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Optimised dimensioning of thermal and electrical storages in synergetic use with micro-cogeneration systems in residential buildings

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Introduction

Germany expressed its commitment to extending the use of renewable energies in combination with highly efficient technologies as one major part of the German energy change process (German: “Energiewende”). By increasing the opportunities for customers to reduce their energy demand and even to generate energy by themselves the consumer is continuously transforming to a prosumer by installing photovoltaic, wind power and combined heat and power (CHP) systems. With its pioneering role in the field of CHP, the state government of North Rhine-Westphalia pursues the target to investigate possibilities to ensure an energy-sustainable future. A technology selection with regard to the end-user specific demand in combination with an optimised dimensioning approach is necessary to pave the way for a large scale expansion of micro CHP in the residential building sector.

To enhance the operation of CHP systems, the influence of the electrical self-use ratio has been identified in [1] as one major magnitude of influence. The central outcome can be summarised to a high interaction of the self-use ratio with the correlating system profitability (based on the German market). The integration of electrical storages has been furthermore identified as one possibility to increase the self-use ratio. The identified research demand leads to an evaluation of the influence of electric storages on the performance of the CHP unit. This paper focusses on derived dimensioning approaches for CHP units. It furthermore evaluates possible enhancements due to electrical storages with respect to an assumed heat-controlled operating strategy.

Methodology

The scientific analysis and evaluation of CHP system combinations in residential buildings focus on an optimisation of sub system dimensioning approaches and target-orientated operating strategies. To analyse the performance of the different sub systems in certain situations on the one hand and to evaluate effects and to quantify interconnections by varying different parameters on the other hand, the author has developed and used different analysis methods.

Temporally differentiated analysis

The temporally differentiated analysis leads to a better understanding of the performance of the overarching system. Reactions and interactions of sub systems can be derived by analysing short time periods. In this analysis approach temporally differentiated values like the electrical power for instance are plotted over time. By focussing on typical and reproducible situations, the performance of any sub system can be understood. A detailed and quantifiable optimisation process can be ensured for single analysed case examples.

Parameter variation (variate analysis)

This method focusses on an increased understanding of the influences of parameter variations. Therefore integral values with respect to a representing period of time (e.g. one year) are commonly used. With regard to the example mentioned above the produced electricity is taken for comparisons as the temporally integrated counterpart to the electrical power. To improve the comparability standardised benchmarks are taken into account.

Univariate analyses are very common by plotting benchmarked results over a single varied parameter. The interconnection between outcome and a certain parameter can be directly derived. The extension of this method with an additional parameter leads to bivariate results. The relation of the two varied parameters can be derived and evaluated. The resulting matrix is commonly plotted in 3D-diagrams against each other or due to an array of curves. The relation between more than two parameters can be derived by an interpretation from the results of a multivariate analysis. This method can be used to understand and describe the magnitude of influence from certain parameters and therewith allows a more generalised optimisation approach.

The scientific overarching analysis on CHP systems in combination with different kind of storages and operating strategies is focussed on qualitative results to derive general dimensioning approaches. With regard to the intended simulation, a large amount of simulations have to be executed to meet requirements for a multivariate analysis. Therefore the simulation time has been reduced significantly by decreasing the level of detail. The hereby achieved primarily qualitative outcomes create a knowledge basis that can be reflected on specific case examples. Crucial system parameters can be roughly estimated for highly detailed in depth analyses.

Benchmarks for system evaluation

To increase the outcome comparability different hereinafter described benchmarks are used to qualitatively evaluate the performance of the overall system combination.

- **Normalised time of operation**
  The nominal time of operation is calculated by dividing the total amount of delivered electricity of the CHP unit by its nominal electrical power. To increase the comparability, the nominal time of operation is normalised with respect to the considered time period.

- **Electrical self-use ratio**
  The ratio of self-used electricity compared to the overall provided electricity by the CHP unit points out a comparable technology and object comprehensive benchmark. Depending on the political framework conditions a high self-use ratio is often supporting the economic efficiency of the CHP system crucially.

- **Electrical / thermal demand coverage degree**
  The ratio between the self-used electrical / thermal energy provided by the CHP and the accumulated amount of electrical / thermal energy demand of the object is designated as the respective demand coverage degree. This benchmark provides a normalised and therewith comparable value to evaluate the combination of CHP technologies, object characteristics and end-user behaviours.

Modelling approach

The dataset for the analyses bases on a batch of simulation results. Generalised object characteristics and standardised end-user behaviours are implemented to temporally differentiate the energy demand. System performances are derived from the different sub systems which can be varied by certain parameters within representative parameter ranges.

Object and end-user characterisation

The total object and end-user associated energy demands can be varied to ensure a large scale field of application. The total energy demands depend on the number of residents, the living space and the building insulation standard. The chosen building insulation standard is connected to a specific space heating demand. The specific electricity and domestic hot water energy demand depend on the number of residents.

The temporally differentiation of the different energy demands is based on a standardised approach for a one year time period which is substantially derived from the VDI 4655 [2] with partially adaptions. It is assumed, that the year can be split up into ten representative typical days. A typical day category is assigned with regard to the average daily temperature, the cloud amount and the weekday. Energy allocation parameters divide the yearly energy demand proportionate to the typical days. Normalised daily demand profiles in a time step resolution of one minute are integrated for each typical day and energy demand. The published fixed energy allocation parameters are applicable for the representative German climate zones. The energy allocation parameters are based on one specific period of time. A parameter adaption method has been developed to enable the implementation of any location and year. The electricity and domestic hot water energy allocation is based on these parameters. In addition to that, the originally space heating energy allocation method has been adapted fundamentally. Thereby a combination of typical days to a representative year is permitted. The daily space heating energy demand is assigned in relation to the quadratic-weighted smoothed intermediate daily outside temperature. This method considers the approach from [3] with some adaptions. Furthermore, the normalised space heating day profile for each typical day has been replaced. An adjusted standard load profile [4] with the focus on the heat demand is used for the simulations. For the further analysis, the daily average temperature and the cloud amount profile of the year 2006 for Düsseldorf in Germany as the North Rhine-Westphalian capital has been chosen.

Heating units

CHP units provide thermal and electric energy simultaneously and represent one of the main sub systems in the comprehensive simulation. The sub system CHP is represented by a set of parameters. Each set consist of parameters within a market representative bandwidth depending on the chosen CHP technology. Beside Otto- and Stirling-engines, polymer electrolyte membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) are implemented in the sub model description. The nominal thermal power of the CHP units represents one of the main parameters for dimensioning focussed evaluations and analyses. This parameter can be adjusted within a wide bandwidth. The power to heat ratio of a CHP unit is commonly used to compare CHP systems in general. This benchmark is very important with regard to the performance evaluation of electrical storages. Based on a batch of parameter sets from different CHP technologies [5], the start-up performance is implemented depending on the chosen technology.

In addition to the single CHP unit an auxiliary heating device (AUX) is commonly installed. It ensures the delivery of the demanded thermal energy at any time. An automated dimensioning approach of the AUX is implemented in the simulation. The assumed thermal AUX power is independent from the thermal power of the CHP unit. The thermal AUX power is equal to the simplified estimation of the maximal heating load of building as described in [6], increased by the yearly averaged load for the domestic hot water delivery. With regard to the field of operation of available heating units, the thermal power of the AUX can be modulated to a minimum of 20 % of its nominal thermal power.

Thermal and electrical storages

A thermal storage is used to decouple the thermal energy demand from the thermal energy supply. This ensures the CHP operation in an optimal domain of efficiency and decreases life-time influencing on-off cycles. The implemented thermal storage represents a conventional water-based storage. The hydraulic connection of the sub systems is not differentiated. The heat storage is implemented with an energy specific thermal storage capacity like applied in [7]. Independent of the height specific heat allocation within the storage, the average thermal capacity can be derived by a mathematically integration of the temperature over the height. On that condition, the maximal thermal storage capacity can be derived from the specific heat capacity of water. It furthermore depends on the covered volume of water and the maximum temperature difference which is implemented with 20 K. The calculation of the heat losses is based on the temperature difference between the average storage temperature and the ambient temperature.

The area of application of an electrical storage is comparable to above mentioned thermal storage. The electrical storage is used to decouple the electric demand from the CHP supply. Analogous to the thermal storage, the electrical storage is integrated as an energy balanced sub model. Depending on the chosen battery technology (lithium and lead-acid batteries are implemented) preconfigured parameter sets are integrated. The major differences are the permitted peak load and the depth of discharge. To realise an electrical connection of the CHP unit, the object and the electrical storage, an AC/DC power inverter is integrated. Conversion losses and battery specific self-discharge rates are implemented.

Heat-controlled operating strategy

A general operating strategy for CHP systems is not available. Manufacturer experiences and different targets are implemented in the specific system controllers. Furthermore the controlling strategies depend on the respective hydraulic connection of the thermal sub systems. As a result of this, a generalised heat-controlled operating strategy has been assumed within the simulation. Five switching conditions are implemented to control the CHP unit and the AUX, which are exemplary illustrated in **figure 1**.

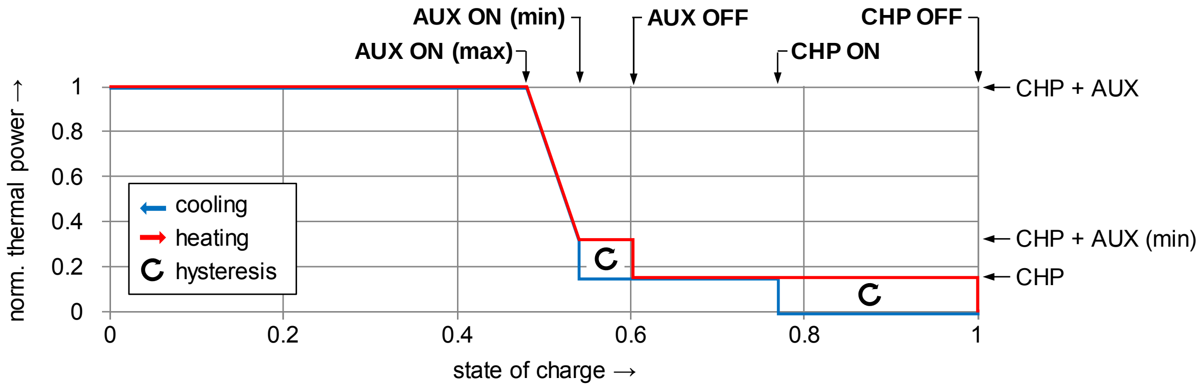

Figure 1: Normalised heat-controlled operating strategy for a covered water volume of 0.5 m³, a nominal thermal CHP power of 2.5 kWh, a maximal AUX power of 13.9 kW and 3 residents

The switching conditions are based on the state of charge of the thermal storage. They depend on different parameters which influence the expected requests to the storage.

- **AUX ON (max)**
  The AUX is forced to operate with its maximum power when the state of charge of the thermal storage falls below a minimal threshold. An interrelation between minimal permitted state of charge and amount of residents is assumed. The threshold is quantified due to an application specific interpretation of [8].

- **AUX ON (min)**
  To avoid a shortfall below the above mentioned threshold, the AUX is switched-on before the minimal state of charge is reached. With regard to an assumed unlimited load change rate of the AUX, a time-based shift of the switching condition is implemented. The resulting switch-on condition is derived from the expected energy delivery of the AUX during an operation of 15 minutes with minimal thermal power.

- **AUX OFF**
  To avoid a fluctuated operation of the AUX, a hysteresis is integrated into the operating strategy. The switch-off condition for the AUX is derived analogous to the approach explained previously.

- **CHP ON**
  In contrast to the switching conditions mentioned before, the CHP switch-on condition is variable. It depends on the remaining thermal buffering capacity. It is equal to the middle state of charge between the AUX switch-on condition and the CHP switch-off condition. If necessary, the switch-on condition is furthermore adjusted to assure a minimal time of operation of one hour of the CHP unit if applicable.

- **CHP OFF**
  The CHP unit is switched off when the heat storage reaches its maximal state of charge.

Results

The presented results in this chapter point out the difference between both mentioned analysis methods. The simulation results are based on the previously mentioned year 2006 with an averaging temperature smoothing factor of 0.5 for Düsseldorf and the following basic parameters. The heat energy demands and the correlating profiles correspond to a living space of 120 m² in combination with a specific space heating demand of 200 kWh/(m²·a). An occupation of 3 residents is assumed. The residents are represented by a specific heat energy demand for domestic hot water of 500 kWh/(person·a). According to these parameters, the accumulated heat demand is 25,500 kWh/a. The CHP unit is characterised due to an Otto-engine specific start-up performance, a thermal power of 2.5 kW, an electrical power of 1.0 kW and a power to heat ratio of 0.4. The AUX is automated dimensioned with a thermal nominal power of 12.9 kW and can be modulated down to 20 % of the nominal load. The thermal storage covers a water volume of 0.5 m³ and contains 11.4 kWh at the maximal state of charge. The above mentioned object, end-user and system characteristics are fixed for the following analyses. The remaining necessary parameters are varied within the different analysis and are explained separately.

Temporally differentiated results

The temporally differentiated analysis takes an electric storage with a gross capacity of 5 kWh into account. The parameter set for a lithium battery is integrated. The electricity demand of the 3 residents is implemented with a specific electricity demand of 1,379 kWh/(person·a). The ratio of electricity to heat demand of the building can be taken as a benchmark for system performance comparisons. The analysed building is characterised by a power to heat ratio of 0.162.

The field of operation of the thermal and electrical storage is indicated in **figure 2**. The daily averaged states of charge of both systems are illustrated over one year. In addition to that, the average outside temperature is plotted to derive potentially interconnections.

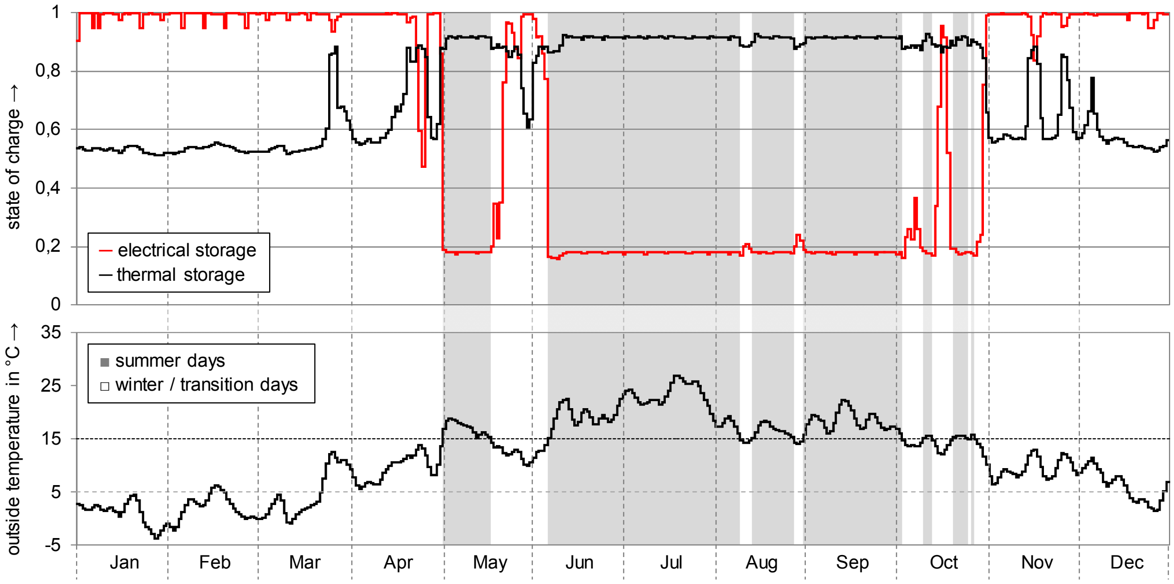

Figure 2: Daily averaged state of charge profiles for the thermal and electrical storage based on the additionally plotted smothered daily averaged outside temperature

With regard to the previously mentioned heat-controlled operation strategy, the state of charge of the thermal storage does not fall below the minimal state of charge threshold. This guarantees the availability of the reserve capacity for domestic hot water demands. A correlation between the state of charge of the thermal storage and the smothered daily outside temperature is identifiable. Mainly during the winter period (on days with an outside temperature of less than 5 °C) the CHP unit is often not able to cover the total heat demand and the AUX is forced to switch on. This can be derived from the low state of charge with respect to the operating strategy. During the summer period (on days with an outside temperature of more than 15 °C) the CHP unit is able to deliver the demanded thermal energy. Consequently the state of charge of the thermal storage is constantly at a high level. During these periods the CHP operation status switches between on and off comparatively often and the AUX is (at least theoretically) not required. During the remaining transition period the state of charge is varying between a high and low state which indicates a combined operation of the AUX and the CHP unit.

In contrast to the performance of the thermal storage, the electrical storage can be described due to a nearly oppositely performance. In time periods of constant CHP operation, the CHP system delivers more electricity than required. The electrical storage is operating at a high state of charge. During the summer period with a fluctuant CHP operation, the delivered electric energy of the CHP cannot meet the energy demand. Consequently the field of operation of the electrical storage is shifted to a lower state of charge range of the storage.

Out of these performance analyses, qualitatively output can be derived for variate analysis. A correlation between the CHP and object characteristics is expected. With regard to the assumed operating strategy, an optimisation of the electrical CHP self-use ratio and the electrical demand coverage degree can be estimated by different actions. A potential for long-term heat storages to enlarge the CHP operation time within the summer period on the one hand and for long term electrical storage to shift surplus electricity from the heating period into the summer season on the other hand can be derived for the analysed case. Due to variation of the power to heat ratio of the building or CHP unit, a better understanding of the influencing parameters can be achieved. The derived knowledge may lead to further optimisation potentials to reach a higher self-use ratio or degree of demand coverage.

Parameter variation results (variate analysis)

With regard to the results of the temporally differentiated analysis above the influence of the object demand characteristic is evaluated. Therefore the object related power to heat ratio is varied from 0.05 to 0.45. Furthermore the influence of an electrical storage is evaluated. The parameter variation has been executed without an electrical storage (0 kWh) on the one hand and an installed electrical gross capacity of 5 kWh on the other hand. A comparison of a batch of temporally differentiated results does not make sense; therefore the self-use ratio and the electrical demand coverage degree are plotted in **figure 3**. The thermal storage performance is equal to the plotted profile in **figure 2**. The heat-controlled CHP performance is not affected, because the heat demand profile has been set as constant.

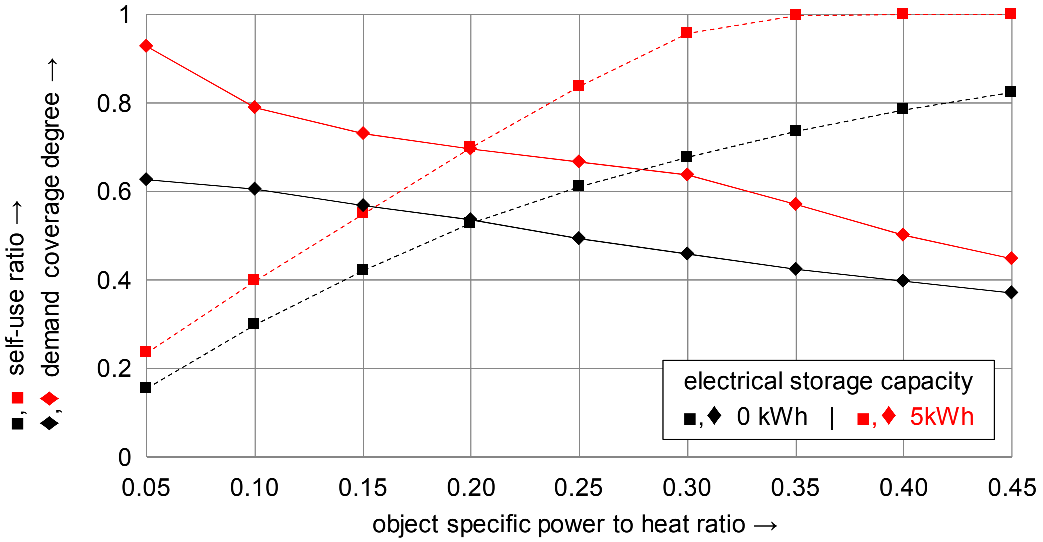

Figure 3: Electrical self-use ratio and demand covering degree plotted over the building related power to heat ratio with a varied electrical storage capacity from 0 kWh and 5 kWh

The influence of the building related power to heat ratio on the electrical self-use ratio can be derived directly. An increase of the power to heat ratio of the building leads to a higher self-use ratio. This correlation can be explained due to the relation between the electricity supply of the CHP unit and the electricity demand especially in the winter period (with a continuously CHP operation). Due to an integration of an electrical storage the self-use ratio can be enhanced. The building specific electricity demand is temporarily higher than the electrical power of the CHP unit, even if the overall electricity demand is very low. By implementing an electrical storage the electricity demand can often be covered by a combination of the electric CHP and battery power output.

An interconnection between the power to heat ratio of the building and the degree of electrical demand coverage can furthermore be derived. The degree of coverage decreases with an increase of the power to heat ratio, because the increase of the self-use ratio is not proportional to the increase of the total electricity demand. Analogous to the influence on the self-use ratio an integration of an electrical storage leads to an enhancement of the demand coverage degree within the analysed parameter range.

Conclusions and outlook

Various parameters influence the optimised interconnection between the object and end-user specific energy demand, the CHP unit and AUX performance and the integrated thermal and electrical storages. The influence of the building related power to heat ratio in combination with a fixed CHP system and a heat-controlled operating strategy has been evaluated. Additionally correlating potentials for electric storages have been examined. One major outcome is high optimisation potential of the CHP performance within transition days. An enhancement of the electrical self-use ratio and the degree of demand-coverage can be realised by various actions.

Beside long-term energy storages, variable and potentially adjustable CHP unit specific power to heat ratios and heat-controlled modulation ranges for CHP units have been identified as optimisation potentials. The development of an optimised control strategy with regard to a synergetic interconnection of all sub systems is considered as a main aspect for further research to exploit the complete potential of electrical storages.

Acknowledgement

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