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Field test with Stirling engine micro-combined heat and power units in residential buildings

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Abstract
The Institute for Energy Economy and Application Technology (IfE), together with the Energie Südbayern (ESB), the local gas supplier in southern Bavaria, are responsible for a field measurement campaign of four gas fired Stirling engine micro-combined heat and power units. These units and the measurement equipment were installed in four different single family houses at the end of 2009. After monitoring over 1 year, it can be said that the Stirling engine micro-combined heat and power units are capable in supplying small residential buildings with thermal and electric power. The data evaluation shows the micro-combined heat and power-units work with a steady-state efficiency above 90%. The main goals of this field test, besides the verification of the Stirling engine's efficiency, are an analysis of the complete system's overall energy performance. Therefore, a detailed examination of not only the heat-consuming devices, space heating and the domestic hot water system, but also the examination of heat-generating devices, the Stirling engine and the auxiliary burner were made. The implementation of heat demand curves helps to assess not only the steady state, but also the yearly performances of each micro-combined heat and power units. For a future integration of micro-combined heat and power units into a smart grid, they have to be predictable. Hence, a detailed analysis was taken onto the electricity generation curves at different ambient temperatures and its hourly behaviour. Lastly, for the economic evaluation, the onsite consumption characteristics were considered in depth.

Keywords
Micro-combined heat and power, Stirling engine, decentalized generation, storage, efficiency, onsite consumption, single family house

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Introduction and motivation

Combined heat and power (CHP) plants contribute to low carbon emissions and high energy efficiency in heating systems. For residential buildings, small-scale CHP-units have become more and more popular. A total of 30,000 mini-CHP units ($5\,kW_{el}$), powered by internal combustion engines (ICEs) have been installed in Germany in the last years. However, for single family houses (SFH), common $5\,kW_{el}$ ICEs are oversized and not economic. Consequently, smaller Stirling engine (SE) micro-CHP units were developed and distributed to several households in field tests.

The energetic and economic performance of a micro-CHP system depends on several factors. Within the field test, the most important ones are the runtime of the CHP system, the thermal coverage, the electric power generation and the quantity of electric onsite generation.

Description of the buildings

The field test is located within the gas net area of the ESB in following towns: Pfaffenhofen (PFA), Hohenlinden (HOH), Bruckmühl (BRU) and Oberau (OBE). All these towns are located close to Munich. Figure 1 shows the average temperatures of the locations.

As mentioned above, SE micro-CHP units are suitable for SFHs. However, to ensure high runtimes, buildings with low insulation resistances and net dwelling spaces ranging from 150 to $210\,m^2$ were chosen. The former average energy consumption was declared approximately 30,000 kWh/y natural gas and 5000 kWh electric energy per year.

For electricity generation all over the year, the domestic hot water (DHW) is centrally generated and distributed with a circulation system. At least four occupants live in each building, to ensure summer runtime.

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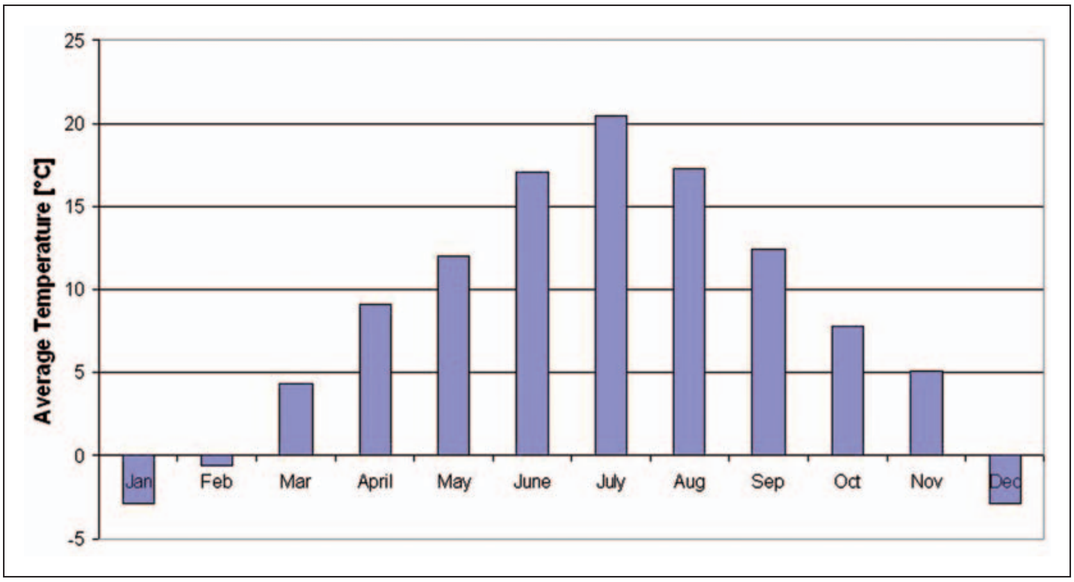

Figure 1. Average temperature in southern Germany.

Description of the SE system

SE micro-CHP system

Compared to the ICEs, SEs use an external combustion, leading to lower maintenance costs and different applicable fuels (wood pellets, solar radiation). On the other hand, the electric output and the CHP coefficient are higher for ICEs.

However, small residential buildings have a low base load demand of electric power. Consequently, the SE disadvantages are mitigated when SE micro-CHP units are used in SFH or other buildings with low electric base load.

Stirling engine

For this field test, a SE unit is applied. It is composed of a SE (rated electric power: 1 kW; rated thermal power: 5 kW) with a free piston, a linear generator and an auxiliary burner (rated power: 18 kW) within the CHP system for thermal peaks. The unit's size (910 mm × 490 mm × 471 mm), weight (around 110 kg) and the installation process is similar to a conventional condensing boiler.[1]

Field test setup

Hydraulic installation schemes

In the field test, two different tank systems are evaluated. The upper part of Figure 2 shows the installation of a combined heat buffer (CHB), as it is often used in Mini-CHP (5 kW_{el}) applications. The aim is to increase the CHP runtime when the heat demand is low and to provide additional thermal power when the heat consumption is higher than the CHP thermal output.

Here, the micro-CHP unit is directly connected to the buffer, whereas the space heating system is independent of the CHP unit. The DHW is heated in a heat exchanger coil within the buffer. The volume of the buffers, which are installed in Pfaffenhofen and Bruckmühl, is 750 L. In Hohenlinden and Oberau, conventional hot water tanks (HWT) with a volume of 200 L are used (lower part of Figure 2). The tank is heated with a heat exchanger. The advantage of this implementation is the easy adaption of a micro-CHP system to a conventional system, because no pipes have to be changed.[2]

Data acquisition

In the field test, all necessary energy flows are detected. Energy input (natural gas[a] and electricity) and output (thermal and electric) of the micro-CHP unit, as well as the thermal energy consumption (space heating, DHW and circulation losses) are metered. Figure 2, shows the position of the measurement devices.

For the measurement of the micro-CHP output power, it has to be noted that only the value of the net electrical output is received. The gross power, including the power consumption of the CHP pump, the blower and the control cannot be detected with the data acquisition. However, gross electric values can be found on the CHP-unit's display.

The data is recorded every second, while the system can be observed and remotely controlled via the internet.

[a]Within this article, the lower heating value (LHV) is used when natural gas energies are regarded.

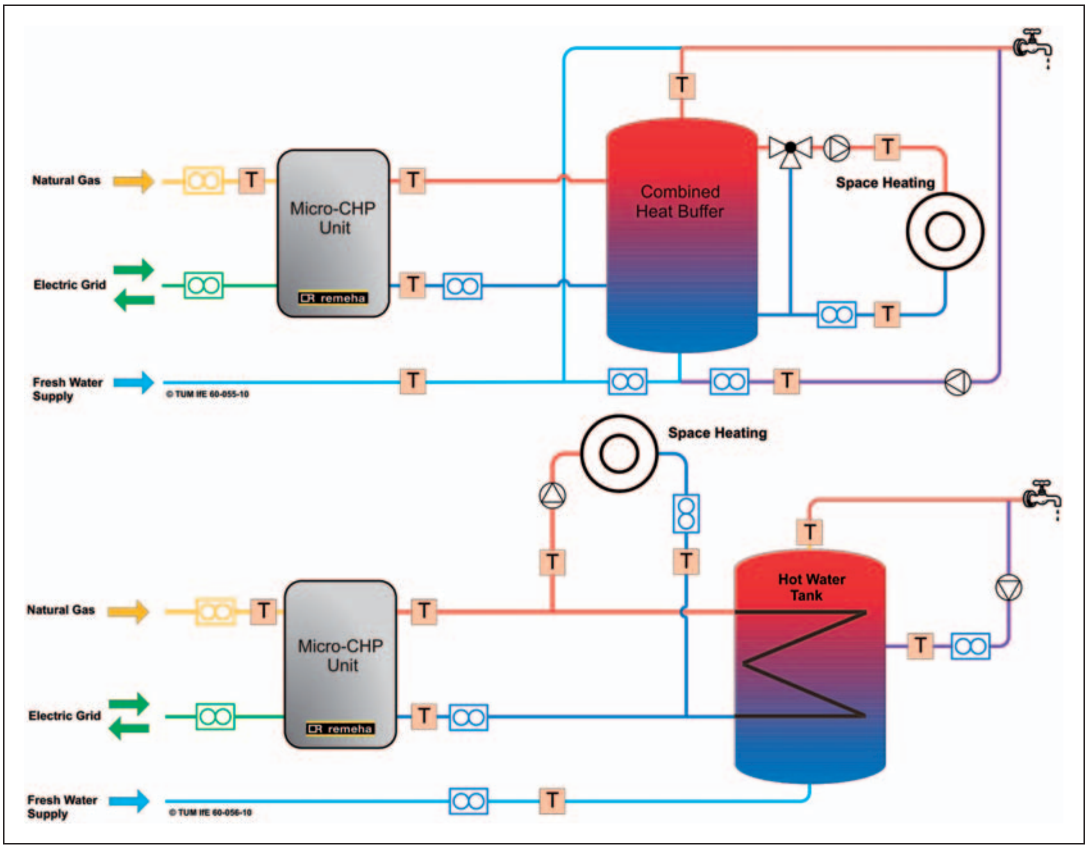

Figure 2. Hydraulic schemes.
Micro-CHP: micro-combined heat and power.

Table 1. Read meter year values.

	PFA[a]	BRU	HOH[b]	OBE
Heat storage	CHB	CHB	HWT	HWT
Natural gas (m^3)	3074	3081	2934	3981
Runtime (h)	2116	4149	2888	5118
Runtime (%)	32.2	47.4	35.1	58.4
Gross/Net electric generation (kWh)	1624/1432	3377/2922	2705/2303	3903/3465

[a]SE not in operation: 1 Jan10 – 30 Mar 10.
[b]SE not in operation: 18 Oct 10 – 9 Dec 10.
PFA: Pfaffenhofen; BRU: Bruckmühl; HOH: Hohenlinden; OBE: Oberau; CHB: combined heat buffer; HWT: hot water tanks.

General performance

Table 1 shows the values of the four SE micro-CHP units for the year 2010. First, it has to be mentioned that the units in Pfaffenhofen and Hohenlinden were not in operation between 1 January and 30 March (PFA) and 18 October and 9 December (HOH). Consequently, the values for the natural gas consumption, runtime and electric generation are lower compared to Bruckmühl and Oberau.

The numbers shown in Table 1 are read values from the gas meter and the micro-CHP unit's display (except the Net Electric Generation). However, the complete heating system is not regarded.

Nevertheless, it can be noticed that the CHP runtime is higher than 4000 h in Bruckmühl and even higher than 5000 h in Oberau. Accordingly, the Gross Electric Generation is above 3300 kWh in Bruckmühl and almost 4000 kWh in Oberau. However, for an overall system analysis, these values are not satisfying and further investigations have to be made.

Micro-CHP performance

For a detailed evaluation of the SE, Figure 3 extracts 1 h of metered data at PFA. On top, the inlet natural gas power (green), the CHP's thermal (blue), electrical (brown) and overall (pink) power can be seen. When the engine is started, the gas consumption is slightly higher (7 kW) as in steady-state operation (5.2 kW). On the contrary, the electrical and thermal

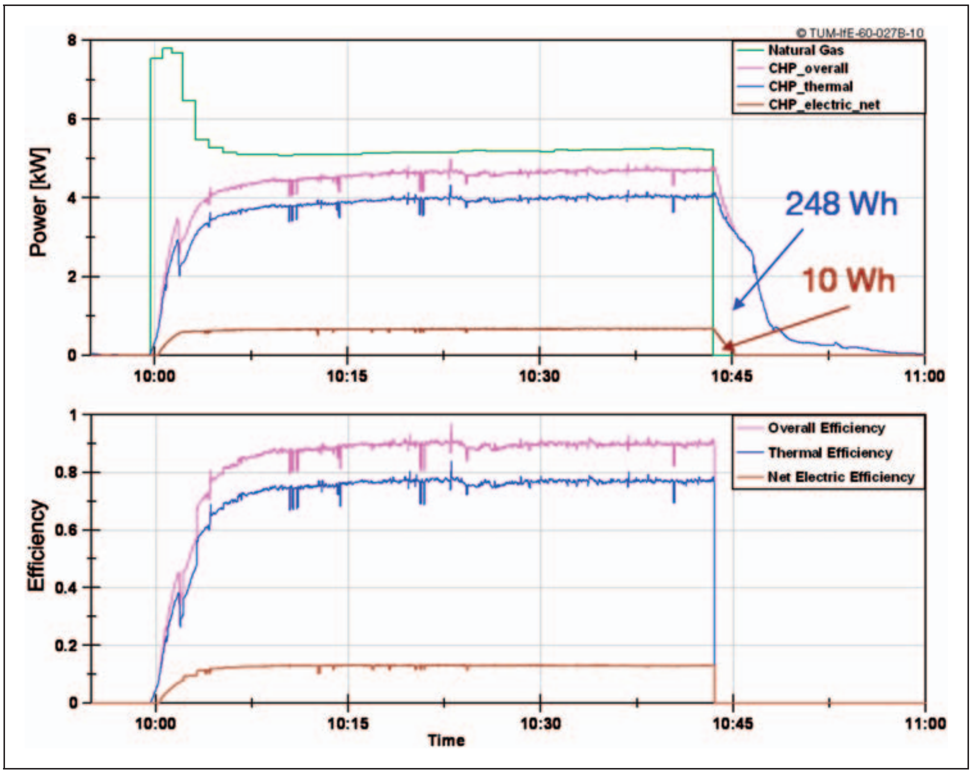

Figure 3. Micro-CHP performance.
CHP: combined heat and power.

power rise exponentially and the thermal power needs almost 15 min to reach steady-state status (4 kW thermal, <1 kW electric).

At the shutdown, the natural gas consumption falls to zero; however, there is still thermal energy stored in the engine, leading to an extended energy generation. The electric energy, which is generated after the CHP shutdown, is 10 Wh, the thermal energy 248 Wh. Within the whole measured period (around 1 h), the net electric efficiency is 12.2%, the thermal efficiency 76.3%. Thus, the overall efficiency is 88.5%. Furthermore, the lower part of Figure 3 shows steady-state efficiency is around 91%. In conclusion it can be said that long running periods should be reached to increase the overall efficiency of a micro-CHP system.

Electrical output

A closer look on the electric power generation (brown curve) is made in Figure 4. It can be observed that the net electric output power is not constant. A correlation between the thermal output (blue curve) and the electric output can be noticed and three different states can be identified:

First, when the auxiliary burner is off (for example 4 a.m. to 5 a.m.), the net electric power is above 0.8 kW. Second, when the auxiliary burner runs (around 6 a.m.), the electric power declines to approximately 750 W. The reason for this is that the CHP pump increases the flow rate of the CHP system and the electric consumption of the burner's air compressor. Consequently, the measured net electric output power is reduced, though the electric gross generation stays constant.

Third, at 2 p.m., there is another drop of net electric output power. Because the thermal power drops at the same time, a second operating point with reduced output power can be identified. As a result, two different operating points can be stated. The high step runs with around 800 W (net), depending on the state of the auxiliary burner, while the value of the low output power step is around 650 W.[3]

One-year performance

To analyze the performance of a CHP system for a whole year, a possible way is to sort the heat consumption of a building and the CHP generation on hourly basis. Figures 5 and 6 show exemplary the heat demand curves (HDC) of the year 2010 for the locations Bruckmühl and Oberau.

The curves show the consumption for space heating (red curve) and the total heat consumption (brown), where DHW consumption and circulation losses are added to space heating. The blue curve represents the generated heat of the CHP unit, while the pink curve stands for the total energy generation (heat and electrical energy). The natural gas input is shown by the green curve.

The advantage of using these curves is that many values (8760 h) can be shown within one diagram. Moreover, the energy values are represented by the areas below or between the curves. For example, the

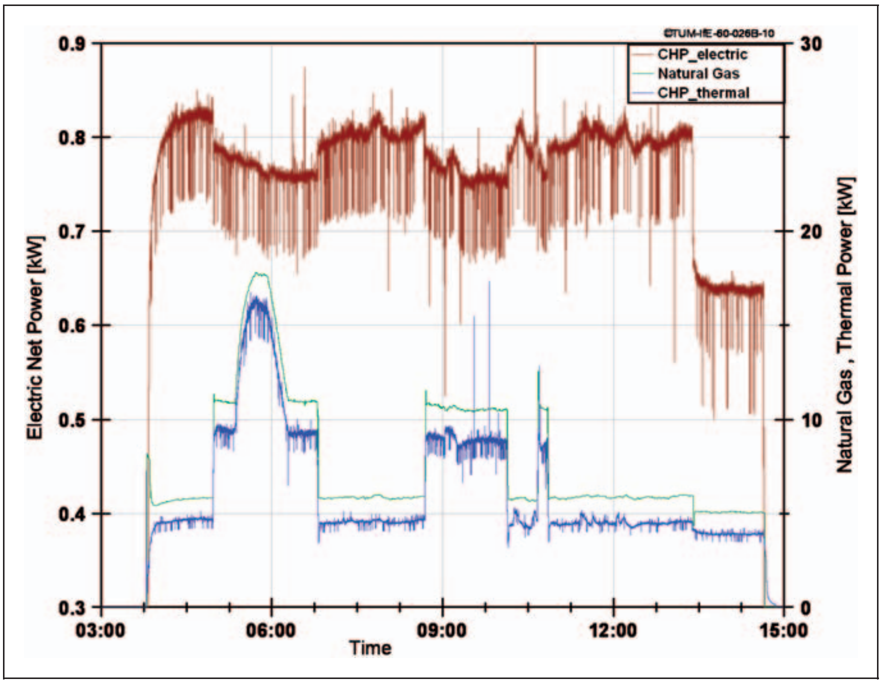

Figure 4. Electrical output.
CHP: combined heat and power.

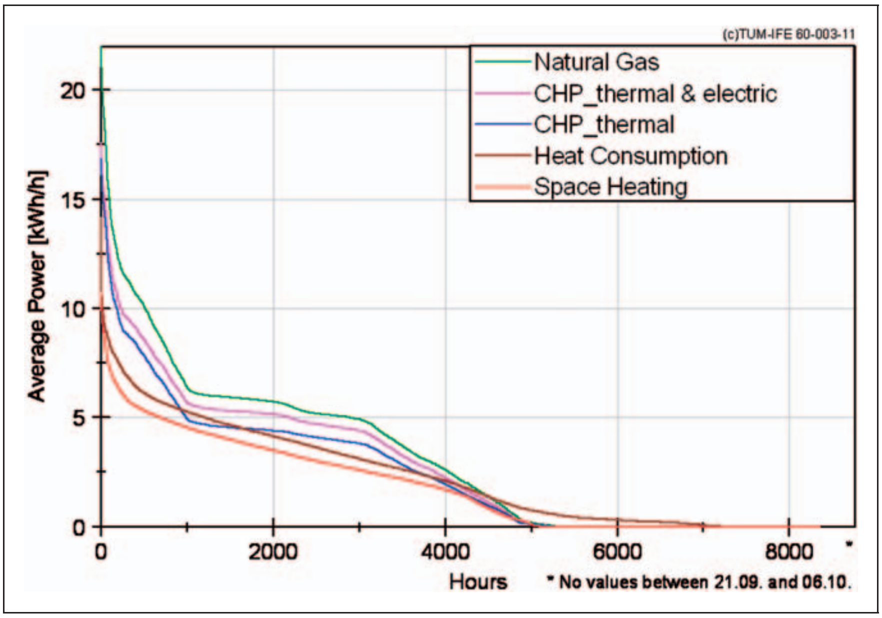

Figure 5. Sorted heat curve Bruckmuhl 2010.
CHP: combined heat and power.

integral of the red curve is the total heat demand. And the area between the green and the pink curves represents the losses of the CHP unit.

Bruckmühl

Figure 5 shows the HDC for Bruckmühl in 2010. However, the values between 21 September and 6 October are missing due to malfunctions of the recording system.

It can be seen that space heating is required at more than 5000 h and, if circulation losses and DHW are included, the value increases to 7000 h. However, the consumed hourly power is only for 1200 h higher than 5 kW. Consequently, the need of a buffer system becomes obvious.

Regarding the CHP system, three operation points can be identified again. For around 1000 h the auxiliary burner is running, leading to a thermal output higher than 5 kW and a natural gas input greater

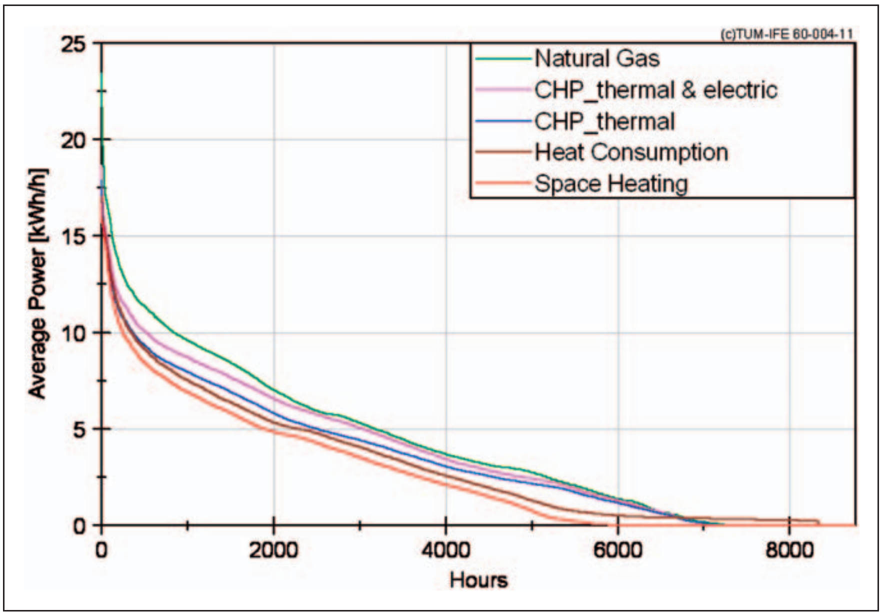

Figure 6. Sorted heat curve Oberau 2010.
CHP: combined heat and power.

than 6 kW. Between hours 1000 and 2000, the high step operation can be identified, while around hour 2300 the low step operation can be seen. After hour 3000, the CHP unit runs less than 60 min, leading to values between low step operation (5 kW gas and 3.8 kW thermal power) and zero.

Oberau

Figure 6 shows the corresponding HDC for Oberau, where a conventional HWT is installed.

The consequence is a high runtime (around 3000 h) of the auxiliary burner and hence less electric generation compared to a possible use of a CHB.

Table 2 shows the energetic year values of above curves. Given a maximum thermal output of the SE (4.85 kW, see Figure 5), the thermal generation of the Engine (SE_thermal), the Load Factor (SE_thermal/CHP_thermal) and the Runtime can be calculated.

It is clear that the amount of electricity generation strongly depends on the heat consumption of a building. Nevertheless, the installation of a CHB augments the load factor and consequently the generation of electrical energy.[4]

Daily electricity generation

For further investigations, like runtime predictions for other buildings or other weather data, the dependence of CHP runtime or electricity generation of the outdoor temperatures has to be taken into account. Moreover, for a smart integration of micro-CHP systems into the electrical grid the correlation of outdoor temperature and electricity generation was analyzed.

Table 2. Measured and calculated year values.

		BRU	OBE
Natural gas	MWh	26.8	36.9
CHP_thermal&electric	MWh	23.4	33.8
CHP_thermal	MWh	20.7	30.5
CHP_electric	MWh	2.7	3.3
Heat consumption	MWh	19.5	27.7
Space heating	MWh	15.8	23.7
SE_thermal	MWh	*17.4*	*23.0*
Load factor	–	*0.837*	*0.756*
Full load runtime	h	*3579*	*4746*

Calculated values are shown in italics.
BRU: Bruckmühl; CHP: combined heat and power; OBE: Oberau; SE: Sterling engine.

Table 3. Coefficient definition.

y	Normed daily electricity generation
x	Outdoor temperature
a	Scaling factor (2* *a*: difference between summer and winter generation)
b	Gradient of the curve; dependence of the outdoor temperature
c	Shift on *x*-axis
d	Reverse point *y*-axis

Theoretic dependence of outdoor temperatures

As shown in Mühlbacher,[5] the relation between daily electricity generation and daily average outdoor temperature can be approximated using a sigmoid curve. When the daily heat, needed for the hot water system

Table 4. Calculated coefficients.

Coeff.	*a*	*b*	*c*	*d*	*d*-a
BRU	0.289	0.124	1.03	0.323	0.034
OBE	0.266	0.155	1.18	0.339	0.073

Analyzing the calculated coefficients (Table 4) indicate the following findings:
[a]BRU > OBE: Difference between winter and summer electric generation is higher in Bruckmuhl.
[b]OBE > BRU: Generation is more linked to ambient temperature in Oberau. The reason for that might be, that only a hot water tank is installed in Oberau.
[d-a]OBE > BRU electricity generation in summer is higher in Oberau, due to the higher hot water demand.
BRU: Bruckmühl; OBE: Oberau.

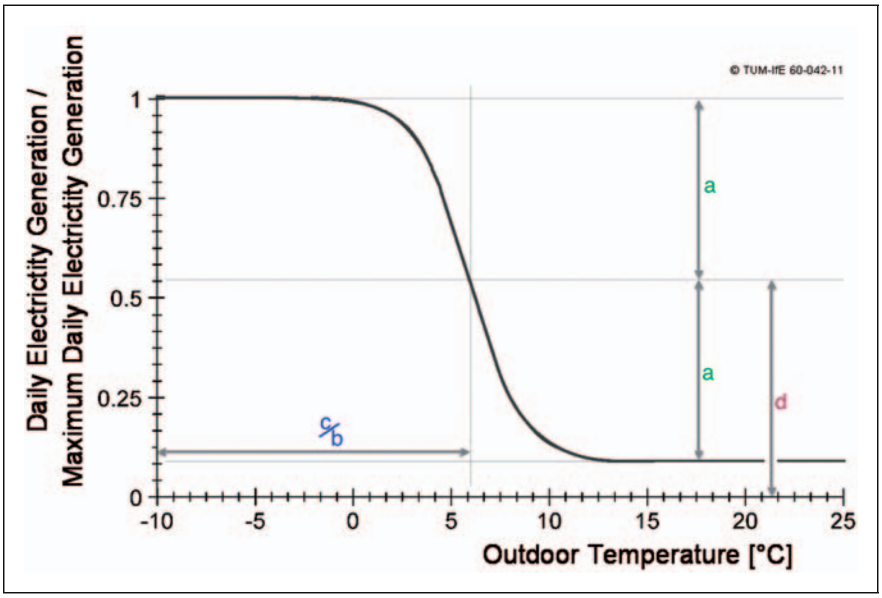

Figure 7. Daily electricity generation: Sigmoid curve adaptation.

is added, a constant value has to be added to the ambient temperature curve.

Figure 7 shows exemplarily a theoretic sigmoid curve. The used equation is

$$y = -a^{*}\tanh(b^{*}x - c) + d$$

The used coefficients are shown in Table 2.

The curve can be characterized by three sectors. In the left sector ('low temperatures'), the electricity generation is almost constant, because of the power design[b] of heat led micro-CHP units. Below a distinct temperature threshold, the additional heat is generated by the peak load boiler.

At the right sector ('high temperatures') the space heating system is off and the CHP unit charges the hot water tank.

Between, in the transition period, the electricity generation corresponds linear to the outdoor temperature. Of course, the threshold temperatures, the minimum and the maximum electricity generation depend strongly on the users' behavior and the buildings design.

Metered dependence of outdoor temperatures

Figure 8 shows the metered (red) and approximated (black curve) values for the micro-CHP units in Bruckmühl (left) and Oberau (right).

First, the daily metered electricity generation values were sorted into one degree steps. Subsequently, for each step, the average values were calculated. These values were applied to the above defined equation using the least mean square error method.

The results can be observed in Figure 8.

One main result is that the maximum daily electricity generation for both CHPs is around 63% of the theoretical maximum. One reason for that is the net electric values are used (Figure 3) where the maximum lies around 820 W compared to a theoretic maximum value of 1000 W. Furthermore, on the coldest days,

[b]To increase the runtime of micro-CHP systems, the units are designed to have about 20% of the maximum heat demand.

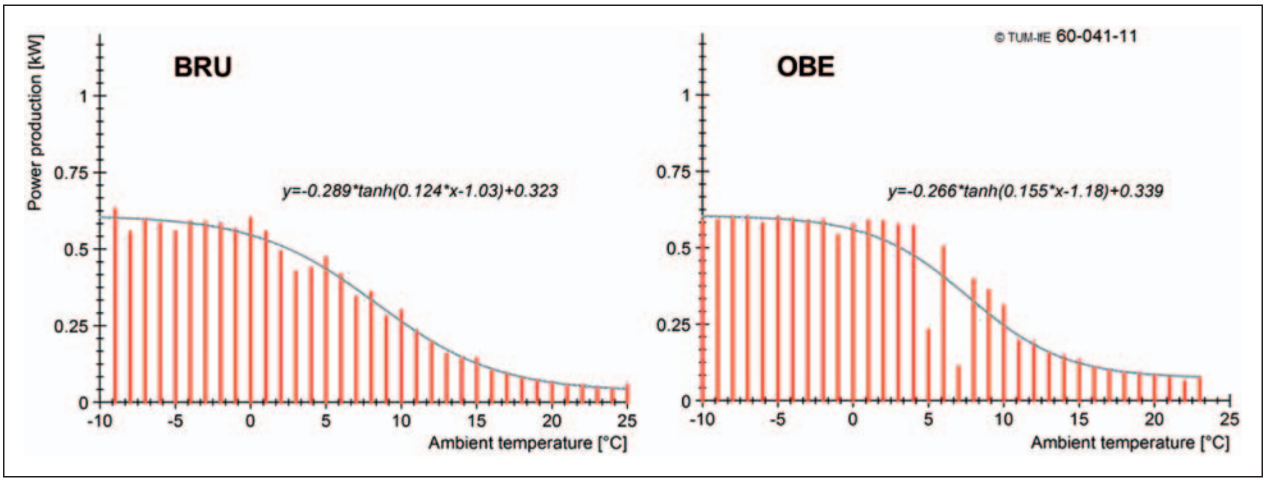

Figure 8. Daily electricity generation.
BRU: Bruckmühl; OBE: Oberau.

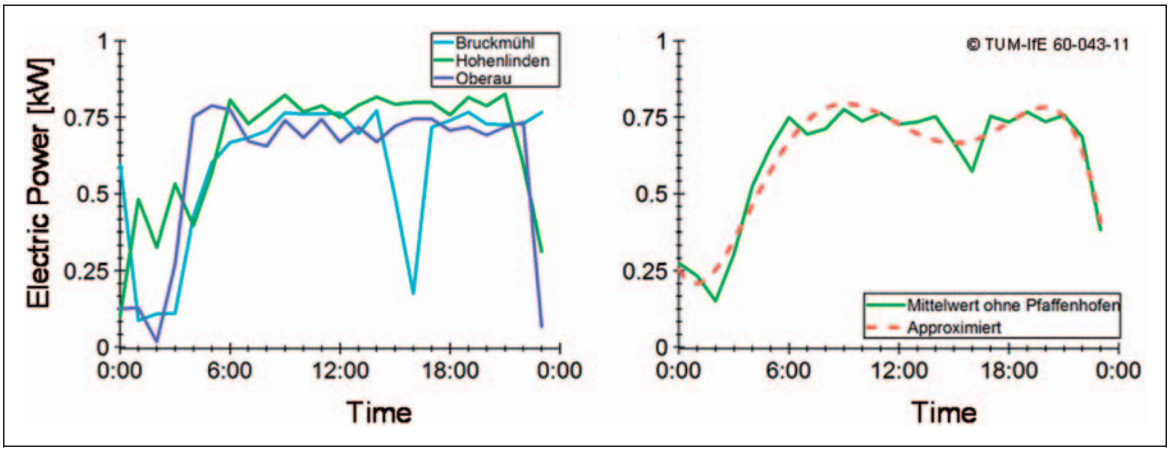

Figure 9. Electricity generation: TA < 5°C.

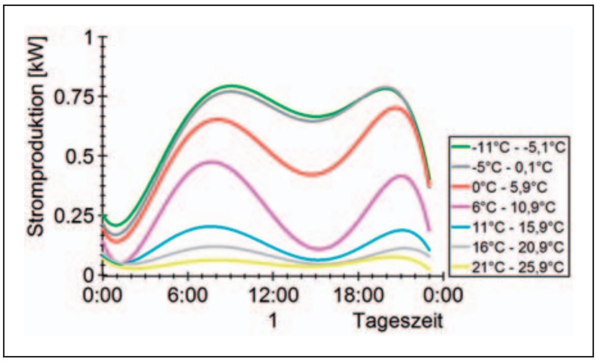

Figure 10. Hourly electricity generation.

the peak load boiler runs and increases the difference between gross and net electric generation. The third reason is that even during very cold days, the space heating is off during the night, which leads to a maximum CHP operation time around 20 h per day.[2]

Hourly electricity generation

For an integration of micro-CHP into a Smart Grid, the standard electricity generation has to be analyzed to define a 'smart' potential. In a next step, the shifting potential using heat storages can be investigated to identify the potential of a future smart generation of micro-CHP systems.

For the analysis of the standard electricity generation, the hourly metered data of Bruckmühl, Hohenlinden and Oberau[c] was sorted by ambient temperature in steps of 5 °C.

Figure 9 shows on the left side the hourly average electric generation for all days with a ambient temperature less than 5 °C. On the right side, the green curve indicates the mean values, whereas the red curve is a polynomial approximation.

These mean value calculations and approximations were done for all temperature steps (Figure 10).[6]

[c]The amount of data in Pfaffenhofen is too small.

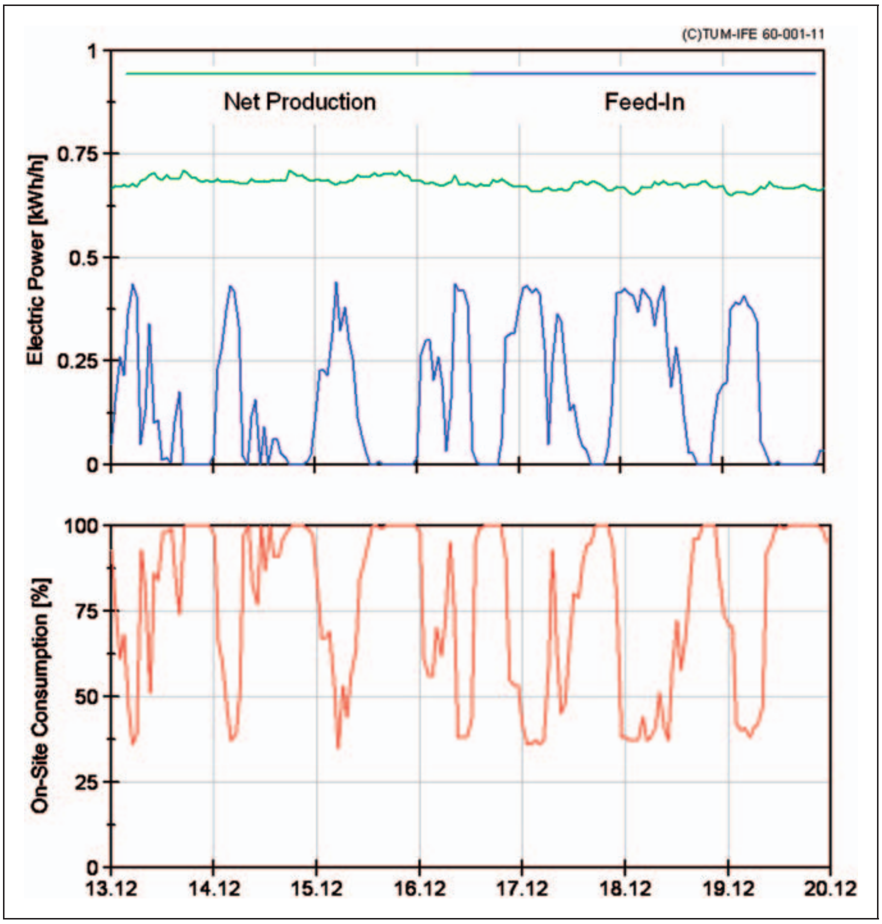

Figure 11. Onsite consumption, 13 December to 20 December.

It can be seen that the curve characteristics is equal for all temperature levels. There is a morning peak around 7 a.m. to 8 a.m. and an evening peak around 8 p.m. to 9 p.m.. At very cold days, the night setback can be identified. On the other hand, during summer days, it is more likely that the hot water charges appear in the morning and in the evening, but not in the afternoon and at night. In the transition period, there is a relative high difference between the morning and the afternoon electricity generation, due to heating-up the building and hot water charges in the morning and quite low heat consumption in the afternoon. However, after dusk, heat consumption increases and the micro-CHP run more likely.

Onsite consumption

In addition to the runtime, the Onsite Consumption Percentage is decisive for the economical success of a micro-CHP unit. It is defined as the ratio of the generated electricity, which is consumed onsite and the electricity net generation of a CHP unit.[4]

On 26 May 2010, IfE installed a measurement for the onsite consumption percentage in Pfaffen-hofen. Therefore, the feed-in power is metered. Using the feed-in power, the onsite consumption can be calculated.

Figure 11 shows exemplarily the net generation (light green), the feed-in (blue) and the quotient (red) for a winter week (because the SE runs continuously). The net generation is almost constant around 680 W, while the feed-in oscillates between 0 and 400 W. No power is fed-in in the late hours between 4 p.m. and 10 p.m., while the onsite consumption is lower than 50 % in the morning hours (around 1 a.m. to 4 a.m.).

The average onsite consumption value for this week is 76.2%. However, for summer and transition days, the CHP unit is off in the early morning hours and running in the evening. Thus, a closer look has to be made on the onsite consumption.

Figure 12 shows the electricity net generation, the feed-in and the onsite consumption on hourly basis in the time of 26 May to 20 December.

It can be seen that most electricity was generated between 5 a.m. and 6 a.m. That is because the space heating starts at this time. However, the average onsite consumption is lower than 50% before 6 am. The best hours to run the micro-CHP unit are between 11 a.m. and 11 p.m. During this time, the onsite consumption percentage is higher than 80% and even higher than 90% between 6 p.m. and 10 p.m.

For the whole measurement period, the average onsite consumption percentage is 73.9%. To achieve

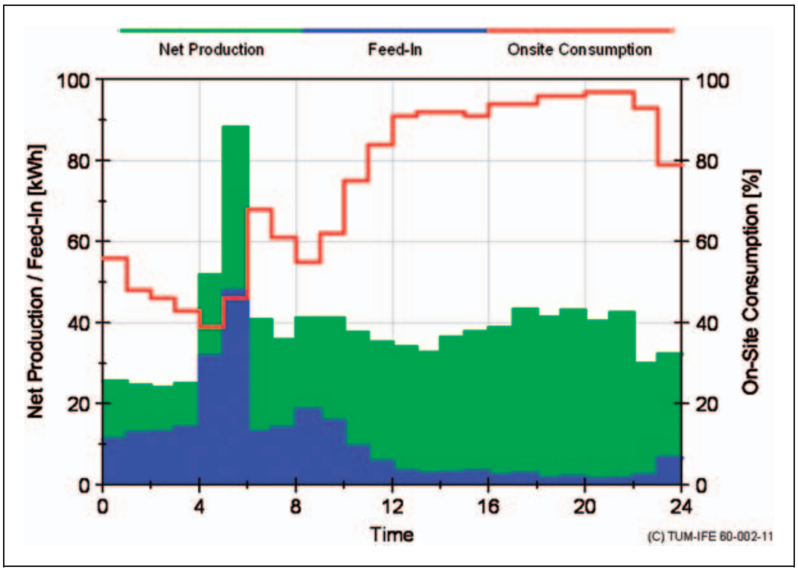

Figure 12. Onsite consumption.

a higher percentage, the micro-CHP should run mostly in the evening. If a heat storage system with a buffer volume of several hundred liters is installed, there is (at least in the summer) enough potential to shift the CHP unit's runtime for a few hours. Consequently, more research has to be made for a better integration of energetic storage capacities to the CHP unit controls.

Conclusion

A field test, operated by the Institute for Energy Economy and Application Technology and the Energie Südbayern, evaluates the energetic performance of four SE micro-CHP units. The main result is, that these units work with high thermal (>76%) and electric efficiencies (net efficiency: 12.2%).

The evaluation of heat demand curves for the year 2010 shows the space heat demand, the total heat demand and the SE unit's year performance. Full load runtimes between 3500 and 4700 can be reached if no breakdown occurs. However, the exact runtime strongly depends on the heat consumption of the applied building. Moreover, using the load factor, it can be noticed that the performance is related to the hydraulic installation type. The installations of combined heat buffers increase the CHP runtime, but particularly decrease the auxiliary burner runtime.

The daily and hourly investigation of several generators shows quite a high predictability when the ambient temperature is known. Consequently, it can be stated that micro-CHP units can be used in smart grids

Finally, to analyze the onsite consumption, the feed-in power is metered at one location. The examination unfortunately shows that most power is generated in the morning, when people are not awake and, thus, the onsite consumption is quite low. However, in the evening hours, more than 90% of the generated power is consumed onsite.

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References

1. Remeha. *Enkundenprospekt - Das revolutionäre Brennwertgerät für Wärme*. Emsdetten, Germany: Warmwasser und Strom, 2010.
2. Lipp J. *Stirling engine Micro-CHP units in single family houses*. Germany: München, 2010.
3. Jungwirth J and Lipp J. *Pilotprojekt zur Wärmeversorgung in Haushalten mit Stirlingmotor BHKW*. Germany: München, 2010.
4. Arndt U, Mauch W, Mühlbacher H, et al. *Innovative KWK-Systeme zur Hausenergieversorgung – Mess-technische Untersuchung, Wirtschaftlich-keitsbetrachtung, Systemvergleich und Optimierung*. Forschungstelle für Energiewirtschaft e.V., München, Germany, 2007.
5. Mühlbacher H. *Verbrauchsverhalten von Wärmeerzeugern bei dynamisch variierten Lasten und Übertragungs-komponenten*. Germany: München, 2007.
6. Mühlbauer A. *Stromproduktions-profile von Mikro-BHKW Electricity Production Profiles of micro-CHP units*. Germany: München, 2011.