BUILDINGS AS ACTIVE COMPONENTS FOR GRID STABILITY

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ABSTRACT

A successful energy transition depends on storage options in order to ensure power supply stability under a fluctuating generation of a growing share of renewable energies (RE). Battery storage is expensive and raw material intensive and therefore not suitable as a sole solution. Surplus electricity may easily be converted to heat, which can be stored inexpensively for a short term. With such simple Power-to-Heat or P2H solutions, lack of electric power cannot be offset by conventional heat storage. However, if a building or an urban quarter is heated by means of cogeneration, so-called Combined Heat and Power (CHP), or heat pumps (HP), the operation can be adjusted in such a way, that the building itself, i.e. its massive structure, serves as heat storage. Electricity generation and consumption is adjusted to the requirements of the grid (reactive power control). For the supply of a Berlin quarter, built in the 1950s and equipped with a district heating network and a CHP plant, the feasibility of the concept could be proved using dynamic building simulation as the analysis tool. Sixteen percent of the total heating consumption may useably be stored and extracted from the building structure. In absolute numbers: 73 MWh/a heat can be buffered corresponding to 34 MWh/a balancing electricity. For each square meter of living area, 3.7 kWh electrical balancing energy can be buffered in the building's thermal storage capacity. Nothing else is required than a re-programming of heating and possibly cooling controls. No capital investment is needed. Well insulated and more massive structures could show a proportion of 27% of such shifted heat.

INTRODUCTION

This paper describes a simulation analysis concerning the usability of the thermal capacity of building structures as active storage components in a smart grid. The work was carried out in the framework of the project ProSHAPE (ProSHAPE 2016) which deals with further development of electricity pricing models using smart building technologies. Practical testing of the technologies developed was done within an existing Berlin housing quarter consisting of six buildings with a total of 224 apartments and roughly 9100 m^2 of living space. The buildings are connected by a district heating network, including a cogeneration plant (CHP plant). It

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was one of the project objectives to assess whether and to what extent heat can be stored in the building and thus a temporal shift and adjustment of the heat supply could be possible while staying within the thermal comfort limits of the residents. For this purpose, the quarter was modeled thermally. Dynamic simulations should determine the magnitude of the thermal energy shifting potential taking advantage of the inertia of the building. Provided the CHP plant operating times could be adjusted in such a way that its electricity production is partially shifted to times with high electricity loads, the thermal building storage could replace an electrical battery storage at virtually no costs.

In addition to the CHP plant system, simulations were also carried out using a compression heat pump instead of the cogeneration plant. Consuming rather than producing electricity reverses the adjustments in the controls operation, while the general idea stays the same.

Finally, the quarter was virtually rebuilt in the simulation model in order to reach a maximum possible massive structure, i.e., storage capacity, and it was well insulated in this model in order to reduce thermal losses as far as possible. With this simulation, it is expected to achieve good estimates of the technical potential of the grid-interactivity.

BACKGROUND

With further expansion of renewable energies, there will be increasing fluctuations in the supply of electrical energy. Load management and storage are the answers for the future. Besides pure electric (battery) storage, thermal storage is gaining importance. Storage options, which exist per se and thus require no further investments are of particular interest. Buildings with their structure are such options, since walls and ceilings form a heat storage capacity by their construction material such as stone or concrete. Lüking and Hauser estimate the thermal capacity of Germany's residential buildings to about 1 TWh/K (Lüking and Hauser 2011).

In the EUREF research campus "Mobility2Grid," research is carried out on the implementation of a sustainable energy and mobility development in urban areas through the utilization of renewable energy sources (Raab et al. 2015). In this context, buildings will be classified as components of an overall energetic system, and can actively contribute to control the energy consumption in dependence of energy production and thus smooth load fluctuations (Riediger et al. 2016). Other researchers work on the analysis and comparison of grid based reference parameters and the definition of an evaluation number in the context of grid-interactivity of buildings (Klein et al. 2014).

The ProSHAPE project provides the opportunity to analyze the grid-interactivity of buildings under realistic conditions of an existing quarter and a district heating system fed by a CHP plant.

SIMULATION

A comprehensive model of the quarter's buildings was created for the simulation environment IDA ICE 4.7 (EQUA 2016). As opposed to a static calculation, such as for the creation of energy bills, a dynamic building simulation as performed in IDA ICE takes into account the thermal capacity of the building, which is essential for the dynamic behavior of the building, because of its heat buffering and thus temperature gradients smoothing effect. This leads generally to lower heating and cooling loads, that beneficially—both technically and financially—affects the plant size. Another advantageous aspect of dynamic simulations is the choice of simulation time steps of any length allowing investigations of different natures. Load calculations typically require time steps in the order of 1 hour. HVAC control strategy investigations, however, are usually performed in one or two minute time steps. IDA ICE uses dynamically adapted time steps.

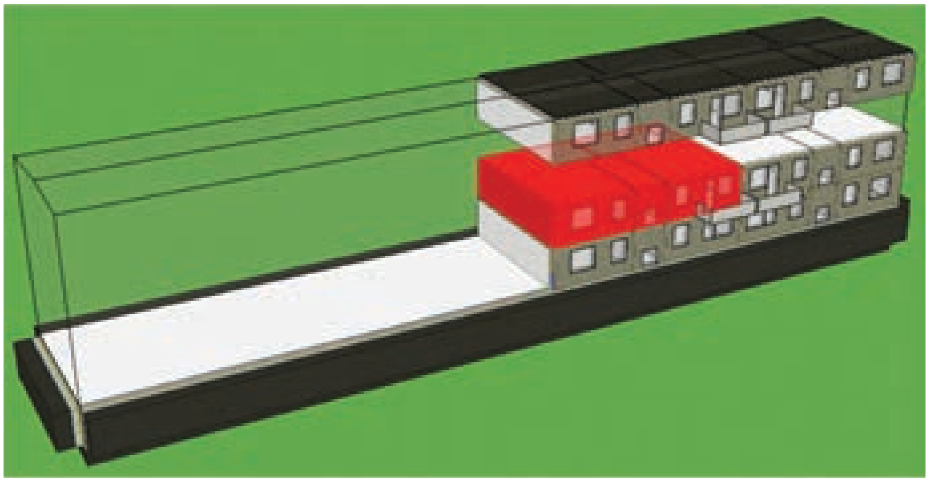
IDA ICE works with a 3D building model and is capable of reading in CAD and also Building Information Modeling (BIM) data. Heat transfer through walls is modeled using finite elements, which generally leads to longer computation times than models based on algebraic transfer functions, such as used in TRNSYS (Klein 2007). The longer computation times of IDA ICE can be partially offset through the dynamically adapted simulation time steps. The finite element method conducts thermal heat transfer and storage calculations for every single material used in the walls using the physical properties conductivity, density and specific heat capacity, thus providing the capability to model thermal mass storage effects with high accuracy.

The subject of the investigations is a quarter in Berlin shown in Figure 1. All buildings are of a prefabricated slab-construction type called the Q3A series of 1961, typical for former East-Germany. As a result of this serial construction approach, the arrangement of several apartments within the buildings shows up repeatedly. Such layouts are called sections. Three different sections are distinguished, which are each composed of two or three apartments, and in repeating themselves make up the entire quarter. The zoning of the model is done considering a whole apartment as one zone. Energy requirements simulated that way as compared to a room-to-room-zoning in a pre-investigation showed a difference of about 1%, which was considered small enough to keep to the large zones. Besides that, power consumption profiles (see below) are generally available only on an apartment rather than a room level. A breakdown into rooms would be purely speculative. Concerning the technical equipment, an optimally dimensioned CHP plant and a buffer heat storage in the actually installed dimension were part of the model.

In the IDA ICE building model, the sections with their apartments (zones) are placed according to the built reality. Multiple sections of the same type are connected to complete building blocks. Some of the sections show up repeatedly in a similar way (i.e., orientation, neighboring sections) according to their location in the block. These need not be a repeated calculation in the total simulation. Thus, only 24 sections must be modeled in order to simulate

FIGURE 1. Satellite view (left, source: Google Earth) and site plan (right, source: district government Berlin-Pankow) of the quarter under investigation.

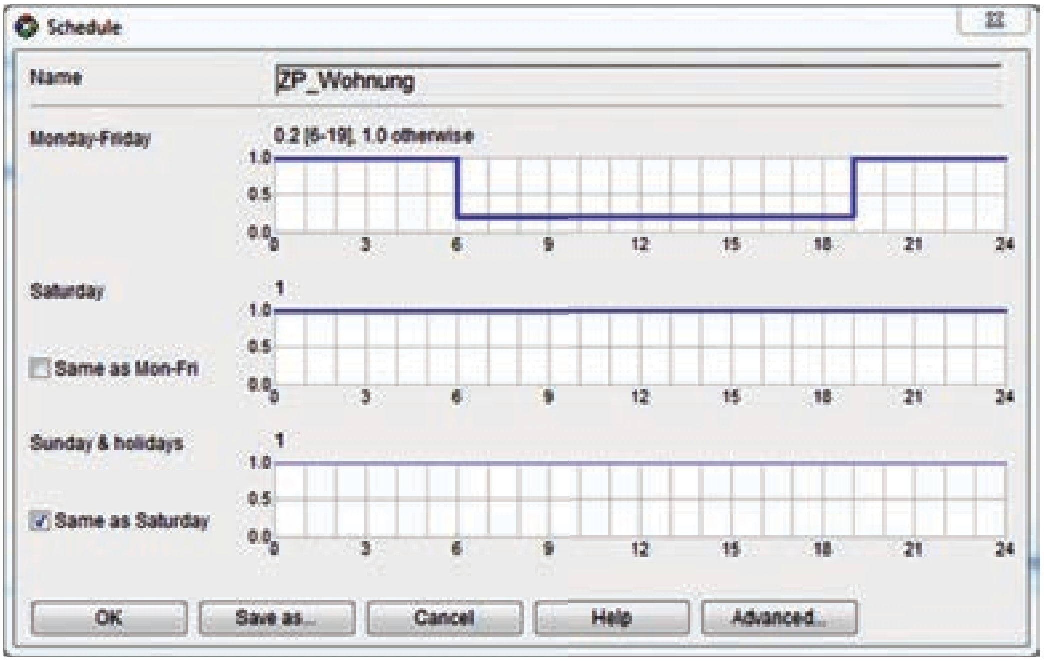
FIGURE 2. Examples of building sections to be modeled. One of them is marked red.



a total of 96 sections. Figure 2 may serve as an illustration: one typical section is colored in red. It is surrounded by other sections to the left, to the right, to the top and to the bottom. In this way, the section shows up a total of 12 times. Other sections may miss one of the neighboring sections being adjacent to the ambient, the roof, or the basement.

Physical characteristics of the building materials are given in Table 1. Double-glazed windows with a u-value of 2.9 W/(m^{2}K) are used. Regarding the usage, profiles for the tenant presence and the power consumption are set in the model. The normalized presence schedule shown in Figure 3 is used for each apartment. For the power consumption, the normalized

FIGURE 3. Presence schedule as modeled in the simulation.



Schedule

Name ZP_Wohnung

Monday-Friday 0.2 [6-19], 1.0 otherwise

Saturday 1

☐ Same as Mon-Fri

Sunday & holidays 1

☑ Same as Saturday

TABLE 1. Material characteristics.

		Thickness m	Thermal conductivity W/(m K)	Density kg/m^3	Heat capacity J/(kg K)	U-value W/(m^2 K)
Outer wall 390mm	Plaster	0.005	0.8	1900	790	
	Recycled tile concrete	0.3	0.64	1600	1000	
	Insulation	0.08	0.035	20	1450	
	Plaster	0.005	0.8	1900	790	0.3405
Roof insulation 60mm	Insulation	0.06	0.035	25	1450	0.5307
Ceilings 185mm	Carpet	0.005	0.18	1100	920	
	light-weight concrete	0.03	0.15	500	1500	
	Concrete	0.15	1.7	2300	880	2.058
Internal Wall 190mm	Plaster	0.005	0.8	1900	790	
	Recycled tile concrete	0.18	0.64	1600	1000	
	Plaster	0.005	0.8	1900	790	2.156
Basement ceiling 245mm	Carpet	0.005	0.18	1100	920	
	light-weight concrete	0.03	0.15	500	1500	
	Concrete	0.15	1.7	2300	880	
	insulation	0.06	0.035	42.5	1450	0.4545

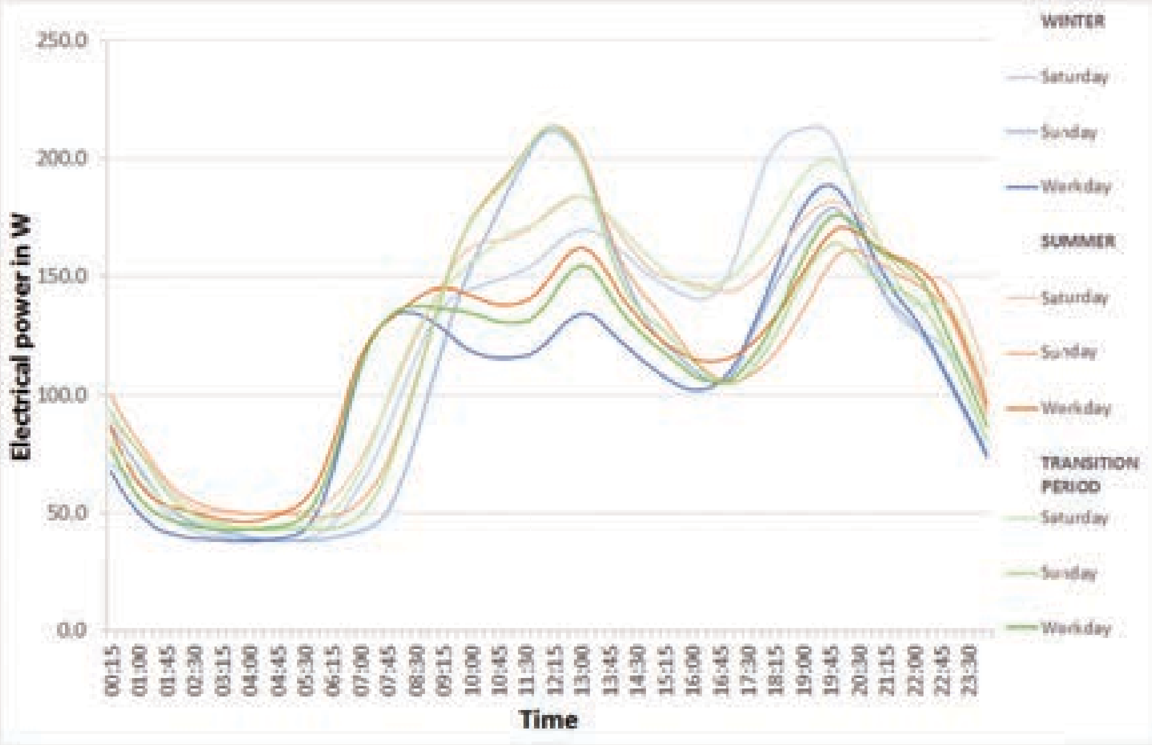
standard load profile (SLP) H0 of the German Federal Association of energy and water management BDEW shown in Figure 4 is used (see, e.g., KommEnergie 2016). An annual consumption of 1000 kWh is assumed in the small apartments in section 2. For all other apartments, the annual consumption is set to 1600 kWh.

Window ventilation is simulated on the basis of CO_2 content in the room air such that windows are opened when the CO_2 concentration exceeds 900 ppm and closed after falling below 600 ppm.

Climate data of the German Test Reference Year No. 4 are used (DWD 2014).

For an operation of the CHP adapted to changing loads, the heating control is adjusted so that the CHP is operated longer than required thermally at times of high loads and shorter at times of low loads. In the base case the room air temperature is set to 21°C between 6:00 and 22:00 and set back to 18°C from 22:00 to 6:00. A control is provided for the power-oriented mode of CHP operation according to the standard load profile (SLP): during periods of high

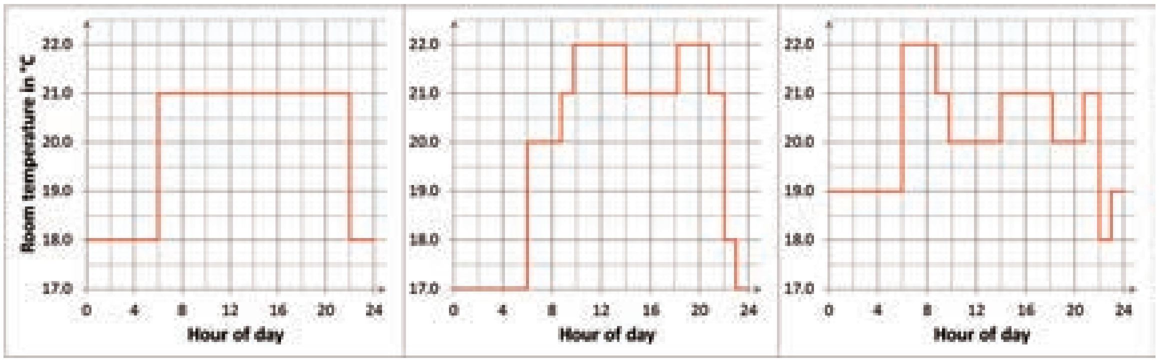
FIGURE 4. Normalized standard load profile (SLP) H0.



electricity demand it is permitted to heat to a temperature of 22°C (+1 K compared to the base case). In periods with low power requirements, lower temperatures are admitted (–1 K compared to the base case). The periods are set arbitrarily as follows: high power requirements: > 150 W, low power requirement: < 100 W, each normalized to 1000 kWh/a annual consumption as given in Figure 4. A compression heat pump (HP) would be operated vice versa for similar effects.

The resulting set temperature profiles for the base case and the case with CHP control according to SLP on a winter Sunday are shown in Figure 5.

FIGURE 5. Temperature setpoints in the base case (left) and controls according to SLP (center: CHP operation, right: HP operation) on a winter Sunday.



RESULTS

All of the following result plots compare the base case (“CHP_Base”) and the power-oriented case according to SLP with CHP operation (“CHP_SLP”).

For the complete simulation of the residential quarter, 24 simulations are carried out for each examination variant: apartments of the type section 1 and section 3 in each 9, type section 2 in 6 positions of the building volume. The sections are divided into zones corresponding to one apartment as mentioned above. The important figures to be determined are the amount of heating energy, the amount of shifted heat in the “CHP_SLP” case into and out of the structure, and the modified operating times of the CHP. The results are given in absolute and area specific numbers, the displaced heat is specified also as a percentage to the total heat. From this information, general potential estimates for the given conditions can be derived. The heating energy demands of the individual sections are compared with the average value of the overall quarter in order to select a representative section. The individual values vary from 4434 kWh/a to 10517 kWh/a. The overall quarter value amounts to 6987 kWh/a. The section showing an individual heating energy demand of 6876 kWh/a comes closest and is therefore selected as a representative section. Its results are shown here for the following example time series, graphical representations and interpretations, thus avoiding an abundance of very similar looking diagrams of all 24 simulated sections. The overall quarter values, however, result from the complete set of sections simulations.

Temperature and heating power during transition periods with CHP operation

The following diagrams contain the time series of the operational (perceived) room temperature for CHP_Base (black) and CHP_SLP (red). Also shown is the ambient air temperature (blue) and (informative as indirect measure of ventilation), the CO_2 concentration (green), which is not the object of analysis here. The dynamics are illustrated for a selected week in the transition period (Figure 6).

Analysis: In general, there are more differences recognizable during weekends compared to weekdays. This is due to the fact that on weekdays SLP values of 150 W defining high loads almost only occur in the early evening hours. There is only a short period of time during the day around 12 noon with power-oriented CHP control. During the weekends, longer periods over the course of the day with CHP_SLP control are observed. The times with loads below 100 W can be observed as well, especially in the morning hours when the CHP remains off for a longer time based on the permissible temperature reduction.

Figure 7 shows the heating power time series in the same week. It shows how the required heating powers differ—depending on the mode of operation—and how they cause the differences in temperature time series. It also becomes clear here that the weekend days have a higher potential than the weekdays.

Energetic impacts with CHP operation

The sorted annual load duration curve of the heating power in Figure 8 gives a visual indication that the CHP_SLP case has a slightly increased heating demand. Nevertheless, the curves are very close to each other, thus indicating visually that the shift of thermal energy does neither result in different power nor in substantially different energy demands.

The CHP_SLP case leads to an increased heating demand of 2.4% in the entire district. This is firstly due to increased heat losses, and secondly to slightly higher average room air temperatures.

FIGURE 6. Operative Indoor Temperatures in a transition period week (Monday, October 10 through Sunday, October 16): CHP operation for basis and SLP control.

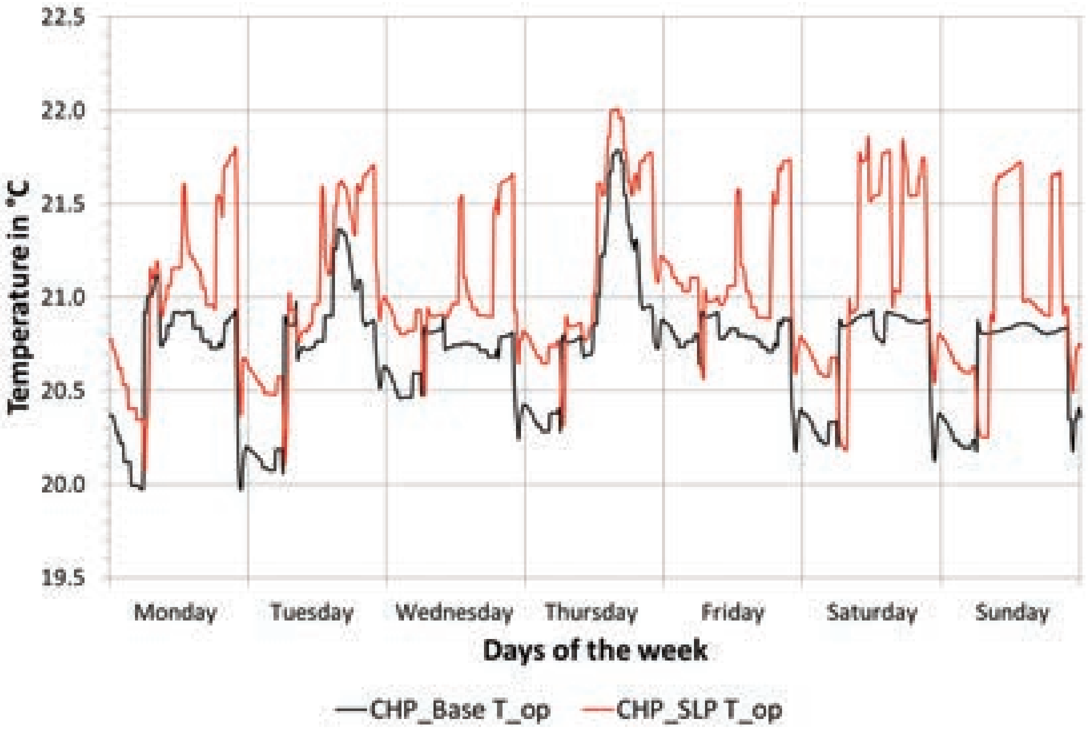


FIGURE 7. Heating power in a transition period week (Monday, October 10 through Sunday, October 16): CHP operation for basis and SLP control.

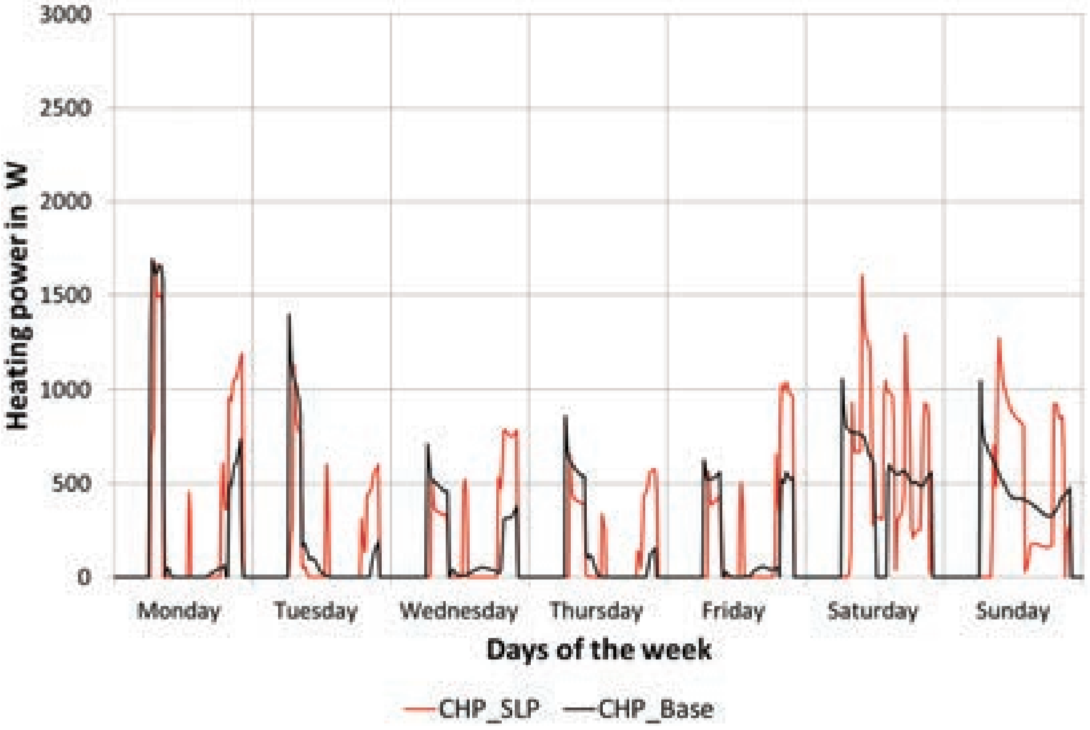
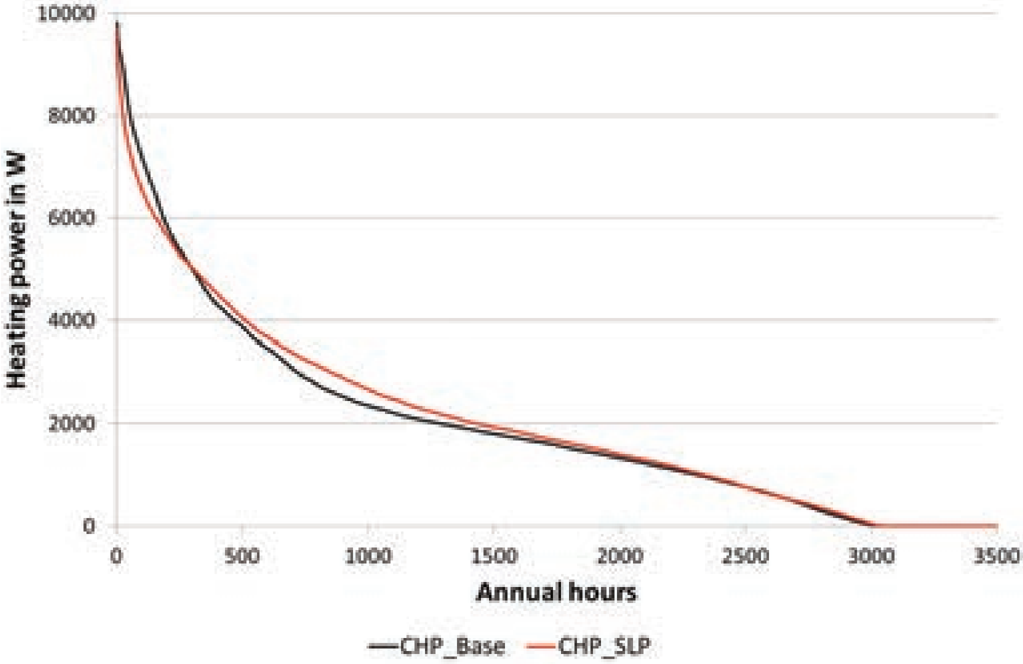


FIGURE 8. Sorted annual load duration curve of the heating power: CHP operation for basis and SLP control.



The carpet plot in Figure 9 gives an annual and daily overview of the changing operation times. In blue, the times are marked where the cogeneration plant is operated in any case, independent of the control strategy. Times at which the CHP runs in the CHP_SLP operation mode only are indicated in green. At these times, additional heat is shifted into the structure. The opposite case is marked in red. Here, heat is removed from the structure. Hours of operation below a 500 W storage buffer threshold are shown in gray. Analyzing this visual result in detail numerically for all sections on both an absolute and area specific basis leads to the following condensed results: Shifted heat into the structure accounts for around 13%–20% of the basic demand, withdrawn from the structure are 11%–18%, i.e., about 2% less. That equals

FIGURE 9. Carpet plot of CHP operation times.

roughly the surplus consumption of heat. The spreading of this percentage data is in large part attributable to the different absolute amounts of heat needed in different sections and their locations. Area-specifically, about 8–10 kWh/m^2 are shifted into the structure and about 6–8 kWh/m^2 are withdrawn. Overall, 16% of the total heating consumption may be usable, stored and extracted from the building structure. In absolute numbers: 73 MWh/a heat can be buffered corresponding to 34 MWh/a or 3.7 kWh/(m^{2}a) balancing electricity.

Results for the use of a heat pump (HP) instead of a CHP plant

While the grid-beneficial operation of a CHP plant leads to additional operation at times with power shortage in the grid (or here: high electricity loads) and reduced operation at times with an excess of electricity (low electricity loads), a compression heat pump would be operated in an opposite way for similar effects, e.g., at times with low electricity loads, i.e., excess grid electricity, the heat pump could run at low cost and produce excess heat to be buffered in the building structure, while at times with high electricity loads with high loads the heat pump operation could be stopped as long as there is enough heat available in the structure. For an analysis of a grid-beneficial HP operation, the representative section is simulated with the temperature profile shown on the right-hand side in Figure 5.

All of the following result plots compare the base case (“HP_Base”) and the power-oriented case according to SLP with HP operation (“HP_SLP”).

Temperature and heating power during winter and transition periods with HP operation

The inverse operation behavior of the HP as compared to the CHP system is observable in the temperature and power curves in Figures 10 and Figure 11, especially during the weekend.

FIGURE 10. Operative Indoor Temperatures in a transition period week (Monday, October 10 through Sunday, October 16): HP operation for basis and SLP control.

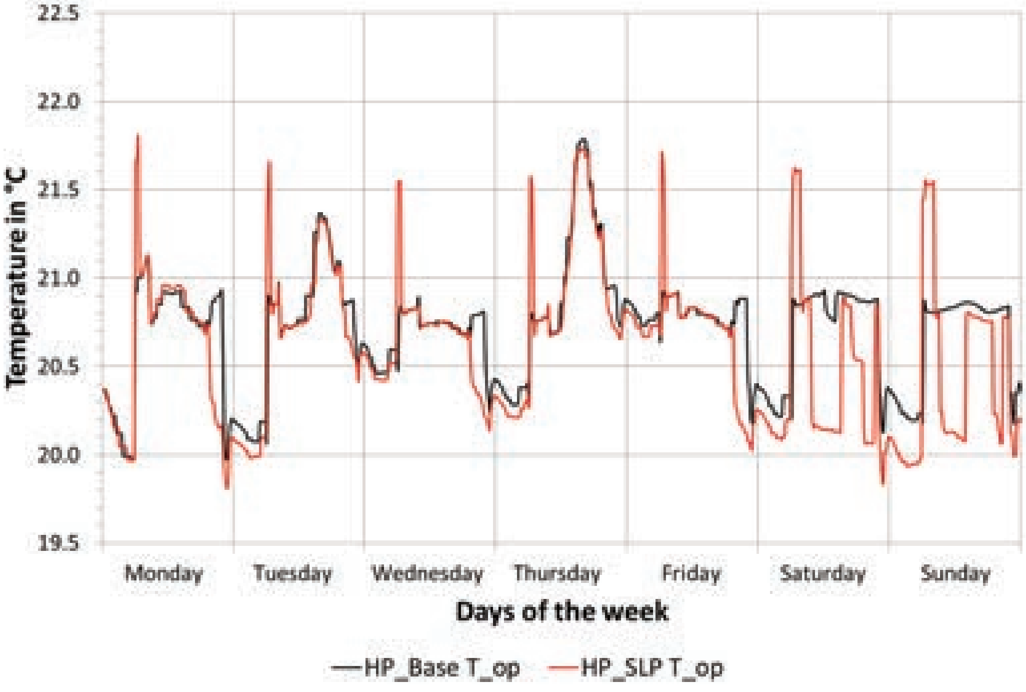
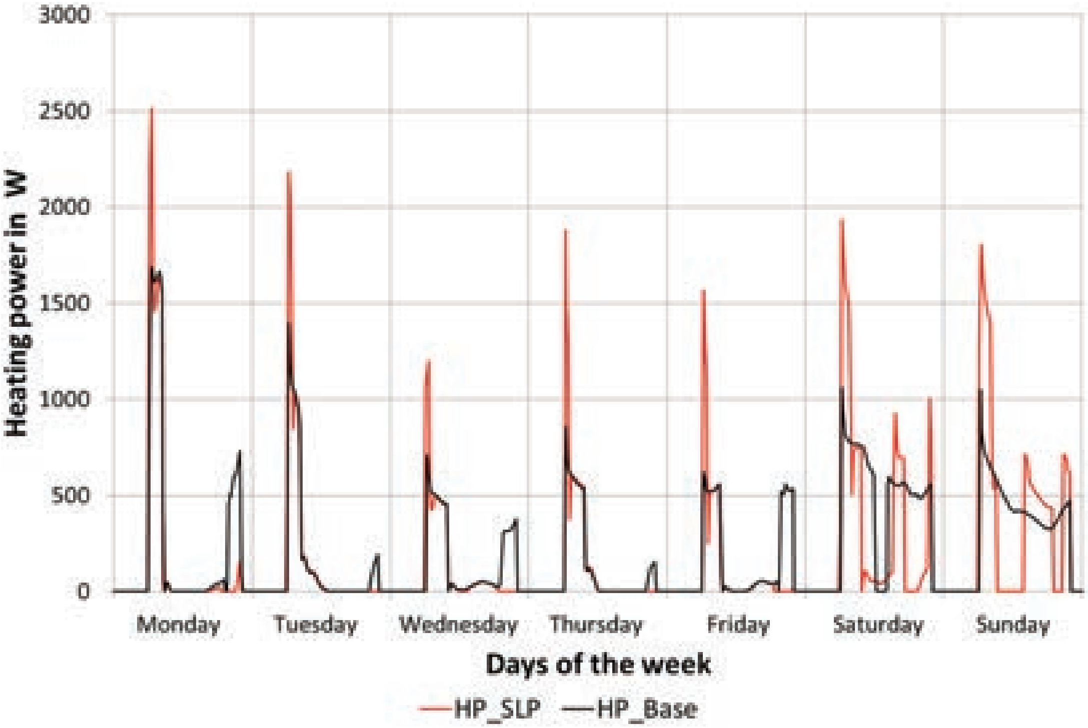


FIGURE 11. Heating power in a transition period week (Monday, October 10 through Sunday, October 16): HP operation for basis and SLP control.



Energetic impacts with HP operation

The sorted annual load duration curve in Figure 12 indicates a somewhat lower consumption of the HP_SLP control as compared to the base control. This is due to fewer hours with room temperatures at 22°C for the selected control strategy. Using other load profiles or grid parameters for the controls might result in a different behavior.

The carpet plot in Figure 13 is to be read in an analogous way to Figure 9. It illustrates well the inverse operational behavior of the HP_SLP case in comparison to the CHP_SLP case.

Results for a heavy, well insulated design

The representative section is "rebuilt" in such a way, that the thermal storage capacity increases and losses are reduced, according to Table 2.

Windows are triple-glazed with glazing u-values of 0.7 W/(m^2K) and frame u-values of 0.9 W/(m^2K).

The amount of heating energy in the base case compared to the actual construction is reduced to 45% and amounts to 22 kWh/(m^2a), which is extremely low. In CHP_SLP mode, this value is 5% higher, while it is 0.6% lower in HP_SLP mode.

The share of shifted heat into the structure is much higher: In CHP_SLP mode 32%, in HP_SLP mode 22% of the total heating energy may be buffered in the building's structure (compared to 20% and 15%, respectively, for the existing building substance). Although the heating is reduced by more than half, the specific shifted energy decreases only from 9.7 kWh/(m^2a) to 7.1 kWh/(m^2a) in CHP mode and from 7.2 kWh/(m^2a) to 4.8 kWh/(m^2a) in HP mode, respectively.

FIGURE 12. Sorted annual load duration curve of the heating power: HP operation for basis and SLP control.

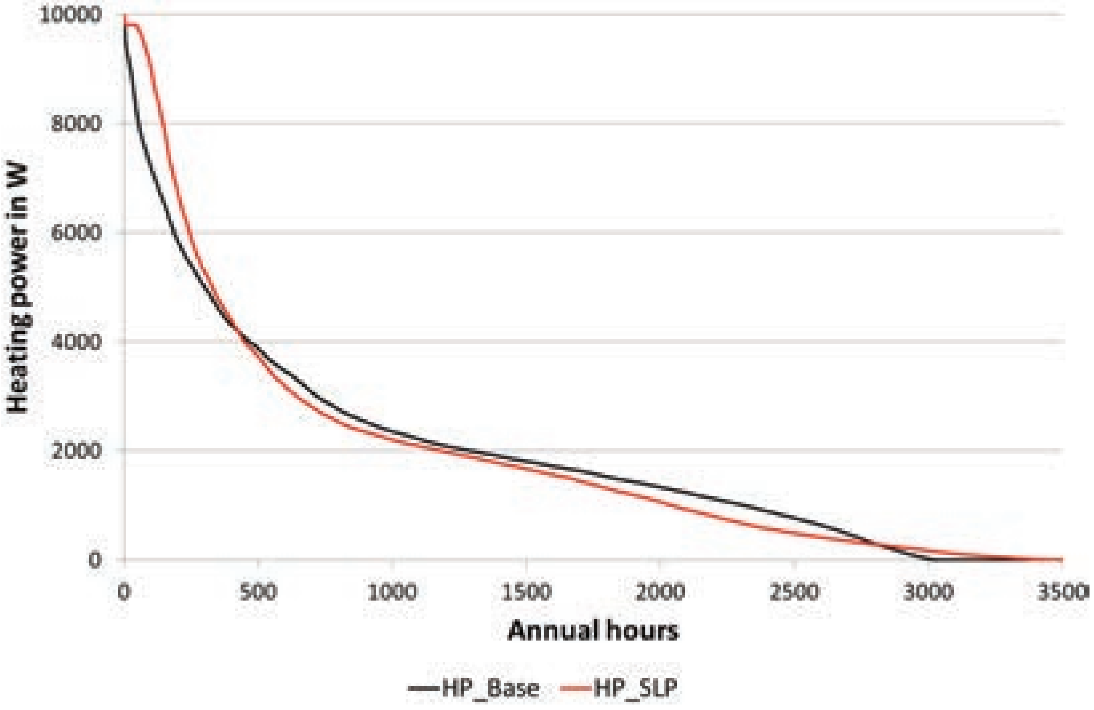
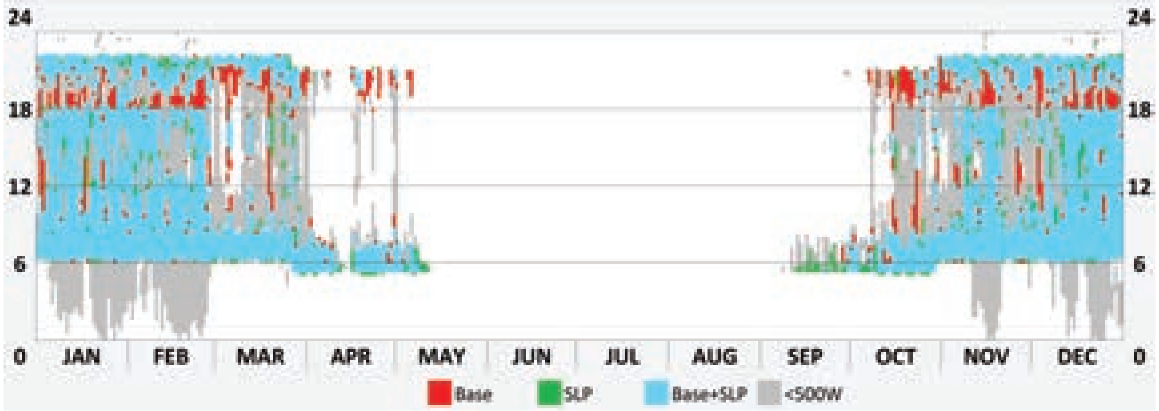


FIGURE 13. Carpet plot of HP operation times.



SUMMARY AND CONCLUSIONS

The results presented here show clearly that a grid-interactive useful operation of buildings is possible by taking advantage of the thermal capacity of the building structure. This is particularly true for existing buildings, i.e., not only buildings which are specially designed for that purpose, such as the buildings in the Berlin residential quarter, which were the subject of the investigation.

TABLE 2. Material characteristics for heavy, well-insulated design.

		Thickness m	Thermal conductivity W/(m K)	Density kg/m^3	Heat capacity J/(kg K)	U-value W/(m^2 K)
Outer wall 450mm	Plaster	0.005	0.8	1900	790	
	sand-lime brick	0.24	1.3	2200	1000	
	Insulation	0.2	0.035	20	1450	
	Plaster	0.005	0.8	1900	790	0.1644
Ceilings 185mm	Carpet	0.005	0.18	1100	920	
	Concrete	0.18	2.1	2400	1000	3.527
Internal Wall 190mm	Plaster	0.005	0.8	1900	790	
	Concrete	0.18	2.1	2400	1000	
	Plaster	0.005	0.8	1900	790	3.728
Basement ceiling 245mm	Carpet	0.005	0.18	1100	920	
	Concrete	0.18	2.1	2400	1000	
	insulation	0.06	0.035	42.5	1450	0.5006

Grid-oriented operation modes of CHP plants and heat pumps can be realized at no significant additional cost. Thus, a free potential of grid interactivity, comparable to cost-expensive batteries, can be developed in all cases where decentralized heat generation by CHP and/or heat pumps is available.

This project only considers heat. Therefore, grid interaction takes place only during winter and transition periods. If cooling can be considered as well, compression or absorption refrigeration machines can be controlled in a similar way during summer. Thus, a year-round grid interaction becomes possible. This will be the subject of further investigations.

For a more detailed analysis, it is also important to keep in mind that the work presented here contains a number of systematic simplifications:

- For the operation control, a standard load profile for residential use was applied. The real load profile may vary substantially, depending e.g., on the type of building usage. Ideally, a prognosis of the load profile should be applied.
- The thresholds applied for high or low loads are set arbitrarily.
- A general grid-oriented operation should consider not only the local loads but also the grid quality as a whole.

- The tolerance bands are set arbitrarily to ±1 K. It is assumed but not yet proven that this band width is acceptable with respect to thermal comfort. Smaller tolerance bands would show smaller effects. Roughly estimated, the amount of shifted heat would be—probably not completely—halved in case of a halved tolerance band of ±0.5 K. This would still be a significant amount of shifted heat.
- The simulations do not include any models of technical equipment, but look at the heat demand in the apartments. Questions of heat transfer are not addressed.

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