economic opportunities, the political framework (that is, the institutional and regulatory framework), innovation policies and consumer acceptance based on investigations of the German market.

4.1 Economic opportunities for micro CHP

The chances for a broad diffusion of innovative micro CHP technologies depend significantly on their economic performance. Reasonable investment costs are a key prerequisite, but other parameters, such as electricity and natural gas prices, technical lifetime, operating costs as well as heat and electricity demand characteristics are also important. To reflect the differences of micro CHP applications, we assess the economic viability of several promising micro CHP technologies in six different types of buildings, representing a range of potential applications in Germany (**Table 3**).

		Detached houses		Apartment buildings		Hotel
		Low heat demand	Av. Heat demand	Low heat demand	Av. Heat demand	
Heating surface	m²	131	112	457	913	1.263
Maximum heat demand	kW	7	11	23	67	75
Annual heat demand	MWh/a	12	18	41	127	122
Annual electricity demand	MWh/a	3	4	22	29	24
Share of consumers selecting the operator of the Micro CHP plant as their electricity provider	-	100%	100%	80%	80%	100%

Table 3: Characteristics of buildings selected for the economic assessment of micro CHP plants

Sources: ZSW 2000, own surveys, estimates and calculations

For each type of building, the economic performance of micro CHP technologies is compared with other heat and electricity supply options. In a *Reference Case* we assume that all electricity is purchased from an electricity supply company and that heat is generated with a conventional condensing boiler. In an additional scenario, several buildings are connected to a *small heat and electricity grid supplied by a CHP plant* with an electric capacity of about 10 to 50 kilowatt. For electricity supply with CHP in apartment buildings, or in small decentralized grids, we assume that only about 80 % of electricity consumers choose to be supplied by the micro CHP plant operator. The remaining 20 % continue to purchase electricity from another supply company.

Economic analysis is conducted for the same five reciprocating and three Stirling engines that were selected above for environmental assessment. These technologies are currently available, or are expected to be brought onto the market until 2006 (see

Table 2). Due to the high capital costs of fuel cells and high uncertainty with respect to the achievable target cost (Krewitt et al., 2004), we do not include fuel cells in the comparison.

Levelized costs of the different supply options are calculated for a time horizon of 10 years, from 2005 to 2014. If the technical lifetime of main components (boiler, district heat grids) is greater than 10 years, the net present value of the component at the end of the time horizon is calculated on the basis of linear depreciation. For all options, a nominal rate of return of 9 % is assumed. We estimate electricity and natural gas prices in our own scenario based on (European Commission, 2003a; European Commission, 2003b; European Commission, 2003c; Schlesinger et al., 2000; Krzikalla/ Schrader, 2002; Deutscher Bundestag, 2002).

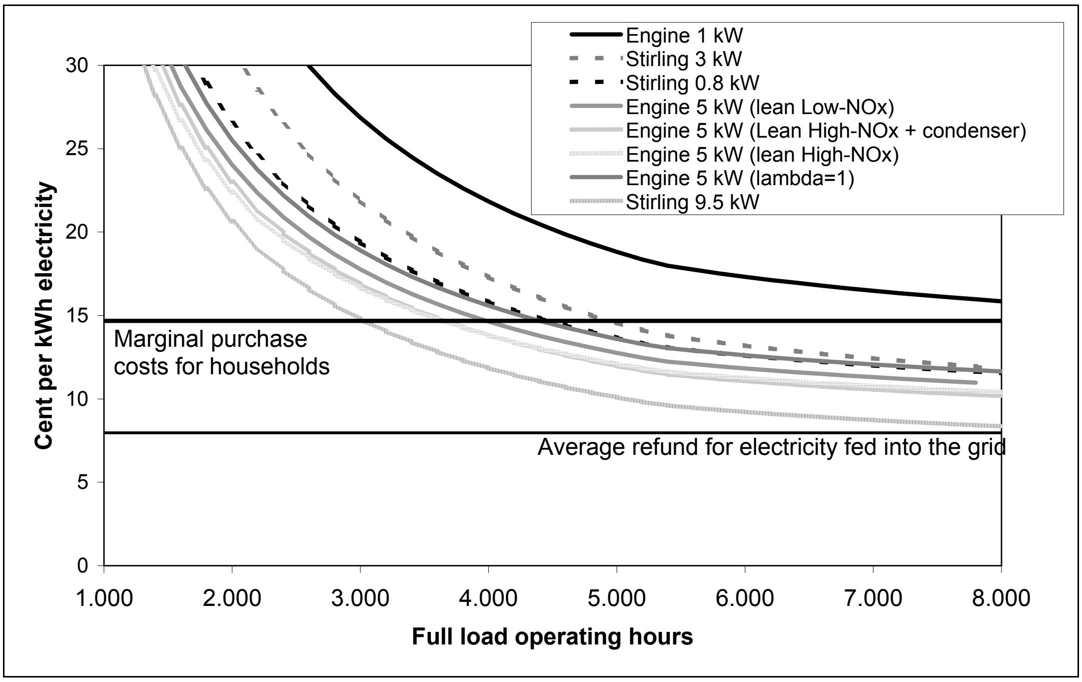

Figure 4: Average levelized electricity generation costs of micro CHP technologies (2000 prices)

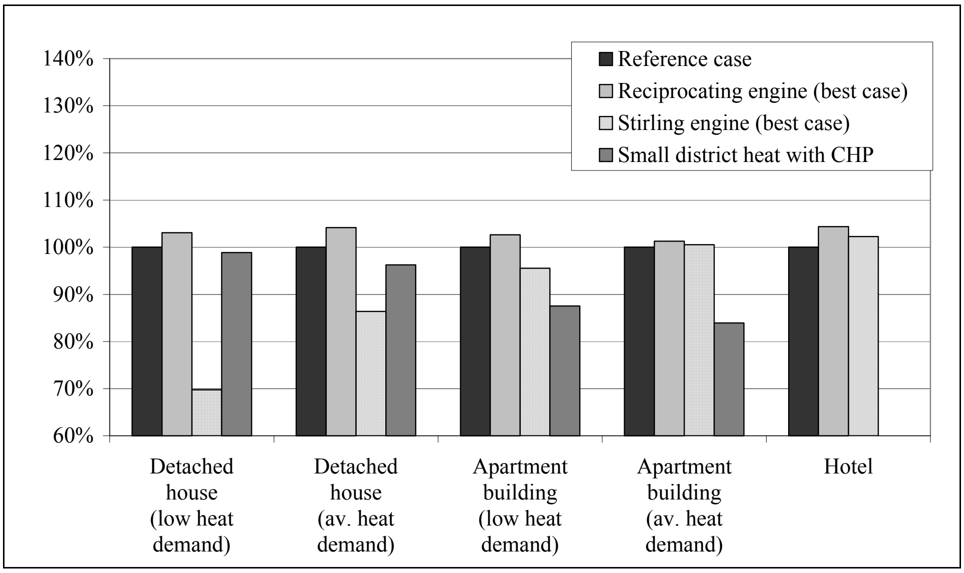

Figure 5: Cost comparison of micro CHP technologies in different buildings. Annual levelized costs for heat and electricity supply of the buildings, relative to the reference case (electricity purchase and heat supply with a boiler), including natural gas and electricity taxation and CHP legislation.

In **Figure 4**, the electricity generation costs of different micro CHP technologies are plotted against full load operating hours; **Figure 5** illustrates the overall costs of different supply options relative to the Reference Case in different building types. The Figures provide some interesting results:

- *Most micro CHP plants are only economically viable if operated for at least 3,500 to 5,000 hours at full load, using the electricity at the production site.* Even after the revision of CHP legislation in Germany in spring 2004, it is economically not feasible to operate micro CHP plants for the purpose of feeding electricity into the grid, as the total refund for electricity fed into the grid – which includes the bonus payment according to German CHP law – is lower than electricity generation costs. Consequently, the availability of a sufficient number of electricity costumers at the micro CHP plant site is a prerequisite for their diffusion. In the case of buildings, generally up to 30 % of the electricity generation is fed into the grid, and a full load operation time of about 5,000 to 6,000 hours per year appears to be a requirement from an operator's perspective.
- *Economically, micro CHP plants are particularly promising when they are able to fully replace boilers.* This is reflected in **Figure 5**, where the heat and electricity supply costs for the small Stirling engine are considerably lower in the detached house with low heat

demand, as the heat capacity of the Stirling engine is sufficient to supply peak heat demand. In the other supply options, an additional boiler is required.

- *Low electric efficiency is not an economic disadvantage in the case of small micro CHP plants*, as it better reflects the heat and electricity demand characteristics of small buildings, and – more essentially – it leads to significant tax advantages. In Germany, heat generation in boilers is subject to natural gas taxation, while heat generation in a CHP engine with 70 % overall efficiency is exempt from natural gas taxation. This legislation cuts particularly the costs of CHP engines with low electric efficiency, reducing marginal electricity generating costs by almost 50 % in the case of the small Stirling engine. However, this taxation effect is not backed by the environmental performance of such CHP plants (section 3.1). In this light, it may be necessary to reconsider the criteria for natural gas tax exemption in Germany.
- *Small heat and electricity grids with CHP (reciprocating engines) are economically the best option for apartment blocks, but less appropriate for areas with detached houses.* A major cost advantage of small grids is the significant lower investment costs per capacity and operating costs per kilowatt-hour of larger reciprocating engines. For this supply option, a major barrier is the risk that some electricity costumers would prefer to be supplied by other electricity companies. However, as the cost reduction is rather significant compared to the Reference Case, a solution is to offer electricity costumers prices about 5 to 10 per cent lower than market prices. This approach has been applied by some third-party financing companies in Germany and has proven to work in practice.

Sensitivity analyses have shown that these results still hold under different economic conditions; for example, where the CHP bonus is not in place, or where prices for natural gas (±20%) or electricity (±10%) differ from the prices assumed here.

All in all, the analysis shows that micro CHP plants can be economically viable, but that the viability substantially depends on the plant type and on the specific conditions of the facility. For detached houses, replacing a boiler with Stirling engines seems to be an economically attractive option. For apartment buildings, a small heat and electricity grid is likely to be economically the most efficient solution. In the case of hotels and commercial buildings, the advantage of a micro CHP plant, compared to the reference case, may be smaller, as such customers enjoy lower electricity prices.

4.2 Consumer expectations and acceptance

Technology does not develop autonomously, nor is its course determined by the quest for technological and economical optimization alone. Rather, technology development is shaped by the actions and interactions of various societal actors. Technology users are an important constituent of this tightly woven network of actors.

As micro CHP is still in the introductory phase, a specific group of users is important: a group called "innovators" by Villiger et al. (2000), which, for conceptual reasons, we will call "pioneers". Pioneers take up a new product in a very early development stage, some even before general market introduction. Their role is to test and help develop the new technology and also to propagate it and pave its way onto a broader market.

In this chapter, we describe the characteristics of micro CHP pioneers. We try to determine how the target group can be described in socio-demographic terms, what they expect of micro CHP, which aspects they consider important, and which economic conditions, institutional frameworks and political instruments are perceived as facilitating or inhibiting the introduction of micro CHP.

The information stems from two sources: firstly, we draw some conclusions from the study of analogous cases, and secondly, we report early results from a current study on persons who had opted to take part in a field test of fuel-cell-based micro CHP. We defined technologies for home production of electricity and/or heat as „analogous cases"; these are, in comparison with established systems, innovative and advanced as far as efficiency and environmental effects are concerned. Twelve studies dating from 1992-2003 were discovered that dealt with consumer aspects (see Bibliography in Pehnt et al., 2005). The studies were analysed with regard to socio-demographic characteristics of the technology adopters and to attitudes (motives and goals, technology evaluation as well as perception of facilitating and inhibiting factors). Hypotheses were developed regarding the transferability of the results to the micro CHP case.

The study on field test applicants is currently being conducted on a sample of 500 persons who had opted to take part in a field test of fuel-cell-based micro CHP. The study comprises a survey of the applicants, focus group discussions with selected applicants and interviews with the persons actually taking part in the field test. In this paper, we present the results of the focus group discussions with applicants. They comprise 26 applicants out of 99 who were contacted. Group members were asked about the reasons for their application, about hopes and fears regarding fuel-cell micro CHP, about preferred ownership models, and about the advantages and disadvantages of fuel-cell micro CHP as compared to other electricity or heat technologies.

Based on this information, we can sum up some preliminary findings about pioneers in promoting micro CHP, their motives and expectations:

(1) The main target group is families living in their own house in rural areas or small towns. While fuel-cell-based micro CHP appeals mainly to academic high-income groups, there may be potential for engine CHP among skilled manual workers and owners of small workshop. Pioneers demonstrate an interest in technology, energy and/or the environment already by their choice of education and career. What is striking is the almost exclusive prevalence of men.

(2) Persons interested in micro CHP value innovation, own "trigger technologies" and are now looking for more. They have a desire for autonomy and perceive micro CHP as a suitable tool for "self production" of electricity. Environmental aspects are important, and they are optimistic that environmental problems can be solved technically. Economic feasibility is necessary in the long run, but economic motives do not feature prominently. An additional finding is that "windows of opportunity", such as heating replacement, can be used to sensitise potential users for new technologies.

(3) Pioneers are a dedicated, enthusiastic group with an interest in spreading their ideas, sharing experience and demonstrating the new technology and its workability. As they are a socially-integrated, high-status group, they can serve as a role model for others. Some of their fascination is specific to the fuel cell (especially the visions of a hydrogen economy), but the more general motives make this group a target group also for other micro CHP types.

(4) Micro CHP pioneers desire feedback on system performance and the possibility to monitor performance oneself. Providing such feedback will most probably increase satisfaction.

(5) Infrastructural restrictions play an important role. This applies to both space requirements and access to the gas grid. Other restrictions are uncertainties about cost and functionality. Helpful tools to overcome these uncertainties are reliable information, especially personal experience, contracting arrangements and support schemes. A combination of investment subsidies and feed-in tariffs will be welcomed by most users. It is important that programmes are administered flexibly, swiftly and unbureaucratically.

(6) As important as pioneers are for the promotion process, they are anything but uncritical mouthpieces. Pioneers critically follow the development process, demand to be kept informed, make recommendations and communicate successes as well as failures to others. They can be a source of valuable advice for developers.

If the goal is broad diffusion of a technology, it is just as important to discover who is *not* among the pioneers. If half the population is missing – as in this case, women – this indicates certain critical blind spots in the technology and/or the diffusion strategy. Reliability, profitability and trustworthiness are especially important if female users, who often exhibit less enthusiasm about technology but more pragmatism, are to be convinced.

4.3 Institutional and regulatory framework

Apart from technological potential, private and social costs, corporate strategies and consumer acceptance, the innovation path of micro CHP is essentially influenced by institutional structures in the field of implementation. Such structures influence the strategies of different actors – producers, consumers and regulators – in choosing or not choosing micro CHP systems. Institutions are defined as the social rules that enable or constrain action by setting incentives, providing orientation or prescribing or forbidding specific behaviour (Voß et al., 2001).

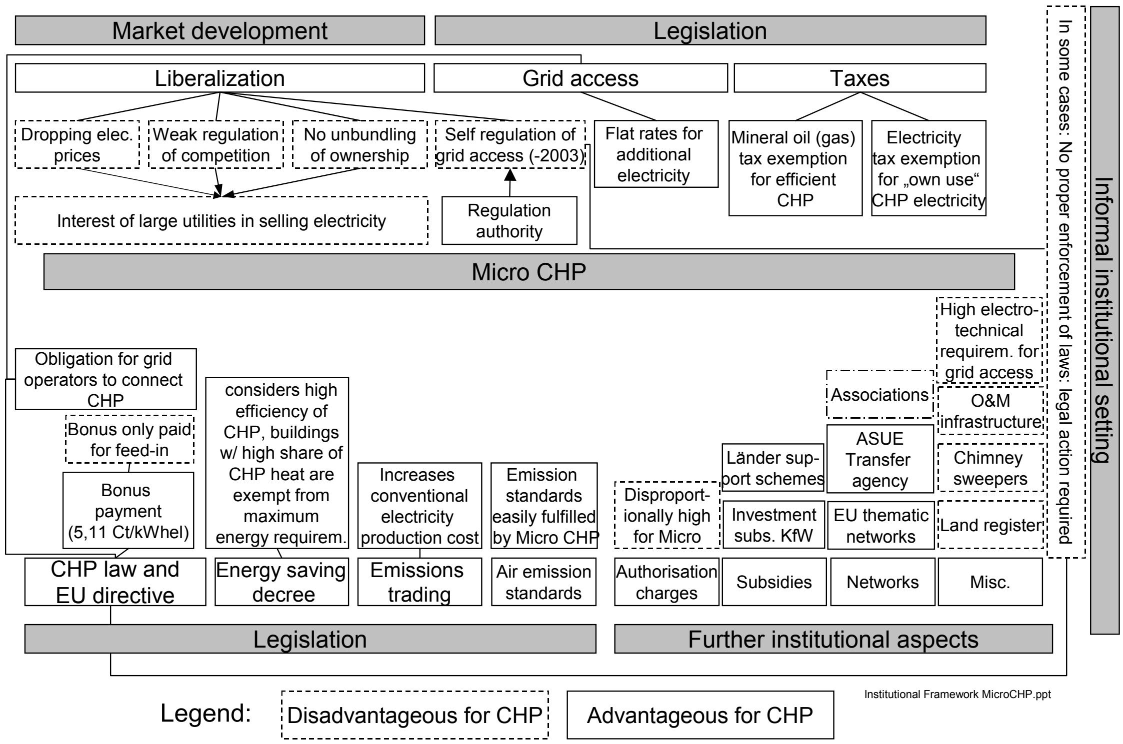

Figure 6: Institutional setting for micro CHP in Germany (Pehnt et al., 2005)

It appears that the institutional setting for micro CHP in Germany shows ambivalent patterns (**Figure 6**). For one, many regulations are in place that give direct incentives to micro CHP or contain favourable conditions for distributed generation, efficient energy use or for CHP in general, which have indirect positive implications for micro CHP. These favourable conditions include a micro CHP bonus for electricity fed into the grid (5,11 Ct/kWh$_{el}$), fixed conditions for additional electricity purchases for that share of demand that is not covered by CHP, compensation for avoided costs in the electricity grid, tax exemptions and the option to use CHP to meet energy efficiency standards for buildings (Pehnt et al. 2005).

On the other hand, some of these formal regulations are ineffective because they are not properly enforced, or because they are overshadowed by more fragmented and informal institutional settings, which encroach upon the overall institutional environment for potential micro CHP investors, operators and users.

This is partly due to path dependency: Our present, centralized energy system is to a great degree determined by high embedded costs and large investments in infrastructure for fuel supply, power generation, transmission and distribution ("technical path dependency"). The stakeholders concerned (for example, large energy utilities) promote existing energy systems and dominate the decision structures of the energy system ("social path dependency"). The main barrier to distributed generation is therefore competition with the existing infrastructure and the associated interest in maintaining and continuing operation of this infrastructure, or as Verbong (2003) puts it, "the critical problems of each era [of electricity supply] are formulated against the realities of the preceding era."

Another important point to explain the strong position of large utilities is the weak regulation of competition in the German electricity market. Existing utilities, which own the electricity network, have a strong interest in hindering the undertaking of generation activities by their customers, and they have many different means to do so; for instance, with low compensation for avoided grid use or denied grid access in spite of the clear legal obligation to connect all micro CHP systems. This is due to a lack of a reliable enforcement of network access regulations and due to the fact that ownership of generation capacities and transmission and distribution systems is not separated. The establishment of an independent regulatory authority in the summer of 2004 may be a step forward in this respect.

Such encroachments are accompanied by several small impediments to micro CHP (Meixner and Stein, 2002). These do not appear influential in themselves, but they may add up to increased transaction costs and uncertainty in respect of some of the benefits introduced through formal regulation. Among these are relatively high registration fees for small micro CHP installations and high electrotechnical requirements imposed by some distribution network operators.

With respect to innovation policy, a comprehensive and consistent federal policy towards micro CHP does not exist. Programmatic orientation of federal policy gives great weight to the expansion of CHP in general, but micro CHP is not explicitly considered part of a future vision of climate-friendly energy provision in Germany. With respect to technology policy, there is a large difference in the attention paid to fuel cells on one hand and other micro CHP technologies on the other hand. Innovation policy follows a clear technology focus in this respect. This one-sided orientation of innovation policy also poses difficulties for communicating the general concept of micro CHP to a wider public, because public attention has been too narrowly focused on fuel cells. Support for fuel cells comes from different levels (Europe, German federal government, German Länder (states), companies and private initiatives) and through different approaches (R&D financing, information management, network support). R&D financing for other micro CHP technologies is negligible. This makes it difficult for products based on other technologies (reciprocating engines, micro gas turbines, Stirling engines) to compete on common ground with fuel cells, although they are partly much further developed with respect to technological reliability and economic competitiveness.

5 Conclusions

Our research on the conditions and impacts of micro CHP shows that micro CHP could contribute to a sustainable transformation of the electricity system in certain application segments and under certain conditions.

First of all, micro CHP has several important **advantages** with regard to key sustainability criteria:

- Micro CHP reduces greenhouse gas emissions and resource consumption compared to average energy supply and even compared to efficient and state-of-the art separate production of electricity in power plants and heat in condensing boilers.
- It complements a smooth process of transformation of the power generation portfolio, since the use of micro CHP allows for more flexibility and better adaptation to unforeseen future changes compared to centralized large power plants.
- Micro CHP plants can have positive effects on the supply security of electricity grids, particularly where heat storage facilities and smart controls / ‘virtual power plant technology’ are used.
- Due to the small unit size and short lead times, micro CHP creates opportunities for new, smaller market players and may, in this way, pave the way to more competition in electricity supply and reduced market concentration.

However, it has to be noted that compared to other energy supply options, micro CHP is confronted with several **limitations** and is therefore the preferred supply option only under certain conditions:

- Up to now, and also in the near future, micro CHP systems will mainly rely on natural gas, a fossil and exhaustible fuel. The use of renewable energy carriers is more difficult in micro CHP plants than in larger CHP plants. Hence, where a large local potential for renewable energy carriers exists (for example, geothermal heat, wood sources etc.), other supply options, such as local district heat grids are better suited to use these renewable energy sources. In the longer run, the operation of micro CHP with non-fossil fuels should be further developed.
- In areas with a high heat density, district heating with larger CHP plants is economically more attractive and is environmentally at least comparable to micro CHP. District heat systems with CHP should therefore be the option of choice in areas with high heat density.
- Other environmental impacts such as acidification and eutrophication may, especially for reciprocating engines, be greater compared to other supply options. Whereas Stirling engines, particularly those with flameless burners, and fuel cells offer very low emission levels, in the case of reciprocating engines, system design and maintenance standards and procedures should allow a stable and low local emission level, in particular of NO_X.
- Availability, current technical performance and economic prospects of micro CHP depend strongly on the specific technology considered. Fuel cell technology is still in the R&D phase, Stirling engines are approaching market introduction, and reciprocating engines are commercially available.
- Micro CHP plants are only economically viable if operated at least about 3,500 to 5,000 hours at full load, and if the electricity is used at the production site. Thus, applications with a rather constant heat demand and an electricity demand matching the CHP electricity production profile are particularly well suited for micro CHP installation. However, there are also operators who select micro CHP not on the grounds of economic competitiveness alone, but who place great importance on energetic self-sufficiency or environmental benefits.

The **framework** for micro CHP is particularly influenced by liberalization, which has led to a sharp decrease in electricity prices and, thus, to a considerably delay in the diffusion of small CHP plants. However, electricity prices, in particular for private households, have started to rise again and are expected to increase even further over the next few years. In addition, emissions trading is likely to further increase the cost of conventionally produced electricity and thus improve the competitiveness of micro CHP due to the higher value of avoided electricity demand. Moreover, German legislation has enhanced the economic opportunities for micro CHP plants, in particular by exempting micro CHP plants from electricity and natural gas taxation, but also by introducing the bonus for electricity fed into the grid. Thus, after the first shock of liberalization, the general institutional framework for micro CHP has improved considerably, and might further improve in the future.

These generally favourable economic conditions for the operation of micro CHP plants, however, seem not to be sufficient to effectively promote their diffusion. Grid operators use the currently weak regulation of grid access to hinder the emergence of independent power producers. An additional barrier is the low level of information on the customer side. Acceptance of novel marketing and operation strategies such as third-party financing is comparatively low. Technologies other than fuel cells are little known and elicit little enthusiasm. Because of small plant size and operation by non-professional electricity producers, complicated rules and failing access to information give rise to relatively high transactions costs and reduce the economic attractiveness of micro CHP plants.

To conclude, a focussed strategy is needed for the objective of creating a level-playing field for micro CHP and of adequately allocating micro CHP to applications for which this innovation is well suited. Much depends on the adequate embedding of the new technology and related investment and operational practices in the expectations, skills, routines and living conditions of those actors that might become involved with micro CHP. Such a strategy should address architects, civil engineers, plumbers, electricians, retailers, owners and users of buildings, maintenance staff etc.

An approach towards the fostering of micro CHP could include the following elements:

- Definition of **areas and conditions** where micro CHP plants appear particularly promising from an environmental and economic perspective (for example, areas with a low heat density, areas with possible grid constrains, areas with fuel poverty problems).
- Definition of **minimum criteria for micro CHP technologies** (for example, minimum efficiency and environmental performance).
- **Independent and reliable enforcement of the rules governing grid access**. The establishment of a German regulatory authority (as of summer 2004) is an important first step towards clarifying the institutional setting in this respect. Moreover, enforced deconcentration of ownership would remove incentives for district network operators to deny grid access to small generators.

- Public R&D efforts should focus not only on fuel cells, but also on the further development of Stirling engines, which may have the same environmental benefits, while being further developed and appearing to be economically more attractive. In doing so, particular emphasis may be placed on the use of **renewable fuels** such as wood pellets in Stirling engines.
- Micro CHP might be a constituent part of visionary technologies such as **virtual power plants** and **smart homes**. R&D efforts to turn micro CHP into an interactive technology, which helps to reduce grid impacts and to improve power quality, balancing of supply and demand and peak power shaving, should be intensified, including intelligent and cheap grid access and intelligent metering technology (for example, time-resolved two-way meters). Standardised electronic equipment for micro CHP plants may help in grouping them in virtual power plants. Home load management (to maximise CHP benefits by prioritising and deferring loads) and feedback information (to couple environmentally-conscious behaviour with micro CHP) might help to incorporate micro CHP in a smart house concept.
- Further **field tests** should be initiated, involving producers, users and service providers, to learn about technological and institutional requirements articulated by users and other parties, and to promote respective technological and institutional innovations. In order to anticipate possible harmful repercussions already at an early stage, other stakeholders, such as environmental and consumer protection groups, could be invited to accompany the process.
- A **campaign** to increase knowledge of micro CHP as an element of a sustainable energy system should be started. The campaign should focus on buildings, areas and consumers where micro CHP technologies fit well. It should be directed at potential “pioneer users” who will work as multipliers.

The above starting points for strategic action are of a preliminary nature and certainly incomplete. They could, however, provide the basis for further discussion on the opportunities and barriers of micro CHP.

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Acknowledgements

The case study presented here has been funded under the socio-ecological research framework recently launched by the German Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF).

We acknowledge valuable contributions from Raphael Sauter (FU Berlin), Katherina Grashof, Sabine Poetzsch and Jens Gröger (Öko-Institut), Regina Schmidt and Bernd Franke (IFEU) as well as Lars Winkelmann (Berliner Energieagentur GmbH).

Final notes

[1] Whereas the EU CHP directive defines micro cogeneration as "a cogeneration unit with a maximum capacity below 50 kW_{el}", we restrict ourselves to systems with a capacity of less than 15 kW_{el}.

[2] Efficiency data refers to yearly averaged efficiencies, not to efficiencies at the best operating point.

[3] One exception is the Stirling engine concept with lower electrical efficiency that lies somewhat above the GHG level of a combined cycle plant. The somewhat lower efficiency of the condensing boiler is based on a large number of systems. It has been shown that the high efficiency due to the condensing operation cannot always be gained, particularly in the summer.

[4] In the 12 months after the new CHP legislation came into effect (1.4.2002 to 1.4.2003). To get the bonus according to the CHP law, CHP units have to be registered at the German Federal Agency for Economy and Export Control.