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RESIDENTIAL GAS UTILISATION

THE CURRENT TECHNICAL STATUS OF MCHP AND ITS FUTURE APPLICATION VARIETY

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ABSTRACT:

Decentralised energy production by mCHP is becoming increasing important. mCHP is a key technology for future gas appliances and can complement natural gas by playing a role in the future energy scenarios by

- fulfilling the German government’s efficiency targets
- putting into action a stabilising factor for future electricity grids
- helping to generate lasting customer relationships by offering new energy services

This paper gives an overview of mCHP technology and outlines the field test activities, results and experience gained from the “mCHP user group” and “Callux”, where in total over 350 units, fuel cells and engine driven mCHP's are tested by E.ON Ruhrgas.

The first results from five heat demand driven Stirling mCHP units in terms of their potential for own power usage substitution are analysed, and the potential for electricity demand controlled mCHP's is rated in terms of energy balancing and economic benefits.

These results will form the basis for a discussion of future applications for mCHP in Germany and for ranking them in terms of technical feasibility and economical viability.

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1. Definition of mCHP

a. Underlying technology

mCHP technologies currently under development or just released are Stirling engines, ICE`s and fuel cells with the latter presumably not reaching marketability in Germany before 2015.
Differences between the technologies can be summed up as follows:

- Stirling engines have low maintenance costs and total efficiencies comparable with condensing boilers, however electrical efficiencies today reach a maximum of 15%.
- ICE’s are higher maintenance products with currently overall efficiencies of non condensing boilers but electrical efficiencies of up to 25%.
- Fuel cells have the potential for high electrical efficiencies of up to 60% with moderate thermal efficiencies, but are currently not robust or cost efficient enough to be placed on the German market.

b. Manufacturers involved in development and production

Currently all major heat appliance manufacturers are involved in the development and production of mCHP units although only four different engine types are used for system integration by the seven manufacturers. Engine types and corresponding system manufacturers are presented in Figure 1.

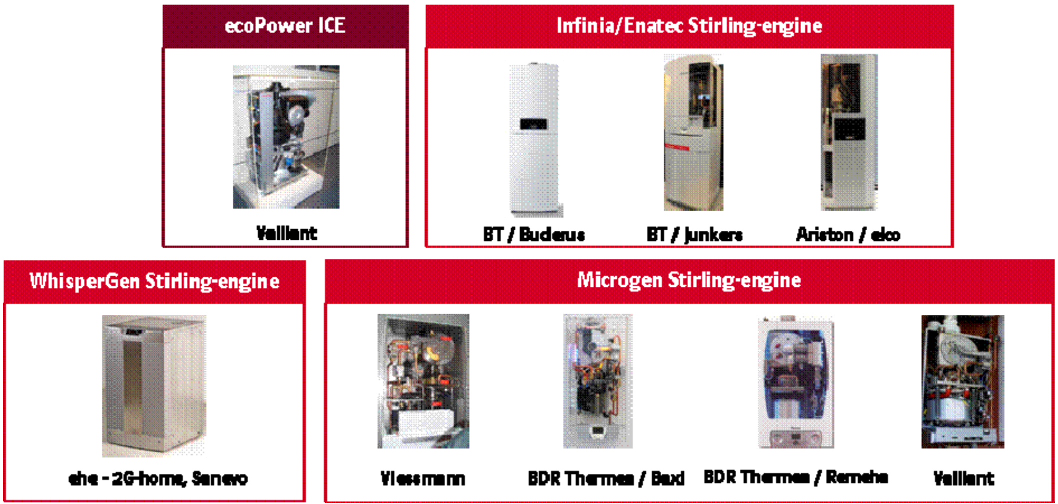


Figure 1: Core technology and system integrators

Remeha, one German brand of the BDR Thermea group, released its Stirling engine based mCHP in September 2010 and the WhisperGen Stirling was also released by eHe in 2010. A number of other manufacturers can be expected to launch their products after the International Sanitary and Heating fair (ISH) in 2011.

This variety of different units and dedication of sound manufacturers are a vital basis for a new technology that on the one hand can be the successor technology to condensing boilers and on the other help meet the CO_2 targets set by the German government.

c. Engine sizes and potential house types

CHP units are not strictly classified in different power output sizes; E.ON Ruhrgas has decided to differentiate micro-CHP from mini-CHP at a power level of 3kW, however the units under test in the field tests all have an electric output of maximum 1kW.
This power output allows a reasonable runtime for CHP systems in older housing stocks with gas consumptions from 15-40MWh, as typical thermal engine outputs are between 2.5kW and 7kW.

d. Economic situation in Germany compared to NL and UK

Although the ‘Impuls Programm’ came to an end last year and its subsidy of EUR 1.550 per kilowatt installed electrical power up to a limit of 4kW ceased, there still is an incentive scheme in Germany. The different types of subsidy are listed below.

EEX Baseload price*	**~2,5-7**	**ct/kWh**
Energy tax refund**	**0,55**	**ct/kWh**
Avoided grid use***	**~0,8**	**ct/kWh**
CHP law bonus****	**5,11**	**ct/kWh**
for every sold kWh electrical power** ** for the gas used in the chp process*** ****** for the electrical power sold*** ******* for every produced kWh electrical power***		

Table1: Economic basis for mCHP`s in Germany.

The current German funding system makes power demand coverage twice as economically viable as selling power to the grid.

Different subsidy schemes operate in Britain and the Netherlands.
The Netherlands compensates every produced kilowatt hour up to a certain limit with the buy-in price for end customers. In the UK the price for sold electricity is almost as high as the buy-in price.

The optimisation of meeting one's own power demand (which we discuss later on) is therefore particularly interesting for German mCHP operators. The Netherlands and UK need different strategies to optimise mCHP’s economic performance.

2. Germany’s largest field tests

a. Reason for and aim of the project

The two field tests “Callux” and “mCHP user group”, in which a total of over 350 fuel cells and engine driven mCHP`s are being tested by E.ON Ruhrgas, have three different phases:

1. Every prototype is tested in the E.ON Ruhrgas lab according to mCHP standards to gain an understanding of its steady state performance and to make it comparable with other mCHP products.
2. A handful of units from each prototype generation is tested in the field under actual conditions and with extensive measurement equipment. Here storage losses and CO_2 savings can be analysed as well as their runtime and performance ratio.
3. In the third phase more systems of the next generation are tested and monitored mainly with smart meters. This phase is seen mainly as a market stimulation exercise that allows local utilities who are members of the mCHP user group for example to evaluate future business cases such as contracting.

The major reasons for the projects can be classified as follows:

- Demonstrate technical maturity, support further development to ensure marketable products
- Develop supply chains by winning binding orders for large numbers
- Enhance public awareness of fuel cells
- Support education/training of market partners
- Validate demands of customers and the market
- Promote the creation of added value in Germany

b. Heat demand driven systems and their potential for own power usage substitution

This work discusses the potential that is currently being exploited by heat-demand-controlled mCHP's in terms of covering their own power demand, and points up the maximum potential which power-demand-controlled mCHP's can theoretically achieve to cover their own power demand. We consider the addressable potential as being an amount of power of less than 1 kW drawn by a home, but not more than the amount of power which is fed in by the mCHP, as any generated amount of electricity above this cannot yet be achieved owing to the heat cap of the mCHP's runtime. In practice it will prove difficult to realise the total theoretical potential because the runtimes of the mCHP's would either have to be divided up, so minimising efficiency, or there are still some periods with outputs between 0 and <1000 Watt in areas with a more consistent power requirement.

As most of the systems were installed after the heating period 2009/2010, currently only a few full year load and production curves exist.

Most of the appliances currently being trialled are installed with combi storage tanks of around 750l capacity. These large tanks make it possible to address thermal output peaks greater than 2.5 to 7 kW which the engines can deliver, depending on the technology, thereby optimising the mCHP runtime and minimising the backup burner runtime.
They also provide a window for covering own power demand of the house owner, as the combi tanks permit decoupling from the direct hot water and heating water demand and the mCHP can address the optimum period of time for covering own power requirement of the house owner so long as the tank covers demand.

The key data of homes in which the mCHP's discussed here are running are presented in Table 2. All homes are existing structures - in the year prior to the installation of the mCHP's they consumed between 20,000 and 48,000kWh of gas and between 3,500 and 12,500 kWh of electricity.

Table 2: Key data of the homes

Key data of the houses	unit	mCHP_1	mCHP_2	mCHP_3	mCHP_4	mCHP_5	Ø
year of construction		1985	1997	1990	1971	1995	1988
gas consumption	**kWh/a**	38000	20000	25000	48000	22000	30600
electricity consumption	**kWh/a**	12500	3500	3500	10600	3500	6720
number of occupants		3	4	5	9	3	5

Figures 2 to 5 show operating modes of Stirling engines for summer, autumn and winter heating and hot water loads. These operating modes correspond to the columns of winter, summer or autumn operation in Table 3, i.e. they represent the operation of one of the 5 mCHP's on one day.

The red curve represents the home's electricity demand, the black line is the mCHP's generation curve. The power that has to be drawn from the grid is the difference between the two curves when the red curve shows the greater amount. If the demand amount (red) is below the CHP output (black), electricity is fed into the grid.

The fluctuations in the power output of the mCHP's shown in Figures 2, 3 and 5 are due to the resolution of the electricity meter and not to any modulating operation of the systems.

Figures 2-5 show an example for operating modes of Stirling mCHP's. Because of the significant differences in demand profiles in terms of the amplitude and distribution of thermal and electrical loads over the day, mCHP's in other properties can return very different generation profiles.

With the load and generation curve shown in Figure 2, the mCHP is only run for a short while in the evening. A substantial portion of energy with a rating of less than 1kW cannot be addressed because of heat capped operation of the mCHP. The peak power demand during the morning (around 4 a.m.) is also not minimised by the heat-demand-controlled type of operation.

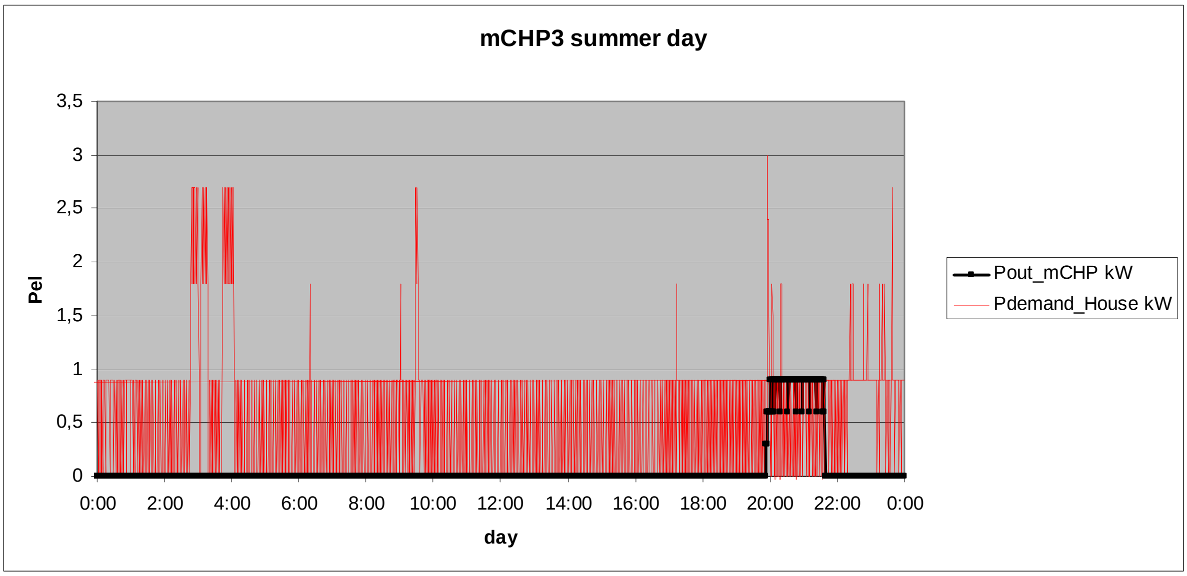


Figure 2: Electricity demand and mCHP performance in 1 min resolution for a single day – example of a summer day with short evening runtime

In the second example, the mCHP is again run in the evening this time in autumn; as well as a demand for hot water which occurs in autumn as it does on summer days, the reason for this may be to heat the home before the night setback. Here again, the mCHP can only make up for a small amount of the power with a rating of under 1kW. Because of the simultaneity of power and heat demand however, a power peak is minimised in the transitional period in this case (balance of 20.30 to 22.30 red minus black).

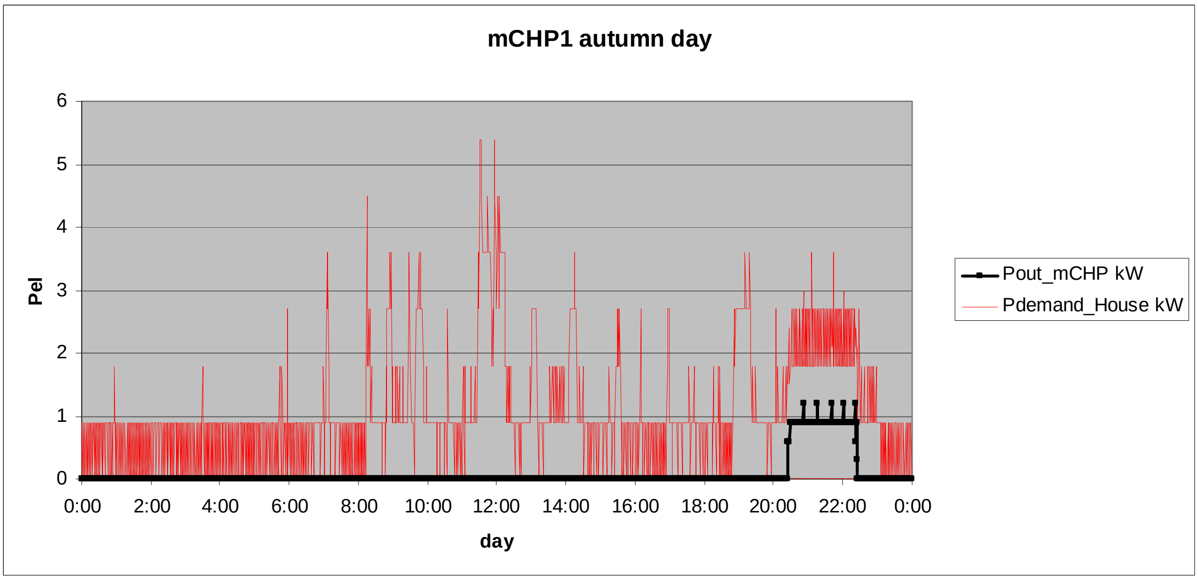


Figure 3: Electricity demand and mCHP performance in 1 min resolution for a single day – example of an autumn day with peak load limitation

Another autumn example (Figure 4) shows two mCHP runtimes of approx. 1.5 hours each, here however there is no complete simultaneity of high electricity and heating demand in the evening, so part of the energy has to be fed into the grid. As mentioned above, customers' specific thermal load profiles can still have an arbitrarily positive or negative effect on the operation of mCHP's in terms of customer own power demand coverage.

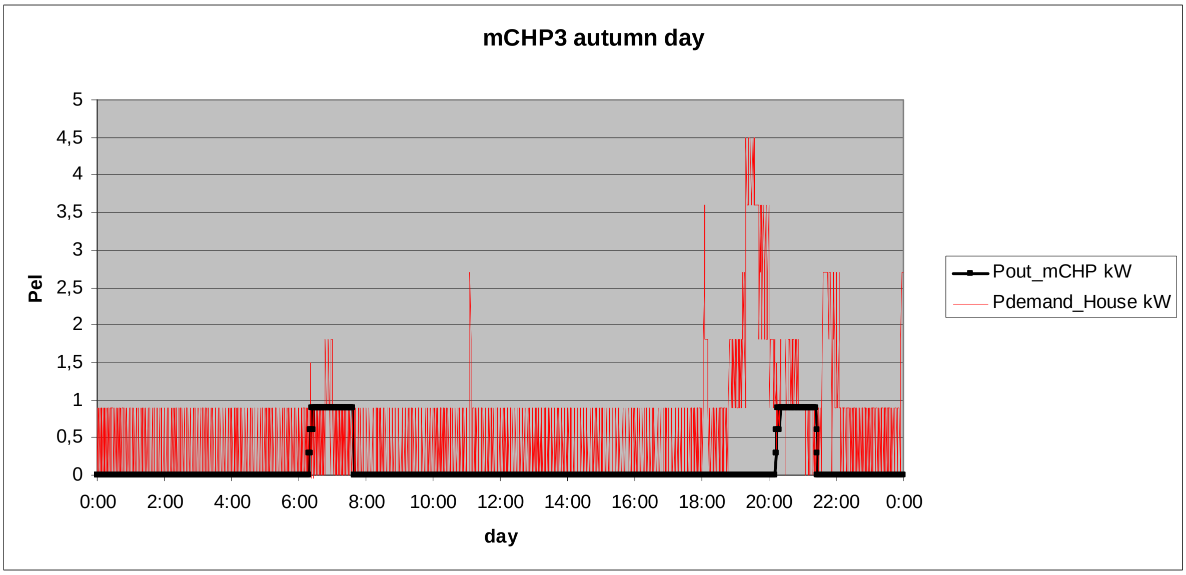


Fig.4: Electricity demand and mCHP performance in 1 min resolution for a single day – example of an autumn day with peak load limitation

The final example (Figure 5) shows the operation of the mCHP in winter – a long runtime by day and in the evening accounts for much of the power below 1kW, with just a small amount of energy being returned to the grid. With high heating demands therefore, even with purely heating-demand-controlled systems the unit's own power demand can be broadly covered.

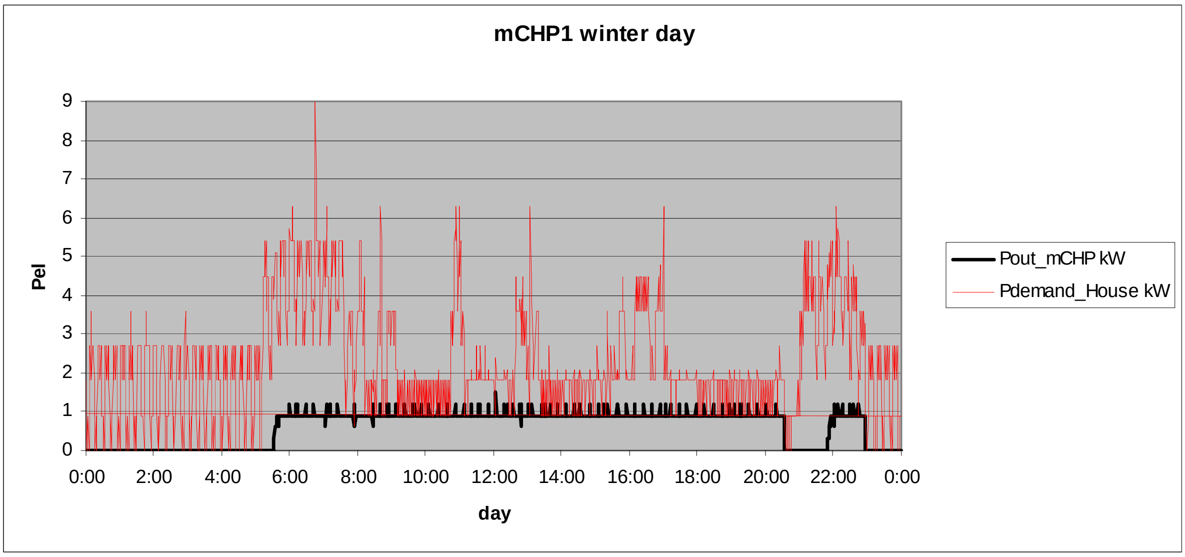


Figure 5: Electricity demand and mCHP performance in 1 min resolution for a single day – example of a winter day with long runtime hours during daytime

Table 3: Overview of house balance key data and performance criteria of the unit

winter day	unit	mCHP_1	mCHP_2	mCHP_3	mCHP_4	mCHP_5	Ø
W_{out}_mCHP	kWh/d	14,82	10,25	12,05	10,94	13,97	12,41
W_{demand}_house	kWh/d	55,20	15,05	13,67	21,50	18,56	24,80
W_{demand}_house_P<1kW	kWh/d	21,36	13,15	10,56	12,66	6,71	12,89
W_{demand}_house_P>1kW	kWh/d	33,85	1,90	3,11	8,84	11,86	11,91
$W_{used_inhouse}$_mCHP	kWh/d	14,82	7,62	5,93	8,70	3,76	8,17
own usage performance ratio*	%	100%	74%	49%	80%	27%	66%
addressable_power_led_smart_potential**	%	0%	100%	76%	100%	29%	100%

summer day	unit	mCHP_1	mCHP_2	mCHP_3	mCHP_4	mCHP_5	Ø
W_{out}_mCHP	kWh/d	1,23	6,27	1,48	3,64	1,27	2,78
W_{demand}_house	kWh/d	30,72	9,43	11,37	17,82	6,85	15,24
W_{demand}_house_P<1kW	kWh/d	18,92	7,60	9,93	12,17	5,22	10,77
W_{demand}_house_P>1kW	kWh/d	11,80	1,83	1,44	5,65	1,64	4,47
$W_{used_inhouse}$_mCHP	kWh/d	1,23	0,57	0,82	3,16	0,08	1,17
own usage performance ratio*	%	100%	9%	55%	87%	6%	42%
addressable_power_led_smart_potential**	%	0%	100%	100%	100%	100%	100%

autumn day	unit	mCHP_1	mCHP_2	mCHP_3	mCHP_4	mCHP_5	Ø
W_{out}_mCHP	kWh/d	1,81	1,87	2,22	5,22	4,33	3,09
W_{demand}_house	kWh/d	25,96	7,73	12,64	15,76	8,57	14,13
W_{demand}_house_P<1kW	kWh/d	17,31	7,35	9,29	10,05	5,18	9,83
W_{demand}_house_P>1kW	kWh/d	8,65	0,38	3,35	5,71	3,40	4,30
$W_{used_inhouse}$_mCHP	kWh/d	1,81	1,16	1,57	3,40	0,17	1,62
own usage performance ratio*	%	100%	62%	71%	65%	4%	52%
addressable_power_led_smart_potential**	%	0%	100%	100%	100%	100%	100%

Ø day (2 x autumn, 1 x summer, 1x winter)	unit	mCHP_1	mCHP_2	mCHP_3	mCHP_4	mCHP_5	Ø
W_{out}_mCHP	kWh/d	4,92	5,06	4,49	6,25	5,98	5,34
W_{demand}_house	kWh/d	34,46	9,99	12,58	17,71	10,64	17,07
W_{demand}_house_P<1kW	kWh/d	18,72	8,86	9,77	11,23	5,57	10,83
W_{demand}_house_P>1kW	kWh/d	15,74	1,12	2,81	6,48	5,07	6,24
$W_{used_inhouse}$_mCHP	kWh/d	4,92	2,63	2,47	4,66	1,04	3,14
own usage performance ratio*	%	100%	52%	55%	75%	17%	59%
addressable_power_led_smart_potential**	%	0%	100%	100%	100%	92%	100%

* How much of the produced energy is used in-house

** How much of the energy produced can be used in-house for energy demand below 1kW by shifting (not extending) runtime?

Table 3 shows the results of all 5 systems for 3 reference days representing the different operating modes of the mCHP owing to the different heat demand requirements during one year. In the fourth section the mean values for an average 'day of the year' are calculated - the autumn day is as transition day used as the spring day as well.

The table gives the production of the mCHP's, the home's demand per day, the amount of the home's demand that is less than 1kW, demand above 1kW, the amount of power generated by the mCHP that stays in the home, and two factors. The first factor describes the percentage of the generated electricity that stays in the home, and the second factor describes whether the fed-in energy could have stayed in the home if the runtime was shifted, i.e. whether the amount of power less than 1kW drawn from the grid is greater than or equal to the amount fed into the grid by the mCHP with its technical output limit of 1kW.

Figures 6 and 7 give examples for the second factor. They illustrate the home's average power demand and power produced by an mCHP for one day (see Ø key figures for the Ø day in column 8 in table 3).
The first figure shows that the power demand (17.0kWh) is on average higher than the maximum production capacity of the mCHP (5.3kWh) but also that the amount of electricity needed below a power level of 1kW (7.7kWh) exceeds the electricity which the mCHP feeds into the grid (2.2kWh), and therefore 100% own power usage of the mCHP-generated electricity would be possible without any demand side management.

The 100% in-house usage of the mCHP power is shown in Figure 7. Here the 2.2kWh that had to be sold in the former scenario could now be used in-house.

Looking at the balances in Figure 6 and 7 from an economic standpoint, the difference can be calculated as follows.

Substituted energy has an amount of:

$$2{,}2kWh \bullet \left(23cent^{1} + 5{,}11cent^{2}\right) = 61{,}84cent$$

Unsold energy, because it is retained in the home, has a value of:

$$2{,}2kWh \bullet \left(5{,}185cent^{3} + 5{,}11cent^{2} + 0{,}8cent^{4}\right) = 24{,}41cent$$

[1] Average electricity buy-in price
[2] CHP bonus according to CHP law
[3] EEX baseload price for Q1 2011
[4] Payback for avoided network usage

The difference summed up for 365 days of a year results in

$$(0{,}6184€ - 0{,}2441€) * 365 = 136{,}62€$$

as a financial opportunity when running the mCHP in perfect balance with the electricity demand of the home but without any load shifting in the home.

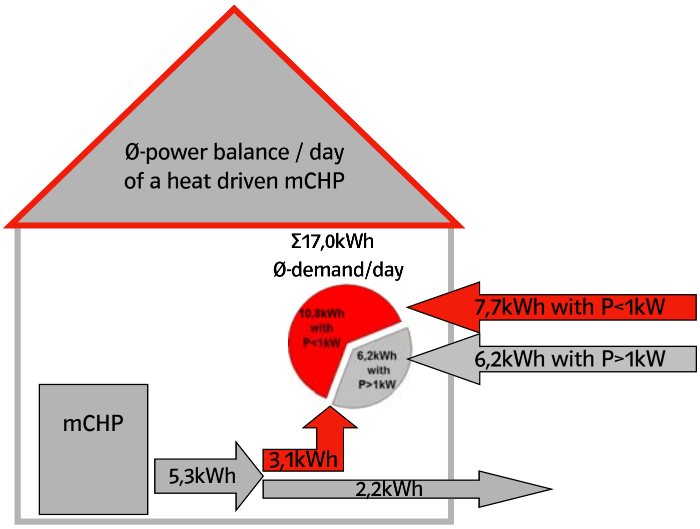


Figure 6: Power demand and power production of a heat demand driven system as a single day balance.

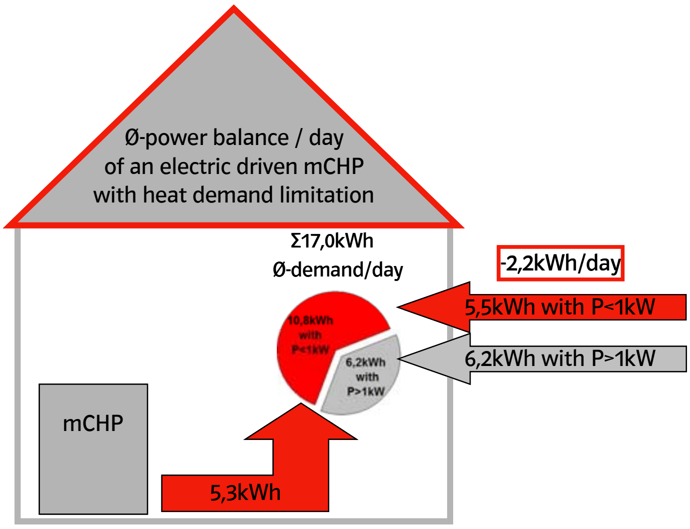


Figure 7: Power demand and power production of an electricity-demand-controlled / heat-limited system as a single day balance.

If it is now considered that the spread of the different mCHP's in the different seasons in Table 3, we obtain 'own usage performance ratios' of between 27% and 100% for winter, 6% to 100% for summer and 4% to 100% for autumn.

The seasonal averages are 66% in winter, 42% in summer and 52% in autumn. This means that more than half of the generated electricity stays in the home on average. Nevertheless we can see that as the mCHP runtime decreases during the summer and transition periods, the likelihood of the unit covering its own power demand falls or – put the other way – in the winter months the demand for electricity rises overall and so in winter the likelihood of an own-power-demand coverage rises as a result of increased electricity demand and longer runtimes.

If the 'addressable power led smart potential' factor, is considered it can be seen that with some exceptions, in the winter the required amount of electrical energy with a rating of less than 1kW is in total always greater than the energy fed into the grid by the mCHP with a rating of less than 1kW. By shifting the runtime therefore, all of this potential could be addressed without the need for load management measures. A monetary analysis of this potential produces the following distribution:

Table 4: Financial potential of the Ø-day for electricity demand controlled systems

monetary theoretical maximum for the Ø day (2 x autumn, 1 x summer, 1x winter)	**unit**	**mCHP_1**	**mCHP_2**	**mCHP_3**	**mCHP_4**	**mCHP_5**	**Ø**
electricity sales and import avoidance for a heat driven system *	**€**	504	368	335	543	307	412
electricity sales and import avoidance for an electric driven (heat demand limited) system *	**€**	504	520	461	642	588	548
Delta	**€**	0	151	125	99	281	136

*in both cases the higher demand for gas and therefore higher gas process have to be considered when examining the total cost, however the focus in this case is on the delta between the two operating modes and therefore gas costs can be ignored.

mCHP1 currently already uses 100% of the generated power in the home, so no additional income can be generated here by moving the runtime. The other properties however could generate between EUR 98 and EUR 280 in addition to their existing earnings from electricity sales and power substitution. The different potentials are a result of the different totals of electricity generation and the amounts of electricity that stay in-house because of the heat-demand-controlled operation; mCHP4 for example has high levels of own-power-demand coverage even during heat-demand-controlled operation, whereas mCHP5 has moderate 'own usage performance ratios' and so still offers great potential.

c. Strategic value for future applications

The above examples of mCHP's and a calculation of the maximum theoretical potential for own-power-demand coverage were used in order to highlight the most economical basis for mCHP operation at the present time. In future there may be other modes of operation which for short periods of time can replace electricity-controlled and heat-demand-capped operation so as to generate additional revenue.

One added advantage of the electricity-controlled and heat-demand-capped operation presented here is its restricted to optimisation within the balance boundaries of the home. There is no need for external communication to request sundry other factors such as electricity prices or trading floors. By predicting load profiles and implementing these control algorithms in existing mCHP heating control system therefore, it should be possible to exploit this theoretical potential in the short term, in part at least.

Other operating modes as referred to above shall now be considered which are assisted by external communication and which can achieve additional revenue in the short term.

3. Future applications beyond heat-led operation
-Supporting functions for renewable energy based grids

Priority is given to the renewable energies being fed into the grid. This can lead to peak prices on energy trading floors and technical off-limit conditions at different voltage levels.
In times of high wind energy being fed into the medium and high voltage level grids and low load connected to the grid, there can be negative electricity prices on electricity trading floors.
In times of high photovoltaic energy and therefore high photovoltaic output, there can be voltage rises in the low voltage grid.

a. Global and local grid optimisation

Smart meters have smoothed the way for cheap in-home communication, reviving the debate about virtual power plants. If mCHP enters the market within the next few years, there is a likely potential for some thousand units to be installed every year. These megawatts can build a basis for balancing wind energy production as they can respond very flexibly to renewable power fluctuations because of their cascading configuration. Virtual power plant and smart grid scenarios are currently being discussed and possible foundations for future standards are being created.

Smaller solutions for optimising local individual low voltage grids might also be a possible application. High photovoltaic output at the end of single feeders can increase the voltage level. High photovoltaic output therefore increases the need to replace transformers as more power is produced in the distribution network than needs to be transformed into it. Systems consisting of storage facilities, electric heating elements and an mCHP can convert the few kilowatt-hours of photovoltaic electricity into renewable heat that would otherwise require an extension of the low voltage grid.
It remains to be assessed how far grid optimising measures can be economically more attractive than expanding the grid, and how far this affects earnings from own-power-usage optimisation discussed above.

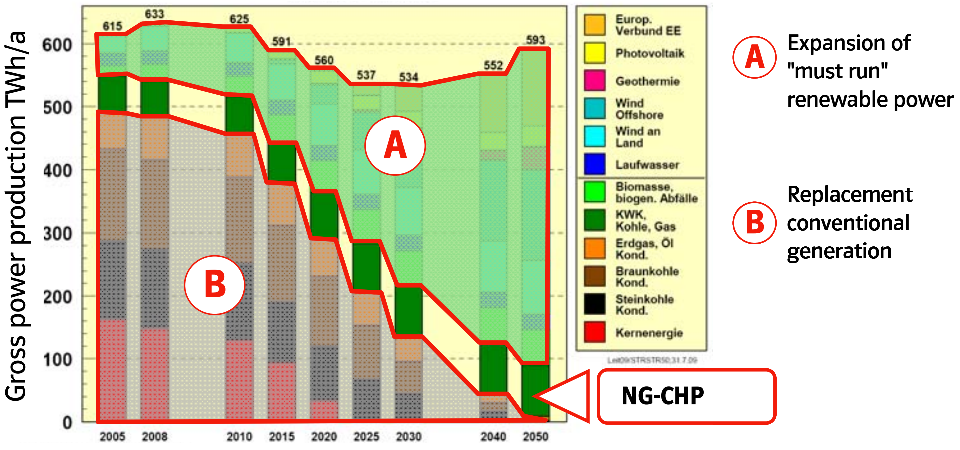
c. Potential balancing power

Any discussion of virtual power plants with an output of more than 15MW must include a consideration of balancing power. There are different response times and also positive and negative balancing power can be offered for regulating energy trading. mCHP's can react to such requirements within a few minutes, so offering, say, negative balancing power as a further application that needs to react for only small amounts of time within one year can generate additional financial benefits for the mCHP system beside its own-power-usage optimisation.

4. mCHP's role in future energy scenarios

a. Benchmark setting for primary energy and CO_2 savings

mCHP's can bring significant CO_2 and PE savings when installed appropriately in a home with a sufficient heat demand. These savings are presently calculated using heat produced by condensing boilers and electricity produced by the power plant mix as a benchmark.
As more and more renewable energy is fed into the grid, the specific CO_2 content of the power mix decreases and so the CO_2 savings of gas driven appliances fall as well. However, taking into account chapter 3 where we said that renewable energy takes priority when being fed into the grid, CHP systems do not compete against the mix but only against the residual generation systems with higher specific CO_2 contents as shown in Figure 8. Consequently mCHP as a flexible generation source can support the decarbonisation of the grid up to 2050.



Source: BMU Leitstudie 2009

Figure 8: NG-CHP long term climate protection up to 2050

b. Natural biomethane and renewable hydrogen

Although climate protection is feasible up to 2050, the specific CO_2 content of natural gas is not fixed. Biomethane produced in biogas plants from new sources like waste materials or wood, and biomethane and hydrogen produced by the electrolysis of peak wind electricity production, can decrease the content. E.ON Ruhrgas is currently involved in a number of research projects, specifically in the field of renewable hydrogen production.

The range of applications for mCHP and the potential for residual generation replacement, along with the potential to be operated with biomethane from new biogenic sources such as wood or renewable wind electrolysis, offer a long-term outlook for mCHP in the current prospect for an energy scenario. The use of own-power-demand coverage also provides an important basis for economically viable operation and load rejection of the low power voltage grids.

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Table 2: Key data of the homes

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Figure 6: Power demand and power production of a heat-demand-driven system as a 1 day balance.

Figure 7: Power demand and power production of an electricity-demand-controlled / heat-limited system as a 1 day balance.

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