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Borehole Heat Exchanger Fields – Do They Know What They Do?

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ABSTRACT

As of the middle of 2019, more than 15,000 geothermal plants with heat pumps have been built in Lower Saxony, a federal state of North-West Germany. Most of these plants are being operated with borehole heat exchangers as closed systems with the majority of them being used for heating family homes. However, more and more plants supply heating and cooling for commercial, residential, office or industrial buildings. Compared to family homes, these buildings have significantly higher requirements with regards to the the development of the heat source, depending on whether, when, how long and how much heating or cooling is required. To comply with these demands, several adjacent borehole heat exchangers need to be built and combined into a field with an output usually in excess of 30 kW. As of the middle of 2019, about 300 borehole heat exchanger fields have been built in Lower Saxony.

Planning these borehole heat exchanger fields requires much more knowledge and input data than planning a borehole heat exchanger for a family home. According to our experience, input data such as monthly heating and cooling demand are usually only based on estimates from an early phase of planning, which may be supplied by the architect or planning company. Dimensioning of the plant, which is part of the application documents in order to obtain the required license issued under German water law, often relies on these estimates. This means that, for example, the length and number of the boreholes are defined by the estimated heating and cooling capacity. First experiences on realized geothermal projects with borehole heat exchanger fields indicate that the actual demand may differ significantly from these estimates. This could be demonstrated by an undersized plant where the heat quantity taken from the field is much larger than the heat flow available to reinstate the required temperature of the ground for sustainable use. As a result, the temperature in the borehole heat exchanger field will drop continuously. This process generally takes place over a period of several years and can only be reversed over a long period of time, typically also in the time frame of years. At a critical point the temperature control of the heat pump would cause the failure of the plant.

To detect potentially problematic temperature changes, it is necessary to undertake a proper monitoring of borehole heat exchanger fields. The monitoring, which is a requirement of the license issued under water law, is composed of several aspects, such as:

- electric power consumption of the plant,
- heat quantity taken from the field,
- heat quantity brought to the field,
- flow and return temperature of the heat carrier fluid,
- subsurface/groundwater temperature at a control point within the field.

This data allows the plant operator and the authorities to compare the estimated demand used for planning with the actual demand during operation, as well as the planned versus the actual temperature changes in the field. The operator can react by adjusting the heat demand covered by the geothermal plant or by adding more borehole heat exchangers or alternative heat sources to the system well before a potential failure of the plant. Therefore, the monitoring allows for the optimized running of the plant.

Hence, the regulation process in Lower Saxony controls the plants from the application procedure throughout the operation and monitoring phase in order to achieve optimum results for economy and ecology.

1. INTRODUCTION

During the last decade Lower Saxony, a federal state of North-West Germany, experienced a steady increase of shallow geothermal plants with heat pumps. About 80 % of these plants are being operated with borehole heat exchangers, 15 % with horizontal heat exchangers (closed loop systems) and about 5 % with open well systems. Geothermal energy isn't only relevant for heating family homes but also for heating and cooling commercial, residential, office or industrial buildings. It can play a major part in the sustainable thermal energy transition.

The State Authority for Mining, Energy and Geology (LBEG) is the geological survey of Lower Saxony. Its main tasks in the field of geothermal energy are to provide geodata and advise authorities, municipalities, planners and builders to help them realize geothermal projects. Most of those projects have the purpose of heating family homes. For these there is a standardized approval procedure according to the German water law. Heating and cooling larger buildings with shallow geothermal plants come with a more complex approval procedure. LBEG supports the water authorities in Lower Saxony in the process of approving.

2. STATUS QUO IN LOWER SAXONY

As of the middle of 2019, more than 15,000 geothermal plants with heat pumps have been built in Lower Saxony. Figure 1 shows the distribution of these plants. The annual growth over the last five years shows a more or less steady development with about 1000 new plants per year. Thus, the market share of geothermal plants in newly built houses in Lower Saxony is about 5 %. Recent political discussions point to a shift in market shares from fossil fuels to renewable energy sources to fulfill the climate targets. This could boost the development of heat pump supplied heating systems. The majority of the existing geothermal plants are borehole heat exchangers for family homes. Such heating systems usually have a heat output between 5 and 15 kW. However, an increasing number of plants supply heating and cooling for commercial, residential, office or industrial buildings. Compared to family homes, these larger buildings have a significantly higher energy demand and therefore require a higher standard with regard to the development of the heat source, depending on whether, when, how long and how much heating or cooling is required. To comply with these demands, several adjacent borehole heat exchangers need to be built and combined into a field with an output usually in excess of 30 kW. The number of connected borehole heat exchangers within a field range from 5 to close to 100 in Lower Saxony. As of the middle of 2019, the LBEG is aware of about 300 borehole heat exchanger fields that have been built in Lower Saxony (Figure 2).

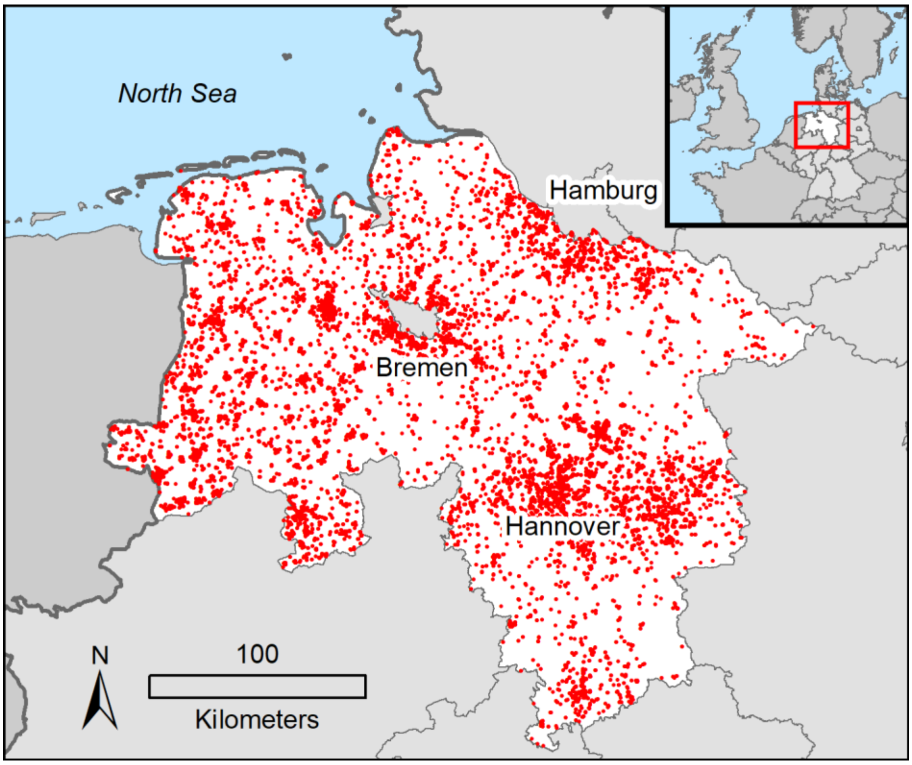

Figure 1: Distribution of geothermal plants with heat pumps in Lower Saxony (Situation as at July 2019).

Since the data from the early period of geothermal development in Lower Saxony, especially from borehole heat exchanger fields that were built prior to 2012, is not completely available at the LBEG, we currently only have detailed information for approximately half of the existing fields. We have analyzed the data with respect to the different building types that use borehole heat exchanger fields for heating and cooling and their average heat output. Figure 3 shows the different categories of building types: hospital/nursing home, office building, residential home, store house/production hall, school/kindergarten and others. The majority of these plants were built for office buildings and residential homes, which have a high market share but a rather low heat output compared to hospitals/nursing homes and supermarkets with an average heat output of more than 130 kW.

3. PLANNING AND LICENSING PROCEDURE

Planning a borehole heat exchanger plant for a family home is usually based on technical guidelines, experiences, published values, and simple estimates. Those plants do not always require a license under water law in Lower Saxony. If the plant is not located in a restricted area (e.g. drinking water protection zone, area of current or historic mining activity), the water authority can decide that the compulsory notification is sufficient.

Contrary to plants for family homes, borehole heat exchanger fields require the exploration of the local subsurface and the site-specific dimensioning of the plant. An exploration well provides information on geological and hydrogeological conditions, and thus helps to estimate possible drilling risks for further drillings. The thermal properties are typically determined by a thermal response test within the exploration well. This ensures that the configuration of the plant is optimized for the local subsurface conditions. As a result, the plant will be neither over- nor undersized and the impact on the subsurface and groundwater is minimized and within permitted limits.

In Lower Saxony, borehole heat exchanger fields require a license under water law. Two steps are required to receive such a license:

The first step is the exploration stage. An exploration well has to be drilled and equipped with a heat exchanger that will be part of the borehole heat exchanger field later on. To determine thermal properties of the subsurface a thermal response test has to be performed in the borehole heat exchanger.

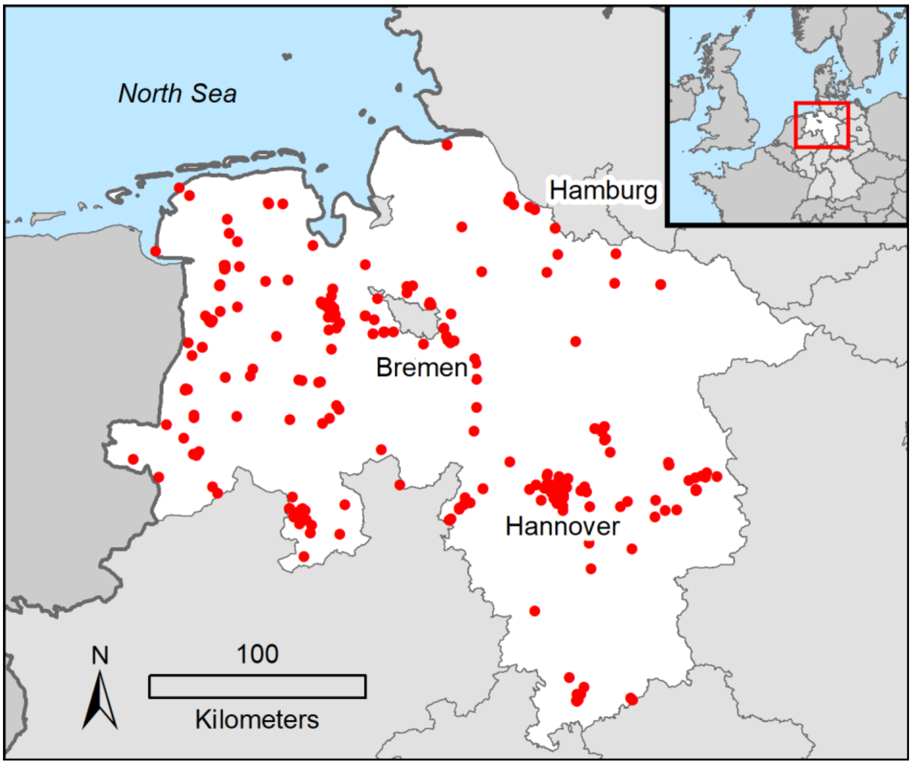

Figure 2: Distribution of borehole heat exchanger fields in Lower Saxony (Situation as at July 2019).

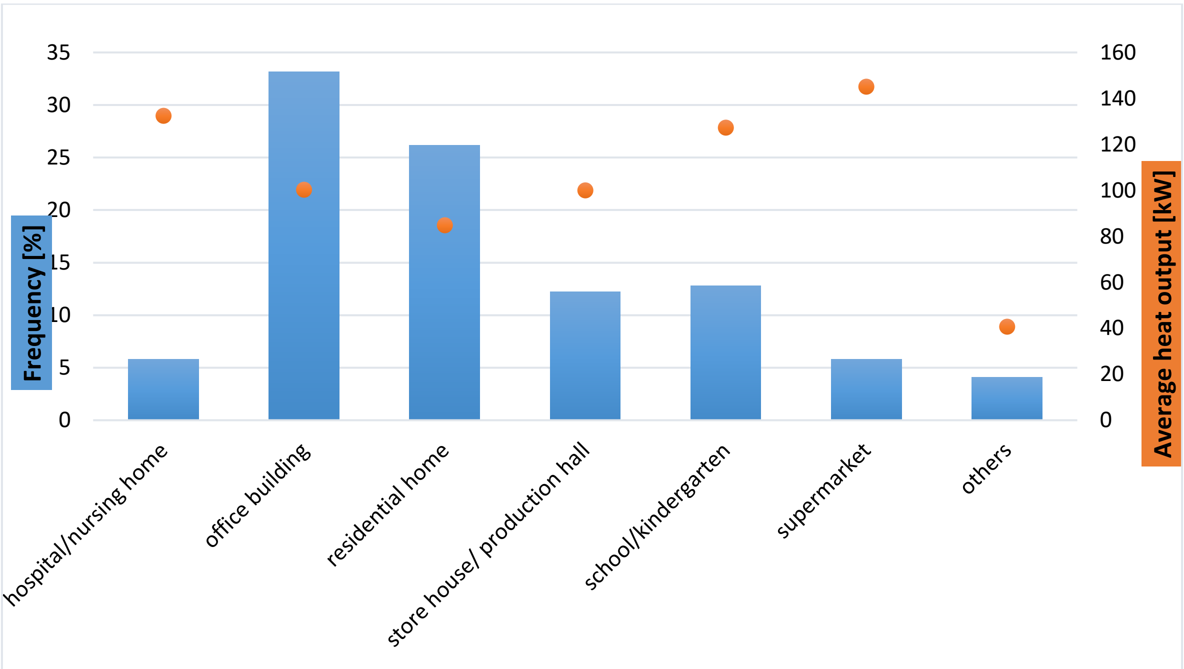

Figure 3: Usage and heat output of borehole heat exchanger fields in Lower Saxony (Situation as at July 2019).

The second step addresses the building and operation of the borehole heat exchanger field within defined limits. As part of the second step, the applicant has to provide the subsurface data from the exploration well and the results of the thermal response test. Additionally, an analytical or numerical dimensioning calculation for the heat exchanger field needs to be provided that shows the projected development of the subsurface temperature for a minimum of 25 years or ideally for the expected lifetime of the building (e.g. 50 years). In order to calculate the projected subsurface temperature development the required monthly heating and cooling demand of the building has to be known. The more accurate this input data, the smaller is the risk of poor performance or even failure of the plant in operation.

4. PLANNING DISCREPANCIES

In our experience, input data for the design of large plants, such as monthly heating and cooling demand, are often solely based on estimates from an early phase of planning, which may have been supplied by the architect or planning company. Dimensioning of the plant, which is part of the application documents in order to obtain the required license issued under water law, often relies on these estimates. This means that, for example, the length and number of the boreholes are defined by the estimated future heating and cooling demand. A first look at some of the completed geothermal projects with borehole heat exchanger fields shows that the actual demand may differ significantly from these initial estimates. The following example of an office building in Lower Saxony clearly demonstrates this: the application documents showed a planned heat extraction from the ground of 175 MWh/a and a planned heat injection into the ground of 200 MWh/a, indicating that a nearly balanced energy flow was to be expected. Table 1 shows the actual energy flow measured by a monitoring program. The actual heat extraction is 75-50 % lower than the planned value while the heat injection is slightly to significantly higher than the planned value. As a result, the subsurface temperature increased by 4.5 K since the beginning of the monitoring, which means a temperature increase of 0.5-2 K per year. If the plant continues to operate in the current mode, it will have to be shut down within the next five years due to exceeding the legal subsurface temperature limit of 20 °C. In order to avoid such a scenario, the operator will have to either increase the heat extraction significantly or decrease the heat injection.

Table 1: Planned and actual energy flow of an office building in Lower Saxony

Time frame	Heat extraction [MWh/a]	Heat injection [MWh/a]	Difference [MWh/a]
Planning status	*175*	*200*	*+25*
After 1 year of operation	45	300	+255
After 2 years of operation	45	280	+235
After 3 years of operation	85	220	+135
After 4 years of operation	75	265	+190

The opposite of the example above would be an undersized plant where the heat quantity taken from the field is much larger than the heat flow available to reinstate the required temperature of the ground for sustainable use. As a result, the temperature in the borehole heat exchanger field would drop continuously. This process normally takes place over a period of several years and can only be reversed over a long period of time, typically also within the span of several years. At a critical point, the temperature control of the heat pump would cause the failure of the plant.

The difference between estimated and actual heat demand is not the only scenario that can cause a temperature development in the subsurface that is far from the initial calculations. As part of the dimensioning calculation, the configuration of the borehole heat exchanger field needs to be defined, as well as the distance between the single boreholes (borehole spacing). In the example shown in Figure 4 the analytical dimensioning calculation with Earth Energy Designer (EED) (Blocon et al. 2017) was based on a linear configuration (1 line with 12 borehole heat exchangers) with a borehole spacing of 7 meters. The estimated temperature at base load after 25 years of operation was still above 0 °C. In contrast, the final site plan showed a rectangular configuration (3 x 4 borehole heat exchangers) and a borehole spacing of 6 meters. If the latter data is entered into the dimensioning calculation the estimated temperature of the base load after 25 years of operation will be below -2 °C. This is below the permitted threshold value of 0 °C (base load) in Lower Saxony. As demonstrated in this example, the design of the borehole heat exchanger field has a significant impact on the dimensioning of the plant. In the linear configuration each of the boreholes (except the outer ones) is directly affected by two other boreholes. In a rectangular configuration the center boreholes are directly affected by four other boreholes. Depending on whether the plant is being used for heating or cooling the subsurface temperature around these center boreholes may be lower or higher than the temperature surrounding the outer boreholes and may not deliver the same performance.

An analytical dimensioning calculation does not consider the groundwater flow and hence the heat transfer by convection. It will be partly considered if the thermal conductivity, as part of the input data, was measured on site at a location with groundwater flow. Depending on the location, heat transfer by convection may have an enormous impact on the subsurface temperature. At these locations, the development of the subsurface temperature during operation of the plant will likely differ from the analytical dimensioning calculation. Nonetheless, planning has to be based on the actual realization of the borehole heat exchanger field as far as that is possible. Planning discrepancies as the ones outlined above can be reduced significantly, if all parties involved base their planning on the same basic information and communicate changes that may be necessary because of external circumstances.

Frequently observed reasons for discrepancies between planning and operation of a borehole heat exchanger field are:

- additional cooling demand due to computer cooling,
- lower heating demand due to a higher occupancy rate (more heat production by people and computers),
- lower heating demand due to energy saving measures,
- higher heating demand due to modernization of the electric lighting system with less waste heat,
- unbalanced load of the heat exchanger field in a bivalent heating system where cheaper fossil fuels are mostly used for heating and the geothermal plant is mostly used for cooling,
- theoretical design of the borehole heat exchanger field does not fit the conditions of the construction site (space problems),
- higher or lower heating demand due to individual comfort zones which differ from theoretical standards.

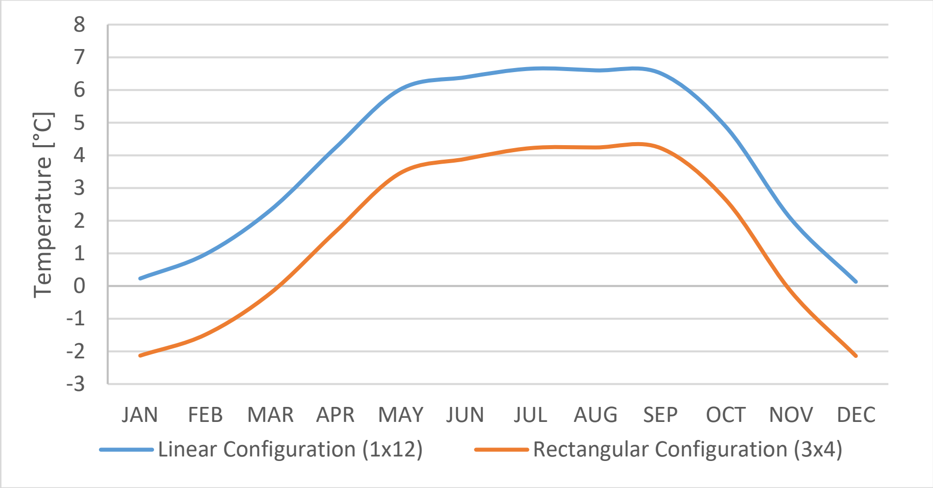

Figure 4: Estimated temperature at base load after 25 years (analytical dimensioning calculation).

To detect discrepancies in the planning phase the LBEG supports the water authorities of Lower Saxony in the process of issuing the required license under water law. To detect discrepancies that occur during operation of the borehole heat exchanger field a monitoring of the plant is necessary.

5. MONITORING

To detect potentially problematic temperature changes, it is necessary to undertake a proper monitoring of borehole heat exchanger fields. The monitoring program, which is a requirement of the license issued under water law, covers several aspects, including:

- electric power consumption of the plant,
- heat quantity taken from the field,
- heat quantity brought to the field,
- flow and return temperature of the heat carrier fluid,
- subsurface/groundwater temperature at a control point within the field (always required for plants > 100 kW).

This data is part of a series of reports about the plant to be submitted to the water authorities at increasing intervals, initially on an annual basis. Once the plant is in stable operation, a five year report interval is usually sufficient.

In the initial report it is essential to describe the planning and construction of the plant. Therefore, several questions should be answered: Was the borehole heat exchanger field constructed as described in the application documents submitted to the water authorities? Did any problems arise during drilling? Were any adjustments necessary that may have an impact on the operation of the field? How many borehole heat exchangers were constructed and to what depth? Where and how were the control points for subsurface temperature constructed if required under the conditions of the license under water law?

It is required to outline the operation of the plant and the operation method in each report: Is the plant used for heating or cooling or both? Are any other heat sources used for the building (e.g. gas)? Were any changes made compared to the planned operation (e.g. additional heating of other building parts, changes in heating/cooling demand)? The evaluation and interpretation of the measured values (especially temperature) is the most vital part of each report. The data has to be compared against the data from the planning phase and the data from previous report(s).

The data contained in these reports allows the plant operator and the authorities to compare the estimated demand used for planning with the actual demand during operation, and also the planned versus the actual temperature changes in the field. The operator can react by adjusting the heat demand covered by the geothermal plant or by adding more borehole heat exchangers or alternative heat sources to the system well before the plant is at risk of failure. Therefore, the continuous monitoring allows for the optimization of the plant performance.

6. CONCLUSION

The development of shallow geothermal energy in Lower Saxony has led to a significant increase in the construction of geothermal plants during the last decade. More than 15,000 geothermal plants with heat pumps have been built. The majority of these plants are being operated with borehole heat exchangers and are used for heating family homes. However, more and more plants supply heating and cooling for commercial, residential, office or industrial buildings with an output generally in excess of 30 kW. Planning and operation of these borehole heat exchanger fields require certain knowledge and input data. Some of this data is frequently based on estimates and can differ from the actual demands during operation. To assure an operation within the legal limits defined by the license under water law, a continuous monitoring is mandatory. Furthermore, the monitoring enables the operator to control the running of the plant and to make adjustments for a long-lasting and economic performance.

REFERENCES

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