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It works - long-term performance measurement of ground source heat pump systems

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Abstract

Long-term studies of GSHP heating and cooling systems for six different buildings (commercial, institutional and multi-family buildings) have been conducted in Germany by SIZ energy+. Three of them are equipped with borehole heat exchangers and the others use energy piles as a heat exchanger. The paper deals with a demonstration of the investigated buildings, the measured values and performance and the obtained results that include important findings and experiences, problems encountered and possible preventive measures to avoid mistakes.
After ten years of operation it can be stated that the systems work and achieve their planned efficiency but require constant control and regulation to avoid faulty operation. An analysis of the implemented control strategies shows that, for all these heating and cooling systems, holistically coordinated control strategies that are verified during commissioning are required.

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Keywords: GSHP systems; long-term performance measurement; efficiency

1. Introduction

The integration of heat pumps in the energy supply of buildings is an increasingly applied technology for heating but also for cooling applications. As the number of available and installed heat pump systems increases, the number of possible usable low-temperature heat sources is also increasing.

In practice, heat pumps still often function unsatisfactorily or at least sub-optimally today. The reasons for this are often insufficient connection to the low-temperature heat source and/or incorrect dimensioning of the corresponding heat exchanger. In some cases, heat pumps are not operated in accordance with the design conditions, which is often due to overoptimistic assumptions during planning, but also partly to user-dependent operating errors. In many cases, the primary energy, ecological and economic potential of a heat pump system is greater than achieved in practice. [1-3]

In Germany, the geothermal systems for heating and cooling of office and non-residential buildings have been implemented since 1990. While the first buildings were still pilot projects, most of the systems used nowadays are state-of-the-art. When the monitoring started in 2004 [1-3], there were no examinations or comparative studies from real operation dealing with the functionality and efficiency of the installed heat pumps and their system components. The advantages of a monitoring during operation have been recognized over time in practice, so that nowadays a pronounced increase in knowledge can be stated.

Within the framework of the IEA HPT Annex 52, the Steinbeis-Innovationszentrum (SIZ) energie+ is investigating the interaction between heat pumps and geothermal borehole heat exchangers as well as energy piles using six different buildings (commercial, institutional and multi-family buildings) in a long-term monitoring period of up to > 10 years. The aim is to obtain and document reliable knowledge about the actual

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performance of the buildings with regard to energy consumption, user comfort and operation. Such measurements can also be used to gain insight in how the various system components and control strategies affect overall performance, to identify best practices, design and installation issues that lead to poor performance and to give guidance on how unanticipated consequences of the design can be partially or totally avoided.

For the majority of the examined systems, errors have been analyzed and rectified so that operation-as-planned could be implemented. Subsequently, optimization measures were carried out with regard to a more efficient operation of the geothermal heat storage system in heating and cooling mode, where it was feasible.

2. Monitoring buildings and systems

Within the framework of a "low-level monitoring", four office buildings as well as a school and a multi-family house are measured and analyzed more precisely (Table 1). The six buildings are newly constructed buildings in different locations in Germany. Three building are equipped with borehole heat exchanger and the other three with energy piles, which serve as heat sources for the heat pump system.

The year of construction and commissioning of the buildings took place in the years 2002 to 2016. However, most of the measurement data is not available from the beginning of the building's use. The buildings will be evaluated in the period from 2006 to 2018. For some buildings, however, the data is only available since 2011 or 2017 (commissioning of the building or data transmission). The geothermal systems are integrated in the buildings for heating via a heat pump and for cooling in free cooling mode and via a reversible heat pump [1,3].

The energy concepts for all buildings contain the combination of floor heating or another low-temperature system to heat the building with a heat pump. In the building, heat and cold are distributed resp. transferred via concrete core activation and ventilation systems. In some buildings, high-temperature distribution systems with convectors or radiators are implemented to cover the peak loads of the heating. These building are either connected to the district heating network or use a gas condensing boiler [1,3].

Concerning the school, it is necessary to add, that in addition to the energy piles, a so-called "Agrothermiefield" was installed beneath the sports field. Agrothermie is basically an area collector, that is installed in a new and innovative process using a special plowing technology. The pipe system is plowed with a newly developed sword plow up to 2 m depth under the sports field of the school.

As part of the monitoring of the six buildings, all relevant data will be collected in order to be able to describe the buildings and their plant technology with sufficient accuracy. The measurement concept provides the recording of all essential heat flows and electricity consumption, so that a balanced assessment including the individual producers and consumers is possible.

For older or already commissioned buildings, additional measuring equipment had to be installed. For the other buildings, the monitoring and measuring concept was already defined during the construction phase so that the data can be obtained directly from the system control. For reasons of cost and time, the additional equipment was installed on top of the existing system technology in such a way that data access was given without intervening the building services or structural changes. Depending on the requirements, this could be achieved through the use of mobile digital measurement technology (additional heat meters with temperature and volume flow sensor at relevant points). The measured datasets mainly were recorded on-site either by a computer or by the building management system. Via remote access, the recorded data could be retrieved.

The measured values are recorded every 15 minutes so that parameters of the system components can also be mapped. The measurements and analysis include among other things operating modes, control strategies, the ground source heat extraction and injection, fluid temperatures as well as seasonal performance factors.

Depending on the building, the monitoring extends over two to more than 10 years, so that at least two heating and/or cooling periods are available for evaluating the performance of individual system components and for determining characteristic values.

Table 1. Buildings, heat exchanger systems and supplied systems of the buildings investigated in the monitoring

	Building (anonymized building code)			Ground heat exchanger		Heat supply system
Borehole heat exchanger	AOV Office building	Year: Net floor area: Heating load: Cooling load: Add. heat source:	2010 6750 m² 262 MWh per year 62 MWh per year Gas boiler	Quantity: Length of borehole: Overall length: Extraction / Injection:	25 100 m 2500 m 174 / 206 MWh per year	radiator concrete core activation ventilation
	GEW Office building	Year: Net floor area: Heating load: Cooling load:	2004 6200 m² 554 MWh per year 166 MWh per year	Quantity: Length of borehole: Overall length: Extraction / Injection:	36 150 m 5400 m 155 / 110 MWh per year	heating/cooling ceiling ventilation floor heating
	KON multi-family house	Year: Net floor area: Heating load: Cooling load:	2016 1100 m² 66 MWh per year -	Quantity: Length of borehole: Overall length: Extraction / Injection:	9 100 m 900 m 60 / - MWh per year	floor heating domestic hot water
Energy piles	EFB Office building	Year: Net floor area: Heating load: Cooling load: Add. heat source:	2003 20700 m² 828 MWh per year 62 MWh per year District heating	Quantity: Length of pile: Overall length: Extraction / Injection:	196 8,50 m 1666 m 85 / 85 MWh per year	concrete core activation
	VGH Office building	Year: Net floor area: Heating load: Cooling load: Add. heat source:	2002 4000 m² 350 MWh per year 24 MWh per year District heating	Quantity: Length of pile: Overall length: Extraction / Injection:	101 17,50 – 21,50 m 1926 m N/A	concrete core activation ventilation
	WGG school	Year: Net floor area: Heating load: Cooling load: Add. heat source:	2015 11500 m² 340 MWh per year 100 MWh per year Gas boiler	Quantity: Length of pile: Overall length: Extraction / Injection:	4400 m² Agroth. / 96 energy piles 8 – 12 m 1004 m Agroth. 61,5 / 70,7 MWh per year energy piles 101,7 / 102,3 MWh per year	concrete core activation ventilation floor heating

3. Monitoring

In addition to technical practicability, energy as well as ecological and economic aspects play a central role in the decision for or against a particular heating or cooling system. When comparing geothermal systems with conventional systems, the question arises as to whether they can guarantee a similarly high level of thermal comfort in buildings and what usable advantages they offer with regard to the above-mentioned aspects.

In the following sections, the monitoring results of the six buildings and systems are used to discuss energy yields and system efficiency as well as system performance.

Some of the systems had already been in operation for several years before they were analyzed in more detail as part of this project. Therefore, in some of the buildings and plants faults were hidden for a long time and were only discovered during monitoring and corrected as far as possible. The measurement results reflect the fault detection and correction as well as the subsequent operational optimization and therefor vary considerably from year to year in some cases.

The results documented in the following are therefore not target or guideline values for other projects, but rather are intended to show optimization successes and potentials as well as possibilities and limits of the geothermal systems.

3.1. Seasonal performance factor

In order to ensure a uniform basis in the evaluation of the heat pump performance, the boundaries for the calculation of the Seasonal Performance Factor (SPF) are set in advance in according to the boundaries defined by SEPEMO [4]. The boundaries can be found in Figure 1.

In the evaluation and comparison of the monitored plants, only SPF2 is described more detailed in this paper. In addition, depending on the available measurement data, the heating and cooling cases are considered separately, so that a seasonal performance factor is determined for both heating and cooling cases.

$$SPF\,2 = \frac{\text{thermal energy of heat or cold supply of the heat pump and free cooling}}{\text{electrical energy of the compressor of the heat pump and circulating pump on earth side}} \quad (1)$$

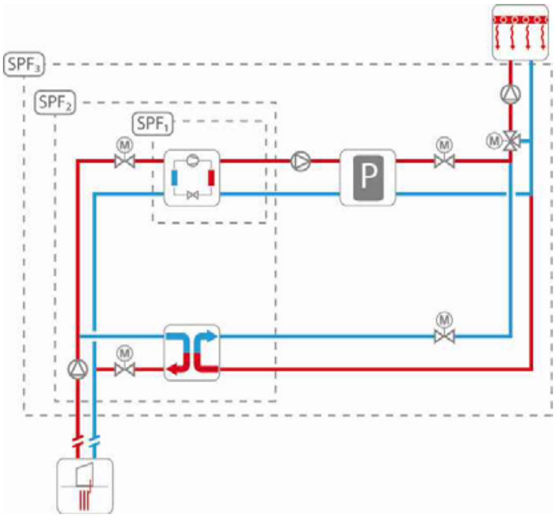

Fig. 1. Boundaries for the calculation of the seasonal performance factor

The seasonal performance factor of heat pumps, free cooling and cooling machines vary widely in their magnitude. From a primary-energy perspective, heat pump operation with a SPF greater than 3 is considered efficient. In active cooling mode, the SPF should reach a value greater than 2.5. Free cooling operation is particularly efficient. Here, electrical energy consumption on the generator side is only required for driving the circulating pumps of the geothermal system. With correct dimensioning and mode of operation, SPFs of 20 to 50 – or higher - can be achieved [1].

With seasonal performance factors of less than 3, the operation of some of the monitored plants was not as efficient as planned when the monitoring started. Within the scope of the monitoring, the systems and the operation could be optimized to such an extent that all plants achieve seasonal performance factors between 3 and 6 (Figure 2 and 3). Larger leaps in the seasonal performance factor, e.g. in the energy pile system of the VGH or the GEW system, are usually due to system optimizations or hydraulic changes. Causes for slight fluctuations, such as in the energy pile system of the EFB building, are, for example, due to varying requirements depending on the weather as well as varying underground temperatures. A decisive influence on the seasonal performance factor of the cooling system is the proportion of the very efficient free cooling operation in relation to the active cooling mode.

The comparatively low seasonal performance factors of the borehole heat exchanger system of the GEW building with almost optimized operation are related to the deviating objective. The building is heated and mainly cooled by the geothermal system. Only the supply air is cooled to room temperature in summer by an independent system. In order to cover the cooling loads from the building even on extreme summer days, the heat pump is reversible and can therefore also provide active cooling during the summer. Since the GEW borehole heat exchanger system, unlike the other systems, is not designed primarily for basic but also for peak load coverage, the reversible heat pump run a large part of the operating time in less efficient partial load operation. Furthermore, this heat pump is not a standard product and was individually designed at the time. According to the age and the construction method, seasonal performance factors > 3 are not to be expected.

The results of the EFB, AOV, KON and WGG buildings show that targeted quality assurance and operational monitoring pay off right from operational start-up. Up to now, seasonal performance factors of up to 5 have been achieved here. (Figure 2 and Figure 3) It should also be noted that operational monitoring is also helpful after a calibration phase. Thus, it can be stated that after the end of the actual research project and the optimization phase (2010/2011), the seasonal performance factor at the VGH fell below 3.0 again. The faults here relate to the plant technology.

On the basis of the evaluations of the buildings and heat pump systems, it can be summarized that (Figure 2 to 5)

- the majority of the buildings meet the consumption calculated in the planning and there are no major user-dependent changes,
- the heat pump systems are generally reliable and efficient,
- for the heating mode, seasonal performance factors larger than 3 are achieved for most systems. SPF over 5.0 were determined for two systems. For one building, the seasonal performance factor is below 3.0 according to the measured data, which is due to the design and the plant itself.
- for cooling operation, seasonal performance factors of around 4 can be achieved for most systems if there is a priority active cooling process (reversible heat pump). The free cooling operation of the EFB system alone leads to seasonal performance factors of around 40 in cooling mode.

The reasons for the low seasonal performance factors include, among others

- the continuous operation of the system (running times),
- non-coordinated operating strategies as well as heating and cooling curves between the operating states of heating, active cooling and free cooling, and
- changed setpoints, e.g. outdoor air temperature as the starting value of the cooling mode, were not reset to standard mode after changes in the settings due to defective equipment, and
- faulty measurement.

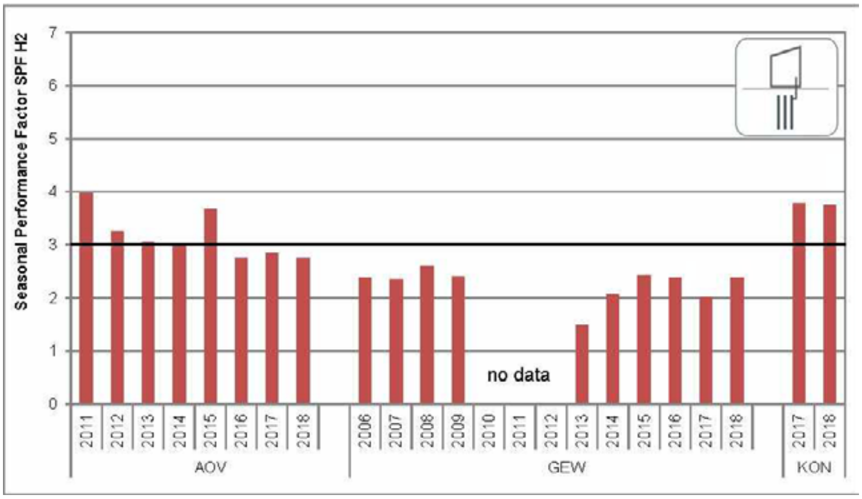

Fig. 2. Seasonal performance factors heating for the monitored buildings with borehole heat exchangers

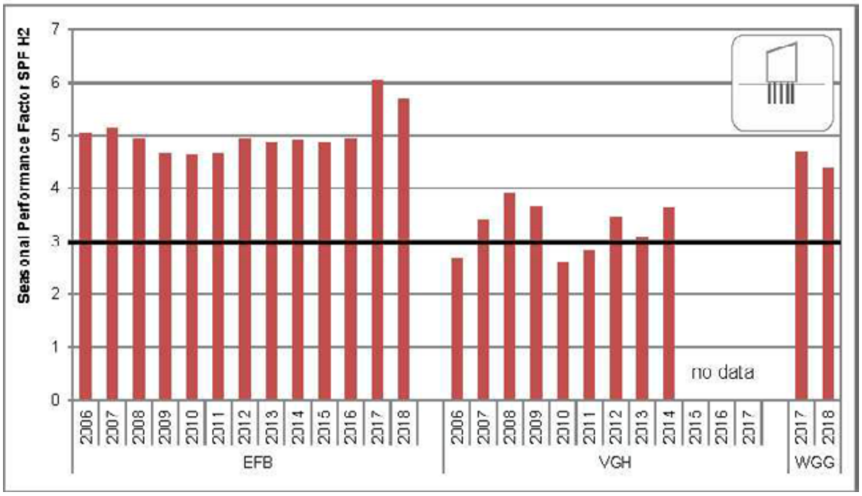

Fig. 3. Seasonal performance factors heating for the monitored buildings with energy piles

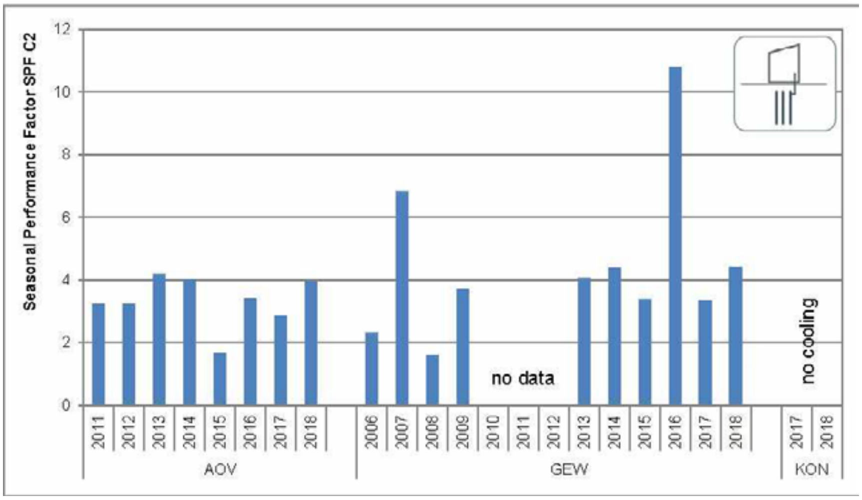

Fig. 4. Seasonal performance factors cooling for the monitored buildings with borehole heat exchangers

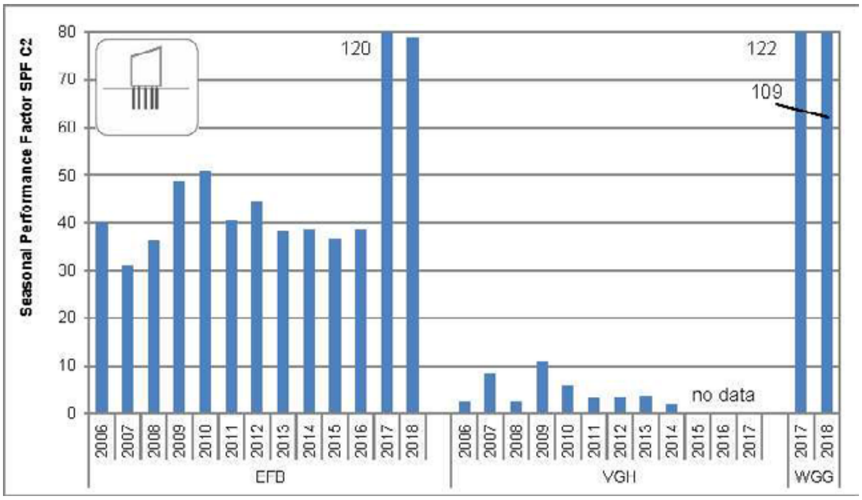

Fig. 5. Seasonal performance factors cooling for the monitored buildings with energy piles

3.2. Heat extraction and injection

The specific annual energy yields for the various heat sources and heat exchanger systems are shown in Figure 6 per meter of borehole heat exchanger or energy pile.

The largest specific energy extraction occurs in the KON and WGG. In one year up to 170 kWh/(m a) and 107 kWh/(m a) are extracted from the ground. The AOV and GEW have the highest specific heat injection. A maximum of 120 kWh/(m a) and 96 kWh/(m a) are injected into the ground. The average specific heat extraction for borehole heat exchangers is 80 kWh/(m a) and for energy pile systems 50 kWh/(m a). The values for heat injection are 75 kWh/(m a) for the borehole heat exchangers and around 34 kWh/(m a) for the energy piles.

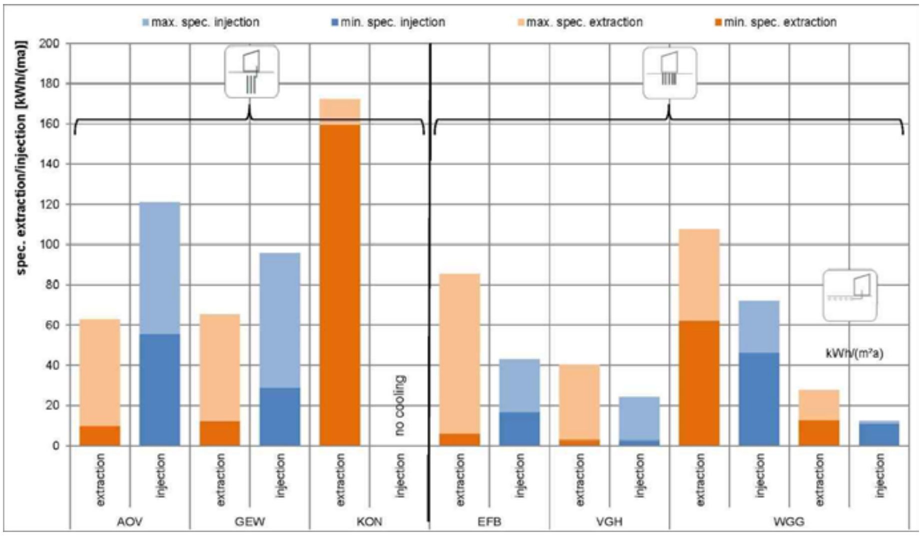

Fig. 6. Specific heat extraction and injection of the monitored heat exchangers

Ground storage systems are planned with the aim of achieving a constant temperature level in the ground over the years and a permanently stable operation for approximately equal yields of heat extraction and injection. The energy yields recorded as part of the monitoring vary from year to year, mainly because of the system optimizations, but also as a result of the influence of the weather and the resulting varying consumption. Overall, the extracted heat corresponds approximately to the planned values. The heat injection, on the other hand, deviates considerably from the planned values for some plants. The reasons for this are faults in current operation or an excessively high temperature level in the ground for free cooling operation as a result of operating faults immediately after start-up. In order to achieve a constant temperature level over the years, some systems require a higher heat extraction than heat injection due to higher than expected temperatures of the underground.

For inner-city areas, monitoring has shown that less deep systems, such as energy piles, which are used as seasonal storage systems, usually require a higher heat extraction rate than the heat injection. Due to the high density of buildings and the high degree of surface sealing, the near-surface layers in inner-city areas are relatively warm. With a well-adjusted balance between heat extraction and heat injection, the temperature level of the heat sink is usually too high for free cooling operation in summer.

For the AOV, it can be noted that the heat injection is noticeably higher than the heat extraction (in 2015: 3.5 times). A well-adjusted heat balance is therefore not available, despite an almost 100% heat supply via the heat pumps. It is therefore essential to ensure that more heat is extracted from the ground or that significantly less heat is injected into the ground due to server cooling. On the basis of the total energy quantities, it can be seen from the annual balance sheets that since 2011 significantly less heat has been extracted than assumed in the planning / design. It can also be seen, however, that the optimizations and modifications to the heat pump have increased heat pump operation and have thus also enabled significantly more heat to be extracted from the ground since 2013. The heat injection could be significantly reduced by outsourcing the servers and the associated server cooling (2017). In 2018, a good balance between heat injection and heat extraction can now be established. (Figure 7)

In the case of the GEW building, heat extraction was significantly increased from 2009 onwards. For the years 2009 to 2018, heat extraction is between 230 and 330 MWh/a. During the years 2011 to 2017, reduced active cooling mode and an increased proportion of free cooling will lead to a reduction in heat injection into the ground. During this period, the heat injections were between 220 and 270 MWh/a. In 2018, 405 MWh/a were injected into the ground as a result of the further increase in cooling machine operation. (Figure 7)

For the EFB, it can be noted that around two times more heat is being extracted from the ground than being injected during the summer. The aim is to cool down the underground and enable a higher proportion of free cooling in summer. In 2009, the heat extraction of 142 MWh/a was almost three times higher than the heat injection which was 53 MWh/a. Both heat extraction and heat injection were significantly reduced in the years

2013 to 2018 due to errors in the heat pump and control problems and amount to 10 MWh/a to 33 MWh/a for extraction and 28 MWh/a to 55 MWh/a for injection. (Figure 8)

At VGH, the planned heating and cooling operation was implemented during the monitoring process until 2009. From 2014, heat extraction from the ground was reduced to between 5 MWh/a and 43 MWh/a due to a new control system and new software for the heat pump. No scheduled operation has been restored since the software changeover. (Figure 8)

The alternating heating and cooling operation of the WGG requires a coordination between the Agrothermie and energy piles. For the years 2017 and 2018 the energy piles have a heat extraction of 63 MWh/a and 107 MWh/a as well as a heat injection of 46 MWh/a and 72 MWh/a. The extraction and injection values of the Agrothermie in the same period are 56 MWh/a and 121 MWh/a for the extraction and 48 MWh/a and 53 MWh/a for the injection. Since beginning of the building's use, adjustments have been made to the control strategies of the two sources on the basis of the brine entry and exit temperatures of the geothermal low-temperature heat sources and their heat exchangers. The inefficient year-round continuous operation of both sources (parallel operation), which was implemented at the beginning, was replaced by a prioritization (addition / removal of one source). To increase the efficiency, the two sources have been controlled separately in the winter months since the changeover. The changeover is based on the higher brine outlet temperatures per source system. During the heating period, the heat pumps primarily use the energy piles (higher brine temperature level). To ensure that the piles are kept frost-free, they are only operated up to a brine entry temperature of > 3 °C. Afterwards the heat is removed from the Agrothermie. A reverse priority is planned for the cooling period. The Agrothermie will act as a priority and then the bored piles will be controlled to ensure, among other things, regeneration of the energy piles.

For an assessment of the efficiency of the Agrothermie, the energy piles were deactivated during the heating period 2018/2019. The control adaptation serves to determine the heat injection and extraction in a heat pump system with the sole heat source of an Agrothermie. It has been shown that the field can serve as the sole source for the heat pumps up to and including December (and beyond). For the future operation of both heat sources, however, it must be ensured that there is a balance in both sources and that the soil is overcooled neither in the Agrothermie nor in the energy piles. Regeneration is necessary in both cases. (Figure 8)

The KON system is running according to plan and without any incidents. The heat extraction amounts to about 150 MWh/a in the years 2017 and 2018. (Figure 7)

The success of the optimization measures and error corrections carried out can be clearly seen in the buildings. Nevertheless, a well-adjusted balance was not fully achieved.

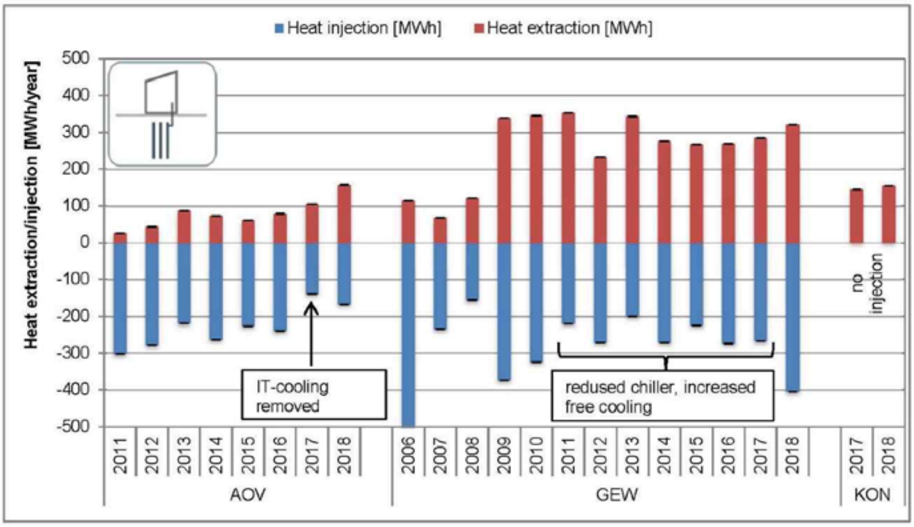

Fig. 7. Annual heat injection and extraction of the borehole heat exchangers systems

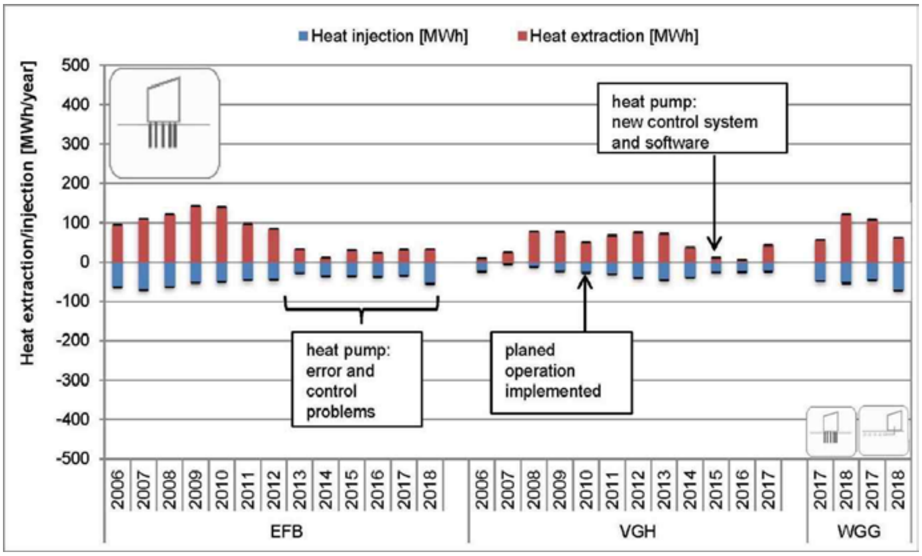

Fig. 8. Annual heat injection and extraction of the energy pile systems

4. Operating experiences

The experience gained from the project monitoring shows that it is possible and sensible to integrate geothermal systems into innovative energy concepts for office buildings as well as schools and multi-family houses. However, a regulation phase is required during which the direct interaction between the geothermal system, the building, other thermal conditioning systems and not least the users is optimized. A lack of experience of contractors and plant operators often significantly prolongs this regulation phase. Compared to conventional heating and cooling systems, geothermal low-temperature sources are subject to a special feature with regard to the detection of system and operating faults due to their inertia and the interaction of base and peak load components. Without targeted operational monitoring, errors due to system inertia remain unnoticed until defined operating parameters can no longer be achieved. As this usually only happens after years, the ground is -in the worst case- already significantly undercooled or overheated. Once the fault has been rectified, the ground may no longer be usable for the intended operating mode - heating or cooling - for a longer period of time. The ground must first be thermally regenerated.

Many of the results presented in this paper have been generalized, as they have not only been found in individual buildings. In one building, the points listed may have been more serious/amplified than in another. We would like to consider the following statements generally valid, although they should also be checked/monitored for all buildings in the future.

Essential points of the performed defect and error removal at the buildings and plants examined by measuring technology and the resulting problems were among others:

- Hydraulic investigation: like incorrect installation of valves and check valves or opening valves without heating or cooling medium.
- Defects in dimensioning and design: system components dimensioned / designed too small, e.g. plate heat exchanger, circulating pumps.
- Control of the geothermal system: poorly coordinated control strategies or circulation pumps running 24/7.
- Coordination of the individual exchange systems and components.
- Faulty operation is usually not due to the geothermal system, but to the technical and operational integration of the single system modules in the complex overall system.
- Errors in design and implementation but particularly faults in control and operation.

Important findings and experience:

- Heat is drawn from other sources instead of using the ground (district heating, internal loads, etc.). In some buildings, an unequal energy balance in the ground was recorded. In addition, other installations did not function reliably, so that no continuous and controlled heat extraction and injection into the ground could be recorded. This led to overheating or cooling of the ground. The supply of district heating or similar must be limited exclusively to covering peak loads.
- Faulty operation: under- or overheated soil, free cooling not possible and temperature level between heat sink and building often not tuned. Adaptation of heating and cooling curves as well as control and release limits of heat pumps, rev. heat pump and free cooling during operation is mandatory.
- Adaptation of room set points and general set points to the actual boundary conditions.
- Control and recording of the function of a building combined with installation of geothermal system is important, it is not a system that works for itself.
- Constant control required: Changes in the operation modes will be forgotten to reset.
- Slow system →late fault detection, long-term consequences.

Fault prevention:

- "Keep it as simple as possible" – simple energy concepts with simple systems and modules are needed.
- Quality assurance during the construction phase as well as comprehensive final inspection and commissioning after completion.
- Improved and early integration of geothermal systems into building concept and control strategies.
- We have to talk! Consultation between architect, building services planner and geothermal planning.
- Monitoring:
  By monitoring the operating condition of most buildings, it is possible to prove that they are not in accordance with the design. For this reason, error analyses and error corrections are necessary at the beginning of monitoring in order to transfer the buildings to regular operation. Only then can the operating data be used for the objective of the project and the actual measurements and evaluation can begin.
  - Minimum measurement equipment for monitoring of operation.
  - Monitoring of operation to detect and eliminate performance faults >> adjust operation to real boundary conditions.
  - Monitoring of annual energy amount (heat injection and extraction) as well as brine temperatures.

5. Conclusion

In addition to reducing the energy requirements of buildings, the sustainable (e.g. CO_2-neutral) coverage of energy requirements is a focus of research and development. From the perspective of the use of regenerative energies and energy-efficient construction, in recent years, the ground has increasingly been integrated into energy concepts as a supplier of heat and cooling in conjunction with a heat pump for the heating and cooling of modern office and administration buildings as well as multi-family houses. Heat pump technology will therefore continue to play an important role in the future supply of heat and cooling. In order to exploit the potential of this energy supply variant as efficiently as possible, the choice of a low-temperature heat source and the most suitable heat exchanger for the respective application is of decisive importance.

The results from the research work and the scientific monitoring of the projects, as well as their implementation in practice—presented in the paper—show that it is generally possible and sensible to integrate ground-coupled heat pumps into innovative energy concepts. By monitoring six buildings and their geothermal systems for more than 10 years, it has been shown that, for a successful and permanent operation of energy pile and borehole heat exchanger systems, a high-quality standard has to be maintained during planning, implementation and operation.

It also becomes clear that it is not only a harmonious energy concept and innovative plant technology that lead to an energy-efficient building. Even with detailed, careful planning, malfunctions often occur during operation, which can cause rising energy consumption or cause discomfort. For this reason, quality assurance (operational analysis and optimization) is of crucial importance for ground-coupled supply concepts, especially in the first years of operation and beyond the project phases. This is the only way to ensure that buildings and systems achieve their planning objectives and long-term functionality, as well as progress in system energy efficiency and user comfort. For all heating and cooling systems in this study, it was found that holistically coordinated control strategies are required, and these must be double-checked and monitored during operation until regular operation is achieved. In cooperation with the building management, possible errors and optimization potentials could be identified step by step, the operation of the systems optimized and the balancing phase shortened. Most of the considered buildings and their ground-coupled heat pumps could be brought into operation as planned and now operate efficiently with an SPF H2 between 2.5 and 6 and in cooling mode between 4 and greater than 100 (depending on the proportion of free and active cooling). The results also show that there is generally no significant difference in operation and performance between a borehole heat exchanger and an energy pile.

In general, it should be stated for all buildings that a balancing phase and continuous monitoring of the injection and extraction quantities should not be neglected. As found in earlier monitoring projects and also in the buildings currently under investigation, it is only possible to detect errors and inconsistencies which have a decisive influence on the operation of the plant through long-term monitoring. Continuous monitoring, adjustment and maintenance is therefore necessary to ensure the intended operation of the plant.

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