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Energy storage and integrated energy approach for district heating systems

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Abstract

This paper deals with the potential of using the thermal storage capacities within local district heating systems to balance the low and medium voltage grids by the use of heat pumps (HP) and combined heat and power (CHP) plants. The state-of-the-art of district heating systems as well as the coupling of the heat and power grid is discussed. The research work of the project NATAR (local heating grids with lowered temperature as provider of balancing power) and the local heating grid of Dollnstein, which serves as an use case, are further described. A first analysis of measured data of the district heating system indicates an optimisation potential regarding to the control strategy of the combined heat and power plant as well as the usage of the available thermal storage capacities.

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1. Introduction

District heating systems include three different parts: Heat production, distribution and consumption. The structure of the producers as well as of the consumers may be highly different. The temperature level of heat distribution varies depending on the requirements, e.g. low-temperature heat or steam. Local district heating systems are able to integrate renewable energies and combined heat and power to the heat supply of rural communities. This is particularly advantageous where refurbishment and installation of solar equipment is limited, e.g. due to the historic character of the buildings. In the southern part of Germany, many district heating systems utilize biomass for the generation of heat, either wood chips or biogas. A further dissemination of these systems is limited by two facts: On the one hand, the heat losses of the grid must be minimized in order to be economical. Therefore, the density of consumers per length of the grid must not fall below a certain limit. On the other hand, the local biomass potential is limited and long distance imports are neither ecologic nor economic [1,2]. In order to reduce the heat losses in an existing heating network, reducing the temperature and therefore the heat losses to ambient is a promising approach to optimise such a system. Low-exergy district heating grids are operated since 1990s. Under certain conditions, these belong to the

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most ecological and economical supply structures [3,4]. The structures of consumers contain typical buildings with modern energy-efficient building standards. Therefore, it is feasible to operate heating grids throughout the year on a basic temperature level. At consumer level, heat pumps (HPs) use that low-temperature level to provide the heat according to the consumers needs. The successful implementation of a central, high temperature heat pump has been demonstrated once [5]. However, this district heating grid does not have the opportunity to reduce the temperature in summer. New concepts are suggesting variable grid temperatures. This approach is quite promising, but still subject of ongoing scientific research projects. Reducing the heat losses and providing a basis for integrating low-temperature heat sources are the main reasons to install local district heating systems with variable temperature levels.

2. Background

Due to the turnaround in the energy policy, the grid has to integrate more and more decentralized and fluctuating power producers as photovoltaics or wind power plants. This leads to higher stress within the power grid. Storage devices are therefore needed to reduce the phases of high stress within the power grid. Beside of, storing electrical energy, the store of sensible or latent heat is an alternative. Local district heating systems have large storage capacities, due to the grid itself and installed storages. If both, coupled electrical producer and coupled electrical consumer exist within the system, there is the potential of multiple coupling between the heat and power grids. The capacity of the heating system may be used to balance the electric demand and supply [6]. Heat pumps, which use electric power to produce heat, may provide negative balancing energy and use them more efficient as electrical heaters. Combined heat and power (CHP) plants can provide heat and positive balancing energy. Both opportunities depend on the installed storage capacities and the status of the system. The integrated operation mode of multiple producers of heat and power leads to a high system complexity. To achieve reliable, efficient and effective control strategies, prior investigation and optimisation is necessary.

There have been some investigations and projects about CHP plants providing positive balancing energy within local district heating systems integrating heat storages [7,8]. The TU Dresden investigated the integration of both, heat pumps and CHP units, using a fictive district heating grid. Mainly the project included computational calculations to optimise the operation modes of the CHP units and of the heat pumps within the district heating system. The research proved that the three actions,

- increasing the temperature of the buildings,
- storing the heat inside the heat grid
- and controlled charging of the water storage,

could relief the power grid. The project results also included that the common operation of CHP plants and heat pumps is a promising economical approach [9]. These theoretical calculations have to be verified by real measurements.

3. Case study: Installation Dollnstein

Dollnstein is a small village in southern Germany. In 2015 the local heating system with approximately 40 connected consumers has been completed. Dollnstein has implemented one of the first local district heating systems with variable temperatures. Three main hydraulic circuits (School, Thorgasse (TG), Papst-Viktor-Str. (PV)) connect private consumers as well as public buildings with the energy central. Since the supply area in Dollnstein has a diverse structure, including historical buildings, there is a large heat demand on a high temperature level, at least in winter. It is economical not reasonable using power from the grid by the decentralised heat pumps to meet the high heat demand in winter. Nevertheless, to improve the technical efficiency and economic viability, lowering the temperature of the grid during the summer is an attractive opportunity. Figure 1 displays the installed hydraulic system. On the right side, the three circuits connecting the consumers with the energy central are shown. Each consumers heat transfer station contains a heat pump and a heat storage. The energy central contains all other heat producers and storages. The high-temperature storage (HT storage) feeds the heat grid. High temperature storage means within this paper the storage with the higher temperature level up to 80 °C. The solar thermal system, the heat pump, the CHP unit

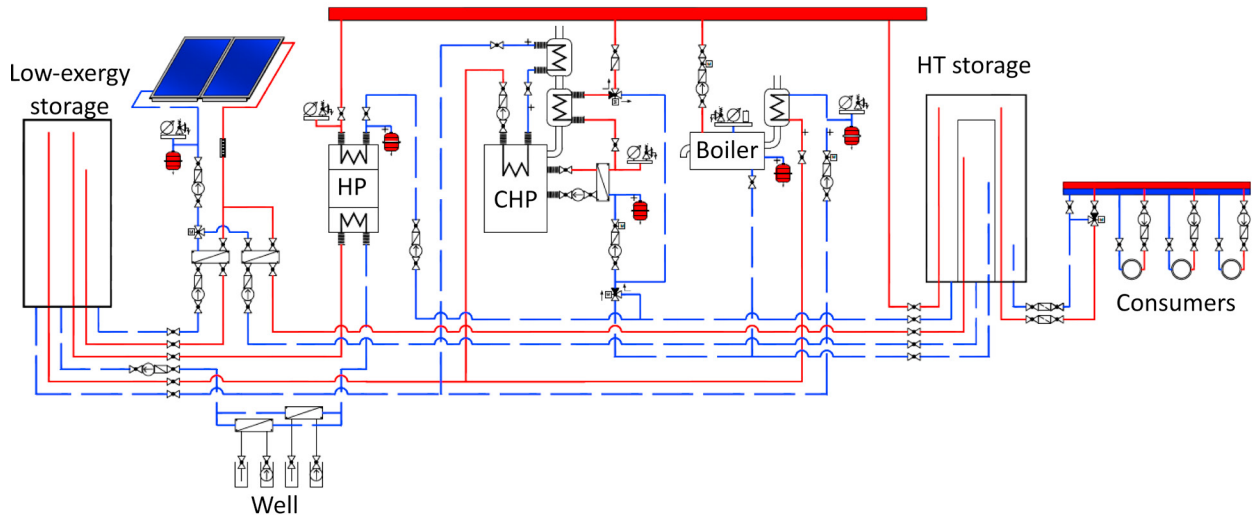


Fig. 1. Hydraulic diagram of the local district heating system implemented in Dollnstein (red lines: supply, blue lines: return) [10]

and the back-up boiler are able to feed the storage on different temperature levels. The CHP unit and the back-up boiler obtain their return flow from the HT storage on lower temperature levels. The solar thermal system may get the return depending on the status of the system from the low-exergy storage or from the HT storage. The heat pump is connected with two supplies and two returns. On the side of the sink (high-temperature level), the HT storage delivers the return and on the side of the source (low-temperature level), the low-exergy storage provides the supply.

The groundwater may feed the low-exergy storage if the return temperature of the heat pump is below the temperature of the groundwater. The ambient temperature determines the temperature within the entire system. Cold weather means a high heat demand and therefore a high operation temperature. Warm weather indicates a low heat demand and low temperatures within the heat grid.

Figure 2 shows the schematic connection of the heating system with the power grid (left side) and the heat grid (right side). The energy central and the decentralised consumer may provide negative and positive balancing energy on different voltage levels. If the line voltage is in the upper range, the central and decentralised heat pumps switch on in order to reduce the stress within the grid. The heat provided by the central heat pump will be stored in the high temperature water storage. Each consumer connected to the grid can use the heat from the storage. The heat, generated by the decentral heat pumps will only be consumed by the single belonging consumers. In this case, the use of the heat pump is much more effective as the use of conventional approaches to heat the systems. The CHP unit switches on if the line voltage is in the lower range. The produced power will stabilize the power grid and the generated heat is stored on different levels. The availability of different heat storage capacities (high temperature storage, low temperature storage, heat grid and decentralized storages) provides the chance to shift the heat from one part to another. In order to organize the loading status of the whole system including every single part, it is mandatory to use the weather and demand forecast as well as a grid capacity forecast. Using such a control strategy ensures the heat supply and helps reducing the stress of the power grid. This energy system is a model project regarding the voltage stabilization of the low voltage grid. Due to multiple parallel grid joint points, it is also possible to stabilize the mid-voltage grid. Also by scaling the investigated energy system to enlarged supply areas, there is a compensation at the mid-voltage level possible.

4. Research agenda

Remarkable features of this project are the multiplicity, the variability and the technical complexity of the heating grid as well as the integrative approach. Combining power and heating grid in a rural environment is the main objective. By coupling both, the power and heat grid, the stress at low- and mid-voltage level can be reduced. As a

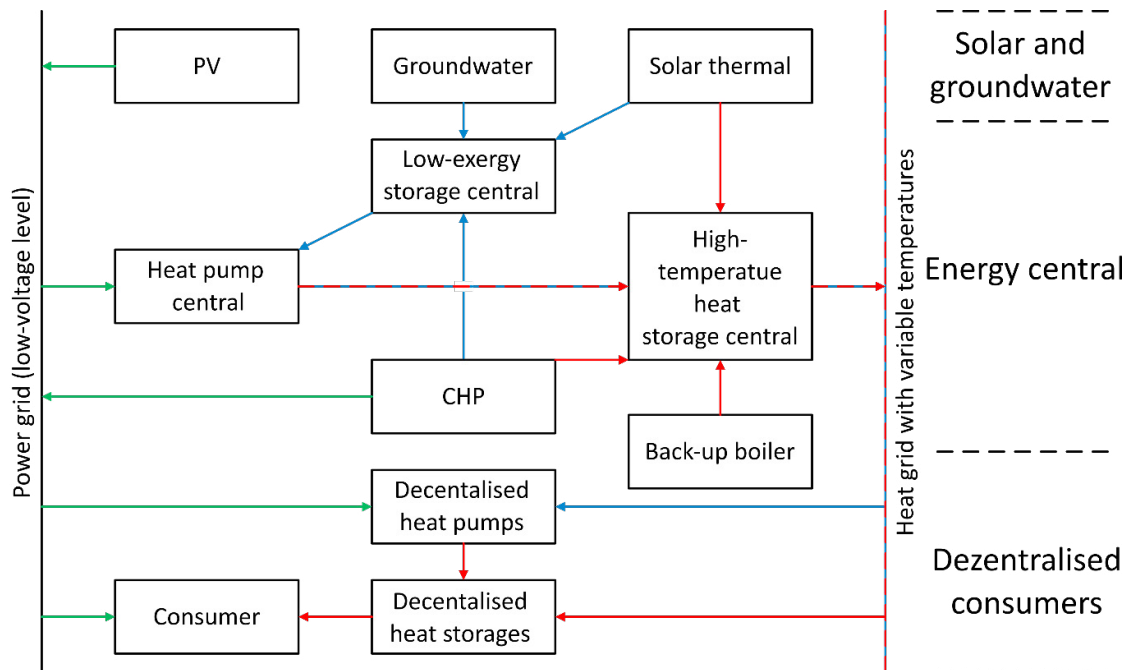


Fig. 2. Principal diagram of the coupled system in Dollnstein including heat and power

consequence, appropriate control strategies stabilize the power grid within the minute and hour domain. Within this research project, the following four work-packages will be assessed.

- **Measurement data acquisition**

The first step is the analysis of the existing heat grid and the previously installed measuring equipment. Subsequently a measurement concept referring to the measurement concept presented in the guideline for measurement concepts in EnEff:Stadt [11] will be developed. An extended measuring concept will be set up, integrated and evaluated. In addition, control requirements for the power grid will be defined.

- **Model design**

In the beginning, an appropriate modelling and simulation tool will be chosen. Afterwards, a computational model will be developed and suitable boundary conditions will be incorporated. All models will be validated subsequently.

- **Optimisation of the operation mode**

The optimisation of the local district heating system is based on the real measurement data and the computational model. The optimisation is divided into four sub parts. First, critical situations within the system will be identified. Second, the house transfer station will be optimised, focussing on the heat pump and its influence to the heat grid. In the third step, the entire local district heat system will be extend with respect to economic and ecologic considerations. Last, control requirements of the power grid in combination with the local district heating system will be considered and optimised.

- **Optimisation of the tariff system**

The idea is to develop a tariff system that meets the requirements of the existing district heating grid at Dollnstein and is beneficial for the providers of heat and power. In this context the control energy market will be considered. It is planned to include an economic model into the simulation model to optimise the tariff system with respect to economic and ecologic effects.



Fig. 3. Temperature profiles of different components for the period from 2016-11-07 to 2016-11-14 (winter) The upper two plots show the temperatures inside the HT storage at different heights, the third plot the supply temperature of the back-up boiler, the fourth the supply and return temperature of the CHP plant and the last one the supply temperature of the heat pump.

5. First Results

Although the project is still in the launch phase measurements are carried out by the operator of the heating grid since the spring of 2016. For this paper the measurement data between March and November 2016 is analysed whereby two typical weeks (one week in winter and one week in summer) are discussed in detail. Fig. 3 shows the storage temperatures, measured in different levels of the HT storage, and the supply temperatures of the gas boiler, the CHP plant and HP as well as the return temperature of the CHP unit from 7th to 14th November. It can be seen that the CHP unit starts as soon as the temperature of the storage is beyond a specific value, which happens in average five to six times each day. This works fine during the most of the time.

Just once in the analysed week the CHP unit does not turn on and the temperature inside the storage decreases until the gas boiler switches on. The remaining time during the week, the boiler does not provide any heat. One possible cause may be the high return temperature at the CHP system. Another reason could be a disturbance within the power grid. The heat pump operates related to the CHP unit. After turning off the heat pump, the belonging supply temperature cools down much faster than the supply temperature of the CHP plant. The fluctuating supply temperatures of the CHP unit and heat pump during operation are also noticeable. This indicates an inappropriate control strategy for the CHP system. Overall, the continuous operating times and downtimes of the CHP unit and heat pump are comparatively short. Frequent starting processes lead to higher costs and increased wear. Achieving longer continuous operating and downtimes would be appropriate.

Fig. 4 shows box plots of the storage temperatures of the high temperature (25 m^3) and low-exergy storage (15 m^3). The values indicate a well stratification inside the HT storage. The difference between the median temperatures at the top and bottom measurement point is 27.9 K. The tall box at the second highest measurement point illustrate that the charging and discharging of the storage is particularly associated with temperature changes in that area. This indicates

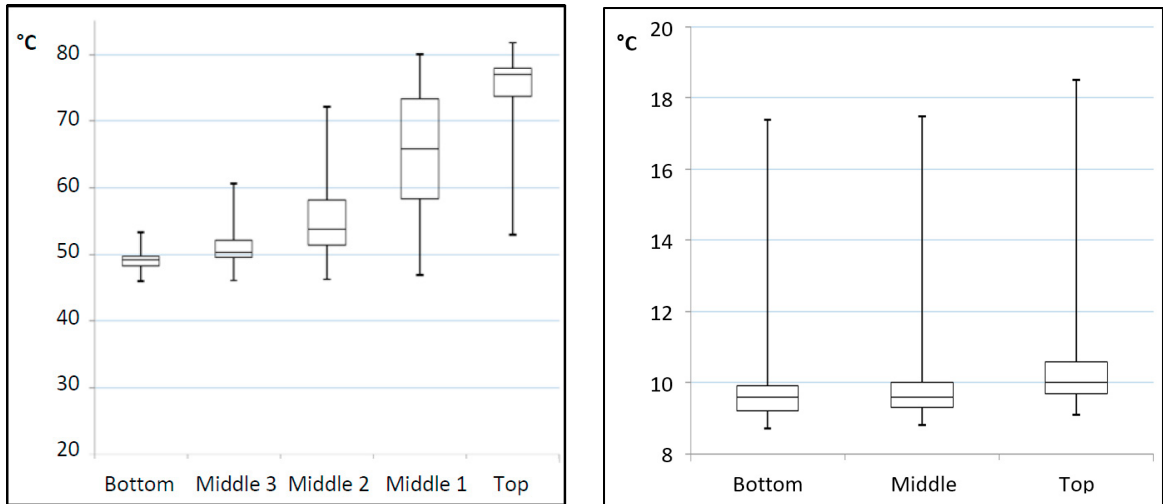


Fig. 4. (a) Box plot of measured temperatures inside the HT storage during winter at different heights, (b) Box plot of measured temperatures inside the low-exergy storage during winter at different heights

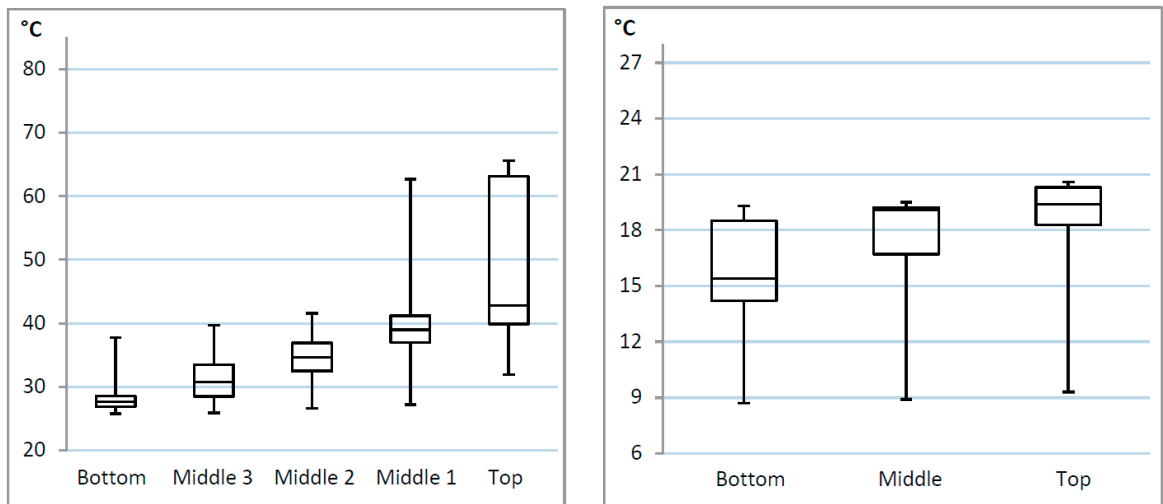


Fig. 5. (a) Box plot of measured temperatures in the HT storage during summer at different heights, (b) Box plot of measured temperatures in the low-exergy storage during summer at different heights

that during the winter there is additional potential for charging and discharging the storage. With longer charging and discharging cycles, the boxes of the other measurement points (middle 1 and middle 2) could be enlarged. The low-exergy storage does not have a distinctive stratification. The entire storage has a median temperature between 9.5 °C and 10 °C. In some periods, the temperatures in the storage rise up to 18.5 °C. The relative small boxes indicate that most of the time the temperature inside the entire storage is comparatively low. This indicates that the additional storage capacity is infrequently used.

The analysis of the two heat storages leads to the conclusion that there is unused storage capacity during winter. Further investigations related to the use of these capacities may lead to longer continuous operating periods. Considering the storage capacities of the grid and the decentralised storages may lead to additional improvements.

Fig. 5 displays box plots of the storage temperatures of the HT and low-exergy storage for summer. Also in summer, the stratification in the HT storage is noticeable. The storage operates on slightly lower temperatures compared to winter and the temperature difference between median top and bottom temperature is smaller (15 K). In summer mostly the temperature of the top volume of the storage changes. This indicates a huge amount of unused storage

capacity. Further investigations have to demonstrate whether it is economical and ecological feasible to use these capacities, or whether there are too high additional heat losses. The median temperatures of the low-exergy storage are above the temperatures during the winter. A minor stratification especially between the bottom and middle temperature is present, but also in summer the charging and discharging is indicated by temperature changes in the entire storage. In addition, this storage would be capable of more frequent charging and discharging cycles. Overall, the measurements show additional storage capacities for both storages. Further investigations deal with the possibilities using these capacities to optimise the operation of the CHP plant and HP related to their running times and opportunities to stabilise the power grid.

6. Conclusion

This paper shows in general the potential of Integrated Energy (thermal and electricity) and particularly in local district heating grids with variable temperatures. By using thermal storage capacities, CHP units and heat pumps, it is possible to couple the electrical with the thermal grid and so to stabilize the low and medium voltage grid. The structure of the local district heating grid of Dollnstein, which is used as a case study, is therefore presented. First results of this local grid indicate that the CHP unit and the thermal storages can operate in a more efficient way. Hence, in a next step, a more detailed investigation of the measurement data of the heat and power grid combined with a computational analysis is planned.

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