UTILIZATION OF RENEWABLE ENERGIES FOR SUSTAINABLE ACCELERATOR OPERATION AT KIT

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Abstract

The Karlsruhe Institute of Technology operates the Karlsruhe Research Accelerator test facility (KARA), which also provides synchrotron radiation at 2.5 GeV. Approximately two thirds of the wall plug power is used for cooling. Optimizing the infrastructure for cooling has a huge impact on overall sustainability. We expect to replace up to 1 MW electrical cooling capacity by a thermal well system to reduce the base heat load of the facility. This paper describes the challenges, such as the iron-manganese rich groundwater, and their solution for our 1 MW passive cooling system. The average energy consumption of 26.5 kW for the thermal well infrastructure is compensated for by a new 540 kWp solar power plant. We elaborate on the commissioning of the wells and show the first results of this sustainable cooling concept.

INTRODUCTION

The electrical cooling requirement of KARA in winter is approximately 1.2 MW, while in summer up to 2 MW of electrical cooling power is required for the 2.5 GeV operation of KARA and the air conditioning of the accelerator hall. Until 2024, this power was conventionally provided by up to three compression chillers. The primary cooling circuit has a temperature of 10 °C. The primary refrigeration circuit serves several secondary warm circuits. More on the distribution of our electrical consumption in [1, 2].

The system is primarily operated with chillers of different generations with energy efficiency ratios (EER) of around five, depending on the outside temperature, humidity, and the gradient between the outside temperature and the target temperature inside the building.

As groundwater should be largely independent of surface temperature, a well system promises a constant cooling capacity.

In summers of the last years, air temperatures reach up to 40 °C in the hottest months of July and August in Karlsruhe. By combining four two-week shutdowns per year into one eight-week shutdown in July/August, the maximum cooling capacity for the air conditioning could be limited to less than 1 MW during this period.

GEOLOGICAL BOUNDARY CONDITIONS FOR A WELL SYSTEM

The KIT Campus North is located in the middle of the Rhine Valley, an area with a high abundance of groundwater 5 m below ground level. The approximately 35 m thick upper aquifer has very good permeability. This allows pumping rates of more than 200 m^3/h at a medium temperature of about 13 °C. The maximum heating allowed by permission of the responsible authority is $\Delta T = 6\,°C$. Thus, the maximum inlet temperature is 19 °C. A flow rate of 142 m^3/h and a cooling capacity of up to 1 MW can be achieved.

Water treatment

In the Upper Rhine Valley, the water has a high natural content of iron (approx. 0.9 mg/l Fe) and manganese (0.09 mg/l Mn). Together with oxygen, iron reacts to form ocher (Fe_2O_3). The expected amount of ocher would require costly annual cleaning of the heat exchangers. The Fermanox® process [3] allows the underground oxidation of all metal ions in groundwater. In this process, oxygen-rich water is fed alternately into each of the three wells 40 m^3/h for 10 h, after which approximately 3000 m^3 water with an iron content of < 0.05 mg/l and the manganese content can be reduced to 0.06 mg/l. Either after this 3000 m^3 water or after 24 h at the latest, the system switches to the next well and that well is regenerated. After regeneration, the well remains unused as a standby well for another day, so that the utilization cycle of each well changes daily from regeneration to standby to pumping.

COOLING CIRCUIT

Thermal well system

The thermal well system consists of three extraction wells and two absorbing wells. Figure 1 shows a sketch of the possible water flows. The water is pumped out of two extraction wells 40 m below ground to the Fermanox® water treatment system from which a small portion (around 10 %) flows back into the extraction well in regeneration mode, which is not pumping. The remaining water flows through one of the three heat exchangers and then into the two absoring wells. The heat exchangers are directly connected to the cooling circuits of the main accelerator and its front ends, the klystrons or the cavities. Their temperatures are typically 24 °C. Part of the water can bypass the heat exchangers and mix with the heated up outlets of the heat exchangers. Temperature, pressure, and flow rates are measured at the wells' positions, and before and after the heat exchangers. The flows can be regulated via valves. The temperature in the absorbing wells is mainly controlled by the flow rate through the bypass.

The conventionally cooled heat exchangers are in line with the same warm side circuits—not shown in Fig. 1—so that they only cool precooled water, but can take over cooling if the flow through the thermal well heat exchangers is stopped, e. g. due to manual intervention.

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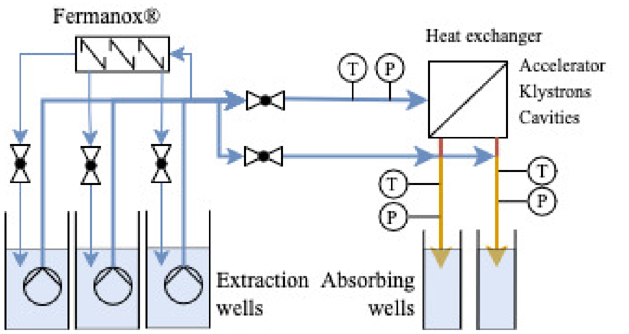

Figure 1: Overview of the water flow. One of three extraction wells pumps water while the other two are not pumping. For 10 h a day oxygenated water is pumped back to one halted well. The third well is on standby. The main water circuit goes through heat exchangers and then back into the ground. There are three individually controlled heat exchangers for the different sub-systems and two absorbing wells. Temperature, pressure, and flow are measured at several locations. It is possible to route and mix the water differently using multiple valves.

Another option would have been to use groundwater as an energy sink for conventional cooling regardless of outside temperature. That would have required replacing all three air-cooled chillers with water-cooled ones. Using free cooling for the secondary circuits running above ground water temperature allows cooling by simply pumping water and switching of the conventional air-cooled chillers, making them much more energy efficient.

Efficiency

When comparing the efficiency of the existing chillers with the thermal well system, the thermal wells outperform the chillers based on their ERR values. For the chillers, we measured an EER close to 5 in the winter 2024/2025. The EN 14511 EER of the main one is given as 5.79. The theoretical maximum cooling power of the thermal wells is $P_{\mathrm{out,cool}} = 1\,\mathrm{MW}$ and its average electrical power consumption is $P_{\mathrm{in,el}} = 26.5\,\mathrm{kW}$. During the test runs, the values were $P_{\mathrm{out,cool}} = 680\,\mathrm{kW}$ and its average electrical power consumption is $P_{\mathrm{in,el}} = 16.5\,\mathrm{kW}$. This results in an energy efficiency ratio (EER) of

$$\mathrm{EER} = \frac{P_{\mathrm{out,cool}}}{P_{\mathrm{in,el}}} = \frac{1000\,\mathrm{kW}}{26.5\,\mathrm{kW}} = 38$$

or 41 during the test runs respectively.

The reduction factor of electrical energy—chiller setup to the well setup—is 7 within our geological and legal limits of 1 MW.

For fine tuning, the idea was to keep only one chiller running. By combining the well and the chiller operated at just $E_{\mathrm{el}} = 150\,\mathrm{kW}$ we have a flexible response to changing cooling requirements. These requirements depend on the weather, different operation modes and injection with a heat load change of about 1 MW/s, as shown in Fig. 2.

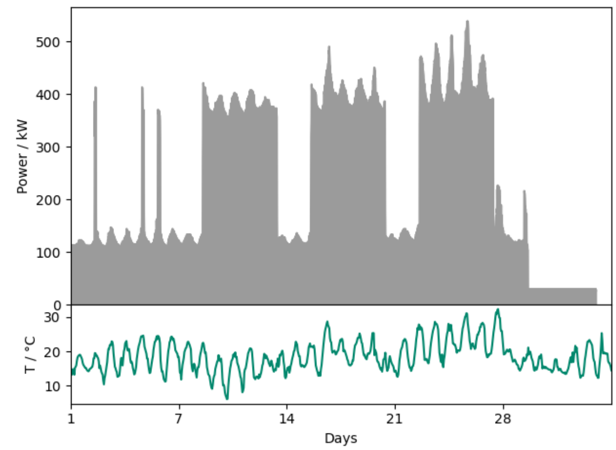

Figure 2: Electrical power used for cooling in June and beginning of July 2024. Days start at June 2$^{\mathrm{nd}}$ till Shutdown in July. The power fluctuates with operation modes (until June 10th: start-up and machine development days), week or weekends (where the cooling requirement drops to ca. 100 kW) and shutdown periods (flat low value at the right). Furthermore it depends on the temperature—intra day fluctuations and weather dependent.

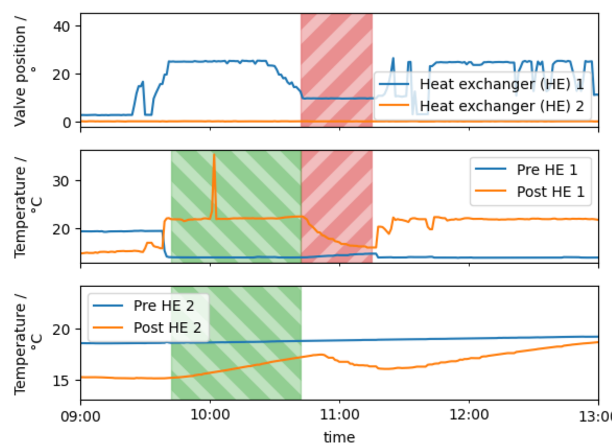

Figure 3: Temperatures at the heat exchangers depending on water flow rate and the control valve position, respectively. The first row shows the valve's position for two heat exchangers. The second and third row show the temperatures up- and downstream of the first and second heat exchanger. Red hatched background marks the acclimation phase after closing the valve again. The green background marks the period where the other heat exchanger's valve is opened.

Our photovoltaic power plant produced 18.8 MWh per month on average in the last two years and is in the process of being upgraded from 240 kWp to 540 kWp.

Commissioning

The first well system test runs were conducted in March and April 2025. On average a well required 10.1 kW at 70 % pumping power and Fermanox® system 4.6 kW electrical power. The expected pump speed for full pumping is 8 kW/100 m^3 to 9 kW/100 m^3 for the main wells and on average 4.6 kW/day for 10 h running at 11 kWh Fermanox® usage. The latter contribution could be saved in scenarios where no Fermanox® system is required.

Figure 3 shows one of the first test runs. One can see that the water temperature before opening the valve of a heat exchanger is at room temperature level (blue line in the bottom plot). At first, more of the already circulating water has to be mixed in with the bypass when opening the valves. In addition, the system to be cooled, e. g. the klystrons, should not be susceptible to temperature jumps. Otherwise, conventional chillers must take over cooling the water. Starting the pumps and opening valves except for those immediately before the heat exchangers lets the water circulate prior to starting the accelerator and limits the amount of too warm standing water while avoiding too cold water for the cavities. Furthermore, downstream of the heat exchangers there is a slight coupling and the temperature of the not used heat exchanger also changes (green-hatched areas in Fig. 3). In the upper two plots one can clearly see the temperature increase with opening of the valve (green hatched areas) and then a gradual temperature decrease when closing the valve again (red hatched area).

The reduced heat load on the chiller results in a reduction of approximately 10 % of the electrical power consumption of the chiller. This non-linear behaviour is caused by the chiller operating in three discrete stages. We were able to turn off one of two chillers saving 150 kW to 200 kW. With the wells and only one chiller we were able to operate the accelerator.

Lessons Learned

When planning the system, we assumed that wells 300 m apart in the same aquifer would all have the same temperature. However, in an area with existing buildings with deep basements, there is an influence on groundwater temperatures. We measured differences of up to 0.8 °C between the wells. With daily switching (maximum 3000 m^3/h per well), we detected temperature jumps in the water flow in the heat exchangers. By regulating the return water temperature on the secondary side of the heat exchangers, possible temperature jump are quickly damped by changing the flow rate, so that no negative effects on the accelerator have been detected so far. A negative pressure of −0.3 hPa is found in the system at standstill. This pressure difference is caused by the water column from the highest point of the system in the building to the groundwater level of the absorption well. As we need a positive pressure in the system, adjustable valves were installed in the pipes to the absorption wells, which keep the pressure constant at about 1 bar when the pumps are running. This regulation also provided that the flow rates through the heat exchangers could easily be kept constant with different cooling capacities required at all parallel installed heat exchangers.

SUMMARY AND OUTLOOK

At KIT, we showed that the installation of a thermal well system that contributes to KARA cooling, has positive effects on sustainability. The installed thermal well system can replace a conventional air chiller of up to 1 MW capacity, demonstrated in first test runs 0.68 MW cooling capacity. It is possible to install a fourth heat exchanger to extend the cooling concept from the accelerator KARA to the hall including all beamlines and a few laboratories thus towards the entire building.

We managed to deal with the risk of sedimentary deposition (in particular inside the heat exchangers) by the installation of the special water refreshing Fermanox® system. The first test runs confirmed that the temperatures of the absorbing wells do not exceed 19 °C, according to $\Delta T_{\mathrm{max}} <= 6$ K. In addition, the well system requires more than a factor of ten less energy than the chiller it can replace.

ACKNOWLEDGEMENTS

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