A new hydraulic concept for geothermal heating plants to achieve maximum geothermal contribution

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ABSTRACT

The analysis of selected projects within the South East Bavarian region has shown different optimization potentials. One of these optimization potentials is called displacement of geothermal energy. The phenomenon of the displacement of geothermal energy occurs when the heat supply to the district heating network exceeds the maximum geothermal heat load. In this situation, the common hydraulic design of geothermal heating plants prevents the optimal use of the geothermal potential. Caused by the control system, changes of the flow rate in the plant result in a reduced flow rate to the geothermal heat exchanger. This leads to significant reduction of the geothermal performance (up to 20 %). The increased contribution of the supplementary heating system in a one year cycle was determined with 12 – 20 %.

Current hydraulic concepts for geothermal heating plants have been derivated from the experience gained from the operation of biomass heating plants. Yet, the sensibility of geothermal heat exchangers to changes of the flow rate differs substantially from conventional heating appliances like wood-fired boilers. As a consequence it is necessary to develop new hydraulic solutions for geothermal heating plants with particular consideration of the requirements of the geothermal heat source.

In this paper we present a new hydraulic concept for geothermal heating plants by which the optimal operation of the district heating network with controlled supply temperatures, flexible and independent operation of the heat generators as well as efficient storing of geothermal energy is achieved. The comparison of the new hydraulic concept with common hydraulic concepts shows that it is possible to charge the heat storage faster and simultaneously reach higher temperatures in the storage. Thereby, significant improvements on the energy performance of geothermal heating plants can be expected.

INTRODUCTION

The responsible usage of energy is one of the main challenges of human civilization. Deep geothermal energy, as a relatively new technology, has significant potential to contribute to a sustainable society. At present in Germany, 33 plants are operated, 3 under construction and 30 systems in planning phase (GtV Bundesverband Geothermie, 2016). 64 % of the already operated plants, representing 94 % of the installed thermal heat load have their location in Bavaria (see Figure 1). With typical production rates of 75 kg/s and temperatures of 80/50 °C in the district heating network approximately 1000 households could be supplied with geothermal energy.

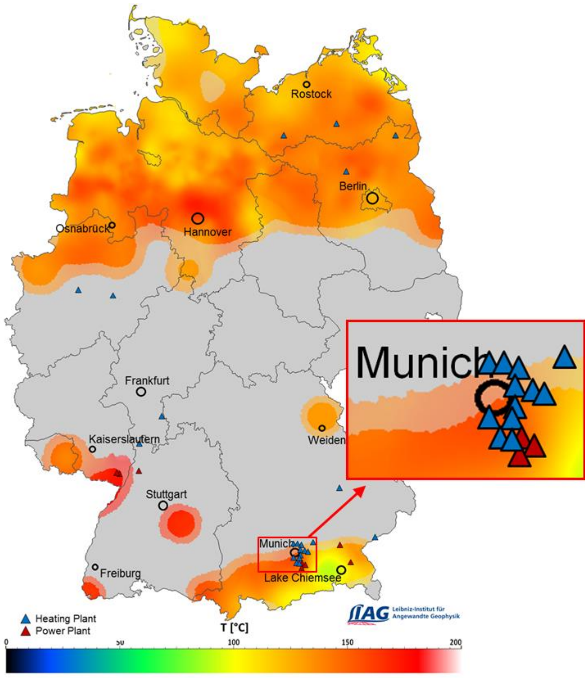

Figure 1: Temperature map from Germany at - 4000 m below mean sea level with the location of the operated geothermal heating and power plants (Agemar, 2014) (modified).

From an economic perspective, the deep geothermal energy in the South East Bavarian region is in direct comparison to the traditional energy sources for heat generation, such as natural gas, oil, biomass or heat pumps. The pricing for the supply with heat from geothermal heating plants is usually slightly below the pricing of natural gas. Caused by the high investment costs for the construction of a geothermal heating plant with the appropriate wells and the district heating network, the operating costs must be kept as low as possible. Therefore, besides the detailed planning of the thermal water circuit and the district heating network, it is also important to focus on the design of the hydraulic concept. Small changes of the concept of the hydraulic design can lead to significant differences of the energy performance.

COMMON HYDRAULIC CONCEPT

The common hydraulic concept of heating plants, as it is shown in Figure 2, is derivated of the experience from the operation of biomass heating plants according to Gabathuler and Mayer (2004) as well as Hammerschmid and Stallinger (2006). In specific, it is based on the concept of Hammerschmid and Stallinger (2006) for the serial, multi-boiler system without a heat storage. The thermal water with temperatures of 85 °C is lifted from the aquifer through the production well with a submersible centrifugal pump. After the thermal water reaches the heating plant, the heat is transferred by parallel connected geothermal heat exchangers. The above-ground plant periphery of the heating plant includes the provision of energy in the heating plant as well as the distribution of energy within the district heating network. When the heat supply to the district heating network exceeds the maximum geothermal heat load, the purposed temperature to the district heating network can be reached by the serial integrated supplementary heating system. To keep the finance investment low, there are usually oil- and gas-fired boilers used for covering peak loads in geothermal heating plants. The district heating network pumps are circulating the heated water from the heating plant through the district heating network to the energy consumers. The returned water with temperatures of approximately 50 °C will be reheated by the geothermal heat exchanger.

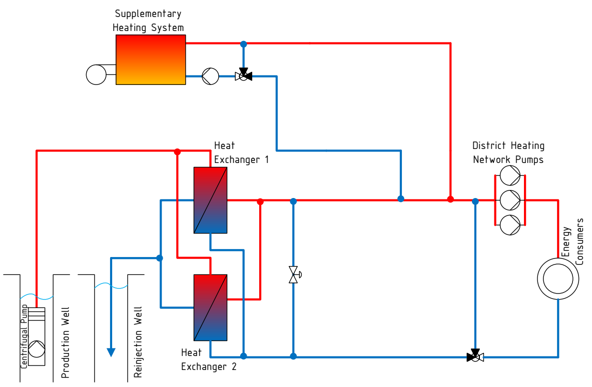

Figure 2: Common, simplified hydraulic concept of geothermal heating plants.

For different reasons, the activation of the supplementary heating system leads to high temperatures in the system. First, a minimum operation time of the supplementary heating system is required by the manufacturer of the boiler. This is justified with the higher energy losses during the flushing of the combustion chamber, as well as the higher pollution contaminants at the start of the combustion process. In addition to the minimum operation time, the limited ability to modulate the fire capacity prevents the optimal use of geothermal energy. Below a specified limit, the unfavourable fuel to air mixing leads to an incomplete combustion process. Therefore, the fire capacity is kept on a minimum of 12,5 – 20 % ((Burkhardt and Kraus, 2006), (Siemens Building Technologies, 2010)) based on the maximum fire capacity. Finally, the current hydraulic integration of the supplementary heating system is not able to compensate the unfavourable features of the supplementary heating system. As a result, high temperatures in the supply pipe will activate the three-way-valve in the return pipe. The three-way-valve redirects a part of the returned water from the district heating network into the supply pipe. Thereby, the supply temperatures into the district heating network can be controlled.

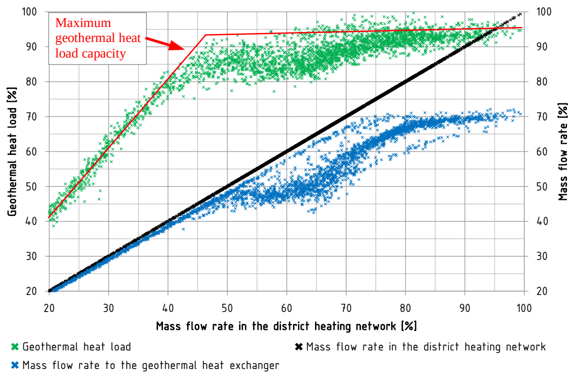

Figure 3: Flow rates in the district heating network, to the geothermal heat exchanger and the geothermal heat load.

Figure 3 shows the flow rate in the district heating network, the flow rate to the geothermal heat exchanger and the geothermal heat load. The maximum geothermal heat load is reached at 45 – 50 % of the maximum flow rate in district heating network. Below that point, the flow rates in the district heating network and to the geothermal heat exchanger are nearly congruent. As discussed before, the supplementary heating system gets activated when the maximum geothermal heat load is exceeded. Above that point it can be seen that the flow rate to the geothermal heat exchangers differs significant to the flow rates in the district heating network. This is caused by the redirection of the return flow from the district heating network by the three-way-valve in order to regulate the supply temperatures. This measure reduces the flow rate to the geothermal heat exchanger. As a consequence of the reduced flow rate, the geothermal performance will be reduced. This is caused by the reduced turbulent flow in the heat exchanger that lowers the heat transfer coefficient of the heat exchanger.

The heat load reduction at the geothermal heat exchanger as shown in Figure 3 can be determined with a maximum of 18 %. For economic reasons, the maximum flow rate to the geothermal heat exchanger is defined with 70 % of the maximum flow rate in the district heating network. The analysis in Bichler et al. (2014) shows the evaluation of different heating plants in the South East Bavarian region in a one year cycle. There, the proportion of the displacement of geothermal energy on the total energy provided by the supplementary heating system was determined with 12 – 20 %.

The integration of wood-fired boilers as it is shown in Hammerschmid and Stallinger (2006) focuses on the required minimum flow rate through the boiler. Thereby, fluctuations above the minimum flow rate are widely irrelevant. Yet, the sensibility of geothermal heat exchangers to changes of the flow rate differs substantially from conventional heating appliances. As a consequence it is necessary to develop hydraulic solutions for geothermal heating plants with particular consideration of the requirements of the geothermal heat source.

STATE OF THE ART OPTIMIZATION POTENTIAL

Based on the state of the art there are different options to prevent, respectively minimize the displacement of geothermal energy. In order to design a reliable, energy efficient geothermal heating plant the following technical requirements have to be fulfilled:

- Optimal operation of the district heating network with controlled supply temperatures.
- Flexible and independent operation of the heat generators to prevent the displacement of geothermal energy.
- Efficient storing of geothermal energy to maximize the geothermal contribution.

These requirements will be analyzed in the following optimization potentials.

<u>Multi-boiler system (boiler cascade):</u>
The displacement of geothermal energy can be minimized with a boiler cascade. A boiler cascade with different, smaller steps of the nominal heat load capacity can replace one or more specific boilers. The lower the nominal heat load capacity of a boiler, the lower the displacement of geothermal energy. However, in addition to the increased space requirements and the higher investment and maintenance costs, the main disadvantage of this measure is that the order of the activation of the boilers should not change. This solution is providing that the boilers with the smallest heat capacity have to start first. Usually, boilers at approximately the same nominal heat load capacity are switched on alternately. This is a practical measure to reduce breakdowns caused by long downtimes. From this point of view, cascading the supplementary heating boilers is not a viable solution to prevent the displacement of geothermal energy.

<u>Thermal storing in the district heating network:</u>
The displacement of geothermal energy can be avoided by the operation of the district heating network with higher supply temperatures. Thereby, the higher temperatures during the operation of the supplementary heating system below the minimum heat load capacity can be lead into the district heating network. The storing of the heat in the district heating network lowers the cost for electricity for the district heating network pumps. This is because the higher supply temperatures lower the flow rate in the district heating network. However, the higher supply temperatures are also leading to higher thermal losses.

In addition to the unregulated supply temperatures, the controllability of the thermal storing in the supply pipe is difficult. During the operation of the supplementary heating system below the minimum heat load capacity, the supply pipe gets charged with temperatures around 90 °C. Then, when the heating plant is reducing the flow rate in the district heating system below the maximum geothermal heat load capacity, the supplementary heating system switches off after the minimum operation time. The reached temperature below the maximum geothermal heat load capacity in the supply pipe is then around 80 °C. Although not necessary, the district heating network gets discharged in this situation.

The higher thermal losses, the uncontrollable supply temperatures and the poorly controllable storing of the heat in the district heating network make this option more to a temporary or additional possible solution.

<u>Technical storage:</u>
A further approach would be the integration of a technical storage in the heating plant (see Figure 4). The difference between a technical storage and a thermal storage is that a technical storage is used in order to protect the operating system from breakdowns or high energy losses in specific operating modes. In addition to that, a thermal storage is able to store cheaper, respectively ecological preferable heat to cover peak loads.

A technical storage, integrated as a hydraulic compensator between the supplementary heating and the main system, is able to prevent the displacement of geothermal energy entirely. The supply temperature to the district heating system can be controlled by the three-way-valve (V-201) in front of the district heating network pumps. The technical storage should be able to storage the minimum heat capacity during the minimum operation time of the supplementary heating system. The necessary size of a technical storage would then be around 40 - 60 m^3.

As mentioned, it is not possible to store geothermal heat with the integration of a technical storage as shown in Figure 4. Furthermore, the size of the technical storage and the associated investment costs cause further considerations to use the storage also as thermal storage in order to cover peak loads of the heating plant with geothermal energy.

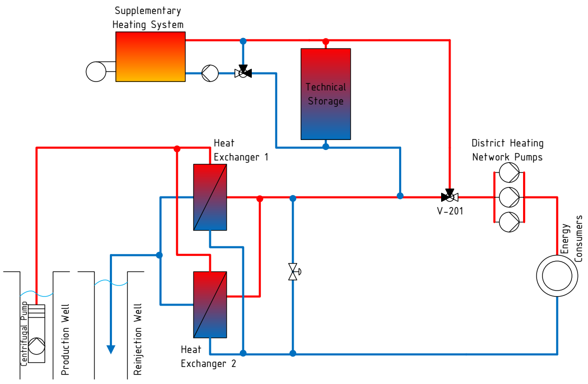

Figure 4: Integration of a technical storage in a geothermal heating plant.

Parallel thermal storage:

The state of the art for thermal storages in heating systems (in exception of the technical storages with heat pumps) shows only the possibility of parallel integration. The parallel integration is discussed in detail in Gabathuler and Mayer (2004), Hammerschmid and Stallinger (2006), Recknagel et al. (2011), VDI 2073 (2014), Richter et al. (2002) as well as Burkhardt and Kraus (2006). The parallel integration of a thermal storage in a geothermal heating plant is shown in Figure 5. By opening the valve V-307 and V-302 the thermal storage could be charged with geothermal energy. To discharge the thermal storage valve V-302 and V-304 are opened, valve V-307 will remain closed. To control the supply temperatures it is necessary to throttle the flow through the three-way-valve V-301.

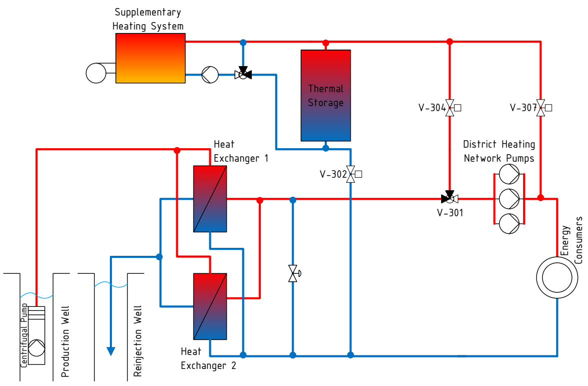

Figure 5: Parallel integration of a thermal storage in a geothermal heating plant.

The displacement of geothermal energy cannot be prevented with this solution. During operation of the supplementary heating system beyond the maximum geothermal capacity a defined flow rate is injected into the supply pipe of the district heating network. As a consequence, the same flow as injected into the supply pipe has to be diverted from the return pipe to the heat exchanger. This leads to a reduced flow rate to the geothermal heat exchanger. However, in comparison to the common hydraulic concept in

Figure 2, the displacement of geothermal energy can be clearly reduced.

Figure 6 shows the results for the theoretical studies on an ideally stratified, thermal storage with 100 m³ in the parallel concept. The theoretical studies were performed with an iterative, steady state calculation of the thermal temperatures and the energy flows in the system. According to the different mass flow rates in the district heating network, the charging and the discharging time varies. The calculations of the system were made with the following assumptions:

- District heating network supply temp.: 80 °C
- District heating network return temp.: 55 °C
- Production well supply temperature: 85 °C
- Maximum production well flow rate: 75 kg/s
- Heat exchanger area: 400 m²
- Heat transfer coefficient of the heat exchanger: 1930 - 3800 W/m²/K
- Adiabatic storing of the heat in the thermal storage

The percentage of the flow rate to the geothermal heat exchanger in Figure 6 is given according to the maximum flow rate in the district heating network. Below the maximum geothermal heat capacity the curves show the charging times of the thermal storage with three different flow rates to the geothermal heat exchanger. This results in three different maximum reachable temperatures in the thermal storage.

In order to charge the storage, the flow rate to the geothermal heat exchanger has to exceed the flow rate in the district heating network. With the increased flow rates to the geothermal heat exchanger the maximum possible temperatures after the heat exchanger cannot be reached. A flow rate of 39 % to the heat exchanger, with simultaneously 30 % flow rate in the district heating system causes a charging time of 2,8 hours. Thereby, temperatures of 80,5 °C in the thermal storage can be reached. Higher Temperatures (e.g. 82,2 °C) can only be reached with lower flow rates in the district heating network.

Figure 6 shows also the discharging times beyond the maximum geothermal heat capacity. Through the different temperatures in the storage, the discharging time varies under the same flow rates in the district heating system. If the geothermal heating plant reaches flow rates of 45 % of the maximum flow rate in the district heating system, the discharging time is 1,7 hours. With temperatures of 82,2 °C in the storage the discharging time can be expanded to 1,9 hours.

Serial thermal storage:
A possible solution to entirely prevent the displacement of geothermal energy was presented in Bichler et al. (2014). In this concept, a thermal storage is integrated serially after the geothermal heat exchanger (see Figure 7). When charging the thermal storage with geothermal energy the two valves V-404 and V-405 are open, the valves V-402 and V-406 remain closed. Upon discharging, the opened respectively the closed valves will change accordingly. The three-way-valve V-401 is able to control the supply temperatures into the district heating network. Since the supplementary heating is connected in the same way to the storage as a technical storage, the displacement of the geothermal energy can be totally prevented.

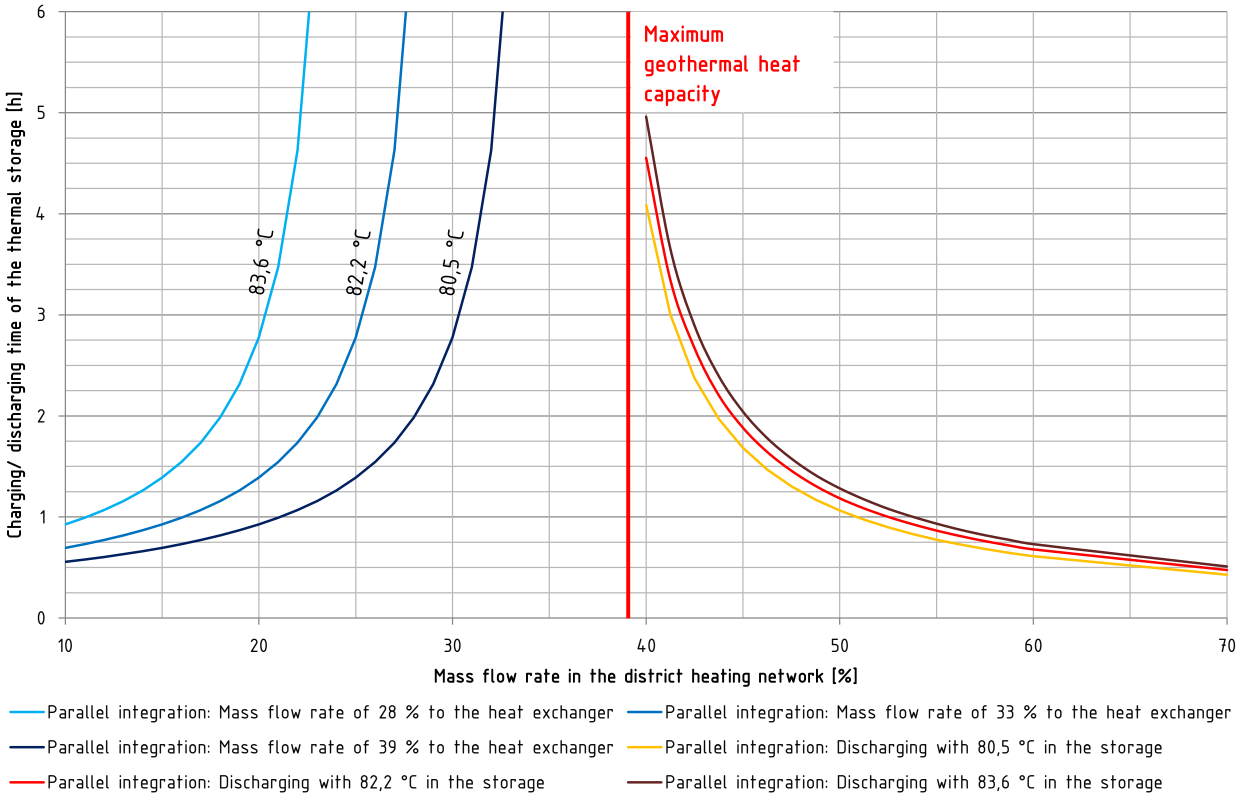

Figure 6: Results for the theoretical studies with a parallel integrated thermal storage with 100 m³.

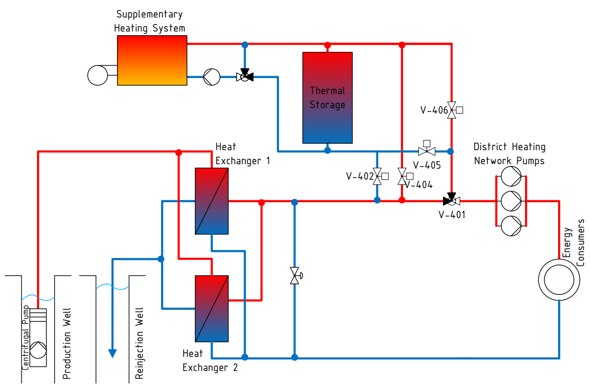

Figure 7: Serial integration of a thermal storage in a geothermal heating plant.

Besides the fulfilled requirement of the flexible and independent operation of the heat generators, this hydraulic concept provides advantages during the charging of the thermal storage. Figure 8 shows the results for the parallel integration, as well as the results for the serial integration of a thermal storage. It can be seen, that it is possible to charge the heat storage faster with higher flow rates in the district heating network. With this solution it is also possible to reach higher temperatures in the thermal storage. This is because there is no difference between the flow rate to the geothermal heat exchanger and the flow rate in the district heating network. But, Figure 8 shows also that the discharging times for the serial integration of the thermal storage are very short compared to the parallel integration. Within the parallel integration, the cold inflow into the storage is connected to the return pipe during discharging. In contrast to that, the serial integration connects the thermal storage with the supply pipe after the geothermal heat exchanger during discharging. As a consequence, higher temperatures remain in the storage after discharging.

For example, by charging the thermal storage with 30 % flow rate of the maximum flow rate in the district heating system, a temperature of 82,2 °C can be reached in 0,7 hours (see Figure 8). The Temperature in the thermal storage before charging is at 79 °C. The discharging time with 45 % flow rate is approximately 0,5 hours.

NEW HYDRAULIC CONCEPT

Figure 9 shows the new hydraulic concept, which combines the advantages of the parallel and the serial integration. This means, that besides the fulfilled requirements on geothermal heating plants, the thermal storage can be charged faster with higher temperatures. Simultaneously longer discharging times can be reached.

The hybrid integrated thermal storage is thereby charged in two steps. In both steps the submersible centrifugal pump is operating at maximum flow rate. During the first step, the thermal storage gets charged in the parallel integration. At the beginning of this step, the thermal storage with a temperature of 50 °C gets charged by opening valve V-507 and valve V-502. To speed up the charging time, the charging temperature will be set at 79 °C. After finishing the first charging step, the thermal storage gets charged in the serial integration. Thereby the highest possible temperatures can be reached in the storage. To charge the thermal storage serially, valve V-504 and V-505 are open.

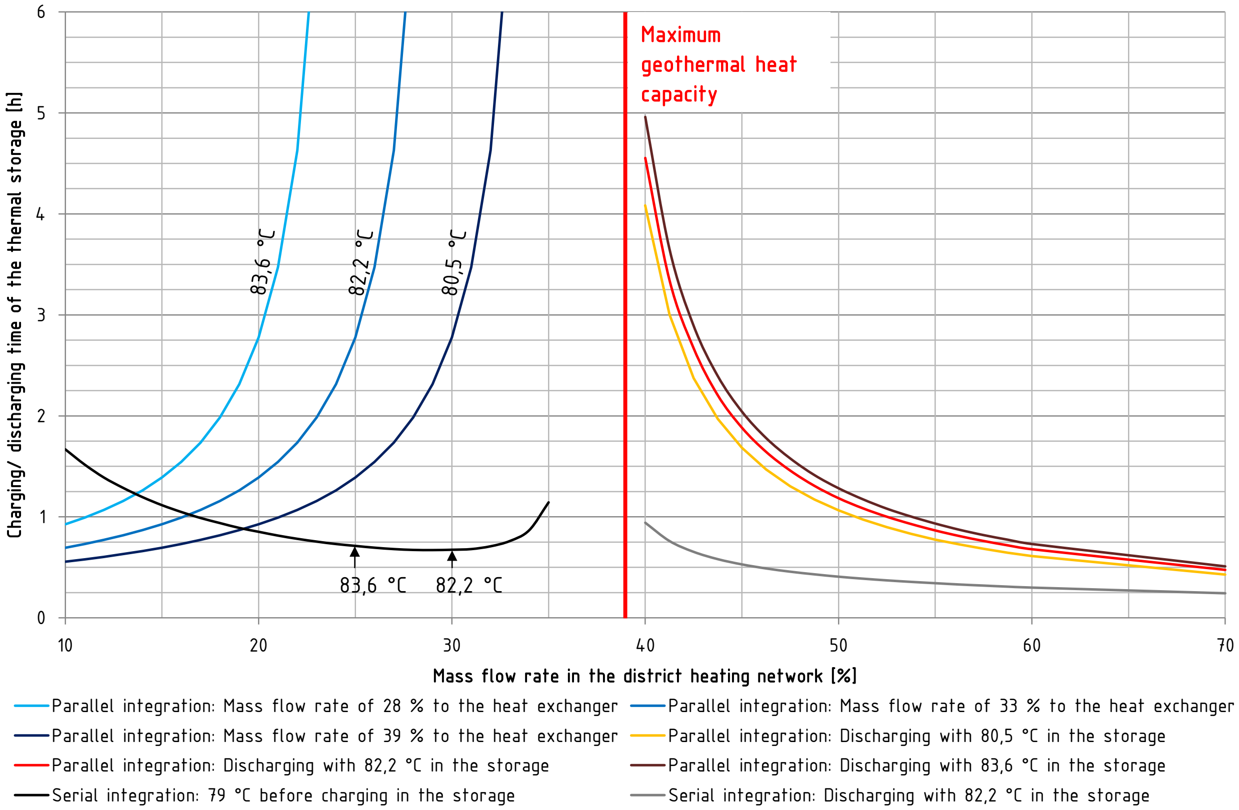

Figure 8: Results for the theoretical studies with a serial integrated thermal storage with 100 m³.

To reach the longest possible discharging times, the thermal storage has to be connected parallel to the system. This can be realized with the connection through the valves V-502 and V-506. During operation of the supplementary heating system below the minimum heat load capacity, the thermal storage can be connected as a technical storage with valve V-503 and V-506. If required, the three-way-valve V-501 is able to control the supply temperatures in all possible operation modes.

Figure 10 shows the results for the theoretical studies with a hybrid integrated thermal storage with 100 m³. By charging the thermal storage with 30 % flow rate of the maximum flow rate in the district heating system, a temperature of 82,2 °C can be reached in the storage in 2,2 hours. Thereby, the hybrid integration can reduce the charging time about 0,6 hours. In order to the higher temperatures in the storage, the discharging times can be expanded from 1,7 to 1,9 hours through the parallel discharging.

Above 27,5 % flow rate of the maximum flow rate in the district heating system, the charging time for the hybrid integration is always shorter compared to the parallel integration. Below that point, the higher temperatures in the storage are still expanding the discharging times. Thereby, depending on the temperature in the storage, small advantages are possible. However, with lower flow rates in the district heating network, the increased complexity of the hybrid hydraulic detracts the advantages of the hybrid integration. Nevertheless, the analysis of different geothermal heating plants has shown that in the relevant time period for a thermal storage (November to March) the potential proportion above 27,5 % flow rate is at 90 %.

CONCLUSION

The hydraulic design of a geothermal heating plant has a significant impact on the energy efficiency. It is not possible to achieve the maximum geothermal contribution with the common hydraulic concept. The heat load reduction at the geothermal heat exchanger was determined with a maximum of 18 %. Furthermore, with the studies in Bichler et al. (2014), the proportion of the displacement of geothermal energy on the total energy provided by the supplementary heating system can be determined 12 – 20 %.

Different optimization potentials according to the state of the art were presented. In order to minimize, respectively prevent the displacement of geothermal energy a thermal storage has to be integrated in the system. With the activation of the district heating system as a thermal storage, the displacement of geothermal energy can be minimized. Yet, the basic requirements on a geothermal heating plant cannot be fulfilled with this option

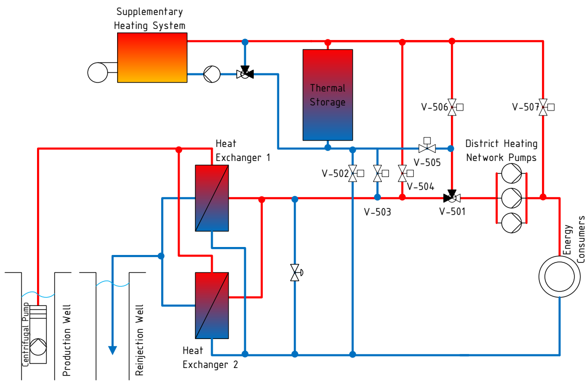

Figure 9: Hybrid integration of a thermal storage in a geothermal heating plant.

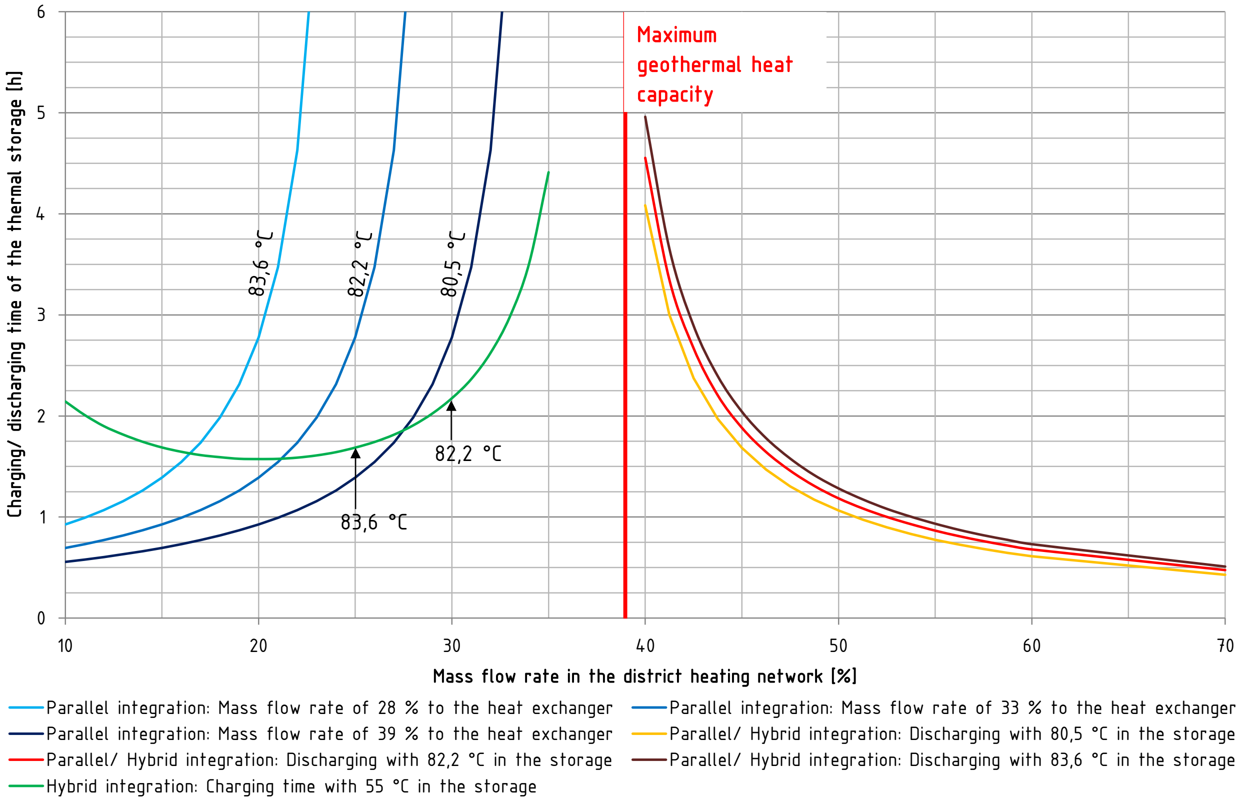

Figure 10: Results for the theoretical studies with a hybrid integrated thermal storage with 100 m³.

A technical storage, integrated as a hydraulic compensator between the supplementary heating and the main system, is able to prevent the displacement of geothermal energy entirely. Especially the necessary size of the technical storage causes further considerations to use the storage as thermal storage in order to cover peak loads of the heating plant with geothermal energy.

For the integration of a thermal storage in heating systems, the state of the art provides basically the parallel integration. The investigations on the parallel concept have shown lower attainable temperatures in the storage, as well as relatively long charging times. Furthermore, the displacement of geothermal energy with the parallel integration cannot be completely prevented. Compared to the serial concept, the long discharging times were advantageous.

The serial integration has opposing properties to the parallel integration. Very short charging times with high reachable temperatures in the storage are advantageous. Furthermore, the serial integration is able to fulfill all requirements on a geothermal heating plant. However, the short discharging time prevents the integration of the serial concept in geothermal heating plants.

This paper verifies that the new hydraulic concept, the hybrid concept, is able to meet all requirements for geothermal heating plants. With the hybrid concept the respective advantages of the parallel concept and the serial concept are combined. Shorter charging times with higher reachable temperatures in the storage are leading to longer discharging times. Thereby the hybrid concept shows a high potential for the optimization of geothermal heating plants.

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