THE POTENTIAL FOR MICRO-CHP TO PROVIDE

LOAD-FREQUENCY CONTROL

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ABSTRACT

To increase cogeneration of heat and power (CHP) in Germany, the enhancement of the quote of micro-CHP in residential buildings is a promising option. The authors have explored the potential for cross-linked micro-CHP systems in the distribution of reserve power to achieve load-frequency control. This paper presents the fundamental elements of a test rig validated and calibrated simulation, as well as the framework conditions for micro-CHP operation in Germany. A brief analysis of the German load-frequency control market has shown the technical and organisational parameters and prices. The technical potential, with regard to the current contractual requirements for tertiary control has also been determined. A methodology, which leads to the calculation of the dynamic potential and the resulting completion ratio is presented. Thereby, the effects on the technical potential by changing the technical and organisational parameters have been analysed. The potential for a network of micro-CHP systems, replacing conventional power plants in providing load-frequency control, has been determined.

INTRODUCTION

A promising option for a better integration of micro-CHP into the existing power system is the concept of so-called `virtual power plant`. This may be achieved by connecting a multitude of small power units so that they may be controlled in a similar way like large power plants. The Research Institute for Energy Economy (FfE) has examined the potential for cross-linked micro-CHP for the distribution of Reserve Energy for load-frequency control, as a key concept in the research of Network `Power Plants for the 21st Century (KW21)` [1]. The load-frequency control power is used to maintain a frequency of 50 Hz.

The current technical and economic potential of micro-CHP to provide load-frequency control power is demonstrated using the example of the SenerTec "Dachs" module, which has an electric output of 5.5 kW_{el}. The possibilities for enhancing the potential by modifying the storage or the design parameters are discussed. Furthermore, the authors show the potential of micro-CHP to substitute conventional power plants in the market to provide secondary and tertiary control power.

CHP in Germany

CHP systems utilise the waste heat from fuel combustion for heating and hence increase the overall efficiency of the power stations up to 80 to 90 percent. The German government has set a 25 percent target for CHP power generation by 2020 [2], which would mean a doubling from the current 12 percent level [3]. As **Figure 1** shows the share of CHP in the German energy market is close to average, compared to other EU states. The graph also shows that the majority of CHP generated power comes from public supply.

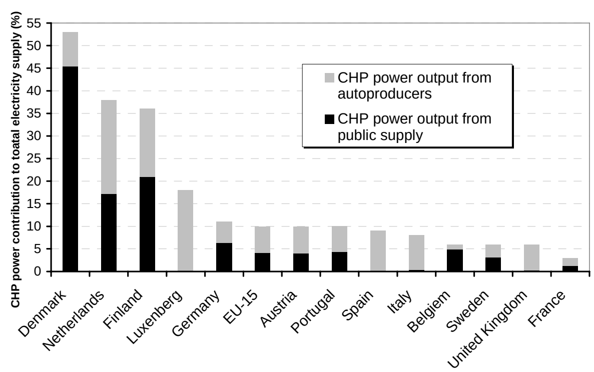

Figure 1: Proportion of power produced by CHP systems in selected European countries.

Currently, CHP systems with high power ratings are used in industrial facilities and for public supply. Only 1.5 GW_{el} of the overall CHP capacity of 34.5 GW_{el} attribute to sites with a specific capacity less than 2 MW_{el} [4]. One option could be the enhanced application of micro-CHP in residential buildings. But even the market leader has sold only about 17,000 units of the micro-CHP unit Dachs since 2002, corresponding to approximately 3,000 sales per annum [5]. Each of these Dachs units produces an electric power output of 5.5 kW_{el} and a thermal power output of 12.5 kW_{th}. The majority of the units were sold for small residential applications (55 percent), 15 percent for multi-family residences and 30 percent for commercial use. The emergence of new technologies suitable for small scale use may encourage growth in this sector in Germany.

Supporting is the legal framework for CHP units that are integrated into the German grid network. CHP operators, who use the produced heat and electricity are entitled to sell excess electric power into the grid system. Households have to pay approximately 20 €c/kWh [6] to purchase electricity from the grid. Besides the extra capital costs for the CHP unit, the costs for self-generation depend mainly on the electrical effectiveness, the charge of the heat and the price for natural gas, with approximately 6 €c per kWh [6]. The feed in rate is consisting of three elements:

– The power value is determined by the prices set at the European Energy Exchange; the average prices for the years 2006 and 2007 were 5.1 €c/kWh and respectively 3.8 €c/kWh [7].
– The “safed network-use fees” depend on the net operator and are in the range of 0.5 €c/kWh [8].
– A CHP surcharge of 5.11 €c/kWh is paid, for units that are smaller than 50 kW_{el} [8].

Considering this all the feed in rate is approximately 10 €c/kWh. Hence, it is an economic advantage for users to produce power by self generation. The study by Arndt [9] has shown that using a CHP system may bring savings when compared with the running costs of heating boilers. The specific annual savings for an ICE system add up to 15.4 percent.

The Load-Frequency Control Market

Since the liberalisation of the German energy market in 1998 a market for load-frequency control has evolved with a volume of 7 GW and about € 750 million per annum [10]. The increased use of renewable energy technology, e.g. wind and photovoltaic will lead to more volatile generation, and hence a higher demand of reserve capacity for load-frequency control is predicted [11]. The four German Transmission System Operators (TSOs) EnBW, E.ON, RWE and Vattenfall are responsible for maintaining a frequency of 50 Hz. As shown in **Figure 2** this is achieved through three control power strategies: primary, secondary and tertiary control.

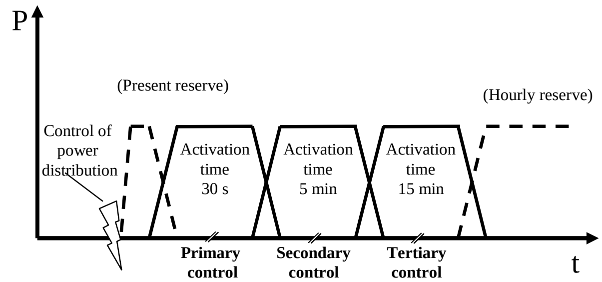

Figure 2: Load-frequency control phases and corresponding products.

In order to provide a secure power supply in the European Union for the co-ordination of transmission of electricity (UCTE), positive and negative load-frequency power needs to be applied. This must be synchronised to manage the following circumstances:

– Over supply: generation is greater than demand and therefore negative load-frequency control is required. This means that power plants which are responsible for load-frequency control have to reduce their actual power output.
– Under supply: generation is insufficient to meet demand and therefore positive load-frequency control is needed. This means that power plants, which are responsible for load-frequency control, have to increase their actual power output.

As schematically shown in **Figure 2** such disruptions to the power supply balance would immediately activate the present reserve, which consists of the electromagnetic and kinetic energy in the rotating units. Subsequently primary, secondary and tertiary load-frequency control power is required. The hourly reserve is used in case of longer disruptions. However, the market for load-frequency control refers to primary, secondary and tertiary control only with individual technical, organisational and economical requirements.

The bid invitation requirements for control power have been changed several times in the last few years, because the market newly. The technical and organisational requirements are described in the Transmission Code [12] and in the legal resolution of the Federal Network Agency (Bundesnetzagentur) [13]. The key points for an operator of a virtual power plant to provide load-frequency control as well as the economic conditions are summarised in **Table 1**.

Table 1: Comparison of the three control frequency phases with the prices from 2006.

Frequency Control	Primary	Secondary	Tertiary
Activation time	30 s	5 min	15 min
Minimum range	± 15 MW	+/- 10 MW	+/- 5 MW
Tender interval	monthly	monthly	daily
Time period	1 (24h)	High Tariff/ Low tariff	6 x 4h period
Average power price (positive)	1.43 €c/(kW·h)	1.04 €c/(kW·h)	0.81 €c/(kW·h)
Average power price (negative)		0.40 €c/(kW·h)	0.43 €c/(kW·h)
Average minimum energy price (+)	-	7.24 €c/(kWh)	12.89 €c/(kW·h)

The minimum range can also be met by the pooling multiple plants and allowing micro-CHP systems to operate effectively within this framework. Since December 2007 primary and secondary load-frequency control is contracted on a monthly basis. Furthermore secondary load-frequency control can be offered at two separate time periods. The tertiary control is determined daily for the following six 4-hour time slots.

If a power plant operator makes a suitable offer, the operator will subsequently sell the power at the same rate for the whole period. If the power is requested by the TSO the successful bidder would additionally get the energy price.

METHODOLOGY

Benchmark tests at the Technical University Munich have allowed analysis of operational behaviour of various applications to be performed. The results are the basis for a Matlab/Simulink® simulation developed by the FfE with a high temporal resolution. Therefore, the characteristics of the whole system and single components are validated by the test results. The simulated CHP-systems have been supplemented with the functionality of an external controller in addition to the heat load-following operation and electric load-following operation. Hence, the operation of the micro-CHP units in a virtual power plant to provide load-frequency control can be simulated and evaluated.

Experimental analysis on the test rig

The test rig at the Technical University Munich was built to conduct benchmark tests for micro-CHP systems under the realistic operating conditions of a residential building. Multiple parameters, such as the heat load of the building and the domestic hot water (DHW) system, the thermodynamic behaviour of the radiators and the size of the implemented heating buffer storages (BS) and DHW storages (or in one case a combined storage (CS)), were all able to be carefully controlled and varied. The test rig was designed to simulate the demand of space heating and DHW preparation of residential buildings up to a maximum thermal output of 70 kW. **Table 2** summarises the technical data of the tested CHP systems.

Table 2: Tested CHP systems

System	ICE 1	ICE 2	SE	FC
Technology	Combustion engine	Combustion engine	Stirling engine	PEM-fuel cell
Electrical power [kW]	1.3 - 4.7	5.5	2 – 7.5	1.5 – 4.6
Thermal power [kW]	4.0 – 12.5	12.5 + 0.8	8-22	3.0 – 9.1
Storage type	BS 1,000 L DHWS 500 L	BS 1,000 L DHWS 500 L	2 x CS 1,000 L	(2 x DHWS 500 L)

To show the diurnal and seasonal influences on the CHP operation, load profiles for space heating demand and DHW consumption were used to represent typical days during summer, winter and transition seasons. A detailed assessment of the rig testing may be found in source [14].

Simulation

A model was developed, which simulated the dynamic processes of the CHP-systems with respect to thermal heat demand, hot water and electrical load. The simulation recreated the same conditions, which existed in the real testing rig conditions. Thus, the effective testing and calibration of simulation parameters were possible. The simulation consisted of various elements, which were developed separately and simulated in clearly defined domains. Thereby the configuration of the simulation allowed reflecting the diversity which existed in the real world configuration, because various different system configurations were possible. In such a way the simulation allows the calling of particular components depending on the system parameters. **Figure 3** shows the main simulation components, each component consisting of multiple modules.

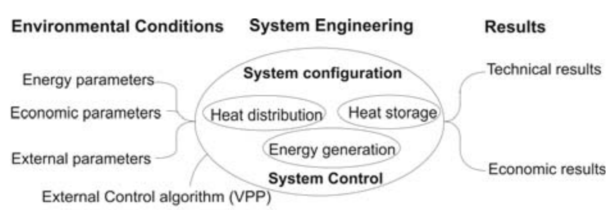

Figure 3: Simulation with the key components

The energy demand for the building of concern (depending on building type, size and the occupants status), economic data (such as electricity/ gas price, feed-in tariff, investment and operating costs) and external factors (such as outside/ target room temperature and atmospheric conditions) served as environmental conditions in this model. In the following analysis the heating demand of different multi-family residences were simulated. Therefore three types of day (depending on season) were chosen.

The basis of the simulation consisted of various generation plants. These CHP units are varying technologies, which are shown in Table 2. However, conventional boilers may be used at times of peak load. The main parameters were the capacity, partial load ability, efficiency and the specific emissions.

In modelling the heat storage system, the type of storage system was depicted. Basically buffer storages and DHW storages were modelled. The storages have been modelled on a basis of 20 layers. Thus, accurate models for the temperature distribution within the storage unit could be obtained. Here the main parameters are storage volume, losses and the different attachment heights.

The simulation also took into account the fact that the system does not only consist of power generators and storage devices, but also of pumps, pipes and valves. All the elements in the simulation have been designed to deal with these components. The devices have different, manufacturer-specific properties, which affect their control. Therefore these parameters (such as losses, flow rates, flow direction and auxiliary power) were also integrated into the simulation.

The simulation allowed for various control combinations of the individual components in series, parallel or prioritisation switching. In the simulation element “system control” the control strategy, the safety criteria and the switching algorithms were depicted. The key parameters were the control hysteresis, the night setback, the heating curve and the minimum running time of the CHP. In this context, the developed external control strategy for the usage in a virtual power plant should be mentioned. Thus, after the external development of a market strategy, the CHP operating characteristics can be determined.

A unique feature of the simulation is that the results have been validated by rig testing. Due to the vast interdependence of the simulation elements and the high detail resolution, the simulation does not recreate the CHP system as one single unit, however as individual components, which have individually been validated. Each element consists of a module, with its own set of parameterised functions and subroutines. These parameters were given, based on the results of the test rig investigation.

A detailed representation of the simulation is contained in the dissertation of Ulli Arndt [15].

Assessing the potential of micro-CHP for tertiary control

The CHP system is designed to meet the dynamics of heat demand of the supplied object (heat load-following operation). If micro-CHP systems were to provide load-frequency control, they would have to be regulated externally in an integrated way. This is, however, complicated by the fact that individual devices have manufacturer specific requirements, such as safety measures and minimum running times.

The control of micro-CHP systems to provide tertiary load-frequency control can occur in one of three ways: (1) the unit provides negative load-frequency control by continuously running and is able to switch off at any time; (2) the unit provides positive load-frequency control by being switched off, with the ability to be activated at any time; (3) the unit does not provide load-frequency control and is switched on and off independently, based on heat load-following operation.

To assess the technical potential of micro-CHP systems to provide tertiary control, the control zone of the German transmission system operator (TSO) E.ON was simulated. The daily tertiary control regime is determined in six four hour periods, despite the fact that tertiary control is regulated in 15 minute intervals in the market. All combinations for each period positive (+1), negative (-1) or no control (0) were adopted by the simulation. Thus, if the micro-CHP device is capable of providing frequency control over the entire period, and (in the worst case) the frequency control is required over the entire period the CHP device may be integrated into the load-frequency control system.

Assessing the potential of micro-CHP for secondary control

The methodology assessing the potential for tertiary control is not feasible for the secondary control. This is because of the contractual conditions associated with secondary control. Until the 1.12.2007 secondary load-frequency control was contracted out on a half-yearly basis. The delivery of the power can not be guaranteed by CHP units over such a long time period. Therefore, a new method has been developed, which allows the determination of the technical potential independently of the duration of the contract period. For that reason the dynamic potential has been defined. In calculating the dynamic potentials, the following assumptions were made:

- The maximum potential energy available in the buffer storages, $Q_{BS,max}$ has been calculated using the maximum flow temperatures given by the control algorithm of each CHP system. The minimum potential energy in the buffer storages Q_{BS}, min is set by the minimum energy, which is monitored in the case of heat load-following operation.
- The thermal heat load, $P_{th,load}(t)$ is known from this point onwards.

The time required for the CHP unit to increase the thermal energy in the buffer storage up to the maximum level was calculated for each point in time (t). Thus, for every interval, the smallest n was found to satisfy the inequality given by the following equation:

$$Q_{Bs,\max} \le Q_{BS}(t) + \Delta t \cdot \sum_{i=1}^{n} (P_{CHP,th} - P_{th,load}(t+i))$$

Figure 4 shows a schematic representation of the variation in buffer storage energy, Q_{BS} with time. The power $P_{th,load}$ (thermal heat) and $P_{th,CHP}$ (thermal power from the CHP unit) are also shown.

At a certain time t_1 the dynamic potential, Pot(t_1) has been determined. The figure shows an example of possible values at various time intervals between points (t_i):

- t_1 to t_2: In this interval $P_{th,load}$ is greater than $P_{th,CHP}$, and thus the buffer storage is discharged.
- t_2 to t_3: When $t = t_2$ the buffer storage system reaches the allowed minimum value of $Q_{BS,min}$ and the peak load boiler takes over the supply deficit.
- t_3 to t_4: At the time t_3 the thermal demand becomes smaller than the CHP output. The buffer storage recharges through thermal energy until the time t_4. Due to safety requirements, the CHP unit must stop operating after reaching $Q_{BS,max}$.

The entire time period between t_1 to t_4 represents the dynamic potential Pot(t_1) at time t_1.

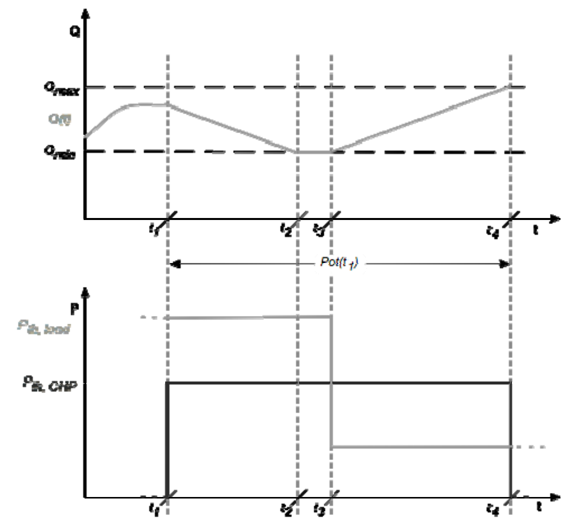

Figure 4: Variation in buffer storage with time, as simulated by the model

Dynamic potential values were determined at each time t_i following the simulation. A variation at one time t_i subsequently leads to a variation of the dynamic potential at subsequent times t_i. Thus, an isolated calculation of the dynamic potential should not be equated with the potential of secondary control, with regard to the power being required for load-frequency control and changing therefore the assumptions in the calculations.

ANALYSIS

The potential of micro-CHP for tertiary control

Based on the three different types of days (depending on season), the provision of tertiary control was simulated. In doing so, all combinations were considered. Therefore, operation providing positive or negative tertiary control power and heat load-following operation may be performed. Hence, for each day type with six 4-hour periods there are 729 combinations. In **Figure 5**, the electrical power of a CHP unit it is shown for one combination on a winters and summers day given the following conditions: From 12:00 am to 8:00 am is under heat-load following operation condition; from 8:00 am to 4:00 pm the plant is operating consistently to provide negative load-frequency control and from 4:00 pm to 12:00 am the unit is also under heat load-following condition.

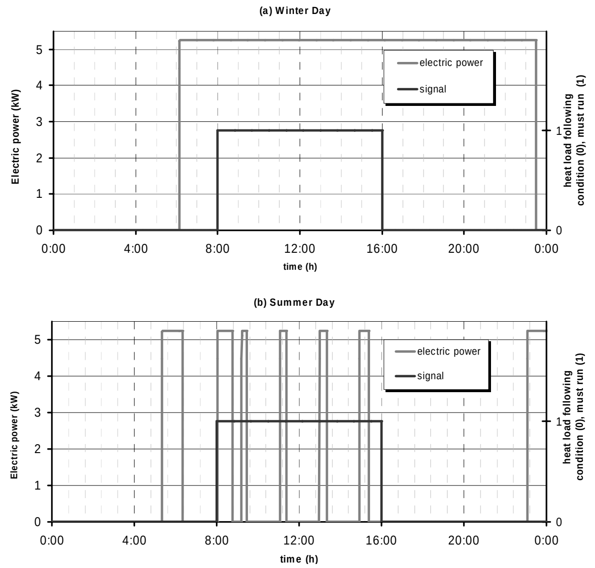

Figure 5: (a) The simulation on a typical winter day. (b) The simulation on a typical summer day.

As apparent in Figure 5 load-frequency control can be offered on a winter but not on a summer day, in both blocks from 8:00 am to 4:00 pm. In the considered period the power can supply constantly during the winter day, whereas the CHP unit has to shut down several times during the summer day. This is because the CHP unit produces excess heat in the summer. With this methodology identified feasible technical options were then evaluated based on their economic performance.

The dynamic potential of micro-CHP for load-frequency control

The dynamic potential was analysed for various CHP systems (as seen in Table 2), with chosen variations in the building layout and storage systems. In order to present the results more clearly and to allow for more distinct comparisons to be made, two further steps were undertaken.

First, time intervals of varying lengths were considered in the simulation. For each time interval, the simulation determined whether the initial dynamic potential was at least as high as the duration of the time period. Secondly, the number of time intervals for which this condition was met was recorded and set as a ratio in comparison to the total number of trials (there were 8760 hourly and 52 weekly intervals). As an example, **Figure 6** shows the analysis of the simulation results using two storages of different sizes and three different house sizes. This resulted in six possible combinations (as shown in columns 1, 2, 4, 5, 7 and 8).

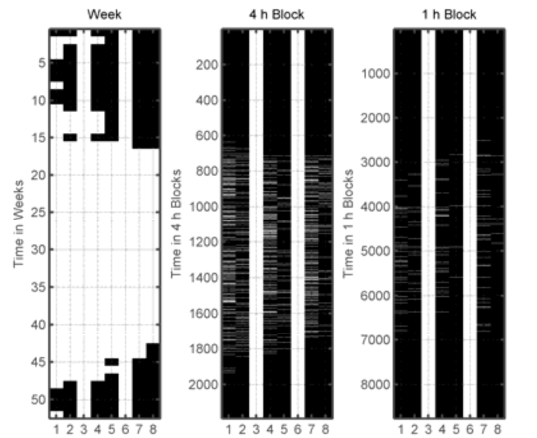

Figure 6: Dynamic potential, dependent on the interval analysed.

It can be seen that the dynamic potential in winter is greater than in summer (the first of January is shown at the top and the thirty-first of December at the bottom of the chart). Also apparent is that load-frequency control can be offered more frequently when the interval is shorter.

The potential of replacing conventional power plants for providing load-frequency control

The described methodology is based on the simulation of a single unit. Through the interconnection of multiple units and their sequential application a constant power supply could be ensured for the TSO. Therefore, only a portion of the installed CHP power is utilized for providing load-frequency control. In order to answer the question how many conventional power plants can be replaced through micro-CHP systems, the following approach was adopted: Only the most critical day type (the summer day) needs to be analysed. The simulation was performed over the period of several days. Starting with a single CHP unit, the number of CHP units was successively increased until a constant power supply was reached. The simulation was designed so that at any time exactly one CHP unit is operating. As soon as one unit needs to be turned off due to safety requirements the next switches on immediately.

RESULTS

The potential of micro-CHP for tertiary control

The technical potential for micro-CHP systems to provide tertiary control was determined with the simulation. The following results apply to a CHP unit with 5.5 kW_{el} and 12.5 kW_{th} in a multi-family residence for ten families:

- Winter day: Every combination of positive and negative tertiary control was able be offered in the four periods between 8:00 am and 12:00 am.
- Transitional season day: Positive and negative tertiary control could only be made available in the period from 8:00 am to 12:00 pm.
- Summer day: Constant operation of the CHP unit could not be maintained to provide tertiary control in any of the four-hour periods.

The economic analysis shows, that it is advantageous to offer negative rather than positive tertiary control. Since tertiary control is required by the TSO on an infrequent basis, it is only through the supply of negative control that a greater utilisation of CHP units could be assured. The supply on all winter days between 8:00 am and 12:00 am in 2006 negative control would have had a benefit of €59 per (CHP) unit.

The dynamic potential of micro-CHP for load-frequency control

Based on the completion ratio the effects on the dynamic potential by varying the bid invitation period duration and the outlayed power and the buffer storage capacity could easily be assessed. In **Figure 7** the completion ratio is shown for three different house sizes.

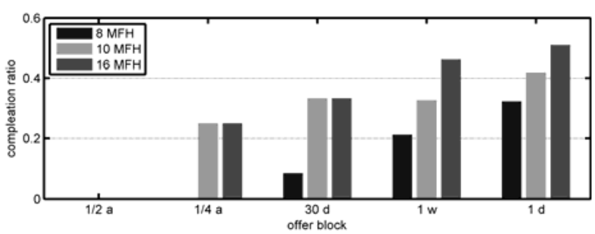

Figure 7: Comparison of the completion ratio of a CHP system with 5.5 kW_{el} in different house sizes.

Load-frequency control could not be chosen for buildings with eight occupancies (8 MFH) in a three month period. However, this was possible for the two larger buildings, since the thermal output was sufficiently large. The analysis of the 30 day blocks is particularly interesting, given that since the 1.12.2007 the provision of primary and secondary control has been announced in monthly, rather than half-yearly contracts. In this case, the CHP unit was able to provide load-frequency control in one sixth of the time periods in the 8 family building and the 16 family dwelling has a value of 41.7 percent. The highest completion rates are expected for the shorter time periods. Thus, rates of 4/12, 5/12 and 6/12 were observed for 8, 10 and 16 family dwellings respectively.

The effects of larger buffer storage devices on the dynamic potential were also examined. In comparing a storage device with the standard capacity of 1,000 litres and a 2,000 litre storage system, for the longer time periods of a quarter year and 30 days no differences were found. The larger buffer storage device was only advantageous for periods greater than a week, given that a completion ratio of 42.3 percent is reached for the 2,000 litre system. The 1,000 litre system had the same completion ratio of one third, as for a 30 days interval. The completion ratio can be increased when considering daily time intervals, with 41.9 and 51.2 percent for the 1,000 and 2,000 litre systems respectively.

The potential of replacing conventional power plants for providing load-frequency control

It was shown, that a constant power supply of 5.5 kW_{el} could be assured on a summer day, when at least seven CHP units in a multi-family residence for ten families were used. When eight units were used instead, the average number of times that each unit had to switch on or off per day was reduced from 4.5 to 1.7. If the 1,000 litre system was to be replaced with the 2,000 litre system six units were found to be sufficient for supplying a constant power supply. Subsequently, approximately 15 percent of the overall CHP power installed were able to replace conventional power plants in the provision of load-frequency control.

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CONCLUSIONS

The Research Institute for Energy Economy (FfE) has conducted computer based modelling using Matlab/Simulink® to test the suitability effectiveness for micro combined heat and power (CHP) systems to provide load-frequency control. These simulations were based on data obtained by a series of experimental measurements by the Technical University Munich. Through the coupling of multiple small CHP systems and their integrated control, the units can act together as a virtual power plant.

As a result of this study, it has been found that it is technically feasible for micro-CHP systems to provide tertiary control using contemporary technology, compatible with the current legal and organisational framework. The potential is strong, with high demand from residential dwellings for heating. Therefore, the potential is greatest especially in the winter from 8:00 am to midnight.

The provision of negative tertiary control is more economically feasible than the provision of positive tertiary control. A 5.5 kW_{el} CHP unit would save € 59 per year, only maintaining negative control.

The reduced ratio of CHP power output capacity to the thermal demand of the domestic housing and increases power storage volume were shown to boost the load-frequency control ability.

A maximum of about 15 percent of the installed CHP power is available to replace conventional power plants in providing load-frequency control.

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