Optimisation of industrial size cold production from a ground source heat pump plant using borehole heat exchangers

Erich Mands, Marc Sauer, Edgar Grundmann and Burkhard Sanner

UBeG GbR, Reinbergstrasse 2, 35580 Wetzlar, Germany

e.mands@ubeg.de

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ABSTRACT

A ground source heat pump installation was designed and built for a factory near Limburg, Germany. The basic design of 50 borehole heat exchangers (BHE) was sized for covering the heating demand and the basic cooling demand. Due to the intended production methods in the factory, a higher cooling load was required than anticipated. Numerical simulations were used to devise an optimum operational strategy for covering a maximum of the cooling load.

The original, classical concept used the ground mainly as a seasonal storage, extracting heat in winter for the heating of the building and injecting heat from cooling in summertime into the BHE. With the increased cooling load, this was no longer sufficient. Re-cooling of the underground also during summer became necessary. This re-cooling can use the colder outdoor air at night to extract heat from the ground and dissipate it into the ambient air.

Because also this operational mode requires energy for pumps and fans, an energetic optimisation is crucial. This optimisation was achieved through extensive numerical modelling, taking into account the temperatures in air and ground in summer nights, the heat transfer to the BHE and further to the air, and the energy input into the system. The simulation had to be done with maximum hourly temperature values in order to correctly simulate the temperature development. The result of the simulation was an operational strategy for the system, but also the concrete control parameters for the direct control of the valves, pumps and fans.

The optimisation resulted in an increase of the available energy for cooling from about 800 MWh in the original design to more than 2000 MWh in the final case, without enlarging the BHE field.

1. INTRODUCTION

A company located in near the city of Limburg, Hessen, wanted to erect a new production hall in immediate vicinity to the existing building. A gas boiler can be used for the peak-load heating of the new building. The extreme cooling demand for the machines and the air-conditioning of the new building should be covered by geothermal borehole heat exchangers. The task set forth for the design calculations was to cover the base load for heating of the new building, and get as much cooling from the underground as possible.

With a pre-feasibility study, the general design of the BHE field was determined to 50 BHE located directly underneath the new building. The input for EED-calculations was set to a total heating load of 250 KW over 3000 h/yr (resulting in 750 MWh/yr extracted from the BHE), and to a capacity of 250-500 KW of cooling, with the limit of corresponding yearly hours of operation set in such a way as to not exceed 750 MWh/yr of heat injection.

Both heating and cooling are operated for the base load of the building. The main emphasis is on cooling, because the conventional cooling is much more expensive in comparison to conventional heating. So the idea was to use other cold sources outside of the heating period to cool down (or re-cool) the underground, so that the building can be cooled mainly from the underground during the main summer period.

2. THE CONCEPT IDEA

The idea was to cool down (or re-cool) the underground with the conventional cooling tower during night time, and to use the cooled underground for cooling the building during day time. The cooling tower should be used for re-cooling the ground only with free cooling. Such a concept had been devised already by UBeG for a large retail store in the South of Spain (Fernandez et al., 2012). While for the retail store the specific climate of Southern Spain, with an extreme imbalance towards cooling, was the determining factor, in the Limburg project the high industrial cooling loads in a moderate climate were the challenge. The common denominator of the two concepts is the use of night-time cold for re-cooling the underground.

The site of the Spanish example is set a little more than fifteen km from the Atlantic Ocean, in Jerez de la Frontera. The region is characterized by mild winters and very hot and dry summers, with 17.7 °C annual average temperature. The extreme temperatures in

August in a long-term average rise to 33.1 °C maximum and fall to 18.4 °C minimum, and the actual readings exceed 38 °C each year on several occasions. Thus cooling demand in this region exceeds any heating demand by far, in particular in commercial buildings with lot of internal heat sources. Designing a GSHP for cooling under these conditions requires unconventional solutions; seasonal storage is hardly feasible, with mean temperatures in winter not lower than 10 °C.

Given the climate of Jerez and the building design and concept used for the retail building, there is a totally unbalanced thermal energy demand:

Heating demand:	75 MWh/a
Cooling demand:	4’104 MWh/a

Thus heat accounts for only 1.8% of the demand for cooling. The monthly building loads are given in figure 1; even in winter, the monthly cooling demand is higher than the heating demand!

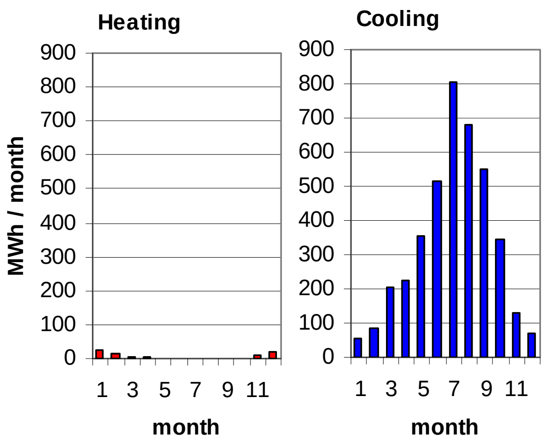

Figure 1: Monthly heating and cooling loads as to building design for Jerez retail outlet

From economic considerations, the maximum number of BHE in Jerez was limited to 50, with a maximum distance of 8 m among each, and a maximum depth of 130 m. So the primary design task was to check what would be the maximum cooling that could be provided by a BHE-field of this size. Calculations using a standard approach resulted in the possible loads as shown in table 1; of the total annual cooling demand of >4 GWh, only about 7 % could be covered from the ground that way.

As the percentage of geothermal coverage of the cooling load is so small, an almost steady operation over the whole year for this very base load can be assumed. The heating in wintertime is only able to reduce the heat injection into the BHE field, but not to turn it into heat extraction. As a result, the operation would be dominated by continuous heat dissipation into the underground, and in consequence the ground temperature would rise constantly.

Even in summertime in Jerez, ambient air at night can be colder than the temperature in the BHE field. As temperature in the underground will rise steadily over the years also when active re-cooling is done (the increase just being slower than in the standard case), the opportunities for re-cooling with nighttime ambient air will improve over time.

Weather data from nearby Cadiz were used to assess the amount of re-cooling that could be done during spring, summer and autumn (example for July given in figure 2). In order to use the cold from the ground efficiently, no geothermal cooling was assumed from November to March, as the lower ambient air temperatures in wintertime will allow for efficient use of air coolers. Using the ground for cooling is more desirable in summer, when ground temperatures are much lower than cooling water from air coolers. The software EED was used here to calculate the temperature development, and eventually the load data as given in table 1 were deemed feasible.

The complete geothermal system consists of borehole heat exchangers (BHE), heat pump and dry cooler(s). The 50 BHE were finished in 2010, and the underground thermal storage volume around the BHE now extends to about 553’000 m^3.

With this innovative design concept, adapted to Mediterranean climate and combining both diurnal and seasonal cold storage, the cooling output from BHE can be increased in a sustainable way. In summer, the underground works as a store of cold during the night and as a sink of heat during the day (diurnal storage). In wintertime, the regular operation of the heat pump for heating extracts some heat from the ground, and additional heat extraction (or re-cooling) is done by dry cooler (seasonal cold storage).

Table 1: Load data on building and ground side for two different scenarios for Jerez retail outlet

	supply to building	geothermal coverage *	expected SPF	BHE extraction for heating	BHE extraction from re-cooling	total BHE extract. / inject.
Standard case						
Heating	75 MWh/a	100 %	5	60 MWh/a	-	60 MWh/a
Cooling	300 MWh/a	7 %	3			450 MWh/a
Maximum cooling case						
Heating	75 MWh/a	100 %	5	60 MWh/a	420 MWh/a	480 MWh/a
Cooling	530 MWh/a	13 %	3	-	-	795 MWh/a

* percentage of total building loads

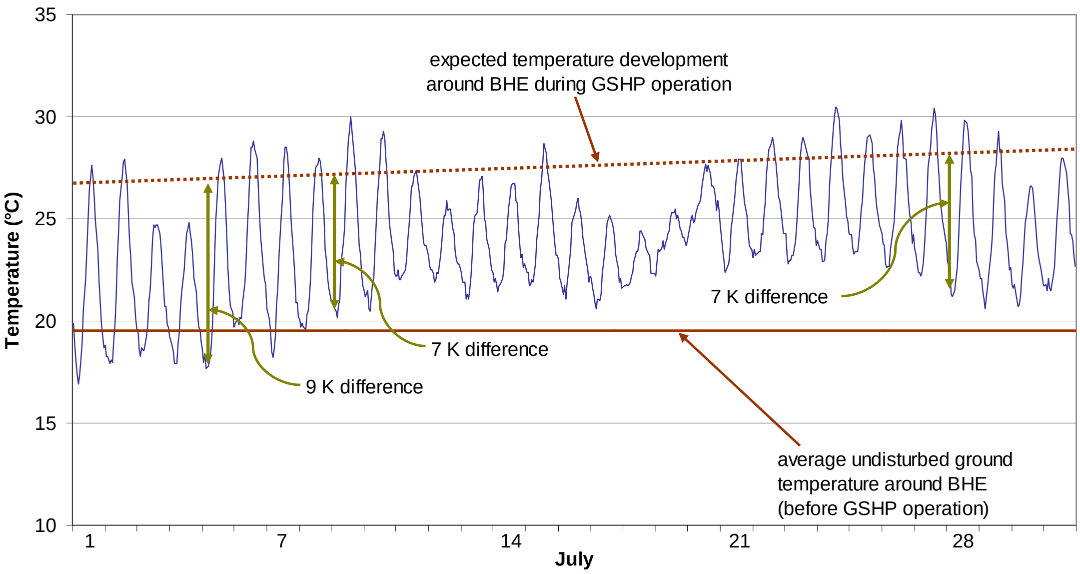

Figure 2: Hourly dry air temperature in July (data for Cadiz, from Spanish Meteorological Service) and ground temperatures in undisturbed situation and during GSHP operation

3. THE COOLING PROJECT IN LIMBURG

For the industrial project in Limburg, the engineering task now was to determine the possible amount of cooling for the building that could be covered from the planned field of 50 BHE, comprising normal heat dissipation, seasonal storage of heat and cold, and diurnal storage with re-cooling at night.

The project area is located close to the town Limburg in Hessen. The underground on site is made up of Devonian shale beneath Tertiary sand and clay with a thickness of 5-8 m in a basin structure (figure 3). The Devonian shale can be replaced by limestone from the same period (outcrops in blue in figure 3), which is used as groundwater reservoir for the town of Limburg. Hence it was strictly forbidden by the water authorities to drill into or even touch this aquifer.

Figure 3: Geological map of the project area.

Four exploration boreholes were drilled to determine the depth of the limestone. It was found that it was not present at the target depth of 150 m. At one of the exploration boreholes a geothermal response test (GeRT) was performed. The thermal underground parameters were measured with:

- λ = 2,4 W/(m·K)
- R_b = 0,11 (m·K)/W.
- T_0 = 10,8 °C (average for the depth 10-150 m)
- geothermal heat flow, taken from literature (Hurter & Haenel, 2002): 0,07 W/m^2

The temperatures in the BHE are limited to a minimum of 0°C into the underground as to a regulation by the authorities. The EED-calculations for the standard approach resulted in figure 4. The total amount of cooling and heating in this scenario is 800 MW$_{th}$/year

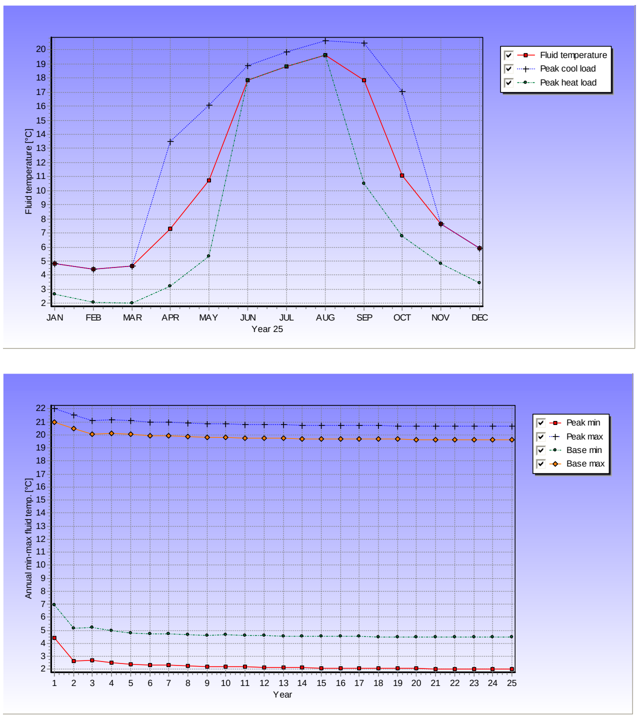

Figure 4: Temperature development in the BHE in the 25th year of operation, and minimum and maximum temperatures over the simulation period of 25 years, calculated with EED.

4. CALCULATION OF POTENTIAL FOR RECOOLING IN LIMBURG

The target of the calculation is to determine the optimum flowrate between cooling tower and underground, in order to achieve the most economic re-cooling of the underground, and to provide as much cooling as possible to the building during the day.

The basic assumption for the calculation is that the underground will be warmed up to 35 °C during the day from the waste heat of the machines and the building cooling system. It was assumed for the calculation that every evening this temperature will exist inside the BHE field.

The ambient temperature in the night will be less than the underground temperature. The difference can be used to re-cool the underground. The minimum temperature difference between ambient air and underground was set to 10 K, with the result that in a case where the ambient air temperature is higher than 25 °C, the re-cooling will not start.

During the re-cooling process the temperature difference will decrease and will come closer to the ambient temperature. So another target was to calculate the temperature stop criterion for the re-cooling.

Furthermore, the flow rate with different in- and output temperatures was calculated together with the efficiency and total amount of re-cooling.

The modelling area was 700 m x 550 m. The total mass of rock involved in the simulation was 0,068 km³.

The underground conditions assumed are the same like before for the EED-calculation. It was also found that no groundwater flow exists, and so the simulation could be based on conductive heat transfer alone. The starting temperature for the whole underground was set to 35°C (end of cooling day). The simulation was performed with the software Feflow, V6.1, P2.

A representative data base was generated from hourly meteorological data for Limburg (Meteonorm) for the last 10 years (figure 6). The simulation time was from April to September, and re-cooling from 20:00 to 6:00. So this time dependent temperature profile was another border condition for the simulation. Figure 7 shows the ambient temperature and the in-put temperature of the brine into the underground.

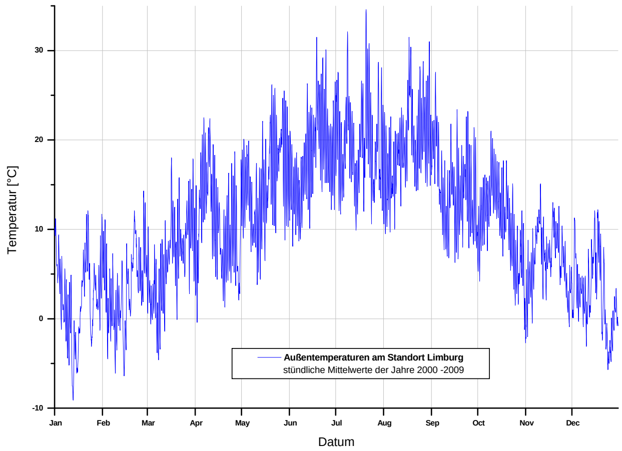

Figure 6: Calculated average annual temperature development over the last 10 years.

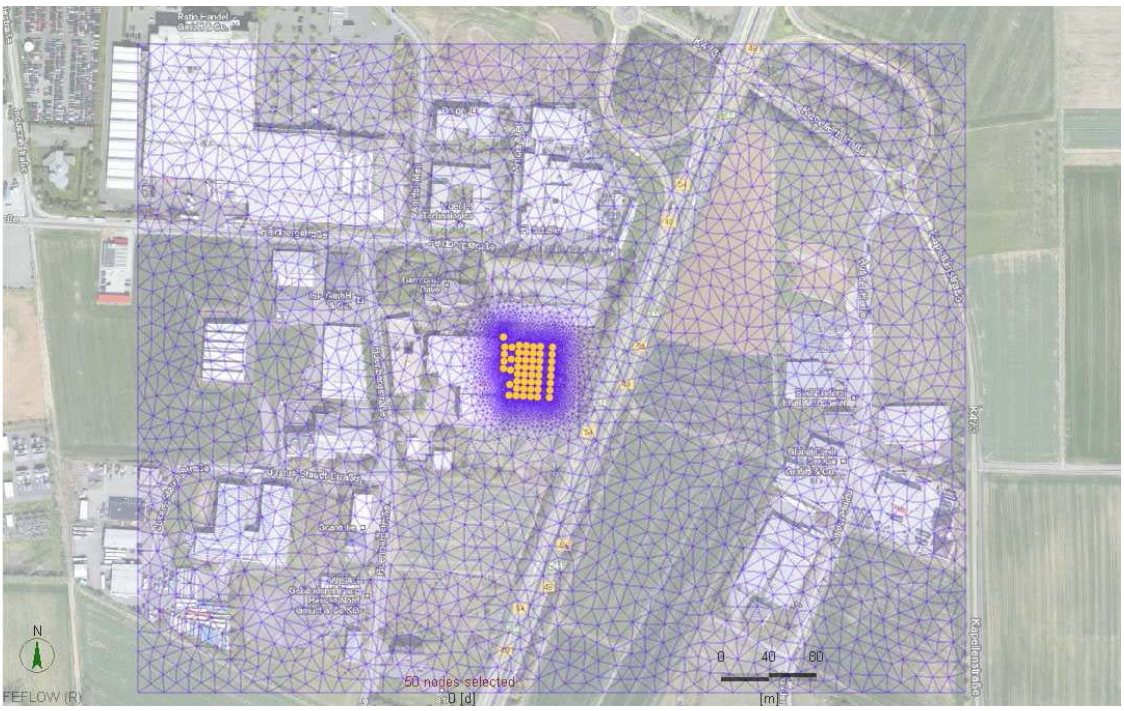

Figure 5: Modelling area for FE model.

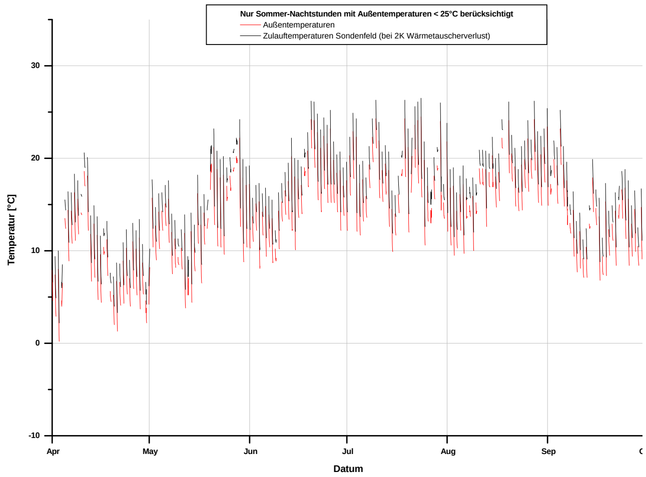

Fig 7: Average night temperatures (red) and possible recharge temperatures (black) from April to September

5. RESULTS OF THE DESIGN CALCULATIONS FOR THE LIMBURG PROJECT

Figure 8 shows the dependency of flow rate and stored cooling energy for two different conditions. The black line shows a constant temperature difference between underground and input temperature of 11 K, and the red line with only 5 K. It proves that in any case a flow rate of >40m³/d/BHE gives the best relation between energy rate and flow rate. Table 2 shows the calculated maximum possible re-cooling of the underground for the cooling period from April to September.

Table 2: Re-cooling from April to September

Month	Re-cooling	
	One BHE [MWh]	Total BHE - Field [MWh]
April	7.20	360
May	6.16	310
June	5.17	260
July	4.78	240
August	4.78	240
September	5.87	290
total	**ca. 34**	**ca. 1700**

For optimum control of the system, one of the main questions is the best lower limit of temperature difference between input temperature and underground temperature. This will enable to set the cut-off point for each re-cooling phase (night), to save on pumping energy when only minor cold storage can be achieved. Figure 9 shows two examples for the amount of re-cooling in MWh during the cooling period with different cut-off temperatures (in total, scenarios for cut-off at 0, 4, 5,6 and 7 K temperature difference have been calculated). From the curve in figure 10 it is obvious that the cut-off temperature difference should not be lower than 4 K, as only little additional cold would be stored with lower cut-off values.

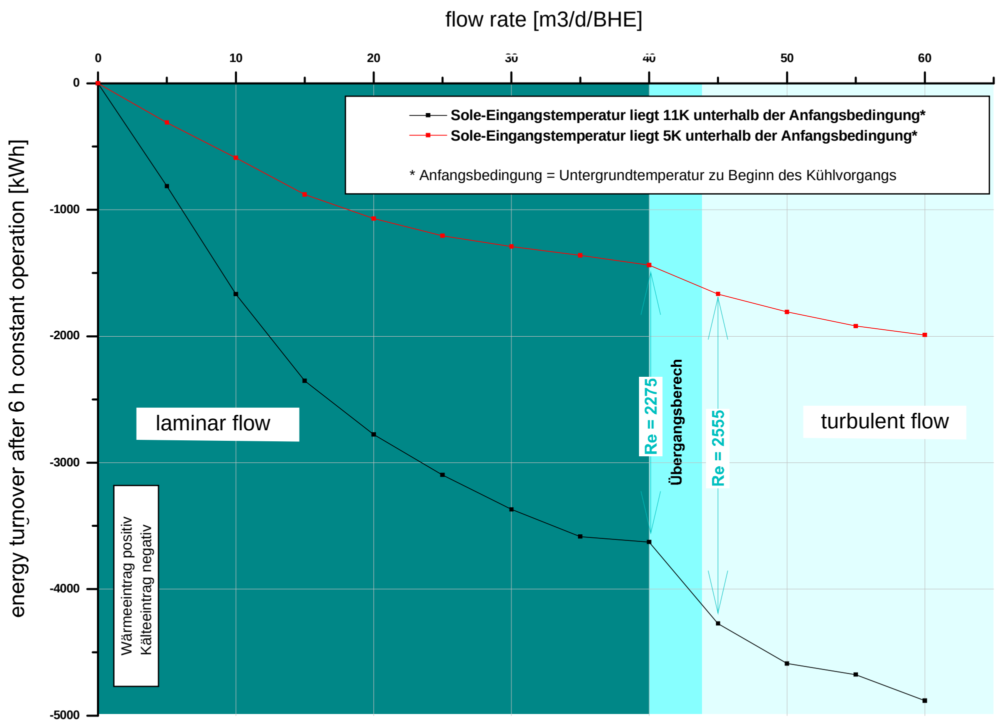

Fig 8: Flow-rate and re-cooling of the underground

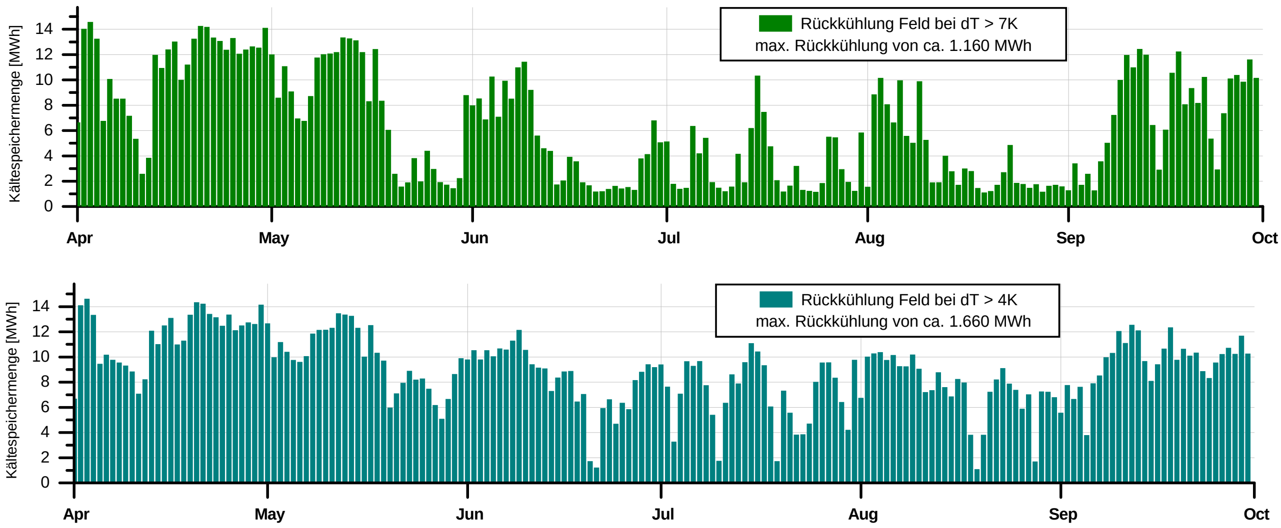

Fig 9: Amount of re-cooling for different temperature differences for cut-off; example for 7 K (above) and 4 K (below).

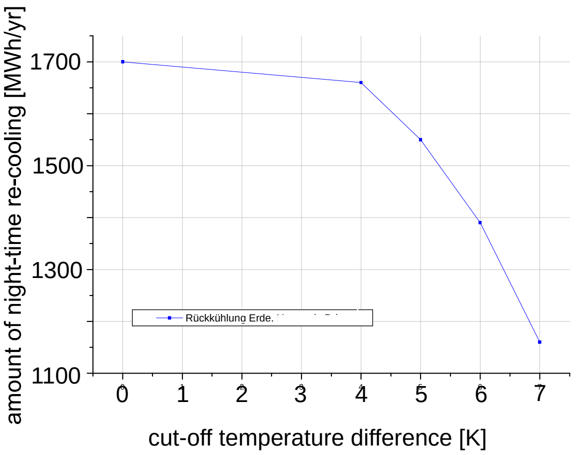

Fig 10: Amount of annual re-cooling from night-time operation against the cut-off temperature difference

5. CONCLUSIONS

The design of the BHE field for an industrial building in Limburg, Hessen, was done using EED calculations and numerical (FE) simulation. The optimisation of cold storage (seasonal and diurnal) resulted in an increase of the available energy for cooling from about 800 MWh/yr in the standard design case to more than 2000 MWh/yr in the final case, without enlarging the BHE field.

Shallow geothermal energy still is not used widely in the industry. There are interesting applications (in particular with underground heat and/or cold storage). From a EU-supported project some interesting applications and market chances had been identified (IGEIA, 2008a, b), and a recent document of the European Technology Platform for Renewable Heating and Cooling had emphasised the importance of increased use of renewable energy in the industrial sector (ETP-RHC, 2013). The example in Limburg demonstrates a promising way in that field.

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