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## Monitoring and Optimization of Building Operations of a Low-Energy School Building

The ambitious design and energy concept of the new Gebhard-Müller-Schule (GMS) school building in Biberach/Riss, Germany proved itself during the first three school years of operation. The intended target value of 30 kWh/(m<sup>2</sup>a) overall heating energy consumption was almost met during the second year of operation in 2006 and finally achieved in 2007, due to well-working optimization measures, which were identified through monitoring of the building operation.

Heating and cooling energy is mainly provided by a groundwater well plant, which serves as a heat source for two heat pumps as well as a direct cooling source for supplying the radiant heating and cooling system that is integrated in the concrete floor and ceiling slabs (thermally activated building component systems – TABS). Indoor air conditioning and server room cooling are also connected to the groundwater cooling system. The main component of the groundwater well plant is a submersible pump on the bottom of the well which is located underneath the building. The pump supplies the building reliably with geothermal energy, but also consumes a significant amount of electricity.

Monitoring and optimization of the building's operation, funded by the Federal Ministry of Economics and Technology in Germany, revealed fundamental findings about the operation of the system and the possibilities to improve the building's performance.

Since 2005, the measurements show a continuous increase in efficiency, particularly in the field of auxiliary energies. This significantly increased performance clearly shows the potential of the use of groundwater for heating and cooling purposes and of thermally activated building component systems. In addition the measurements reveal the sensitivity of the system efficiency in terms of operating parameters.

### INTRODUCTION

The new Gebhard-Müller-Schule (GMS) building, which is part of the local vocational school centre, was designed as a low-energy building providing an excellent high comfort educational environment for about 1.650 students (2006) and approximately 100 teachers (Figure 1). Since the beginning of operation in September 2004, the building proved itself in several different evaluations; compare Münter (2006), analysis of the project EULEB (2005-2006), Hennings (2006), Pfafferott et al. (2007) and Kalz et al. (2007).

Since the building's design includes a sophisticated and ambitious energy concept, it became part of a German federal research, monitoring and evaluation program on low-energy buildings. The main questions posed to the scientific monitoring and evaluation comprised how well the planned concept would perform in practice and how the operation of the building services could be optimized.



Figure 1. West view of the Gebhard-Müller-Schule (GMS) school building.

In order to answer these questions, a large volume of data was measured, recorded and reported. The building monitoring system (BMS) data recording comprises a total of 1,300 data points, including main components such as electricity consumption of individual components (heat pumps, ventilation systems, pumps, controllers, lighting, server, etc.), room temperatures, and consumption of heating and cooling energy.

In this paper, the analyses of the heating and cooling system in terms of performance and the main optimization measures that were conducted within the research project during ongoing operation are presented. Focus is laid on the overall energy efficiency of the groundwater heating and cooling system and especially on optimization of the electricity consumption of the groundwater well pump.

**HEATING AND COOLING SUPPLY** Room-conditioning in the GMS is provided by thermally activated concrete floor and ceiling slabs (thermally activated building component systems – TABS) in conjunction with mechanical ventilation. The supply air is supplied at room temperature isothermally, and, thus, does not contribute significantly to heating and/or cooling. However, the mechanical ventilation contributes considerably to energy saving by recovering energy from the return air.

Due to the favourable groundwater conditions at the building's location, a groundwater well plant was chosen as the sole cooling source and main heating source in conjunction with heat pumps. An additional wood-fired boiler was installed to cover peak loads, see Baumann (2004).

Figure 2 shows a scheme of the geothermal groundwater-well plant of the GMS. A suction well that is installed below the underground garage underneath the building and two injection wells outside the building (all with a depth of approximately 16 m) serve as the groundwater supply system. The groundwater is fed into two heat exchangers that are located within the main plant room on the attic of the building, thus supplying the building with thermal energy for heating and cooling.

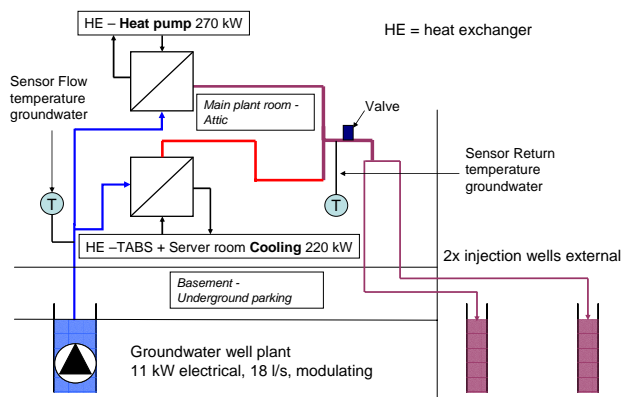


Figure 2. Basic scheme of the geothermal groundwater well plant.

One heat exchanger unit serves as the heat source for a heat pump system that consists of two compression heat pumps, each of which contains two compressors that allow a two-stage capacity control. A separate heat exchanger unit is used for direct geothermal cooling and supplies all cooling energy consumers year-round.

The following operation modes of the groundwater well plant occur when supplying the building with heating or cooling energy:

- heating of the TABS via the heat pump system,
- heating of the supply air via the heat pump system,
- direct cooling of the TABS via groundwater heat exchanger,
- direct cooling of the supply air via groundwater heat exchanger,
- direct cooling of the server room via groundwater heat exchanger.

TABS and air-handling units together can be supplied either with heating or cooling energy. Therefore, operation modes a) and b) as well as c) and d) can occur simultaneously which is not possible for a) and c) as well as b) and d). However, server room cooling can be operated independently so that operation mode e) may occur together with each of the other four modes.

The core piece of the geothermal groundwater well system is the submersible pump in the suction well underneath the building. The ratio of thermal energy delivered by the groundwater to the electricity consumption of this pump is crucial for the (non-renewable primary) energy efficiency of the geothermal groundwater plant.

### TOTAL ENERGY CONSUMPTION FOR ROOM-CONDITIONING

Figure 3 displays the development of the building's heating energy consumption in the period from 2005 through 2007. It reveals the high energy-efficiency standard of the building.

In addition to the actually measured heating consumption values, figure 3 also shows the specific consumption corrected for outdoor air temperature (degree days) according to the German engineering guideline VDI 3807 (2007). The heating degree days (HDD) required for outdoor temperature correction were determined from the outdoor temperatures measured by the meteorological station of the building's control system.

The outdoor temperature corrected heating energy consumption amounts to 36.9 kWh/(m<sup>2</sup>a) for 2005. This value was decreased to 32.8 kWh/(m<sup>2</sup>a) in 2006 and even to 27.8 kWh/(m<sup>2</sup>a) in 2007.

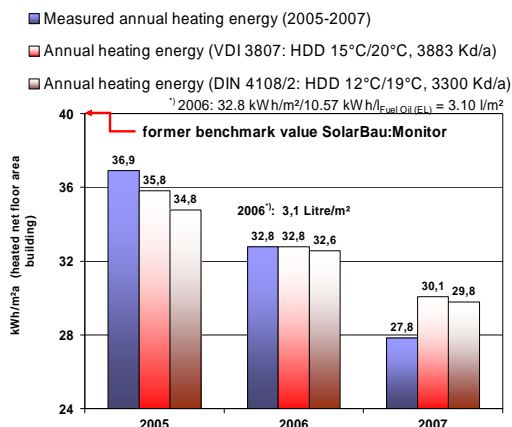


Figure 3. Heating Energy consumption 2005 to 2007 (characteristic values refer to the heated and conditioned net floor area).

Besides the heating energy consumption, the total energy consumption for the overall conditioning of the building, i.e. heating, cooling, conveyance of air, lighting, as well as all associated auxiliary energy is crucial for the building's performance. According to German standards, primary energy consumption caused by these functions has to be used for benchmarking. In this context, primary energy means the total (non-renewable) energy input into the energy supply chain including expenses for extraction, conversion and transportation of fuels and energy transfer media.

A target value of 100 kWh/(m<sup>2</sup>a) primary energy consumption was given by the guidelines of the federal research program involved. This goal was first met in 2006, see figure 4. In 2007, the value could even be reduced to 81.7 kWh/ (m<sup>2</sup>a). In case of the GMS, this value consists mainly of electrical energy which had to be multiplied by a factor of 3 in order to account for the primary energy expense for delivering electricity in Germany. Thus, the 2007 primary energy value results from 26.9 kWh/m<sup>2</sup>a x 3 (electrical) + 0.97 kWh/m<sup>2</sup>a (wood boiler) = 81.7 kWh/m<sup>2</sup>a.

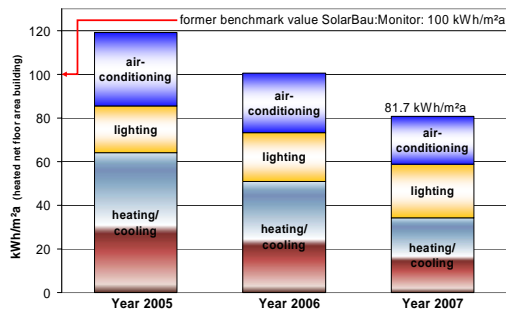


Figure 4. Total annual primary energy consumption heating, cooling, air-handling and lighting from 2005 to 2007.

This significant decrease of heating and primary energy consumption of more than 30% over the first years of operation is mainly due to the continuous optimization of the building's operation in the course of the scientific monitoring and evaluation conducted. Since the improvement of the operation of the groundwater system, the heat pumps and the associated distribution pumps was the main reason for the energy savings achieved, these systems are discussed in the following.

#### OPERATION AND PERFORMANCE OF THE GROUNDWATER WELL PLANT

Figure 5 shows the intake temperature of the groundwater over the whole monitoring period. The temperature stays below 12 °C and, thus, allows the supply of cooling energy for all consumers year-round.

The hourly mean values shown in figure 5 seem to indicate a slight increase of the groundwater temperature over the three years of operation. However, the flow rate supplied by the groundwater well pump was decreased as an optimization measure to reduce electricity consumption. Thus, the observed change in the groundwater temperature level might not show an actual trend, but is rather due to the changed hydraulic conditions within the well and its surroundings (groundwater drawn from a different height and region). Moreover, the temperature is not measured within the well, but close to the heat exchangers within the main plant room. Therefore, some disturbance of the actual temperature of the groundwater on its way up to the attic might have occurred.

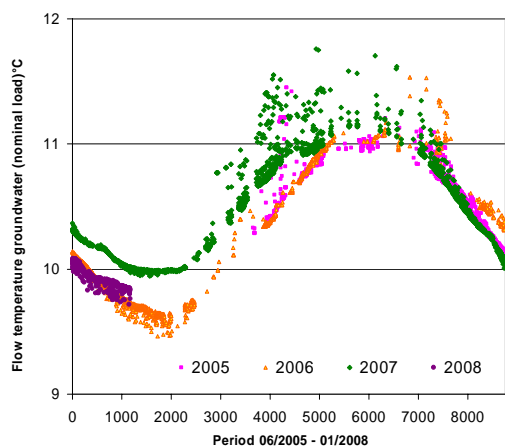


Figure 5. Hourly mean values of the groundwater intake temperature, measured before the heat exchangers in the main plant room.

Since the beginning of the building's operation in autumn 2004, more than 740,000 m<sup>3</sup> of groundwater passed the heat exchangers. So far, the heating and cooling demand of the building was met completely by the groundwater well plant (in conjunction with the heat pumps during

heating). The contribution of the wood-fired furnace, which is supposed to cover peak loads, to the annual heating energy supply is negligible ( $< 1\%$ ).

In early August 2007 the groundwater pump had to be replaced. Amongst other reasons, this was mainly necessary because of a malfunction of the check valve within the well. This malfunction caused groundwater flowing back into the suction well and emptied the riser pipe completely when the pump was stopped. The ground water had to be pumped up to the plant room again when the pump re-started. This impaired the performance of the groundwater system significantly.

From June 2005 to September 2007, approximately 420 MWh of thermal energy were extracted from the groundwater for heating purposes and approximately 490 MWh were delivered into the groundwater during cooling the building (figure 6). Within that, the energy amount for server room cooling is about 66 MWh. Approximately 21.5 MWh of this amount were consumed during heating periods (more details on this are published by Heinrich und Koenigsdorff (2007)). The well balanced usage of the geothermal groundwater system for heating and cooling can be considered sustainable.

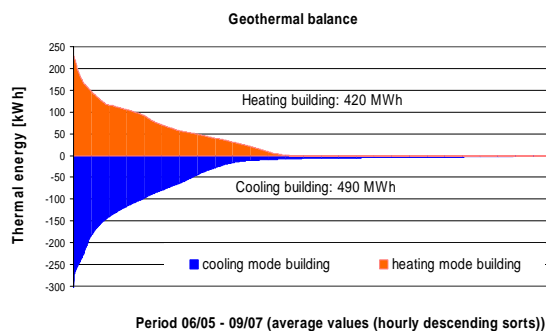


Figure 6. Extracted and introduced thermal energy from and into the groundwater (average hourly values, descending sorted).

Figure 7 describes the daily amount of total thermal (heating and cooling) energy delivered by the groundwater as well as the daily thermal energy consumed from the groundwater for

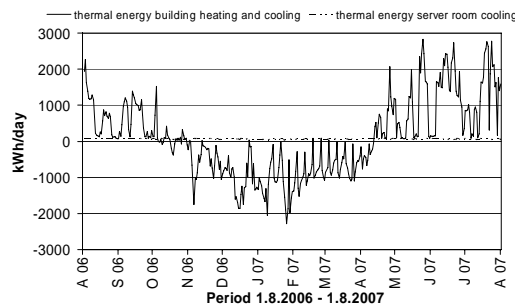


Figure 7. Daily total thermal energy delivered by the groundwater and daily thermal energy consumed by server room cooling (heating  $< 0$ , cooling  $> 0$ ). server room cooling during the heating and cooling periods 08/2006 to 08/2007.

It has to be mentioned, that during summer 2007 the maximum daily energy delivered to the building exceeds the corresponding values of 2006 by more than 600 kWh/d. However, during 2007 the energy consumption of the groundwater well pump was significantly lower than 2006, see figure 8.

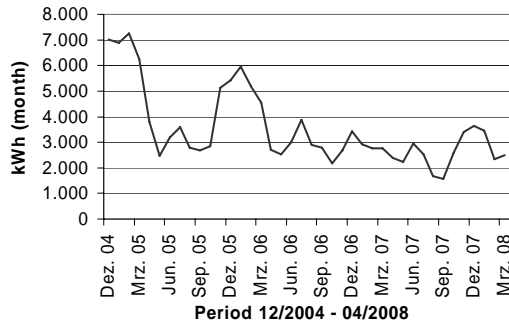


Figure 8. Monthly electricity consumption of the groundwater pump, including electrical cabinet for frequency-controlled operation.

This substantial increase in energy efficiency was achieved by thorough analyses of the systems' operation and taking corresponding actions. For example, a frequency converter was installed to control the well pump in conjunction with the building control system. However, the intended frequency-modulated operation mode of the pump could not be put into effect immediately, because of malfunction messages sent by the frost protection unit, the cause of which was unknown in the first. To ensure the heating and cooling supply of the building during the initial operation phase, the well pump ran at full load and without interruption.

The resulting high electricity consumption of the groundwater pump due to the continuous and non-modulating operation during the first half school year can be deduced from figure 8. After solving the underlying technical problems, the intended frequency-modulated operation mode was put into operation in spring 2005, resulting in a significant reduction of the electricity consumption of the groundwater pump. This reduction is not only achieved while heating the building, but also during cooling mode, what can be seen by comparing the periods 06-08/2006 and 06-08/2007.

Figure 9 depicts the resulting seasonal performance factors (ratio of thermal energy delivered to corresponding electricity consumption) which could be increased significantly from 2005 to 2007.

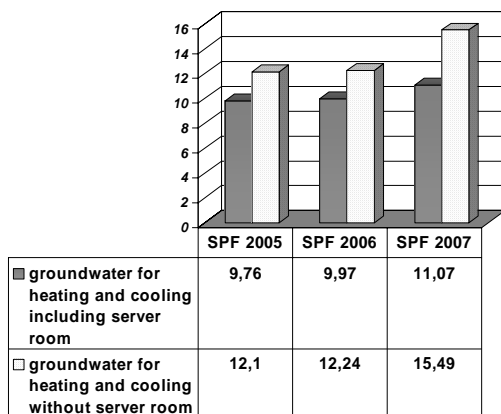


Figure 9. Seasonal performance factor (SPF) cooling of the groundwater well plant.

### ENERGY CONSUMPTION OF DISTRIBUTION

The energy consumption of the pumps which distribute water for heating and cooling within the building is not to be underestimated, too. Detailed investigation of an optimum charge and discharge operation of the radiant heating and cooling system in the concrete floor/ceilings (TABS) are still to be undertaken, see also Baumann (2003). But nevertheless, substantial energy savings could be achieved by adapting flow rates and supply temperature ranges, see figure 10.

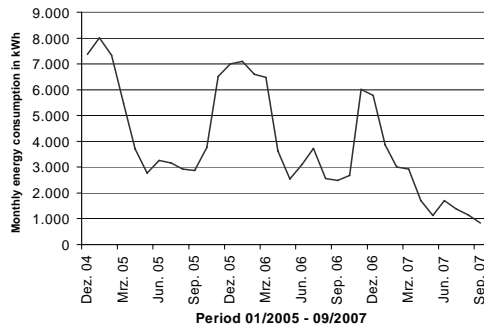


Figure 10. Monthly energy consumption of heating and cooling water distribution pumps including according control systems from Jan. 2005 to Sept. 2007.

### PERFORMANCE OF THE HEAT PUMPS

The operational performance of the heat pumps was also subject to optimization. Figure 11 shows the improvement of the seasonal performance factors (SPF) achieved. Besides the SPF values of heat pump devices themselves, additional SPF values were evaluated also including the energy consumption of the groundwater well system and the energy consumption for distributing the heat delivered by the heat pumps respectively.

Improvement of the single performances of the groundwater well plant and the distribution system are discussed above. Additionally, the operational performance of the heat pump devices was increased by decreasing and adjusting the heat supply temperature down to the minimum required value and by restricting the time of operation of the heat pumps as much as possible.

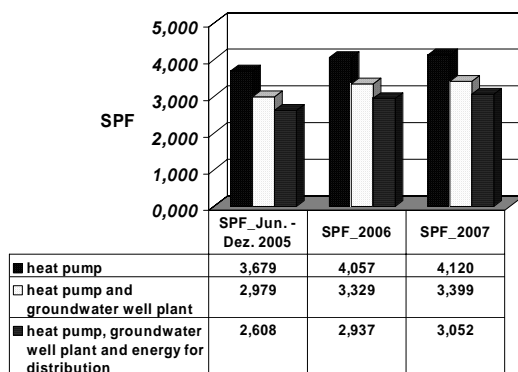


Figure 11. Seasonal performance factor (SPF) heating of the heat pump system.

### CONCLUSIONS

The research project described in this paper reveals that a continuous and systematical monitoring and optimization of operations is indispensable for the success of complex buildings and building services; see also Baumann (2005). Only the feedback from a thorough analysis of real operation delivers the detailed information necessary to transform an innovative design concept through successful construction into the targeted operational performance.

From the example of the Gebhard-Müller-Schule in Biberach/Riss the following recommendations for an energy-efficient geothermal use of groundwater can be drawn for future comparable buildings:

- The hydraulic difference in altitude between the wells and the building heat exchanger should be minimized in order avoid the danger of backflow and to reduce the energy consumption of the groundwater feed pump. In particular, the groundwater system should be a closed system rather than an open system.
- Variable, i.e. frequency-controlled operation of the groundwater pump according to the demand profile of the building is crucial for achieving high energy performance.
- Due to the sensitivity of the system's performance to the operating conditions, continuous monitoring of the groundwater and heat pump plant is necessary. Professional monitoring is a prerequisite to be able to carry out adjustments of the operation modes in order to ensure energy efficiency.

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