IGEIA
Integration of Geothermal Energy
into Industrial Applications

> Deliverable 10

> FEASIBILITY STUDY: GEOTHERMAL HEAT PUMP FOR STANDARDIZED SUPERMARKET

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UBeG Dr. E.Mands & M. Sauer GbR
Zum Boden 6
D-35580 Wetzlar
Tel. +49 6441 212910 – Fax +49 6441 212911
www.ubeg.de

UBeG
Umwelt Baugrund Geothermie Geotechnik

1 Introduction

A solution is suggested for covering the space heating and cooling loads of a standardized supermarket building by the use of shallow geothermal technology. The energy needs of such a standardized supermarket have been determined in a previous phase (WP 3) and been described in Deliverable D8. A summary is given below in chapter 4.1.

In a typical supermarket, heat and cold is required in the following areas:

- Space heating for the market area, offices and storage
- Space cooling for the market area, offices and storage
- Heat for hot water in offices and social rooms (DHW)
- Cold for cold display cases in market area and for cold storage
- Cold at low temperature for deep freezers in market area and storage

The classical energy supply in summertime uses individual refrigeration equipment for space cooling and for cold display, for storage and deep freeze storage. In winter, space heating is provided by natural gas boilers (sometimes fuel oil boilers), while the refrigeration equipment for cold and deep freezing continues running. DHW, for which there is typically a minor demand only, can best be covered by a small electric boiler near the kitchen sink in social rooms. Deep freezer chests in the market area are independent units, each with own condenser; plugged to the electric main.

The geothermal system shall replace the refrigeration equipment for space cooling and the boilers for space heating, and also provide as much of the cooling for cold display, storage and deep freeze storage as possible, in combination with the related refrigeration equipment.

2 Geological Situation

As the standardized supermarket building is constructed in larger numbers throughout all of Germany (with some local variations in size and layout, to accommodate to specific site conditions), there will be no specific geological situation for the geothermal system. Hence a solution has to be selected that allows for application under almost any possible geological conditions. Furthermore, the available area at any site has to be considered; the ground under the standard-sized car park typically should serve as the geothermal reservoir. So from the various shallow geothermal technologies, the Borehole Heat Exchanger (BHE, fig. 1) serves these purposes best.

For sites with suitable groundwater conditions (fig. 2), the direct use of groundwater through wells (open system, fig. 1) could be an alternative. However, as BHE are also suitable at those sites, the more general solution of BHE is investigated in this study.

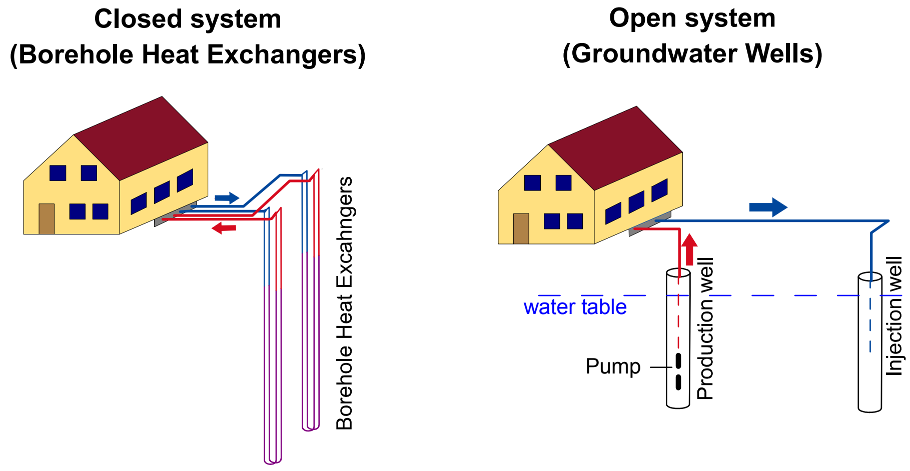

Fig. 1: Shallow Geothermal System with Borehole Heat Exchangers (BHE, left) and with Groundwater Wells (right)

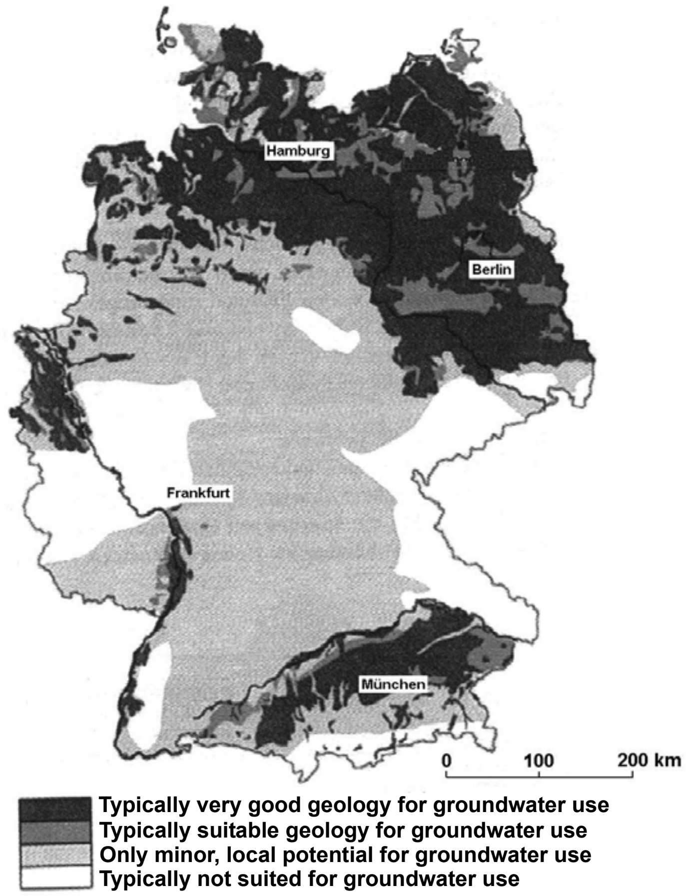

Fig. 2: Map showing areas in Germany suitable for thermal use of the groundwater; BHE are feasible throughout all of Germany (based on a study by GTN, Neubrandenburg, 2002)

For the exemplary detailed design of the geothermal system, a specific site of one standardized supermarket has been chosen, and the relevant geology investigated. The ground on that site consists of thick layers of gravel, sand and silt of Quarternary and late Tertiary age, down to a depth exceeding that of typical BHE (some 100 m).

Drilling in this geology requires a temporary casing in order to keep the borehole open while installing the BHE, and removing the casing before grouting of the borehole. The thermal conductivity of the ground was estimated on the basis of the expected geology with λ = 2,0 W/m/K. This value later was confirmed using a thermal response test.

3 Principle of “Total H&C” Geothermal System

The conventional energy supply for a standardized supermarket, as described in deliverable D8 and summarized in chapter 1, results in rejection of heat in summertime and a need for external energy for heating (natural gas, fuel oil, etc.) in winter. The optimum solution would be to use the rejected heat from cooling for meeting the heat demands. However, as the main heating and cooling demand fall into different seasons, a further integration can only be achieved by adding a seasonal storage component. The earth can act as thermal energy storage, and geothermal technologies can be used to access this storage volume.

First application of this idea can be reported from USA, where in 1997 a filling station and “convenience store” of company Philips 66 in Prairie Village, Kansas, was equipped with a relatively simple system integrating all cooling/refrigeration devices and heat consumers into a single loop, balanced seasonally by a group of borehole heat exchangers (BHE, fig. 2). This concept later has been replicated a few times by Philips 66, but also by other companies as Texaco and Conoco, e.g. for a Conoco service station in Skunk Creek, Minnesota. Compared to a standardized supermarket, the demand for heating, cooling and refrigeration of these installations is relatively low.

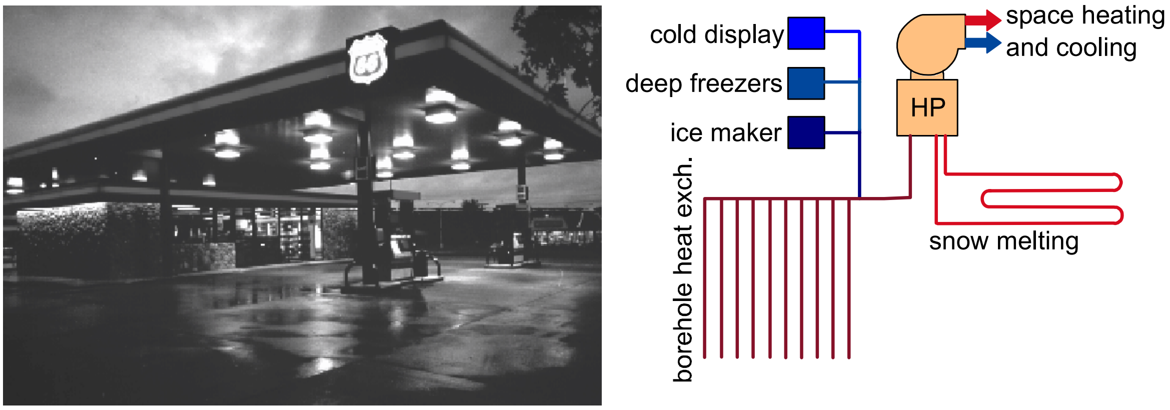

Fig. 3: Philips 66 service station and convenience store at Prairie Village, Kansas, USA (left, photo Geothermal Heat Pump Consortium / Washington) and simplified system schematic (right, UBeG drawing)

A system suitable for a supermarket, and adapted to European practice, has been designed under leadership of UBeG in the framework of the IGEIA project. The geothermal system here allows for seasonally balancing heating and cooling loads, for rejecting surplus waste heat from cooling/refrigeration, and for supplying additional heat for winter heating. The various consumers of heat and cold are integrated as completely as possible. Fig. 4 shows the basic schematic of such a „total heating and cooling“ geothermal system.

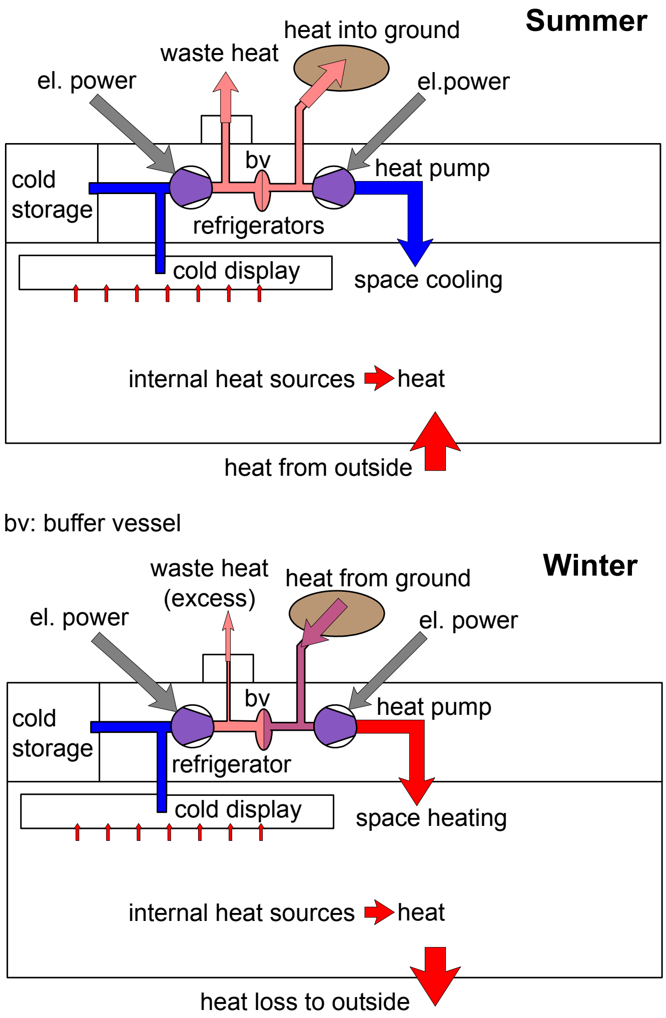

Fig. 4: Schematic of a “total heating and cooling” geothermal system for standardized Supermarket

The gas boiler now becomes obsolete, the heat for heating in winter is supplied by the geothermal heat pump only. The heat source for the heat pump is provided by the borehole heat exchangers (BHE) and, if operating at the same time, the condenser waste heat of the central refrigeration system. However, because the condenser waste heat is considerably more than can be absorbed by the earth in a long term, a conventional air cooler to the outside still has to be retained to cover the excess condenser cooling load.

During summer, the geothermal heat pump supplies space cooling for market area, office and social rooms. The condenser waste heat of the heat pump always is directed towards the earth via the BHE. Of the condenser waste heat from the central refrigeration, only a part can be absorbed through the BHE, and the rest goes to air coolers. One task for the correct sizing of the system was to find an optimum share of waste heat to go to the underground, and to size the BHE accordingly (see chapter 4). Fig. 5 shows in a schematic way the energy flows in such a geothermal system.

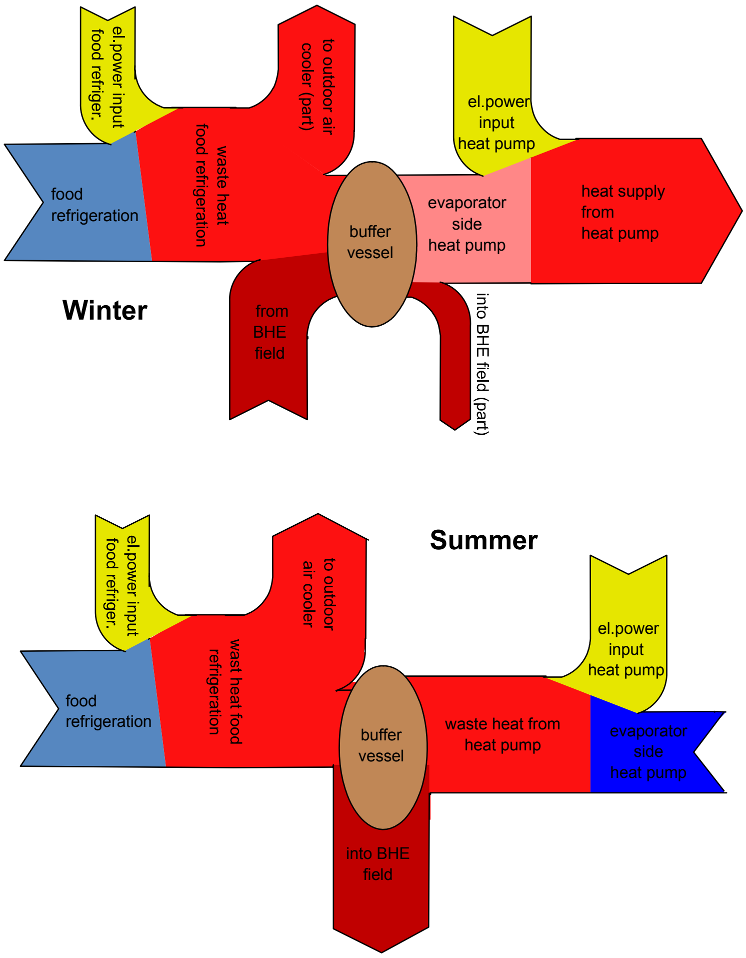

Fig. 5: Schematic of energy flows with integration of most heating and cooling demands of a standarized supermarket into a geothermal system

4 Performance of the system

4.1 Energy Demand

The energy requirement for a standardized supermarket has been investigated closely and results are given in deliverable D8. A summary is repeated here, as starting point for sizing the alternative geothermal system.

Beside space heating and cooling, the most important energy consumer in a supermarket is the cooling for food storage, consisting mainly of the following items:

- Cold for cold display cases in market area
- Cold for cold storage cells in storage area
- Cold at low temperature for deep freezers in market area
- Cold at low temperature for deep freezing storage in storage area

The heat and cold required for all of the thermal energy needs in the standardized supermarket is listed in table 1. The final energy input for the covering of these needs in a conventional system (natural gas, electricity) is listed also in table 1, in italics.

Table 1: Summary of thermal energy need of standardized supermarket, in arbitrary energy values EV for heating/cooling work (instead of kWh or MWh), and arbitrary power units PU for heating/cooling capacity (instead of kW); final energy required for conventional supply is given in italics.

	Annual work	Momentary output
Space heating requirement	14’690 EV per year	13.8 PU
Natural gas for space heating	*15’460 EV per year*	*14.6 PU*
Space cooling requirement	942 EV per year	6.9 PU
Electricity for space cooling	*314 EV per year*	*2.3 PU*
Food cooling, storage, freezing	73’370 EV per year	18.1 PU
Electricity for food cooling etc.	*24’260 EV per year*	*6.0 PU*

The relevant heating and cooling loads (tab. 1) now are transferred to the geothermal system according to fig. 4, and the resulting energy flows are calculated. Table 2 lists the annual total, while fig. 5 shows the development over an average year. For space heating and cooling, both the actual demand (cf. tab. 1) and the part that has to be covered by the geothermal system are differentiated. Because heat pumps and chillers require some final energy input,

- the amount of heat from the ground is smaller in the heating mode (the additional energy becomes part of heating),
- and the amount of heat into the ground is larger in cooling mode (the additional energy becomes part of the waste heat to be rejected).

For the central refrigeration system, only the sum of waste heat from the condenser is shown, which keeps constant over the year. As with space cooling, the waste heat is larger than the cold demand.

Table 2: Summary of thermal energy need of standardized supermarket, in arbitrary energy values EV for heating/cooling work (instead of kWh or MWh); resulting energy flows from and towards earth (and air cooler) are given in italics.

	Annual work
Space heating requirement	14’690 EV per year
Heat from the earth (BHE)	*10’820 EV per year*
Space cooling requirement	942 EV per year
Heat into the earth (BHE)	*1’130 EV per year*
Food cooling, storage, freezing	73’370 EV per year
condenser waste heat (into earth and air)	*98’090 EV per year*

As fig. 6 shows, the waste heat from the central refrigeration system (food cooling) exceeds by far the energy to be extracted from the ground for heating purposes. It is obvious that a certain balance of heat and cold towards the ground is impossible to achieve with rejecting 100 % of this waste heat. The net heat balance to be rejected into the ground would amount to 88’400 EV annually, and the related borehole heat exchanger field would have to be gigantic!

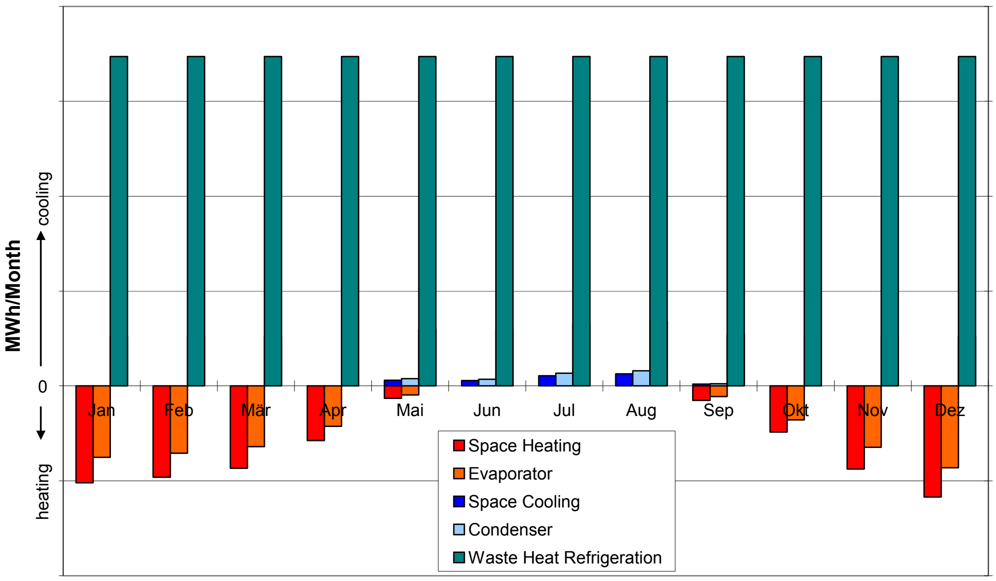

Fig. 6: Heat and cold demand for total h&c geothermal system, with heat to be produced from the ground or rejected into the ground; for the central refrigeration, only waste heat from condenser is shown

4.2 System Design

Hence three different scenarios have been investigated, with decreasing coverage of the central refrigeration waste heat (the rest of the waste heat is dumped in the ambient air by air cooler):

Scenario 1: Maximum amount of coverage possible inside the limits of the lot 65 % coverage

Scenario 2: Coverage reduced in attempt for coming closer to balancing 30 % coverage

Scenario 3: Optimized for small BHE field and covering of heating demand 15 % coverage

The resulting values of heat to be extracted from and injected into the ground for the three scenarios can be seen in fig. 7, with 100 % coverage for comparison.

In fig. 8, the monthly net heat balance in the BHE is shown for the three scenarios with 15-65 % coverage, and with 100 % coverage for comparison. The total annual values of heat to be rejected in to the ground, after balancing the heat extracted for heating in winter, are as follows:

Coverage	100 %	65 %	30 %	15 %
Heat into ground	88’400 EV	54’050 EV	19’700 EV	5’000 EV

The calculations for the necessary BHE number and length in sub-chapters 4.2.1-4.2.3 have been done using the standard software tool EED, developed jointly by Lund University, Lund, Sweden, and Justus-Liebig-University, Giessen, Germany in the 1990s. EED Version 2.01 from 2001 was used for this task. EED currently is the most widely used software tool for BHE layout in Europe.

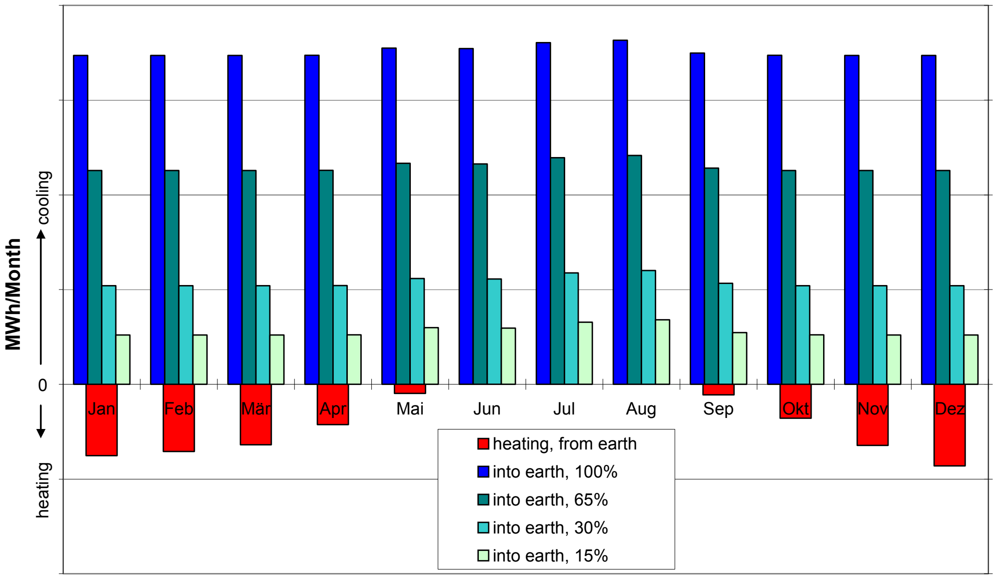

Fig. 7: Heat to be produced from the ground or rejected into the ground for total h&c geothermal system, for different scenarios with 15-100% coverage of the waste heat rejection from central refrigeration into the ground

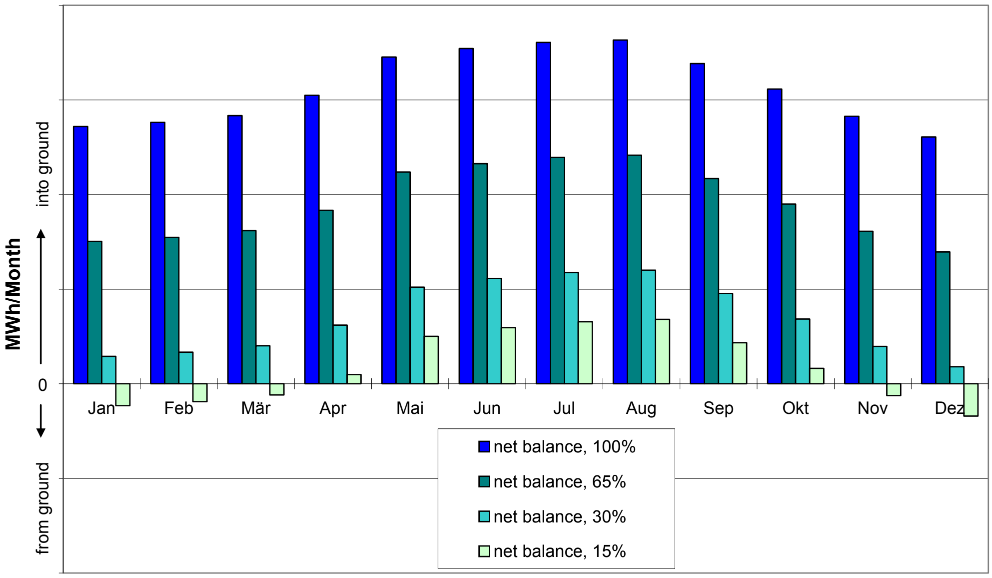

Fig. 8: Net heat to be produced from the ground or rejected into the ground as a monthly total for total h&c geothermal system, for different scenarios with 15-100% coverage of the waste heat rejection from central refrigeration into the ground

4.2.1 BHE layout for scenario 1

This scenario is optimized to allow a maximum rejection of waste heat from central refrigeration into the ground, over a given time period (15 years). The idea behind this scenario is that a standardized supermarket only has a limited lifetime, and probably will not be operated in the same form, building, site for more than 15 years. A gradual warming up of the ground due to heat rejection is accepted, because a longer recovery time can be expected after the closing of the supermarket. It should be clear that this recovery period has to be guaranteed, and an operation of the cooling system beyond the 15-year-period cannot be expected. For this scenario, the following BHE layout would be sufficient:

Number of BHE	28
Depth of each BHE	100 m
Pattern of BHE	2 or 3 parallel lines
Type of BHE	Double-U-tube

The heating and cooling load to be covered by that system would be:

Space Heating	14’690 EV (100 %)
Space Cooling	942 EV (100 %)
Waste heat from Refrigeration	64’700 EV (65 %)

Fig. 9 shows the development of the annual minima and maxima of the fluid inside the BHE for this scenario, over 15 years operation. In year 15, a maximum temperature of 30 °C will be reached.

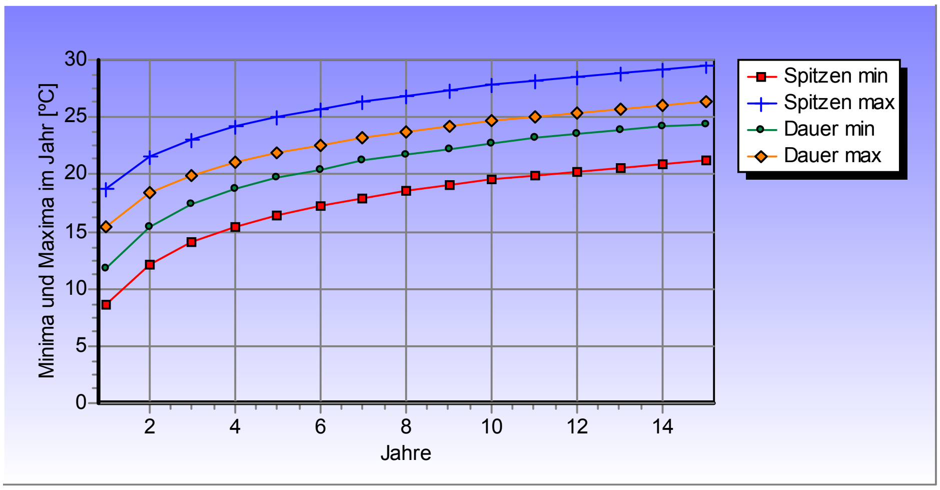

Fig. 9: Development of minimum and maximum fluid temperatures over 15 years for scenario 1, simulated with EED

4.2.2 BHE layout for scenario

This scenario is optimized to allow a safe operation over 25 years and beyond. The maximum possible rejection of waste heat from central refrigeration into the ground is desired, while the number and depth of BHE should be limited to an economically reasonable size. The waste heat from refrigeration still can be injected with the full thermal power over most of the time. For this scenario, the following BHE layout would be sufficient:

Number of BHE	16
Depth of each BHE	100 m
Pattern of BHE	2 parallel lines
Type of BHE	Double-U-tube

The heating and cooling load to be covered by that system would be:

Space Heating	14’690 EV (100 %)
Space Cooling	942 EV (100 %)
Waste heat from Refrigeration	30’500 EV (30 %)

Fig. 10 shows the development of the annual minima and maxima of the fluid inside the BHE for this scenario, over 25 years operation. In year 25, the maximum temperature is still below 30 °C, and the curve starts to level out.

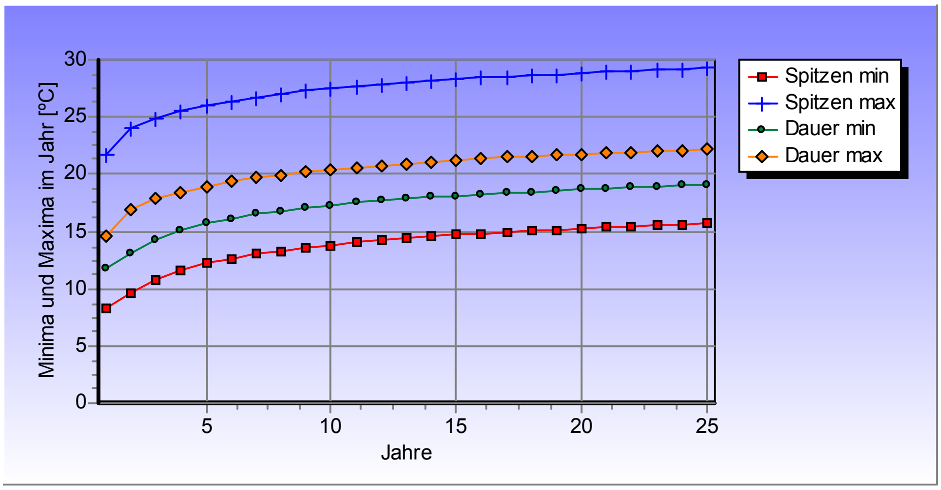

Fig. 10: Development of minimum and maximum fluid temperatures over 25 years for scenario 2, simulated with EED

4.2.3 BHE layout for scenario 3

This scenario is optimized to allow for covering the full heating load with a minimum of BHE, and to find the amount of rejection of waste heat from central refrigeration into the ground which still can be safely done with such small layout. The thermal power of waste heat from refrigeration to be injected into the ground has to be limited to 50 % of the full capacity. For this scenario, the following BHE layout would be sufficient:

Number of BHE	7
Depth of each BHE	100 m
Pattern of BHE	1 line
Type of BHE	Double-U-tube

The heating and cooling load to be covered by that system would be:

Space Heating	14’690 EV (100 %)
Space Cooling	942 EV (100 %)
Waste heat from Refrigeration	15’800 EV (15 %, at 50 % capacity)

Fig. 11 shows the development of the annual minima and maxima of the fluid inside the BHE for this scenario, over 25 years operation. In year 25, the maximum temperature is still below 30 °C, and the curve starts to level out. In the first years the minimum temperature at peak heating load are close to 0 °C, so the addition of antifreeze could be required.

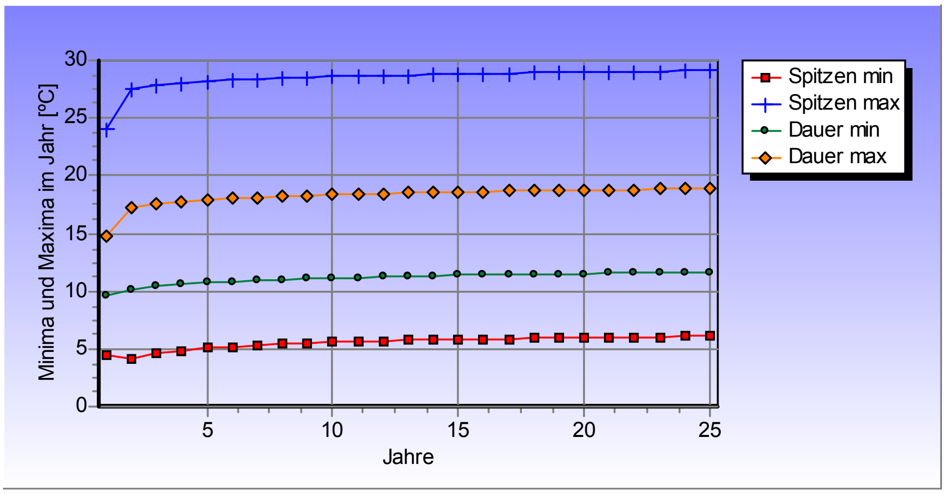

Fig. 11: Development of minimum and maximum fluid temperatures over 25 years for scenario 3, simulated with EED

4.3 Energetic Performance

The energetic performance has to be calculated in comparison to the conventional reference system. Table 3 list the final energy input required in the conventional system (natural gas, electricity) and in the geothermal system (electricity). For the geothermal system, a seasonal COP (SPF) of 4,0 was considered both for heating and cooling, with a value of 20 for (direct) space cooling. The total final energy input in the geothermal system is 37 % lower than for the conventional reference case.

Table 3: Comparison of conventional with geothermal energy input required to satisfy thermal energy need of standardized supermarket, in arbitrary energy values EV for heating/cooling work (instead of MWh)

	Annual work	Final energy input conventional	Final energy input geothermal
Space heating requirement	14’690 EV p.y.	15’460 EV p.y.	3’673 EV p.y.
Space cooling requirement	942 EV p.y.	314 EV p.y.	47 EV p.y.
Food cooling, storage, freezing	73’370 EV p.y.	24’260 EV p.y.	18’343 EV p.y.
Total	89’002 EV p.y.	40’034 EV p.y.	22’062 EV p.y.
Reduction			**45 %**

4.4 Environmental Balance

The environmental benefit of geothermal energy systems compared to conventional systems is primarily given by the reduction of CO_2-emissions resulting from the energy supply. In table 4, the emissions of CO_2 related to the different heating and cooling purposes are listed both for the conventional reference system and for the geothermal system. The emission units EU are based on the CO_2-emissions for natural gas and for electricity, where appropriate, and are given as follows:

Natural gas	0,254
Electric power	0,641

These values are taken from the guidelines for CO_2-related financial incentives of the state of Baden-Württemberg, where there use is mandatory for calculation of CO_2-emissions (see more under: www.um.baden-wuerttemberg.de/servlet/is/37809/).

With the geothermal system, a reduction of 28 % could be achieved.

Table 4: Comparison of CO2-emissions from conventional with those from geothermal system for standardized supermarket, in arbitrary emission values EU for heating/cooling work (instead of kg CO_2)

	CO_2-emissions conventional	CO_2-emissions geothermal
Space heating requirement	3’927 EU p.y.	2’354 EU p.y.
Space cooling requirement	201 EU p.y.	30 EU p.y.
Food cooling, storage, freezing	15’551 EU p.y.	11’758 EU p.y.
Total	19’679 EU p.y.	14’142 EU p.y.
Reduction		**28 %**

5 Financial Balance (investment, operation, and pay-back)

For all three scenarios, the incremental construction cost over a conventional system have been estimated, as well as the possible energy savings due to the use of renewable energy and due to better system efficiency in the central refrigeration system when using geothermal cold for condenser re-cooling. The cost data are given in table 5, in arbitrary currency units (CU).

Table 5: Incremental investment cost and annual savings for the three scenarios of chapter 4; values estimated based on generic data for geothermal heat pump systems in Germany (in arbitrary currency units CU)

Scenario	incremental investment cost	annual operation cost savings	simple payback time
1 maximum coverage	140’000 CU	6’000 CU/year	23 years
2 balanced operation	80’000 CU	5’000 CU/year	16 years
3 optimized to cover heating load	35’000 CU	2’000 CU/year	18 years

As can be seen from table 5, the payback times with current energy data are not very favourable. Scenario 2 achieves the best value, with 16 years. Scenario 3 is only calculated for an operation of 15 years, so a payback time of 23 years means no payback at all. In all scenarios, energy price increase has not been considered; this fact and the importance of reducing CO_2-emissions can influence investment decisions also.

6 Conclusions

The geothermal total heating and cooling system for standardized supermarkets offers a technically sound option to reduce both final energy consumption and related CO_2 emissions. The use of borehole heat exchangers (BHE) as ground coupling technology will allow for safe adaptation to almost any possible geological site condition. The calculations were done for a specific site with somewhat less than average thermal conductivity of the underground (λ = 2,0 W/m/K), so it can be concluded that in most other cases the BHE layout can be somewhat smaller and thus the investment cost lower.

Three alternative scenarios have been investigated, with coverage of the heat rejection of the central refrigeration system ranging from 15-65 %. The lowest pay-back time could be achieved with 30 % geothermal coverage, i.e. rejecting 70 % of that waste heat to the ambient air. However, the straight payback time of 16 years is not very good, so future energy price increase as well as decreasing investment cost due to the replication und optimisation of technology should certainly make things look better. For the final energy consumption a reduction of 45 % and for the related CO_2 emissions a decrease of 28 % can be expected (under German electric power production values).

As there is no more technical risk associated with the application of shallow geothermal energy and BHE, and as the incremental cost over conventional technology are tolerable, the adoption of the technology, and demonstration and replication can be highly recommended.