PowerGen Europe 2007 paper (ID-95)

Micro CHP implementation

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Introduction

Cogeneration or combined heat and power production (CHP) is an efficient way to obtain primary fuel savings, significant reductions of CO_2 emission and less losses in the power transmission and distribution network.

Cogeneration can be established within a wide power range, and it is possible to use various fuels and technologies. Utilisation of both electricity and steam generation or production of hot water is attractive for a large number of industries or commercial buildings and in district heating networks.

The European Union has set a target for CHP /1/ and launched a Directive /2/ to be implemented in the national energy planning. The target is a doubling of the CHP share from 9% in 1994 to 18% of the total gross electricity generation in 2010 by doubling the generation capacity and increasing the plant load factor.

Figure 1 shows the share of electric energy generated at decentralized plants, mostly CHP, in a number of countries in 2004-2005 /3/.

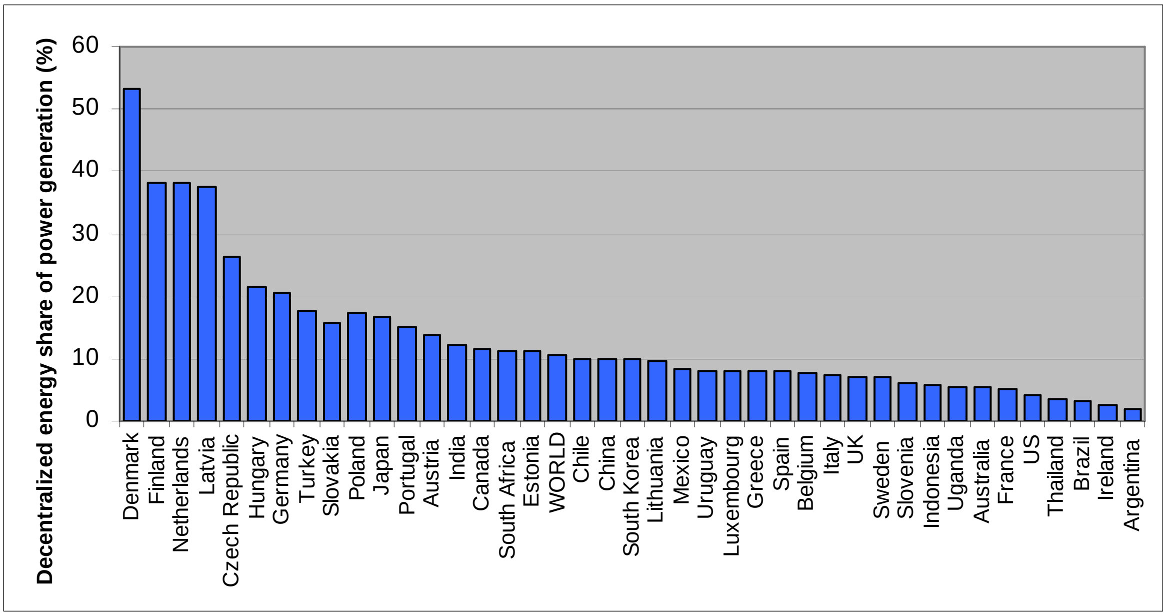

Figure 1 Decentralized energy share of electric energy generation in a number of countries

In many countries, CHP is now widely used at large- and medium-scale plants and the interest for further implementation has turned to remaining installation potentials in the mini/micro-scale.

This paper will focus on small cogeneration units for use in single-family houses ("micro CHP") and will discuss

- Market segments to be addressed
- Operation strategy possibilities (for CHP operation and other services)
- System design and sizing (control, heat storage, water side coupling)
- Technologies available (advantages, disadvantages, matureness, key performance parameters)
- Ownership and service/maintenance models

Is micro CHP competitive from an efficiency point of view?

Small CHP units often have lower electricity production efficiency than larger ones. Despite this, small domestic unit solutions <u>may</u> be advantageous from an electricity generation point of view compared to a larger unit in a heating network for a number of remote houses. This can be illustrated by the two simplified cases below. In each case a limited number of houses are considered and given the same conditions in regard to heat and power consumption.

Individual domestic micro-cogeneration units are installed in each house (Figure 2, left side). The domestic cogeneration units produce electricity and heat based on the heat needed. Excess or shortage of electricity is exported/imported to/from the public grid.

From a bird's perspective <u>fuel in</u> crosses the system border. The heat needed and an amount of electricity is produced based on this fuel input. The <u>electricity is first hand exported across the system border</u> to keep things simple.

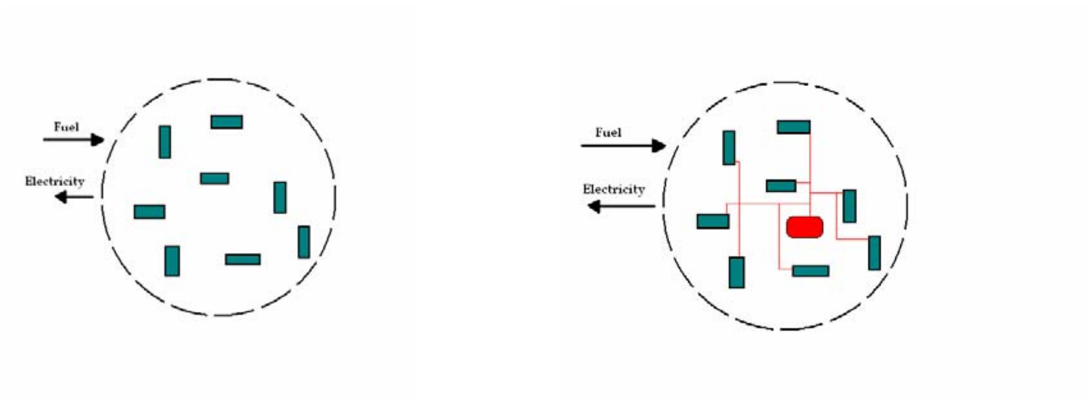

Figure 2 Comparison of individual micro cogeneration (left) and cogeneration in a (limited) district heating network (right)

Instead of individual CHP units in each house, a central CHP plant is now established for supplying heat to the houses (Figure 2, right side) as an alternative solution. More electricity than in the first case will be produced as the larger cogeneration unit has a higher efficiency when producing electricity, thus giving a higher electricity-to-heat ratio. The amount of electricity produced is also increased due to the fact that the heat demand now consists of both the heat demand in the houses and the heat distribution losses. In case 2 more fuel is passing the city/system border in order to fulfil the heat demand in the houses, the grid losses (heat) and the increase in production of electricity. All the electricity produced is first hand exported as in the first case. The increase in the production of electricity is illustrated by the size of the arrows in Figure 2.

Given these conditions, the consumption of fuel in case 2 is higher then in case 1, and more electricity is exported across the border of the system, see Figure 2. In both cases, the heat demand in each house is covered and establishes the base for the production of electricity.

If an analysis is made concerning the <u>additional fuel</u> used and the <u>additional electricity</u> produced for the central CHP solution, the marginal electricity production/generation efficiency for case 2 can be found. The result will depend on the losses in the district heating network and the power production efficiency of the micro CHP versus the larger CHP unit. The result is shown in Figure 3.

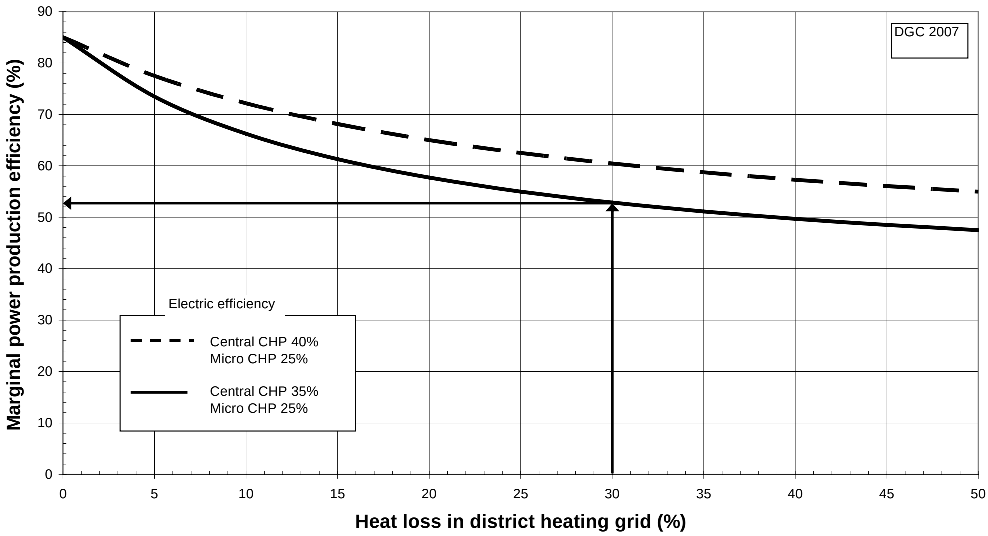

Figure 3 Marginal power generation efficiency for larger CHP units compared to small domestic micro CHP units

Example derived from Figure 3

A central CHP unit with an electrical efficiency of 35% (LHV) is installed in a heat distribution grid with 30% heat distribution loss. Even new district heating grids can have losses in the range of 20-40% in areas with low housing density /4/ or reduced heat demand /4/. Compared to individual micro CHP installations (assuming 25% electrical efficiency) the <u>marginal cross city border power production efficiency</u> for the central CHP solution will be 52%. The rest of the (marginal) fuel is lost. Such power can be bought from centralised power plants where also heat may be produced and utilised leading to better fuel utilisation.

This means that a considerable potential for the establishment of micro CHP exists in areas not supplied with district heating. If district heating is considered, it should have a low annual distribution heat loss; otherwise individual micro CHP may be advantageous from an energy point of view. The analysis made also shows that it is important to keep up the total efficiency of micro CHP units; otherwise larger units may be beneficial both from a marginal electricity and total efficiency point of view.

Today, mini/micro cogeneration is entering the Japanese market. In Europe, Germany is closest to a wider use. The Netherlands and the UK are countries also mentioned to be among the first in Europe to introduce micro cogeneration on a larger scale.

Virtual power plant

The term virtual power plant is often used together with micro CHP. A virtual power plant consists of several decentralized power generating units, gathered in a cluster, thus giving the controller of the grid the possibility to control a large number of micro-scale power plants in the same way as he normally would control a single large unit. The units may be micro CHP, windmills, photovoltaics etc. Several advantages can be mentioned for virtual power plants and thus for micro CHP. The central control can make estimates based on weather data on the expected energy from windmills and operate the micro CHP units according to this. Peak shaving using micro CHP reduces the need for older, less efficient peak load units such as gas turbines. Distribution loss in the electric grid is also reduced. Both the pollutants generated at the combustion and greenhouse gas emissions due to higher overall efficiency are reduced.

The interaction between virtual power plants and the electrical grid including the operators and brokers on a deregulated market is outlined in Figure 4. It is obvious that not only technical topics are interesting but also non-technical aspects on a deregulated electricity market. The non-technical aspects are not discussed in this paper.

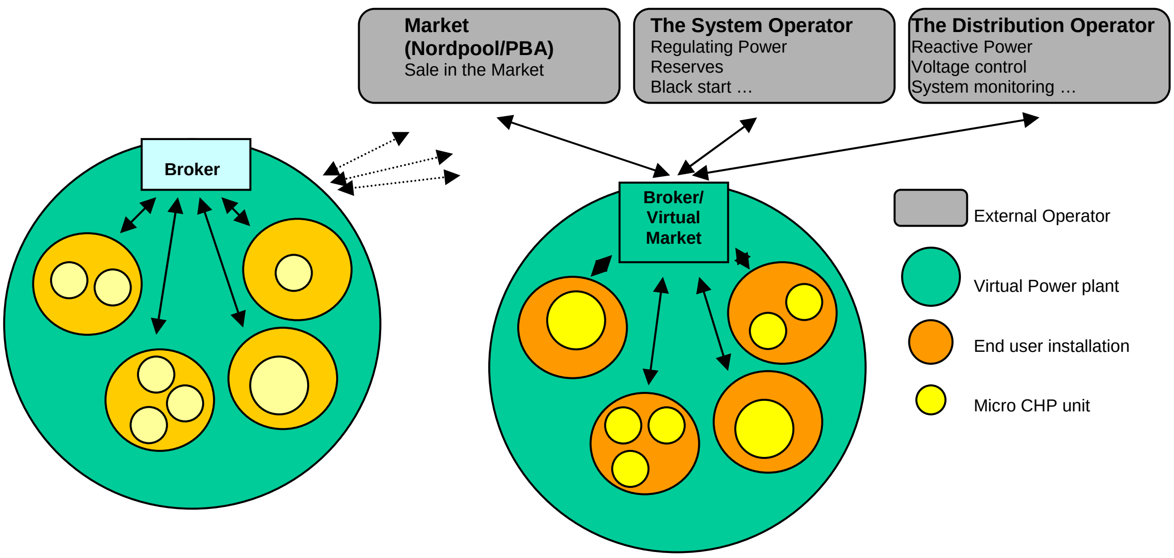

Figure 4   Virtual power plant layout

Operation strategies

The micro CHP operation can follow the demand for power or heat. If the unit is controlled by the heat demand of the house, a connection to the electric grid enabling import and export of electricity to the house will be needed in most cases.

Many houses in northern Europe, electrical heated houses excluded, will have an electricity-to-heat rate on an annual basis of some 1:2 to 1:4, which in principle should match various micro CHP technologies well. However, the annual consumption of both heat and power consists of seasonal, daily and also hourly demand profiles, which may damage the favourable annual 1:2 to 1:4 ratios.

The demand for electricity varies a lot during the day, depending on the equipment connected and load profiles. Each family or household has their own consumption pattern. If a micro CHP unit is controlled by the demand of electricity (power load following) it will need an ultra fast dynamic response and cover a wide power range. The average power generation will be low, which may lead to poor efficiency in the generation of electricity. Even base load varies significantly from household to household. According to a Swedish study /5/ 10 terraced houses showed that night electrical base load varied from 100 to 1200 W, which leads to problems if an "individual house base-load" strategy is followed regarding the production of electricity.

Operation based on the individual demand of electricity (base load) often leads to smaller units, less/lower annual electricity and heat production compared to a heat controlled unit. This is especially the case if the latter is allowed to export possible surplus electricity production to the grid.

Figure 5 shows the difference in operating a micro CHP unit in electricity or heat demand control mode. The diagrams show the principle coverage of a North European house's annual heat demand for the two different strategies.

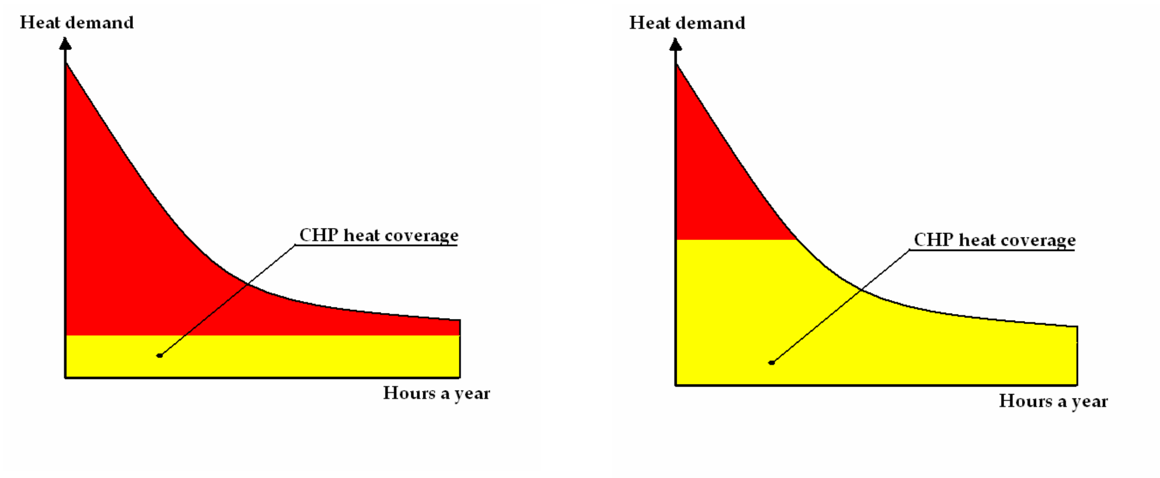

Figure 5 Annual heat coverage in an electricity demand (left) and heat demand (right) micro cogeneration/CHP operation

The influence of various operation strategies was studied at the Danish Gas Technology Center and results are shown in Table 1 and Table 2 /6/. The data shown in the tables are made for a house with an annual consumption of 5000 kWh electricity, 12000 kWh heating and some 5000 kWh for hot tap water. A micro CHP unit with an electricity-to-heat rate of 1:2 is assumed. The aim was to identify the strategies for the CHP operation, to obtain a high number of operating hours during the year and a high production of electricity and heat. Since the cogeneration unit in Table 1 is operating strictly according to the in-house electricity demand there is no export to the grid. A load following strategy will give heat surplus in some cases. A system including heat storage, see also Figure 6, is in many respects necessary for an overall high-efficiency operation.

Table 1 Electricity controlled operation strategy for a micro CHP unit in a typical Danish single-family house

	Electricity Production		**Heat production**		**Max. power CHP unit**	**Annual operation hours**	**Full load eq. hours**
	(kWh_e/yr)	**(%)[4)]**	**(kWh/yr)**	**(%)[4)]**	**(kWh_e/h)**	**(h/yr)**	**(h/yr)**
Base load 1[1)]	535	11	1070	6	0.1	8760	5350
Base load 2 [2)]	1070	21	2140	13	0.2	8760	5350
Load Following	4675	94	9350	55	5.3 [3)]	8760	880

1) Based on all time lowest 24 hours demand (=night).
2) Double up base load during daytime compared to Base load 1.
3) More peak-power is presumably needed; calculations are made on an hourly basis.
4) The micro CHP coverage of house consumption

Table 2 Operation strategy based on heat demand for a micro CHP unit in a typical Danish single-family house

	Electricity production	**Electr. export to grid**	**Electricity production in-house use**		**Heat production**		**Max. elec. output CHP unit**	**Actual operation hours**	**Full load Eq. hours**
	(kWh_e/yr)	**(kWh_e/yr)**	**(kWh_e/yr)**	**(%)[3]**	**(kWh/yr)**	**(%)[3]**	**(kWh_e/h)**	**(h/yr)**	**(h/yr)**
Base load	4545	2307 [2]	2238	45	9090	53	1.0	8760	4545
Load following	8500	5175 [2]	3325	67	17000	100	3.3 [1]	8760	2575

1) More peak-power is presumably needed; calculations are made on an hourly basis.
2) If a sophisticated predictive control/algorithm is available, some of the heat production might be moved even more to release less electricity for export.
3) The micro CHP coverage of house consumption

If an electricity demand control strategy is used, the CHP unit should be either a very small (0.1-0.2 kW_e) base-load unit or a larger unit to enable load following, thus operating part-load most of the time.

The heat demand control strategy will lead to a CHP unit with the size of 1-3 kW_e and the largest coverage of heat and power. To secure the full potential of this strategy, import/export of power to the grid should be established and heat storage should be included. In connection with EU and national initiatives for reduced energy consumption in buildings, the phrase "energy neutral houses" has been mentioned. Seen from a micro-CHP point of view, this will prevent reaching the full potential for CHP production, as some import/export of electricity will be beneficial as mentioned in connection with a heat demand operating strategy.

The influence of the electricity-to-heat ratio is shown when comparing a few international studies and field tests. In a German study /7/ the importance of electric efficiency was clarified. A Stirling engine based cogeneration plant with an electric efficiency of 9-14% over the modulating range was compared to a fuel cell plant with 25-32% electric efficiency. Both had 1 kW electric output and operated according to a heat demand strategy. Calculations of plant operation based on measured electricity and heat demand showed that the Stirling engine had shorter operating time due to more heat produced. The annual electricity production was 2500 kWh and 62% was consumed in the house. The fuel cell produced 5500 kWh electricity and slightly more than 50% was consumed in the house. The heat for the house was equally split between the fuel cell and the gas boiler.

A Belgian /8/ field test of an engine-based 5.5 kW_e cogeneration plant in a house with 12 dwellings showed that 55% of the heat demand was covered by the cogeneration plant. The CO_2 reduction was calculated to 32%.

A field test with German fuel cells /9/ showed the various performances with identical appliances. Approximately 30 fuel cells with 4 kW_e and 11.5 kW thermal energy were tested and showed that 25-70% of the electricity demand and 15-40% of the heat demand was covered by the fuel-cell unit. Up to 90% of the electricity produced was delivered to the building.

In Japan, where annual electricity and heat demand is approximately equal in the average dwelling, 6000 kWh each, continuous operation is sought in order to get a longer lifetime /10/. Development of residential fuel cells has reached almost a commercial stage and a 0.7-1 kW_e unit will cover 50-60% of the electricity demand and almost 100% of the heat demand /11/.

The examples show a great variation in characteristics and performance and this can be explained by the fact that two independent services are met in the domestic sector, a heat demand much controlled by the climate and an electricity demand often determined by the human behaviour and consumption pattern. In future housing where the heating demand is lower the need for the supplementary heat source, e.g. a gas boiler, is reduced and the importance of high electric efficiency is clear.

As mentioned earlier, a number of micro CHP units may be operated as a virtual power plant. In this case the micro CHP operation is controlled by an external electric demand and the system boundaries are expanded. It may influence the system design in order to both manage for example a heat demand operation and power demand to be covered by the virtual power plant. One example is the size of the heat storage, which will play an important role, decoupling the momentary heat demand of the house from the demand of electricity specified by the controller of the virtual power plant. The importance of the ability to control the production (and consumption) of electricity produced and delivered to the grid from a number of different production technologies and facilities rises along with the integration of more wind energy.

Technologies used

In 2006, Danish Gas Technology Center (DGC) made a survey /12/ of commercial or near-commercial mini/micro CHP products up to approximately 15 kW_e. The term near-commercial in this context means that the products are being field tested or are close to such testing.

Some 30 different products or units were found using the prime mover technology listed below:

- Reciprocating engines (often single-cylinder)
- Stirling engines (various Stirling-engine principles)
- Fuel cells
- Rankine cycle

Combustion engines are generally commercial and available in sizes from 5 kW_e with an electric full-load efficiency of 25-30%. One exception is the Ecowill unit, a 1 kW_e gas engine based cogeneration unit. Smaller units in the 1-2 kW_e range are usually based on Stirling engines or fuel cells. Stirling engines have lower electric efficiency, approximately 10-15%, which generally is lower than internal combustion engines. Fuel cells offer electric efficiencies equal to or better than combustion engines, better part load performance and lower emissions. However, there is R&D needed in the areas of Balance of Plant and lifetime. Differences between expected and measured efficiencies have been observed in field tests, see /13/. A few of the large European gas boiler manufacturers are involved in fuel cell development and integration and development of other micro cogeneration technologies. There is also a limited work on development of Rankine cycle micro cogeneration technologies with steam as working media. All technologies offer an overall efficiency of 80-90%. The fuels suitable are natural gas for all technologies, LPG, hydrogen, biogas and liquid fuels, in some cases liquid fuels from renewables. Some key performance parameters for the different technologies are summarized in Table 3.

Table 3 Current micro CHP technology overview (1-5 kW_e output range), natural gas fuelled

Technology	Electric Efficiency (%)	Total efficiency (%)	Emissions	Remarks	R&D needed?	Market introduction (year)
Engine based						
Reciprocating-engine based CHP	20-25	85-90	Some emission	Well proven technology Needs noise insulation	O/M cost reduction	On market
Stirling-engine based CHP	10-15	85-90	Less emission	Low electrical efficiency	Improved electricity-to-heat ratio	Close to initial market intro.
Fuel cells						
PEM-LT[1)]	25-35	80-90	Low emission	Needs natural gas reforming and high CO and sulphur cleaning CO<10 ppm	Cost reduction, reforming/gas cleaning, reliability improvement Balance of Plant optimisation	2010 Earlier in Japan
PEM-HT[2)]	25-35	80-90	Low emission	Need some natural gas reforming and some cleaning	Cost reduction Reliability improvement Balance of Plant optimisation	2012
SOFC[3)]	25-35	80-90	Low emission	Needs little natural gas reforming and some cleaning	Cost reduction Reliability improvement Balance of Plant optimisation	2015

[1)] PEM Fuel Cells, low temperature (operating temperature approximately 60-80 °C)
[2)] PEM Fuel Cells, high temperature (operating temperature approximately 180-200 °C)
[3)] SOFC Fuel Cells, operating temperature approximately 750-800 °C

Closest to market are the units based on reciprocating engines. A number of Stirling-engine based units are expected to reach the market in 2007/2008. No significant difference in unit price (per kW_e) can be seen between units with these two different prime movers /14/. A number of Stirling-engine based units in the interesting 1-kW_e range are under development. Cost information given concerning fuel cells are often market-based reference prices, as even cost prices for fuel cells still are much too high compared to other more mature technologies. Further development and mass production is expected to cut this price significantly. Little information is offered on operation and maintenance costs.

Fuel cells

Much effort is today put into market introduction of fuel cells including small fuel-cell based cogeneration units. Fuel cells are quiet, have a potential for high electricity production efficiency and often have more flexibility concerning the electricity-to-heat ratio than other technologies used. Fuel cells will be an excellent technology in future hydrogen distribution networks. Fuel cells and CHP units based on these are still very costly. Further development and reduced production costs concerning the fuel cells themselves are needed. This is also valid for the so-called Balance of Plant components (heat exchangers, burners, fans etc) and the inter-action between them. Figure 6 gives an idea of a possible system design.

The PEM-based type will need reforming of feedstock if used in connection with the natural gas grid. This reforming needs space, is another cost increasing component and is expected to limit the excellent dynamic performance of PEM fuel cell based cogeneration units. A hydrogen fuelled PEM fuel cell delivering DC electricity has an immediate response to electric load changes and a wider modulating range.

The SOFC-based units can be operated on natural gas with less reforming and cleaning. SOFC units operate at high temperatures (≈750 °C) and in general they need controlled heating and cooling down rates, e.g. 1-5 °C per minute. This means hours are needed for more proper heating up and cooling down. Such units should, therefore, be used for steady-state base-load operation. In a single-family house this often means quite low nominal power. This is quite a challenge with regard to production cost. Reliable operation is also a key issue as the cost of a service technician inspection for a 0.5 kW unit probably will be in the same range as the service inspection for a unit that is several times larger with respect to the electricity generation capabilities.

In Figure 6 a principle drawing showing key elements of a SOFC-based fuel cell unit can be seen. This illustrates the many components besides the fuel cell stack that go into a CHP unit and need to be optimised to achieve performance, cost and reliability targets.

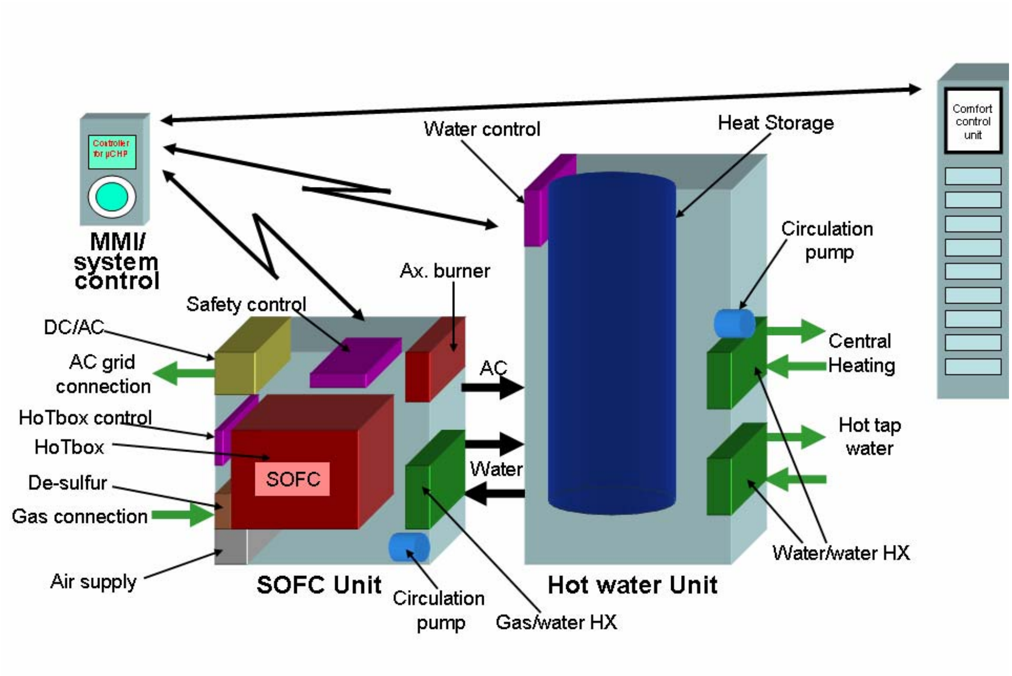

Figure 6 Schematic layout of a Solid Oxide Fuel Cell (SOFC) based micro CHP unit. Stack, balance of plant (BoP) and control system can be seen. Also, heat storage for water-side coupling to the in-house heating and hot water system is shown.

Why micro cogeneration in a country with a mature CHP market?

Cogeneration has a strong position in Denmark and approximately 50% of the power produced is from cogeneration plants. These plants range from large gas and bio-mass fuelled cogeneration units in district heating networks to smaller combustion-engine based units. The total generating capacity in the gas-engine driven cogeneration units is 1000 MW_e and similar for gas-turbine driven CHP units. The interest for even smaller cogeneration plants has focussed on fuel-cell units for residential units. Today, technology based on both low-temperature PEM and high-temperature SOFC units are developed. A strong Danish research history is one of the foundations for this development work. The fuel cells are intended for natural gas, but a hydrogen network in southern Denmark is now used for fuel-cell micro-CHP demonstration.

The micro CHP potential in Denmark has been estimated theoretically up to 2000 MW_e in individual gas and oil heated houses, respectively. The total generating capacity in the Danish electric grid, including wind power and back-up/peak-load plants, is today 12000 MW_e. The peak electricity demand is close to 6000 MW_e

Addressing the micro CHP market

Micro CHP will be used in houses, replacing or substituting normal heating boilers. No matter what technology is used inside the unit, micro CHP will be more costly than e.g. gas boilers.

The advantage is the electricity produced and the savings or profit related to this. To achieve an acceptable payback time for the unit or the extra expenses paid compared to a boiler, micro CHP units as a starting point could beneficially be sold in connection with planned boiler replacement or at the time the building is constructed/erected. The savings or profit from the electricity production should then be compared to the extra hardware and installation costs.

From a customer point of view, heating and electricity are nowadays mostly regarded as a commodity. This means that a personal involvement in restarting, servicing and any other activities related to the unit cannot be expected from customers. Reliability in heating and electricity supply should at least be at the same level as for traditional heating systems, which in most countries means a high reliability and fast response time if problems occur.

To achieve the above goals, addressing and keeping micro CHP units in the market should be undertaken by larger professional energy and service companies/providers. Installation, servicing etc. is obviously a target for energy service providers or energy suppliers as ESCO business (Energy Service COmpanies). Units can be bought in large quantities that ensure low price and uniform installation methods and service tools can be provided. Such companies are better at providing practical or administrative business with regard to oil, gas and electricity connection. Service contracts can often be handled, possibly with guaranteed response time.

Energy utilities such as gas suppliers may have a special interest in micro CHP implementation in the domestic sector since new houses (or renovated ones) typically use less gas than previously. In Denmark, the latest building standards lead to annual gross fuel input for heating and hot water supply of less than 1000 m^3 of natural gas, for low-energy houses as low as 500 m^3 in new single-family houses. Micro CHP will increase gas consumption and improve payback on the connection costs for domestic customers. In Germany and the UK examples of gas utility involvement are seen /15/.

If a mini or micro CHP unit is a part of a virtual power plant an electric utility has an interest in the operation as previously described in the section “Virtual power plant”. It is obvious that a large-scale use of micro CHP makes it possible for a number of new business opportunities for both utilities and other companies.

A comparison of the total costs from /14/ and manufacturers' unit prices reveals that installation of such units often will cost as much as the unit itself. To address this market with a large number of units, it is important to avoid individual solutions to install the units to the actual heating system etc. One solution may be a kind of standardised coupling box between the CHP unit, heat storage and heating system. Some vendors of engine-based systems already use such a component.

Successful implementation will depend on:

- Low cost (unit cost, installation and O/M costs)
- Low noise
- Low space requirements (should fit in standard furniture module space requirements)
- Reliability (high quality, fast service response business model)
- Easy operation for the customer/host (ESCO business models)
- Easy grid access/connection; no legal and administrative barriers

Conclusions

There are promising and emerging technologies for domestic micro cogeneration applications. A large market potential can be identified with considerable fuel savings and CO_2 reduction. Gaseous fuels are preferred and one may use natural gas or biogas and hydrogen in the future.

Calculations show, that an electric output of 0.1-0.2 kW_e is suitable for continuous base load in North European single-family houses. Larger units producing some 1-3 kW_e are suitable when the operation is controlled by the heat demand. The entire energy demand of the buildings will generally not be covered by micro cogeneration. Depending on cogeneration technology and demand pattern it is realistic to expect that roughly 20-70% of the electricity demand and 50-100% of the heat demand is covered. Combustion engines and Stirling engines are close to a commercial stage while the more efficient and cleaner fuel cells need considerable cost reductions and enhanced lifetime documentation.

Micro cogeneration may be a future business opportunity for companies offering energy services. At the same time, this may give advantages regarding uniform and reliable installation procedures and make the introduction and public acceptance easier.

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