Scenario Catalogue

Integration of Geothermal Energy into District Heating and Cooling Networks

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D 2.2 Scenario Catalogue – Integration of Geothermal Energy into District Heating and Cooling Networks

The following catalogue of scenarios was developed in the project SAPHEA by the project team in the framework of WP 2 to identify existing basic and complex scenarios for the integration of shallow and deep geothermal energy into heating and cooling networks (HC networks) of different scales. These settings were complemented by new developments, which are not state of the art now, but could be promising scenarios for the future. The networks cover in this case all categories of grid generations used for heating and cooling. Based on these scenarios the SAPHEA project will work on providing information about the potential to implement geothermal Energy into heating and cooling networks in Europe. How geothermal energy can be used in different networks is shown in *Figure 1*.

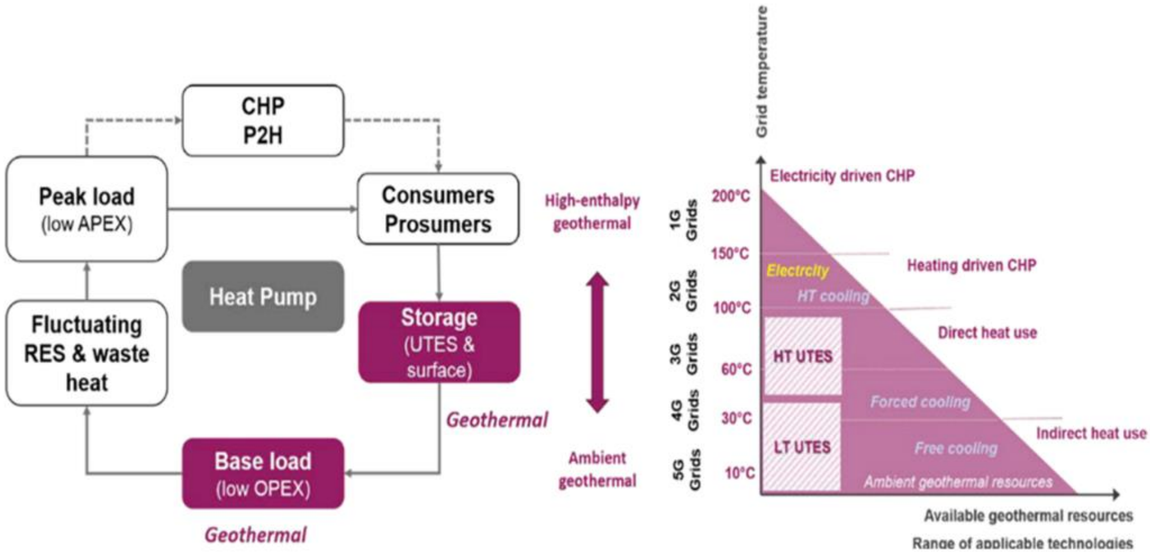


Figure 1: Sketch of geothermal uses in district heating and cooling networks, from [1]

Glossary

Abbreviation	Full name
ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
CHP	Combined heat and power plants
COP	Coefficient of performance
DC	District cooling
DH	District heating
DHC	District heating and cooling systems
DHW	Domestic hot water
geoHC	Geothermal Heating and Cooling networks supplied by geothermal energy as a source, sink or storage for heat
GWHP	Groundwater heat pump
H&C	Heating and cooling
HP	Heat pump
HT	High-temperature
HTHP	High-temperature heat pump
LT	Low-temperature
LTHP	Low-temperature heat pump
MT	Medium temperature
RES	Renewable Energy Sources
UTES	Underground thermal energy storage

1 DEFINITION OF SCENARIOS

In this context a scenario represents a certain technological setup comprising geothermal installation (source or storage), a district heating/cooling network, and in some cases, an additional heat pump.

- Geothermal installations are classified based on their depth as shallow, medium, or deep geothermal systems. Those installations extract heat from the surrounding ground or an aquifer with a specific source temperature from low single-decade temperatures to high temperatures above 100 °C. Additionally, underground storage systems, such as Aquifer Thermal Storage Systems (ATES) or Borehole Temperature Storage Systems (BTES) belong to the geothermal installations and are characterized by their volume and temperature, which define the amount of energy that can be stored. In the specified scenarios geothermal energy systems are focussed on the use for heating and cooling. Producing electricity is not addressed.

- The district heating/cooling network is categorized into generations (1st to 5th GDHC) based on the operational temperature and the method of heat transport within the network [2], [3]. In some cases, a low or high-temperature heat pump can be employed to raise the network temperature either centrally (central heat pump) or at the end-user level (decentralized heat pump).

Scenarios now comprises in general a network with a specific inlet operation temperature and a geothermal source providing an explicit temperature. The geothermal source can be directly used for the network or, if the source temperature is too low, combined with a heat pump. Additionally for covering e.g., peak loads an underground storage system (UTES, comprises ATES and BTES) can be implemented into the network as geothermal component. The optimization of heat supply relies on several factors, including the geothermal conditions unique to the location, the characteristics of the district network, and the heat demand of the city, thereby enabling various combinations for optimization.

In the following discussion, we offer a detailed insight into the methodology employed for both the creation and classification of the various scenarios. The Figure 2 serves as a visual representation, outlining the potential combinations of available geothermal sources, along with their corresponding temperature ranges, with the specific network inlet temperatures. As an example, the red arrow on the right of the figure shows a scenario wherein Hydrogeothermal direct use (deep geothermal) with a relatively elevated source temperature aligns with a network operating at a high temperature (e.g. 3rd generation).

In the case that only a geothermal source with a lower temperature is available, a high temperature heat pump can be integrated which represents a different scenario then following the blue arrows. In a further case depending on the local situation, a network with a lower operation temperature can be used and a geothermal source with lower temperature can be directly integrated, which shows a next scenario (green arrow). The defined scenarios in this catalogue are following this logic.

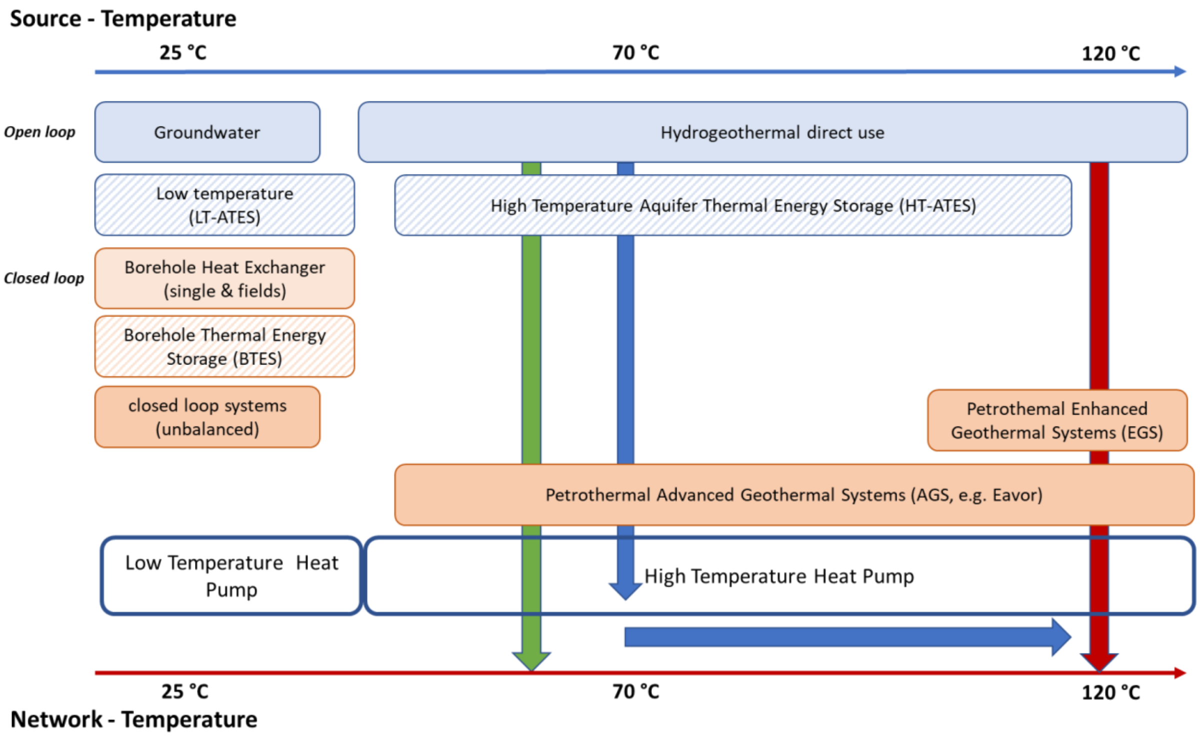


Figure 2: Simplified Scheme combining the available geothermal sources and their source temperature range with the network inlet temperature. The arrows show examples of possible scenarios explained in the text above.

Further, the scenarios are classified into three categories: Basic, Complex and Future developments, which are explained in the following.

- **Basic Scenarios:** Basic scenarios are simpler in design and are already commonly used throughout Europe or in single countries.

- **Complex Scenarios:** Complex scenarios consist of a combination of different technologies such as storage scenarios or scenarios using a HTHP, and are already installed in some places.

- **Future Developments:** Future scenarios are based on technology that is not yet market-ready. These are especially scenarios using enhanced or advanced geothermal systems (EGS, AGS) or uncommon combinations.

Table with Summary of Scenarios:

Number	Scenario name	Type	SourceT [°C]	Aquifer/ ground	GridT [°C]
Basic scenarios					
B 01	Shallow geothermal & Free cooling - DC Network	basic	5-25	aquifer/ground	0-15
B 02	Groundwater + decentral LTHP - LT Network	basic	10	aquifer	10-25
B 03	Hydrothermal Direct Use - HT Network	basic	90 <<	aquifer	80 - 120
B 04	Hydrothermal Direct Use - MT Network	basic	40 - 90	aquifer	40 - 60
B 05	Groundwater + central HP - MT/HT Network	basic	10 - 30	aquifer	25- 90
B 06	BHE + central HTHP/BTES - MT/HT Network	basic	-4 - 30	ground	25 - 90
B 07	BHE + decentralized LTHP - LT Network	basic	-4 - 25	ground	10
Complex scenarios					
C 01	Basic + LT ATES + LT/MTHP - LT/MT Network	complex	30 >	Aquifer	40 - 60
C 02	Hydrothermal + HTHP - MT/HT Network	complex	30-90	aquifer	60 - 120
C 03	Hydrothermal + Sorption Chiller - DC Network	complex	60 - 100	aquifer	6 - 15
Future scenarios					
F 01	Basic + HT-ATES – MT/HT Network	future	90 >>	aquifer	90
F 02	Advanced Geothermal Systems (AGS)	future	90 >>	ground	90
F 03	Enhanced geothermal system (EGS)	future	90 - 120	ground	90
F04	Deep BHE + HTHP – MT/HT Network	future	20 – 50	ground	90

B 01 Shallow geothermal & Free cooling - DC Network

	T Source [°C]	T Grid [°C]	aquifer / ground		storage	heating / cooling	type
	5-25	0-15	Aquifer	Ground	no	Cooling	Basic

Technology

- Groundwater wells
- District cooling network

Description

Cooling energy in the form of cold water is produced centrally using groundwater. The cooling water is transported to users via a closed circuit. Free cooling systems are cost-effective with low running and maintenance costs, and hazardous substances such as refrigerants removed at source are avoided. This can be delivered by direct use of the groundwater or by use of additional chillers. Typically, supply temperatures lie around 4 - 8 °C and return temperatures of 13 - 16 °C are common [4]. The main drivers for energy efficiency regarding temperature levels include a high delta-T between supply and return water. Since this temperature spread is much higher in DH, DC pipelines in general have to be wider than in DH to deliver the same capacity [5]. 'Free cooling' refers to cooling without using a cooling machine to save energy. This implies that the temperature of the resource is low enough to use it directly for cooling. In principle, all different shallow geothermal systems are suitable for free cooling. In practice however, if the temperatures of the resource are too high this is not an option. In this case, a heat pump/chiller is required to generate appropriate temperature levels. Even if a system has an installed heat pump, it can be run in passive mode to provide free cooling during times when temperatures suffice for direct cooling [6].

Parameters

- Location of aquifer for groundwater wells
- Aquifer parameters to assess groundwater availability

Limitations

- Nature/water protection
- Artesian groundwater condition
- Underground structures

Examples

Perth, Australia; *Shallow aquifer well doublets, Free cooling* [7]

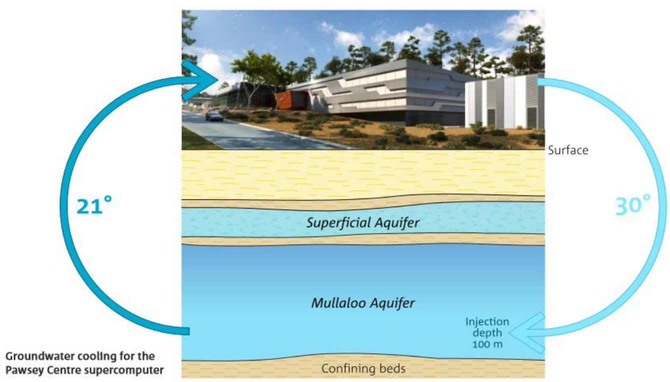


Figure 3: Groundwater cooling concept in Perth. [7]

Two wells produce 45 l/s of 21 °C groundwater from a shallow (35 – 120 m depth) aquifer. The water constantly cools a supercomputer before it is reinjected to the same aquifer further downstream. The system provides a cooling capacity of 2.4 MWth.

Munich, Germany*; Shallow aquifer well doublets/culvert wells; Free cooling/District Cooling*

The Munich City Cooling Grid, operated by the City Energy supplier (SWM Services GmbH), is implemented to cover cooling purposes mainly for data centres, office buildings and industry. The main source in the grid is surface water and groundwater. The grid is in general designed as several island units. At present six groundwater plants with several wells are in operation producing also about 13 MW_{th}. Two additional groundwater plants with about 4 MW_{th} are under construction. To tap the groundwater source, different types of wells are in operation: i) normal vertical groundwater wells (with a general abstraction rate of 20-40 l/s), ii) horizontal wells to increase the volume flux productivity if the groundwater thickness, ii) culvert wells (see figure below).

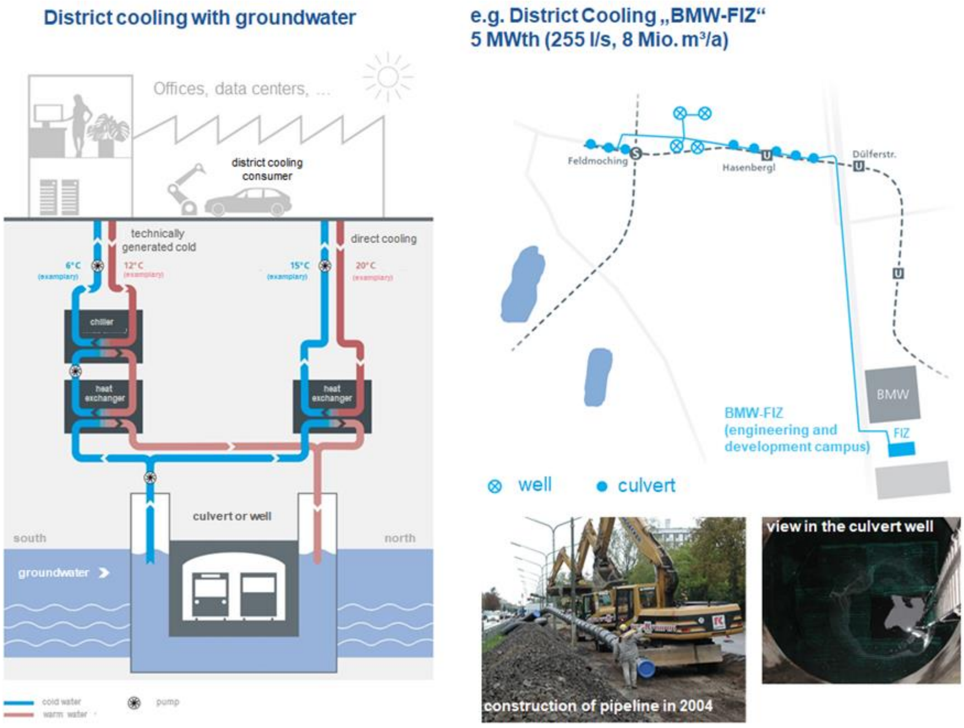


Figure 4: Example of one of the island units of the cooling grid in Munich. Source: SWM Services GmbH, Munich.

<table>
<tr><td>B 02</td><td colspan="7">Groundwater + decentral LTHP - LT Network</td></tr>
<tr><td></td><td>T Source [°C]</td><td>T Grid [°C]</td><td>aquifer / ground</td><td>storage</td><td colspan="2">heating / cooling</td><td>type</td></tr>
<tr><td></td><td>10</td><td>10-25</td><td>Aquifer</td><td>no</td><td>Heating</td><td>Cooling</td><td>Basic</td></tr>
<tr><td>Technology</td><td colspan="7">Groundwater wells
Grid to transport water
LTHP to lift temperature at end users (decentralized)
5G DHC</td></tr>
<tr><td>Description</td><td colspan="7">Scenarios with a groundwater well and decentralized heat pumps are also known as anergy networks, ambient loops, tampered water loops, cold district heating or balanced energy networks. The supply temperature is too low to heat the building directly, therefore decentral heat pumps are installed in every building to raise the temperature to the required level. Thus, 5GDHC networks only serve as a provider of low-temperature ambient heat for heat pumps.

Scenario strengths
Less expensive as each building is connected only to its heat pump instead of its geothermal collector
Often negligible heat losses in the network (depending on the ground and network temperature)
Suitable for cooling (see B 01 Free Cooling and Groundwater District Cooling)
Pipelines can be uninsulated
Pipelines can be made of polymeric materials
Ground and network can be used as thermal storage
Scenario weaknesses
Complex planning process: need to account for heat pumps and their characteristic operational behaviour, and also for balancing effects of heating and cooling demands to determine the residual thermal demand of the grid; complex calculation of heat losses/gains for uninsulated plastic pipes; there are no general design guidelines available for 5G DHC systems, leading to a substantial level of uncertainty and thus to a preference for proven technologies by decision-makers
Electricity costs (and related primary energy consumptions) for HPs
High pumping costs per unit of energy due to small operative ΔT and higher fluid viscosity</td></tr>
<tr><td>Parameters</td><td colspan="7">Location of aquifer
Aquifer properties such as hydraulic conductivity, transmissivity, groundwater level and direction, hydraulic gradient</td></tr>
<tr><td>Limitations</td><td colspan="7">Nature/water protection
Artesian groundwater condition
Underground structures</td></tr>
</table>

Examples

Friedberg, Germany [8]; *Shallow aquifer well doublets, 5GDH; only Heating*

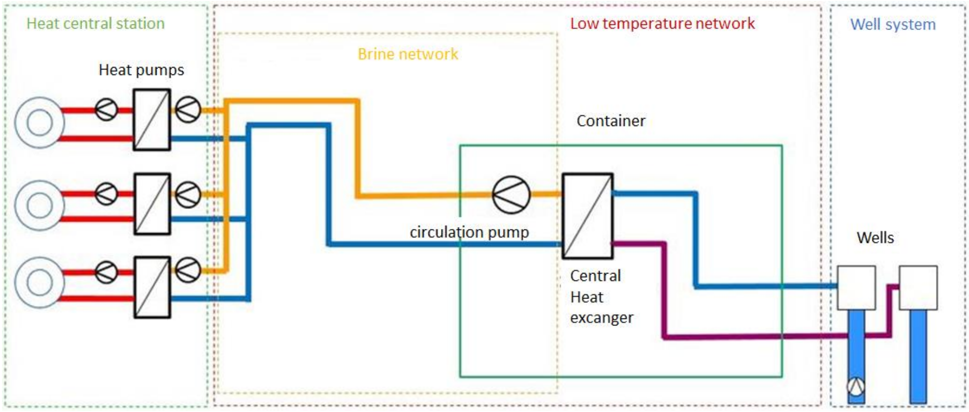


Figure 5: Scheme of the low temperature network operating with groundwater in Friedberg.

The low-temperature heating network in Friedberg for a residential quarter (Afrastrasse), operated by Stadtwerke Friedberg/Lechwerke AG, supplies 250 residential units with heating and hot water. With three extraction wells with a depth of six to ten meters groundwater is pumped with a temperature of 10 °C, which transfers the heat to a brine circuit via intelligent heat exchangers and injects it back into the aquifer in two injection wells. The brine circuit extends over the entire distribution network with connection points for each residential unit. The companies involved laid the entire distribution network with pipes for the low-temperature local heat even before the construction of the residential units originally began. The heat exchangers and the connection of the wells are bundled in a functional building. A water-to-water heat pump in each residential unit generates the required heating and hot water. The conversion process is highly efficient. Operating the heat pump with electrical energy generates around 4 to 5 kWh of heat energy. The great advantage of the cold local heating network here is the low to non-existent heat loss at the supply lines to the connection points due to the low temperature. The water-to-water heat pumps could also feed cold into the building network. The heating capacity of the network is about 850 kW at the moment.

Troisdorf, Germany [3]***:** shallow aquifer well doublets, 5GDH*

Since 2015, the Troisdorf municipal utility has connected the new housing developments of the "Grüne Kolonie" and "Im Moselfeld" to a specially constructed low-temperature heating network. In the system, groundwater at a temperature of around 10 °C is fed into an underground network of pipes via two production wells and conducted to the buildings connected in each case. There, a brine-to-water heat pump extracts the thermal energy required for heating and hot water from the groundwater. The cooled groundwater is then transported via the return flow of the cold local heating network to one of two injection wells. The groundwater is located in Troisdorf near Cologne at a depth of around eight to ten meters. One of the new housing developments is supplied entirely by contracting from Stadtwerke Troisdorf; in the other area, some owners commissioned the installation of the heat pump themselves. If the subscriber purchases green electricity, he heats in a quasi-climate-neutral manner. The network is an open system to which other customers can connect.

	Mageløse, Zealand, Denmark: *remediation groundwater well*
	The Mageløse (Zealand) thermonet uses an existing remediation groundwater well, that imposes hydraulic control of a subsurface contamination, as the sole, primary energy source. Individual 8 kW Thermia HPs connected to the thermonet, supply 29 dwellings (90-180 m2 heated area per dwelling) and a communal building with a heated area of 350 m2. The pumping rate is 35 m3/h and the cold return brine exchanges energy with the pumped water, elevating the brine temperature to 8-10°C, after which it is forwarded once again to the heat pumps. The remediation well has an estimated maximum capacity of three times the coincident peak load of the 30 buildings in Mageløse. Sector integration and economies of scope are achieved, as the remediation well serves, not one, but two purposes: remediation of an existing groundwater contamination and as an energy source for a thermonet based district heating system. The local homeowners' association owns the thermonet and the heat exchanger between the thermonet and the remediation well while the house owner finances the domestic heat pump. The thermonet was financed with a mortgage on each dwelling and the total investment cost for the thermonet and 30 heat pumps was DKK 2.75 million (DKK 95,000/home). The combined cost for heating and total electricity consumption is DKK 8,000 annually for a 135 m^2 dwelling, corresponding to a total electricity consumption of approx. 3,500 kWh/year. The electricity consumption for heating is not measured separately but is estimated to be approx. 1,500 kWh per dwelling per year.
	Dorsten-Wulfe; Germany [3]***:*** 66 single and double households and a multi-dwelling is supplied by a 5G DH network operated by groundwater (10-12°C) and brine water heat pumps at every unit (7.9 kW) and with a SPF of 4.4.
	"Neumatten" area in March-Hugstetten; Germany [3]***:*** 38 building with 151 living units (420 inhabitants) is supplied by a 5G DH network with a heat capacity of 700-850 kW_{th}, operated by groundwater (10-11°C) and heat pumps at every unit.
	Ospitaletto; Italy [3]***:*** A 5G DHC network with a 2.3 km length is operated with groundwater at a temperature of 13-25 °C and with an installed heat capacity of 1.36 MW.
	Sale Marasino; Italy [3]: A small 5G DHC network is operated with groundwater at a temperature of 12 °C and with an installed heat capacity of 0.14 MW and in combination with a thermal storage tank.
	Jardins de la Pâla, Bulle, Switzerland [3]: A 5G DHC network with 2.3 km length is operated with groundwater at a temperature of 9-12 °C and with an installed heat capacity of about 2 MW.

B03 Hydrothermal Direct Use – HT Network

	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling	type
	90 <<	80 – 120	aquifer	no	Heating	Basic

Technology

- Hydrogeothermal Well Doublets
- 2-3rd generation DHC grid, high temperatures used directly

Description

Hydrogeothermal well doublets extract groundwater with a temperature range of 90-120 °C from geothermal reservoirs at depths (generally 2-6 km);

A heat exchanger transfers the heat directly to the district heating network. The network transports hot water (90-120 °C) to the end user.

Parameters

- Location of aquifer
- Temperature
- Volume flux (defined generally by permeability and aquifer thickness)
- Hydrochemistry

Limitations

- Nature/water protection
- Seismic activity

Examples

Munich, Germany; Energy supplier: SWM

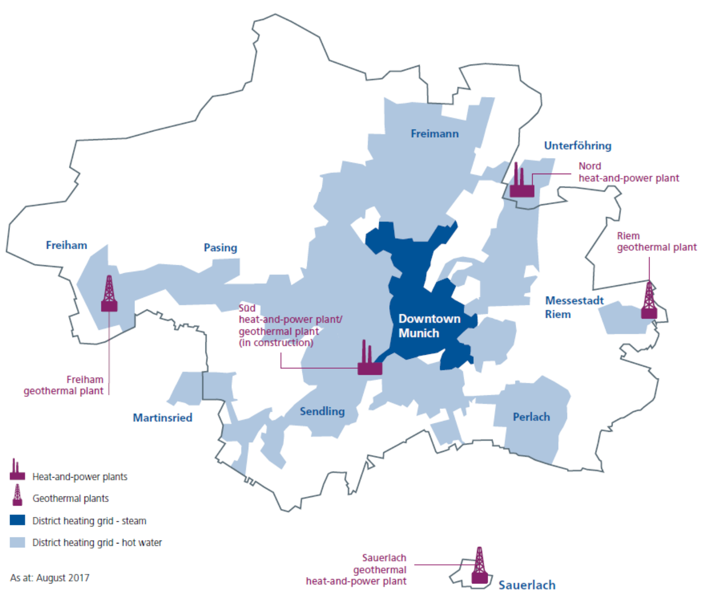
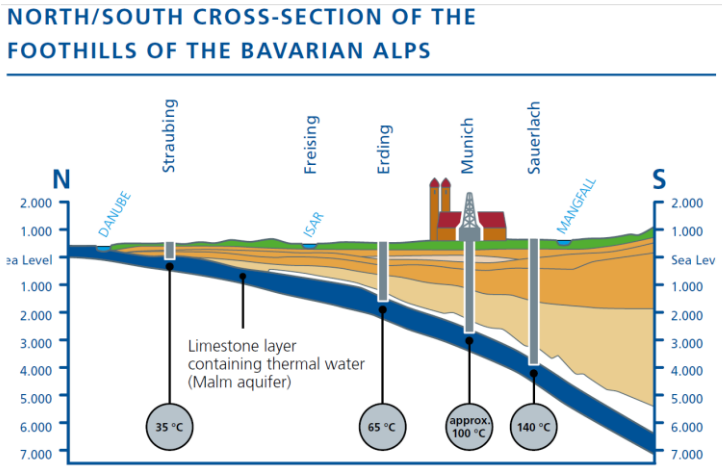
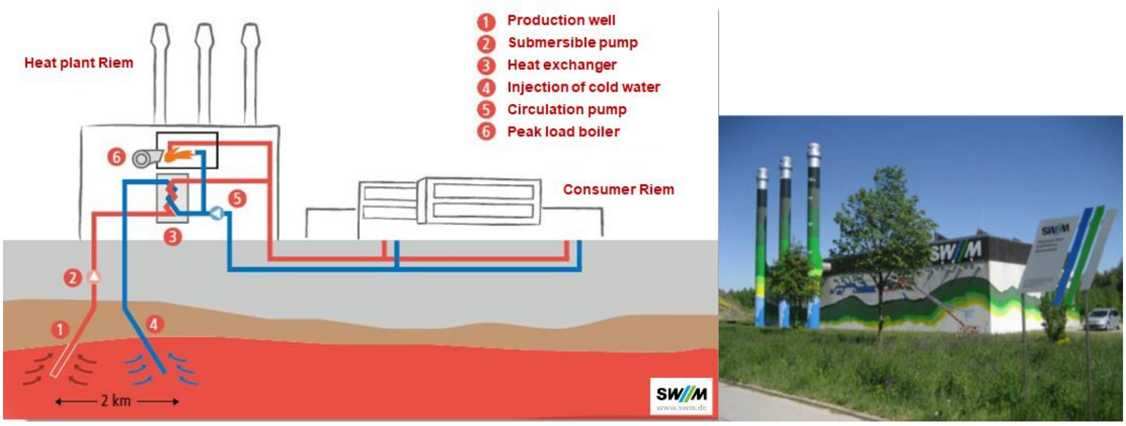


Figure 6 District heating areas in Munich with Geothermal Plants (Source: SWM Services GmbH).

Deep Hydrothermal Geothermal Heating Grid in the City of Munich operated by the Munich Energy Supplier (SWM), using the Upper Jurassic carbonate reservoir in an average depth of 2,000 to 6,000 m. The production temperature depends on the location of the wells and is between 80 and 120°C in the greater area of Munich. Six Geothermal Plants are already feeding in the DH-Grid with an operation temperature of 90-120°C. One more is already planned, and two sites should be expanded. By 2040, Munich Energy Supplier (SWM) will cover Munich's entire district heating requirements on a CO_2-neutral basis based on geothermal energy. Several more geothermal plants

	supplying district heating networks are located in the greater area of Munich, respectively the so-called German Molasse basin [9].
	
	North/South cross-section of the foothills of the Bavarian Alps
	
	Figure 7: Details for the geothermal installation in Munich-Riem, Germany (source: SWM Services GmBH).
	Hódmező-vásárHely; Hungary [10]**:** 18.7 MW_{th}; 2725 flats and130 institutional consumers; 8 production wells, 2 injection wells; Production Temperature 90-105°C; Injection Temperature 30-50°C; Operating District Heating temperature: 80-87°C; sandstone reservoir
	Emilia Romagna – Ferrara- Casaglia, Italy [10]: 14 MW_{th}, 578 connected substations, 2 production wells, 1 injection well, Production Temperature 85-105°C; Operating District Heating temperature: 90-60°C; combined with natural gas.
	Coulommiers, France [10]: 13.6 MW_{th}, about 1850 households, Production Temperature 84°C; Operating District Heating temperature: 81°C; 'dogger' aquifer
	Podhale, Poland [50]: over 70 MW_{th}, heat sales of about 533 TJ/y, 1563 heat consumers and 1870 facilities connected to the network. 3 production and 3 injection wells (the project is expanding). Design operating temperatures of 85/55°C. The total length of the heating networks is 118 km, while the length of the transmission main is 14.3 km.

B 04 Hydrothermal Direct Use – MT Network

T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling	type
40 – 90	40 – 60	Aquifer	no	Heating	Basic

Technology	• Hydrogeothermal Well Doublets • 2G DHC-3G DHC grid
Description	Hydrogeothermal well doublets extract groundwater with a temperature range of 40 - 90 °C from geothermal reservoirs at depths of some 1,500 m and below. A heat exchanger transfers the heat directly to the district heating network. The network transports hot water 40 - 60 °C to the end user.
Parameters	• Location of aquifer • Temperature • Volume flux (defined generally by permeability and aquifer thickness) • Hydrochemistry
Limitations	• Nature/water protection • Seismic activity
Examples	***Lendava, Slovenia*** [10]
	Local community Lendava covers 123 km2 in the Pomurje region. In Lendava there is one of the few Slovenian geothermal district heating systems. Production borehole Le-2g was drilled in 1994 and reinjection borehole Le-3g in 2007. At a district heating system with a length of about 3200 m school, kindergarten and multi-dwelling houses are connected. The installed capacity is about 2.7 MW_{th}. The production temperature of the well is 74°C and the operation temperature of the network is about 40-66 °C.
	Mórahalom, Hungary [10]
	Mórahalom has 6 100 inhabitants A geothermal cascade system was developed to reduce dependency on natural gas by using a renewable heat source. This system consists of two drilled wells, a 1.26 km-deep outflow well and a 0.9 km injection well. Within the project a new district heating system of 2.85 km was established to supply public buildings. The GHG emission is now reduced by 80%. A capacity of 1.5 MW_{th} is produced by the three production wells. The operating temperature of the district heating network is about 69-40°C. The maximum production temperature of the wells is about 70°C.
	Trnava Sereď, Slovakia [10]: about 6 MWth, about 3760 apartments, Production Temperature 66°C; Operating District Heating temperature: 65°C; combined with natural gas

B 05 Groundwater + central HP – MT/HT Network

	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling		type
	10 – 30	25 – 90	Aquifer	no	Heating	Cooling	Basic

Technology

- Groundwater wells
- Heat Pump to lift to grid temperature
- 4G DH Networks
- Possible supply in the return circuit (unlikely in the case of CHP)
- Often in combination with other sources (often CHP)

Description

For this scenario groundwater wells with generally low source temperatures and at, normally, shallow depths are joined with central large heat pumps to increase the temperature for the heating network. Often the groundwater source covers a part of the heat demand, generally the base load, in the network and is combined with other sources as CHPs. This scenario is quite similar to scenario C03 but the source temperature is lower and the wells are normally located in shallow aquifers. The difference to scenario B02 is, that central heat pumps are used and not heat pumps in every consumer unit.

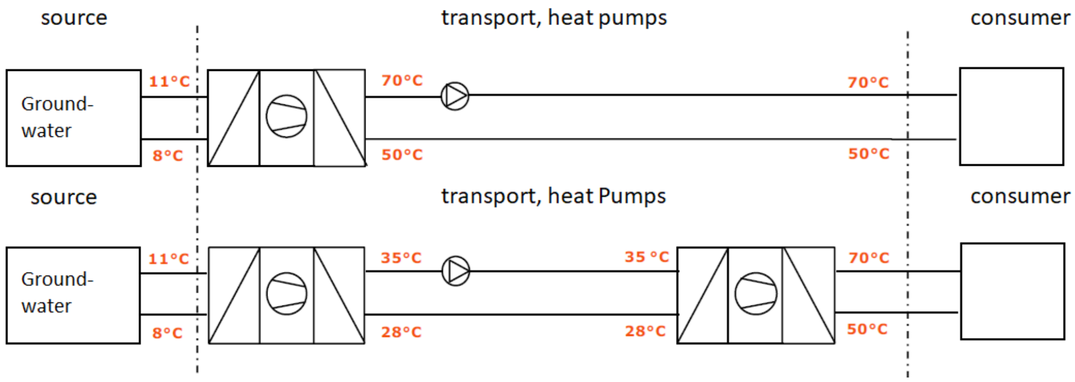


Figure 8: Schematic Views of combination with groundwater source and central heat pump for space heating and hot water at 70°C (top) and with groundwater source and central heat pump for space heating and decentral heat pumps for hot water (modified after [11]).

Parameters

- Location of aquifer
- Aquifer properties such as hydraulic conductivity, transmissivity, groundwater level and direction, hydraulic gradient

Limitations

- Nature/water protection
- Artesian groundwater condition
- Underground structures

Examples	***Königsbrunn, Germany*** [12]: shallow aquifer in combination with CHP
	In 1983, heat energy supplier "Schwaben GmbH" established a local heating supply in Königsbrunn near Augsburg for a residential area with about 600 households and an adventure pool, which is located near the heating centre. Due to the very good hydrogeological conditions, it was decided at that time to provide approx. 90% of the heat in the heating centre via groundwater heat pumps. Only about 10% of the heat demand is produced by gas boilers during peak load periods. The three heat pumps with a thermal output of approx. 1.2 MW each was in operation until the modernization of the technical centre in 2009. Currently, the heating centre is operated with two large heat pumps, each with a thermal output of 1.0 MW and an annual performance factor of approx. 4.0. In addition, three gas boilers with a total output of 7.8 MW and two CHP plants with a thermal output of approx. 275 kW are in operation. A power-to-heat plant with 600 kW, which was installed in 2016 to take advantage of the flexibility of the electricity market, can be switched on if necessary. In addition to the residential area with 600 customers, the heating centre now also supplies a school and two other municipal properties.
	Dollnstein, Germany [8, 13]: local district heating network use groundwater as part of heat generation.
	Since 2014, a local heating network has been supplying the small community of Dollnstein, a community of 300 inhabitants with heating energy. At the heart of the network is the heating centre with two large stratified storage tanks: a central 27,000-liter buffer tank with a temperature of around 80 °C and a 15,000-liter low-temperature storage tank with a temperature of around 25°C. A 440 kW groundwater heat pump in combination with a solar thermal system is feeding the central storage tank.110 m² of solar thermal collectors on the roof of the heating centre raise the temperature of the 10°C groundwater in the interconnected storage tank. The second major heat supplier for the central storage tank is a liquid gas cogeneration plant with 250 kW thermal and 150 kW electrical output for powering the heat pump, as well as a gas peak load boiler with 300 kW. All components are interconnected via a central building control system. The heating capacity is about 980 kW. The SCOP of the large heat pump is 2.5-3 and of the decentral heat pumps is 5-7.
	Paris-Saclay DHC, France
	Saclay, a former rural area west of Paris is home to one of the most modern DE systems in Europe. Here, a cluster of universities and private companies as well as students and family housing has been planned from scratch [13]. This urban development zone features a modern demand-driven district energy system to provide heating and cooling to all customers in the area [14]. The main production system is a geothermal well doublet that reaches an aquifer with 30°C water at 700 m depth [15]. Geothermal waters feed a medium temperature network (15 – 30°C) with a length of 6 km indirectly via heat exchangers. Each customer can reinject energy into this system and therefore act as a prosumer. This enables a recovery of residual energy as for example heat from data centres. Also, thermal storage is included in this loop. These factors allow for a balancing of heat and cold demand between the different types of customers to a certain degree. Seven individual hot water (63/45 °C) and seven individual cold water (6/12°C) networks feed off this medium temperature loop. Heat pump stations at the connection to the medium temperature loop de- or increase the levels accordingly. In addition to the thermal storage, two natural gas boilers help to cover peak loads. Overall, the energy mix of the DHC system is made up of 60% geothermal energy, 36% electricity to run the heat pumps and 4% natural gas used as backup [16]. The whole system is structured as a smart energy network to further enhance efficiency. On the customer side, all buildings are equipped with management systems that send information to a centralized operation system. Especially concerning peak energy shaving this helps by anticipating and acting on the demand side. About two-thirds of the planned urban development zone has been successfully finished and connected to the DHC. In 2022, the district

cooling system has a capacity of 15 MW_{th} and the heating system 37 MW_{th} but an extension of the area and the DHC are running until 2028 [15].

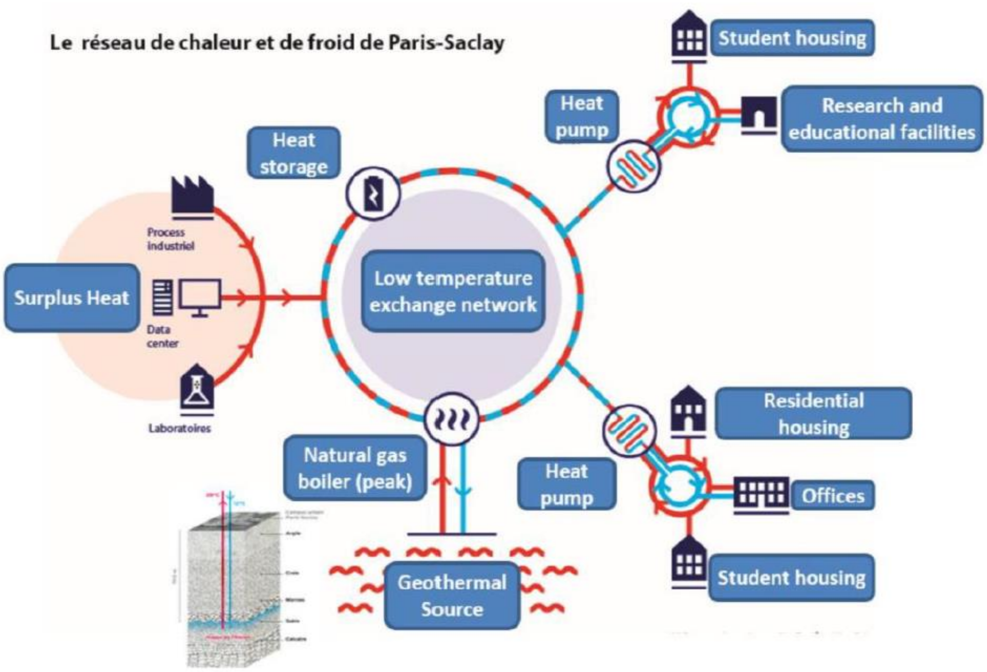
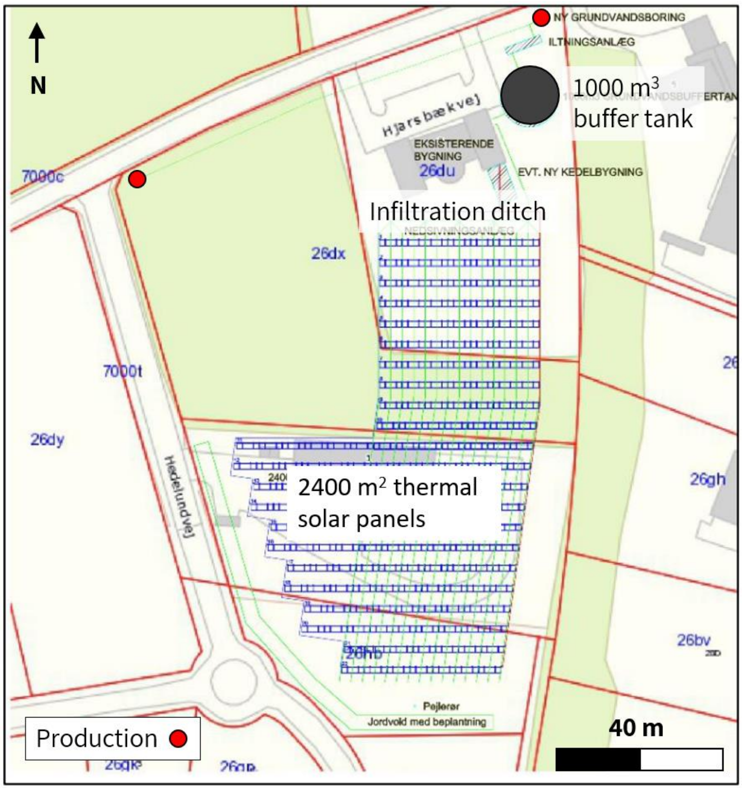


Figure 9: Simplified technical principle of the Paris-Saclay DHC.source: [13]

Rye Combined Heating and Power plant, Denmark



Two groundwater production wells with a combined capacity of 100 m3/h feeds a 1000 m3 buffer tank from which the central HP extracts thermal energy. The 2 MW heat pump can be operated 10 hours per day and is able to cover up to 80% of the district heating demand in the winter. The return water is infiltrated on the ground surface.
The CHP company also uses 2400 m2 of thermal solar panels for heat production during summer. Because there are no injection wells, it is not possible to store excess solar panel energy during summer.

Figure 10: The Gammel Rye CHPs ATES system with surface infiltration instead of injection wells.

B 06	BHE + central HTHP/BTES - MT/HT Network						
	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling		type
	-4 - 30	25-90	Ground	yes	Heating	Cooling	Basic
Technology	• Borehole heat exchangers (type: 1-U, 2-U, coaxial; depth: 50-200 m; spacing: 6-8 m) • Borehole heat exchangers (type: 1-U, 2-U, coaxial; depth: 20-50 m; spacing: 2-3 m) • Central HP • 4GDHC networks • Short-term storage (buffer tanks) • Solar panels or waste heat (e.g., data centre, industrial excess heat, chillers from supermarkets or ice rinks, etc...)						
Description	BHE field with more than 10 BHE (spacing 6-8 m) with general depth comprised between 50 and 200 m. The BHE field delivers energy all year long which is used by the heat pump to produce either heating or cooling depending on the season. For the seasonal use scenario heat can be produced in summer via solar panels or waste heat and stored in the subsurface via BHE of less than 50 m depth. Spacing (2-3 m) is reduced compared to a design with 'BHE + central HP' and with B07 (BHE + decentralized LTHP) because BHEs have to interact with each other. In winter, heat is extracted and delivered to the grid for heating and DHW production. Short-term storage tanks (50-100 m^3) act as intermediary connection between the BTES and the grid to improve the overall efficiency of the system.						
Parameters	• Subsurface thermal conductivity • Subsurface undisturbed temperature • Groundwater flow						
Limitations	• Risk areas (e.g. landslide risk areas) • Nature/water protection • Underground structures Limitations to very low overall efficiency in case of • Very low thermal conductivity (< 1 W/m/K) • Very low subsurface undisturbed temperature (permafrost)						
Examples	***Kassel Feldlager, Germany*** [17]						
	An innovative heat supply concept for the new housing area „Zum Feldlager“ of the city of Kassel in Germany with about 130 houses has been set up. The main objectives and challenges with this particular project are a high share of renewable energy sources for the supply of about 500 persons. So, the use of renewable energy sources such as geothermal and solar energy for low-temperature supply has been elaborated [10]. A low-temperature heat supply with implementation of intelligent storage system and thermal load-shifting concepts is installed. For the heat generation both a renewable gas-powered combined CHP plant and a low-temperature heat generation via a ground-coupled (boreholes) central heat pump are used. For the domestic hot water preparation solar thermal						

systems with an additional electrical backup heater are used. The supply temperatures of the low temperature district heating grid are designed to be 40°C, the heat supply for space heating is preferably done via floor heating systems or via low-temperature radiators. To increase the efficiency of the heating systems and to optimise the hydraulic integration of the heat generation systems the use of smaller water storage tanks in all buildings is intended. Hygienic preparation of domestic hot water is realised by fresh water stations [17]

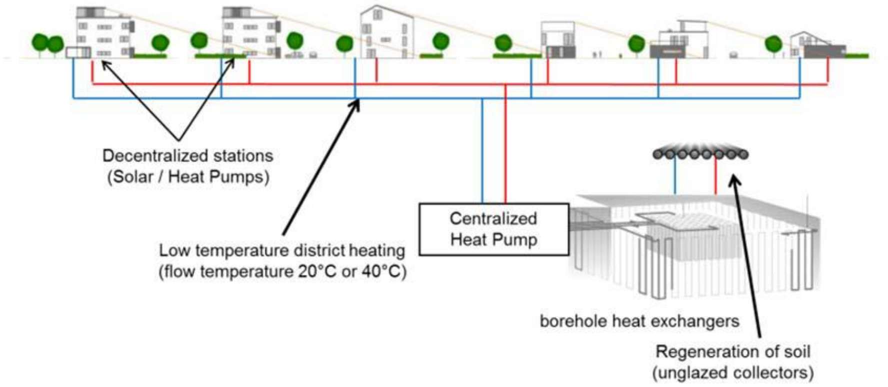


Figure 11: Example Kassel Feldlager.

Brædstrup, Denmark

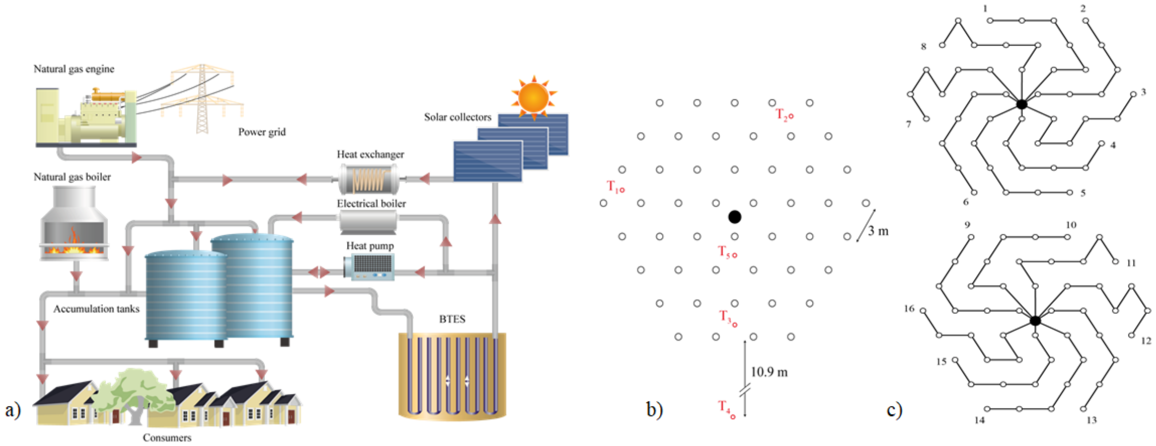
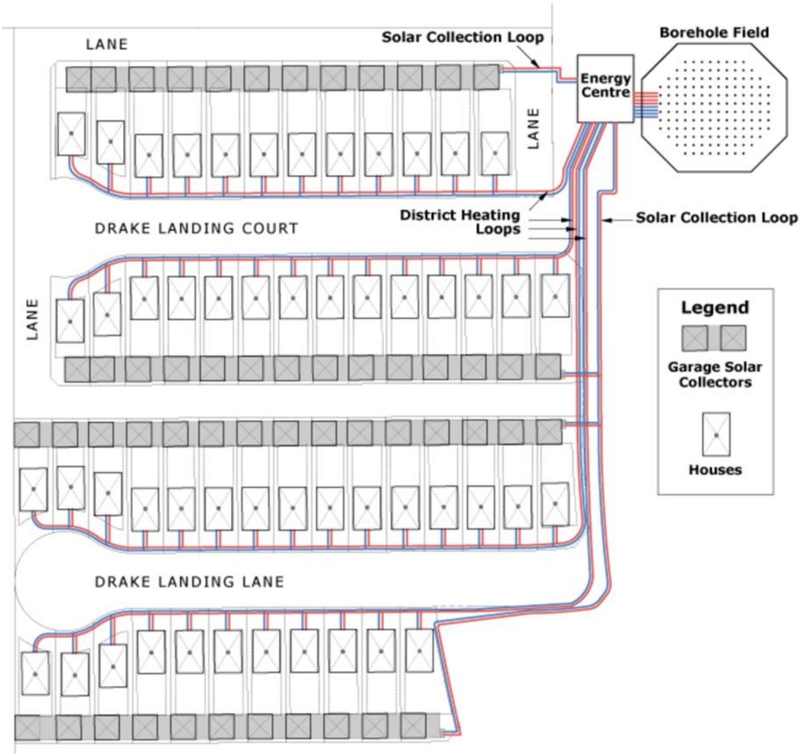


Figure 12: Braedstrup demo-site. a) DHS design. b) Temperature monitoring installation. c) BTES system configuration displaying BTES strings

Brædstrup District Heating in Denmark delivers heat to ca. 1,500 households. This amounts to 30 GWh of power and 45 GWh of heat annually. The heat is distributed to consumers at a temperature of 72-80 °C, depending on the season. The plant has two gas boilers as well as two gas generators that both run on natural gas. As a pilot project, a 19,000 m3 BTES was constructed in 2012 for seasonal storage of surplus heat from an 18,600 m^2 solar collector field. Short-term load balancing is supplied by two steel accumulation tanks with a combined volume of 7,500 m3 and heat is extracted from the storage using a 1.2 MW heat pump. In addition, the facility has a 10 MW electric boiler that can use surplus power from the electrical grid. The analysis of operating data from this demo-site will enable the assessment of the underground storage to contribute to the energy grid. The BHE-system consists of 48 boreholes arranged in a hexagonal pattern, with a distance of 3 m between the boreholes, each of which contains a 2U heat exchanger. The two U-tube heat exchangers in each borehole are connected to different strings. This way, if a string is taken out of operation, the boreholes in that string will still be in use. The BTES is charged from the centre of the storage, and during discharge, the direction of the flow is reversed such that discharging proceeds from the outside of the storage volume. The tubes are located beneath the insulation, so there is no risk of freezing and therefore the heat carrier fluid can be pure water to avoid soil contamination in the event of a leak.

	Drake Landing Solar Community, Okotoks, AB, Canada [18]
	 *Figure 13:* Example Drake Landing Solar Community, Okotoks, AB, Canada The Drake Landing Solar Community (DLSC) is a master-planned neighborhood in the Town of Okotoks, Alberta, Canada, which is heated by a district system designed to store abundant solar energy underground during the summer months and distribute the energy to each home for space heating needs during winter months. One of the first BTES ever built worldwide was put into operation in 2007. 798 flat plate solar panels produce heat that is stored underground by 144 35-m-deep BHEs in summer. The BTES extracts energy in winter and provides heating and DHW to 52 individual houses without HP. Gas-fired furnaces serve as a back-up system but solar fraction is always more than 90 %, contributing to overall COP > 30.
	Bordeaux, France [19]: A solar feed BTES was built and put into operation in 2021 in Cadaujac-Bordeaux, France to produce heating and DHW for 67 individual houses.

B 07 BHE + decentralized LTHP - LT Network

T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling		type
-4 – 25	10	Ground	yes	Heating	Cooling	Basic

Technology

- Borehole heat exchangers (type: 1-U, 2-U, coaxial; depth: 50-200 m; spacing; 6-8 m)
- One or several heat pumps for each user
- 5GDHC distribution grid

Description

BHEs or BHE fields with more than 10 BHE (spacing 6-8 m) exchanges thermal energy with the grid all year long. In heating mode energy is extracted from the ground, while in cooling mode energy is injected into the ground. Each user has its heat pump unit, which uses the grid as a source or a sink depending on the need. The grid is generally made of 1 loop, but it can also have 2 loops at different operational temperatures (unidirectional/bidirectional).

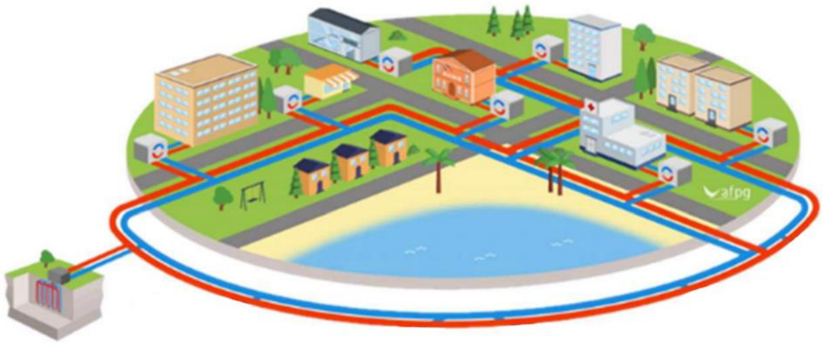


Figure 14: Scheme of a LT Network (5G DHCN) using BHE as source [20]

Parameters

- Subsurface thermal conductivity
- Subsurface undisturbed temperature
- Groundwater flow

Limitations

- Risk areas (e.g. landslide risk areas)
- Nature/water protection
- Underground structures

Limitations to very low overall efficiency in case of

- Very low thermal conductivity (< 1 W/m/K)
- Very low subsurface undisturbed temperature (permafrost)

Examples

Embassy of Sharing, Malmö, Sweden [21]

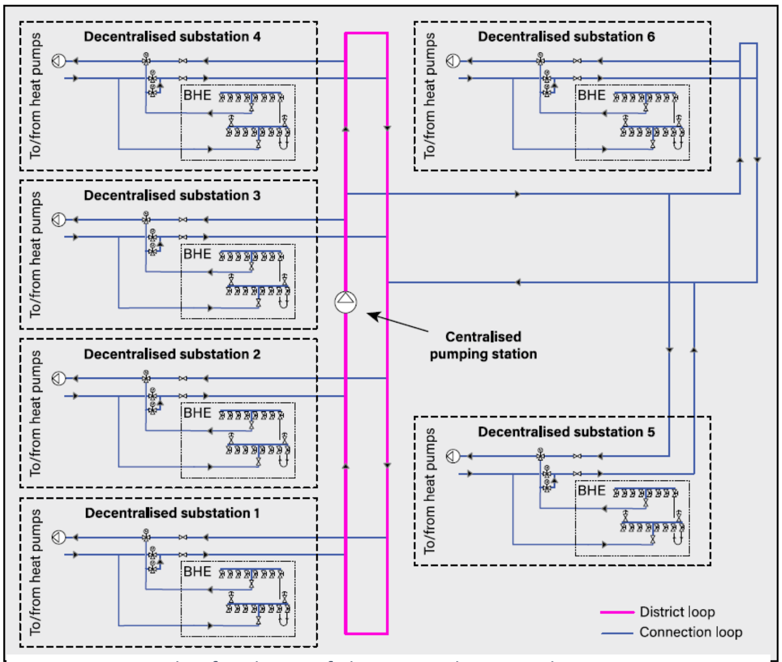


Figure 15: Example of Embassy of Sharing, Malmö, Sweden

The new neighborhood in the Hyllie district consists of 6 decentralised substations (DSS) that supply both heating and cooling to 7 buildings with different space use. The system layout illustrated in the figure presents the mechanism for sharing energy flows between DSS through a geothermal energy-sharing system. Here, each DSS is equipped with several borehole heat exchangers (BHE) that provide heating and cooling throughout the year, whereby HPs adjust the temperature of the heat carrying fluid (HCF) to the desired supply temperatures. The three-way valve is controlled such that it injects/extracts energy into/from a one-pipe loop to balance the system demands. 111 BHEs are installed covering the heat demand (about 2 MW) and cooling demand (about 1 MW) of offices, retails and residential. The operating temperature in the network is between 5-20 °C.

ETH Campus Hönggerberg, Zürich, Switzerland [3, 22]

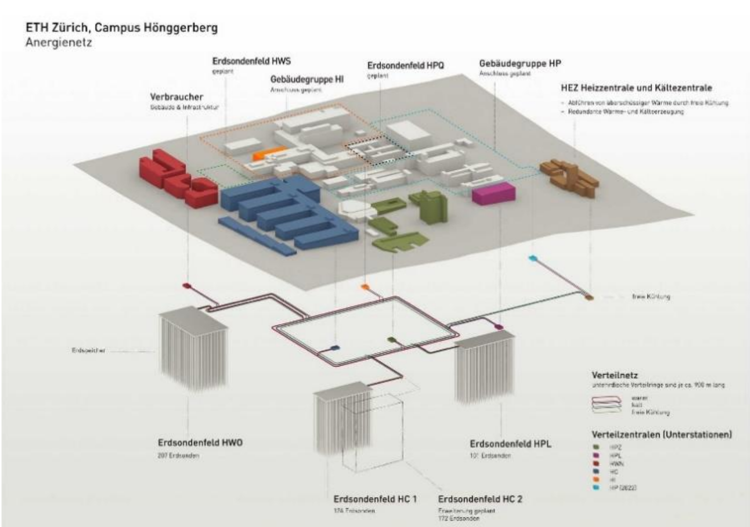


Figure 16: Example of ETH Zurich's Hönggerberg campus

ETH Zurich's Hönggerberg campus is a veritable city quarter with over 12,000 students and employees. They are housed in more than 30 buildings and consume almost 77 GWh/y of energy (electricity and heat). (electricity and heat), of which around 22 GWh are used for heating alone. The anergy network - a dynamic BHE-field system - will provide central heating and cooling production in the HEZ heating centre. The system comprises an intelligent networking of heat sources and sinks in combination with seasonal shifting. There are 431 BHEs installed with a deph of 200 m in the BHE fields with a maximal capacity of 5.2 MW. The network in general supplies 6.5 MW heating capacity and 5.3 MW cooling capacity.

The Norrlands Universitetssjukhus (NUS) in Umeå, Sweden [21]

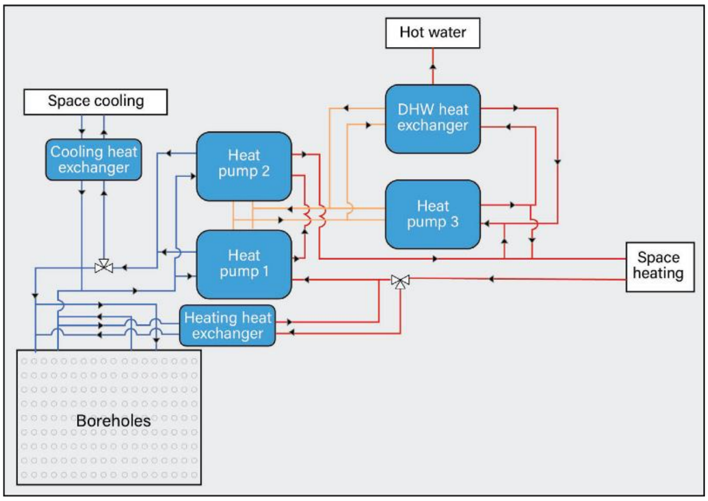


Figure 17: Example of the Norrlands Universitetssjukhus (NUS).

The geothermal system installed at the university hospital in Umeåcovers about 90 and 30% of the respective annual cooling and heating demands while the rest is provided by conventional DHC. The system consists mainly of three HPs with one being used for domestic hot water production and is connected in series with the other two HPs. Overall, the system has two chillers, three connection points to conventional DC, and four borehole thermal energy storages that have been expanded since 2014 to reach a total of 202 boreholes. In summer, heat from the space cooling loop and the available heat from HPs are injected into the BHE, while in winter the BHE act as a heat source. The components of the 5GDHC network operate in an economic sequence for simultaneous production of heating and cooling by optimising the buildings' power demands and power supply from DC.

Silkeborg. Denmark

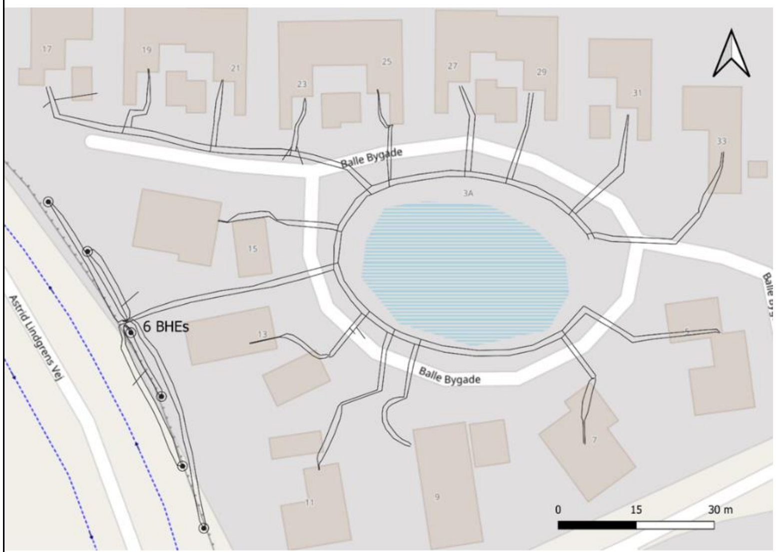


Figure 18: The thermonet at Balle Bygade in Silkeborg with 15 connected consumers. Balle Bygade no. 9 is the existing house built in 1979 (lower center of figure).

The 5GDH grid/thermonet consists of ca. 1340 m uninsulated PE forward and return pipes including the consumer connections with dimensions Ø40, Ø50, Ø63 and Ø90 mm. The thermonet connects six 120 m long borehole heat exchangers (BHE) with single-U Ø40 mm SDR probes, and a drilled diameter of 15.2 cm, to individual brine-to-water heat pumps in 15 (14 6kW and 1 10 kW) family houses. The annual heating consumption amounts to approximately 167 MWh and SCOP is 3.3 at the system level.

Hochvogelstraße" area in Biberach, Germany [3]: A 5G DHC network with 34 BHEs at 200 m depth and an operating temperature of 0-20 °C.

Max-Ernst-Straße" area in Schifferstadt, Germany [3]: A 5G DHC network with 28 BHEs at 100 m depth ,an operating temperature of 12 °C and an installed heat capacity of 0,23 MW.

Familienheimgenossenschaft district, Zürich (FGZ), Switzerland [3]: A 1.5 km long 5G DHC network with 332 BHEs at 250 m depth ,an operating temperature of 8-28 °C and an installed heat capacity of 3.9 MW.

	Brooke Street – Derby, England [3]: A 5G DHC network with 28 BHEs at 100 m depth ,an operating temperature of 6-10 °C and an installed heat capacity of 0.12 MW.
	Richti Wallisellen, Switzerland[3]: A 5G DHC network with 220 BHEs at 225 m depth ,an operating temperature of 8-22 °C.
	Saas Fee, Switzerland[3]: A 5G DHC network with 90 BHEs at 150 m depth in combination with air-driven heat pumps and a thermal storage tank The operating temperature is about 8-20 °C. The capacity is about 0.56 MW.
	Suurstoffi district-Risch Rotkreuz, Switzerland [3]: A 5G DHC network with 218 BHEs at 150 m depth and 180 BHEs with at 280 m depth in combination with other sources. The operating temperature is about 8-25 °C. The capacity is about 5.4 MW.

C 01	Basic + LT ATES + LT/MTHP – LT/MT Network					
	T Source [°C]	**T Grid [°C]**	**aquifer / ground**	**storage**	**heating / cooling**	**type**
	<30	40 – 60	Aquifer	yes	Heating	Complex
Technology	• GWHP and Well Doublets (Injection and extraction of groundwater) • Heat exchanger to transfer the heat between the geofluid loop and the user circuit.					
Description	LT ATES systems provide sustainable heating and cooling energy for different building typologies and can be integrated at a district/urban level. They require a suitable subsurface which allows water to flow easily and can store water (i.e. an aquifer). In the summer season, cold groundwater stored during the previous winter season, is extracted from the cold well to cool the building. Usually, the temperature level is enough to provide direct cooling without the application of a heat pump, but it can also be utilised for active cooling. The excess heat from the cooling process is then reinjected in the warm well and stored in the aquifer, which can be used during the winter season for heating purposes.					

Parameters	• Location of aquifer
	• Underground temperature
	• Aquifer properties such as hydraulic conductivity, transmissivity, groundwater level and direction, hydraulic gradient, aquifer thickness, porosity, groundwater level
	• Hydrochemical parameters
	• Storage specific parameters
	  ○ Recovery efficiency
	  ○ Coefficient of thermal dispersivity					

Limitations	• Limitation from the basic scenarios LT ATES: • Nature/water protection • Artesian groundwater condition • Underground structures • Unsuitable hydrochemistry					
Examples	***Hästskon, Sweden*** [21]					
	The two blocks Hästskon 9 and Hästskon 12 located in the centre of Stockholm are typical examples of integrating several subsystems for increased synergy. The main energy source consists of an ATES with 2 cold wells and 4 warm wells as shown in the figure. Cooling is mainly provided by the 2 water chillers and the refrigerant coolers in addition to conventional DC. Heating sources are realised in the available waste heat from server rooms, waste heat from chillers, and conventional DH. After its operation in 2016, cooling was provided solely by the aquifer and the purchased energy from					

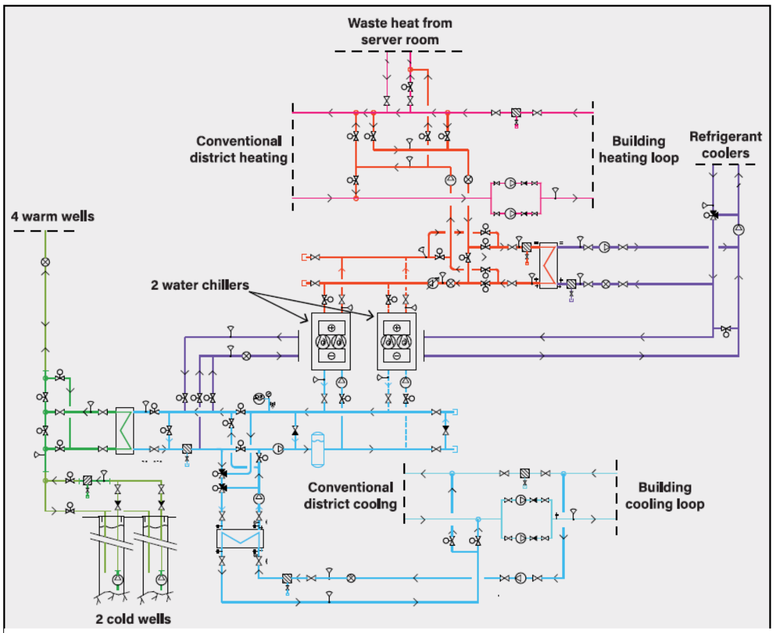


Figure 19: Hästskon, Sweden

conventional DH was reduced by about 68%. The system provides 1.5 MW of heating and 3.0 MW of cooling energy. The operating temperature of the network is about 2-17 °C.

Hospital Antwerp, Belgium [23]

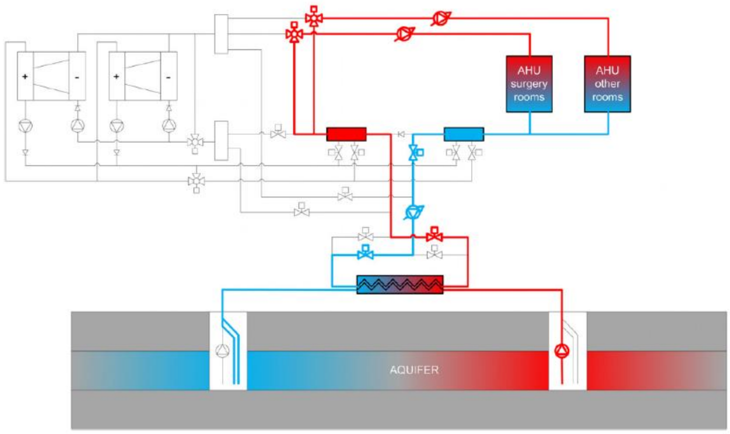


Figure 20: Hydraulic scheme of the installation in regeneration mode (Tambient < 4 ◦C).

The ATES and heat pump system is installed at the "Klina" ("Klinieken Noord Antwerpen") hospital in Brasschaat, Belgium. The ATES system went in operation in August 2000. Over three years, an aquifer thermal energy storage system was monitored in combination with a heat pump for heating and cooling of the ventilation air in a Belgian hospital. The installation was one of the first and largest ground-source heat pump systems in Belgium. Groundwater flows and temperatures were monitored as well as the energy flows of the heat pumps and the energy demand of the building. The resulting energy balance of the building showed that the primary energy consumption of the heat pump system is 71% lower in comparison with a reference installation based on common gas-fired boilers and water cooling machines. The overall seasonal performance factor (SPF) for heating was 5.9 while the ATES system delivered cooling at an efficiency factor of 26.1. The wells for the ATES are drilled in a 30-40 m thick aquifer, having a depth of 65 m. The injection temperature to the warm well is about 18 °C and to the cool well about 8°C. The undisturbed underground temperature is about 11.7 °C. Ventilation of the rooms is provided by in total 40 air handling units (AHU), containing water coils designed to work with low-temperature heat (45/34 ◦C). This heat is provided by two heat pumps (195 kWt) coupled with the ATES system. The same AHU's provide cooling for the rooms in the summer time. The design temperature regime for cooling is 11/21 ◦C, except for the surgery rooms where the AHU's are designed to work at 6/12 ◦C. The lower temperature allows to dehumidify the supplied air.

Rostock, Germany [24]

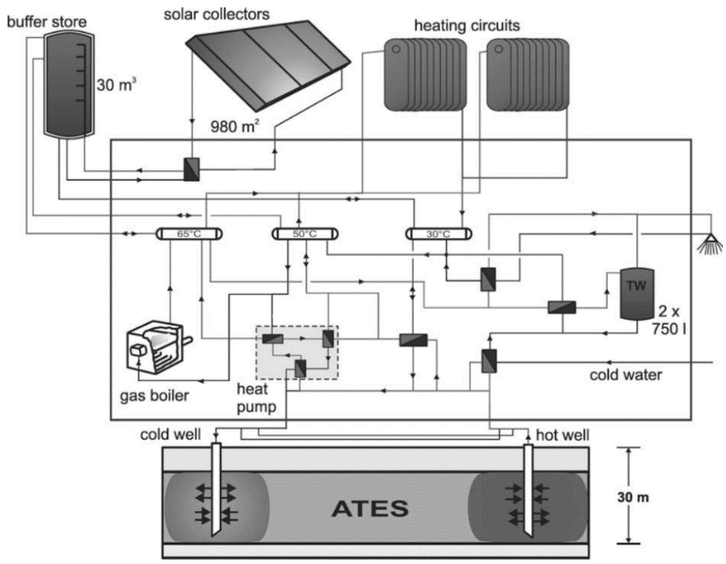


Figure 21: Hydraulic scheme of the installation in Rostock.

In May 2000 a central solar heating plant with an aquifer thermal energy store (ATES) was realized in Rostock, Germany. The heating system supplies an apartment building with 108 flats and a gross area of 7000 m2 with thermal energy for space heating and hot water preparation. The network is designed in such a way that half of the heat demand for space heating and hot water preparation is covered by solar thermal energy. In 2005 a solar fraction of 57% was achieved. A collector area of 980 m^2 integrated into the roof of the building charges a 30 m3 buffer store (Fig. 8) with thermal energy. The heat is either used directly in the heat distribution net or the surplus is charged into the ATES located partly underneath the building. The ATES is equipped with two wells. The maximum temperature is limited to 50 °C as higher temperatures may cause a change in the ground water chemistry. Due to the temperatures of 45/30 °C of the heating net only a small amount of the heat stored in the ATES can be used directly at the beginning of the discharging season in autumn. A custom-made heat pump with a power of 110 kW_{th} is applied to discharge the ATES more effectively down to temperatures of 10 °C. The heat pump offers a temperature of 45 °C at the condenser and a higher temperature of 65 °C at the superheated refrigerant position. Depending on demand these two heat sources can directly be used for space heating and hot water preparation.

Broager District Heating (DH) Company, Denmark

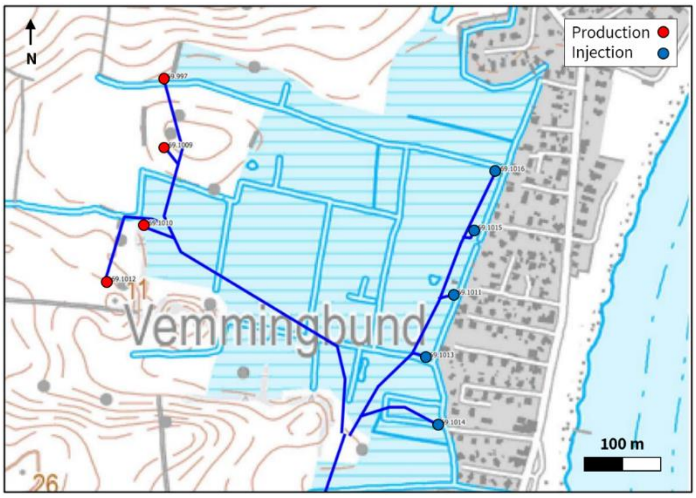


Figure 22: The Broager DH ATES production- and injection wells and connection pipes (blue lines). Source:https://planenergi.dk/wp-content/uploads/2019/05/EUDP-13-I-Drejebog-til-grundvandsbaseret-varmepumpeanl%C3%A6g-dec.-2018.pdf .

The Broager DH company operates 4 production and 5 injection wells, respectively, yielding a maximum capacity of 400 m3/h. The groundwater feeds a 4 MW central heat pump to supply the total need for district heating during winter. The sandy groundwater reservoir is situated in a deeply incised buried valley from the Weichselian glaciation reaching depths of 400 m below terrain. The upper ca. 200 m. consist of confining layers of clay. The screened thickness is 50-100 m.

	Scarborough, Canada[25]: A low-temperature network for heating and cooling office buildings and integrating an ATES with temperature of 4-50°C and a storage volume of 530,000 m^3.
	Mersin, Turkey[25]: A low-temperature network for heating and cooling a supermarket integrating an ATES with temperature of lower than 18°C.
	Aulnay, France [25]: A low-temperature network for 225 houses and integrating an ATES with temperature of 4-14°C and a storage volume of 85,000 m^3.
	Further ATES applications can be found in [26]

C 02 Hydrothermal + HTHP - MT/HT Network

	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling	type
	30 – 90	60 – 120	Aquifer	no	Heating	Complex

Technology

- Hydrogeothermal well doublets
- 3G/4 DHC grid, lower temperatures are lifted with high temperature heat pump or return temperatures are further decreased via HTHP.

Description

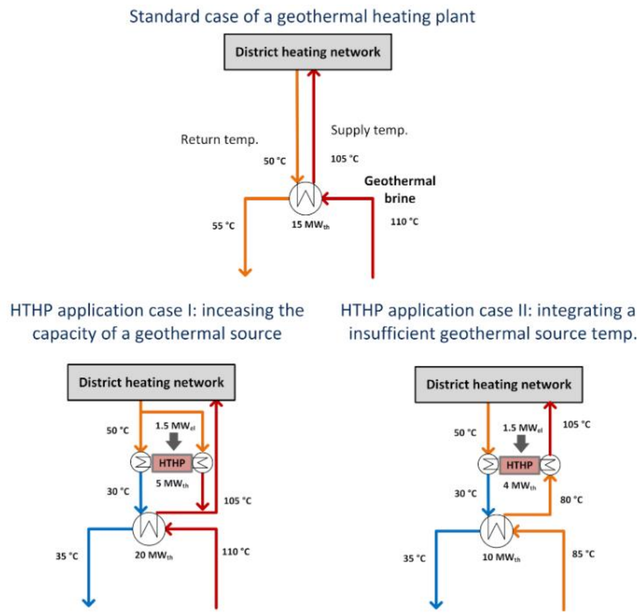


Figure 23: Application scenarios for HTHPs within geothermal heating plants.

A promising market trend that can significantly affect the dissemination of geothermal heating projects is the mounting availability of commercial high-temperature heat pumps (HTPHs), which can provide heat to a temperature level of up to 150°C [27]. HTHP uses a certain amount of electricity to "upgrade" heat from a lower to a higher temperature level. This technology can play a pivotal role in two ways regarding medium and deep geothermal projects. In a normal geothermal heating project, the geothermal heat source is (at least slightly) higher than the required supply temperature of the DH network. The geothermal brine is cooled down to a temperature slightly above the return temperature of the DH network. However, two potential issues can occur: firstly, the heating capacity that can be provided by the geothermal source is lower than the heating demand (especially during the winter). Secondly, the geothermal heat source temperature is lower than the required DH network supply temperatures. As visualized in the figure below, HTHP can provide a solution for both issues. Thus, they enable to increase in the thermal capacity of a geothermal heating project significantly (resulting in a lower demand e.g. fossil fueled peak load burner) and to utilize geothermal reservoirs with lower heat source temperatures than required by the DH network [28].

Parameters

- Location of aquifer
- Temperature
- Volume flux (defined generally by permeability and aquifer thickness)
- Hydrochemistry
- Required temperature level

Limitations

- Nature/water protection
- Seismic activity

Examples

Riehen Switzerland*; hydrothermal wells using heat pumps to decrease the return flow.*

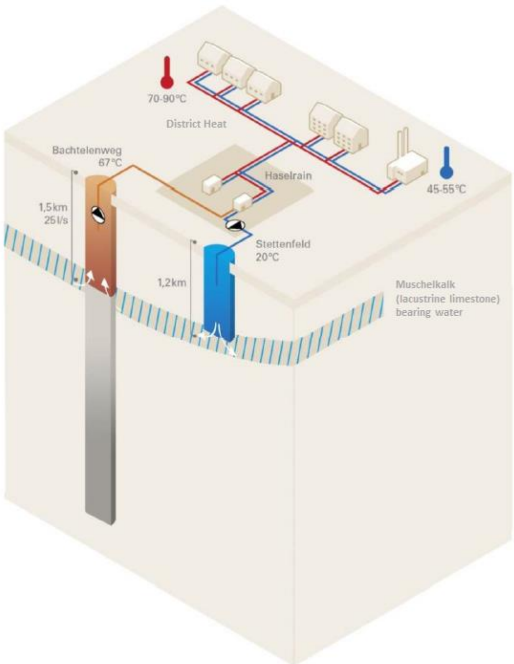


Figure 24: Example of Riehen, Switzerland (Source: [29])

Geothermal heat has been used for heating in Riehen (Switzerland) since 1994. At the plant near Basel on the Swiss-German border, the energy of the thermal water is increased with two heat pumps and transferred to the district heating network with an operation temperature of about 60-90°C. In 1988, both boreholes RB-1 Bachtelenweg and RB-2 Stettenfeld were drilled. The use of geothermal energy has been extended since 2000 with the local heating network between Riehen and the German town of Lörrach. More than 37 kilometres of district heating pipelines transport the regenerative heat to customers. The plant is integrated into the district heating system through heat exchangers, heat pumps and combined heat and power plants. The peak load/redundancy is still covered by oil and gas boilers. The return temperature of the district heating system is designed for 55 °C. The geothermal system first transfers the heat to the district heating network via heat exchangers. In the process, the return flow of the network is heated as much as possible. The thermal water is then further cooled down by two heat pumps and injected back into the well at 22 °C. This allows the heat supply capacity to be increased from 700 to 3,500 kilowatts. Two combined heat and power plants are installed in parallel with the heat pumps. On the one hand, they supply the electricity to operate the geothermal circuit and the heat pumps, and on the other hand, they deliver the heat to the district heating network. The level of the heat pumps is 65 to 69 °C and that of the cogeneration units is 65 to 90 °C [29].

Schwerin, Germany*; hydrothermal wells using HTHP to increase the inlet temperature.*

The city of Schwerin is located in the Northeast of Germany is has around 96,000 inhabitants. The local energy supplier has the goal to decarbonize the existing DH network. Geothermal energy is to be used as one measure in this context. However, due to the rather low achievable geothermal heat source temperature, the application of a HTHP is pivotal. The geothermal heating project with a reservoir depth of 1200 m has a geothermal brine temperature of 55°C. However, since the existing local DH network has a required supply temperature of around 80°C and a return temperature of around 55°C, the geothermal brine could not be utilized without the application of a HTHP. The HTHP system, which is currently under construction, will cool down the geothermal brine from 55°C to 20°C, while heating the DH network with an overall thermal capacity of 6.9 MWth [30, 31]. Thus, the project demonstrates how large-scale HTHP can be applied to match promising geothermal reservoirs (but rather low temperatures) with existing DH networks. A special feature of the heat pump in Schwerin is that not one single heat pump stage is applied, but that the temperature lift takes place over three different temperature steps. Thus, each heat pump has to provide a smaller temperature lift. While the higher number of stages increases the investment costs and the plant complexity, it significantly reduces the operational costs due to a higher achievable COP. As shown for an ideal case in the figure below, the application of a three-staged can result in a pivotal increase of the COP.

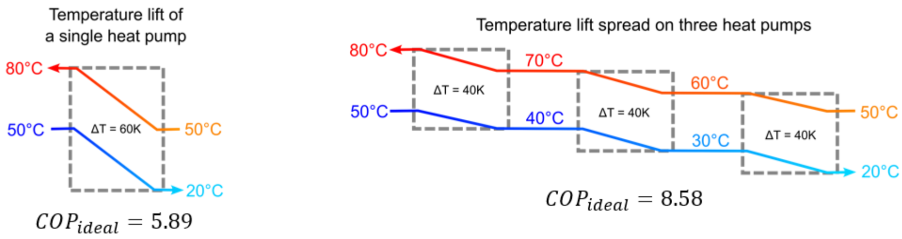


Figure 25: Effect of several heat pump stages on the overall COP (figure adapted from [27]).

Mszczonów, Poland [32]***:*** Hydrogeothermal source with medium-temperature, medium-temperature network combined with high-temperature network.

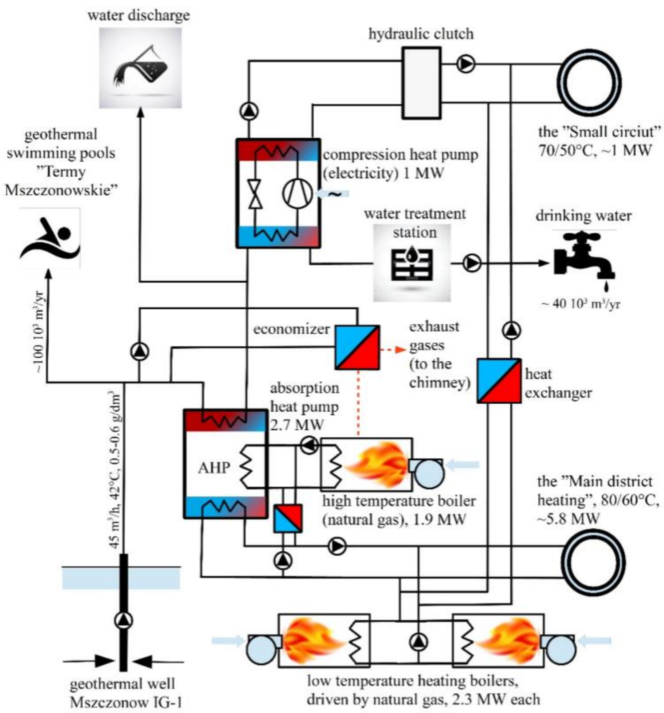


Figure 26: Example of Mszczonów, Poland.

Within the District Heating (DH) system, two parts with different operating temperatures have been distinguished. The first DH system is the main one, and it operates temperatures ranging from 80/60◦C (supply/return temperature at outdoor temperature -20◦C). The second one is the smallest, and it operates between 70/50 ◦C (at outdoor temperature -20◦C). In both DH systems, heat pumps are used: in the main zone, an absorption heat pump with a thermal power of 2.7 MW (driven by 1.9 MW high-temperature natural gas boilers) operates, and a compression heat pump with a thermal power of 1 MW is used in the small circuit. In addition to heat pumps, the geothermal system uses two boilers driven by natural gas from the grid with a capacity of 2.3 MW each. The total installed capacity of the heating system in Mszczonów is 8.5 MW, and the peak capacity at 5.8 MW. The amount of energy sold to customers annually is around 40 TJ of which 15 TJ is geothermal energy. Once the energy accumulated in geothermal water has been used, its temperature decreases to 17 ◦C, leading to effective water cooling within the cascade system assisted by heat pumps. The difference in temperature between the extracted and cooled water (ΔT) here is ca. 25 ◦C. The effective geothermal power generated is around 1.3 MW. After treatment, around 40,000 m^3 of cooled geothermal water is used annually as drinking water and for other household purposes.

Thisted, Denmark [11]: Production from the Gassum formation reservoir, situated at 1250 m depth, started in 1984. The single doublet extracts water at 44 °C and re-injects it at 12°C, delivering 7 MW of thermal power. An additional injection well was drilled in 2017, allowing for a 50% increase of the heat production.

	Aéroport de Paris (ADP), France [11]**:** 135 MWth; One Doublet; Airport heating and sanitary water; Production Temperature 74°C; Injection Temperature 40°C; Operating District Heating temperature: (max) 105°C; Absorption Heat Pumps
	Decin, Czech Republic [11]***:*** One Doublet; more than 4600 households; Production Temperature 30°C; Operating District Heating temperature: (max) 110°C; 2 Heat Pump units
	Sønderborg; Denmark [11]: 12MW, One Doublet; more than 9500 inhabitants; Production Temperature 48°C; Injection Temperature 15°C; Operating District Heating temperature: 83-80°C; Absorption Heat Pumps.

C 03	Hydrothermal + Sorption Chiller - DC Network					
	T Source [°C]	**T Grid [°C]**	**aquifer / ground**	**storage**	**heating / cooling**	**type**
	60 – 100	6 – 15	Aquifer	no	Cooling	Complex
Technology	• Hydrogeothermal well doublets • Ab-, Adsorption chiller					
Description	Against the background of increasing cooling demand due to global warming and higher requirements regarding thermal wellbeing, cooling demand will significantly increase in the next decades. Compared to single-building solutions such as vapor compression cycles, medium and deep geothermal energy can be an attractive source for centrally supplied district cooling systems. Such systems have a similar general working principle as conventional district heating systems. It consists of a two-pipe system (one supply and one return pipe). The supply temperature might vary between 6 and 10 °C. A typical return temperature is around 15 to 17 °C. District cooling systems are characterized by significantly smaller average network lengths and higher average installed capacities per customer compared to district heating networks. This effect can be mainly explained by the fact that district cooling networks currently mainly supply larger commercial, public or industrial clients and no standard residential buildings. Next to shallow geothermal (e.g. in the form of groundwater), heat from medium and deep geothermal energy is a highly attractive source for an energy-efficient cold production by both ab-and adsorption chillers. Such chillers are capable of providing cooling by using heat as a main driving source of the cooling system, resulting in a significantly lower electricity demand compared to a conventional vapor compression cycle. Depending on the required local cooling temperature and the chosen technology and cycle configuration, sorption chillers can operate from a heat source level between 60 and 80 °C on. An indirect alternative way of cooling with medium and deep geothermal energy is using the heat from the district heating system to drive the sorption cooling process at the customer's site directly.					
Parameters	• Location of aquifer • Temperature • Volume flux (defined generally by permeability and aquifer thickness) • Hydrochemistry • Local cooling demand					
Limitations	• Nature/water protection • Seismic activity					

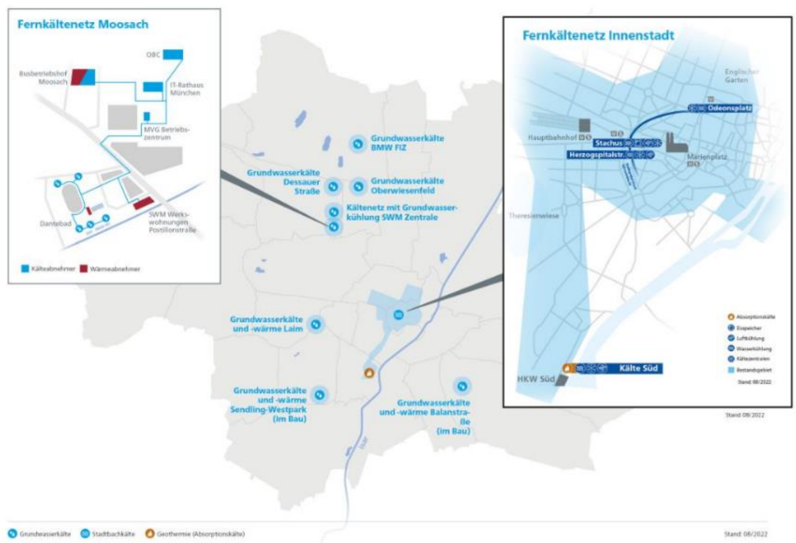
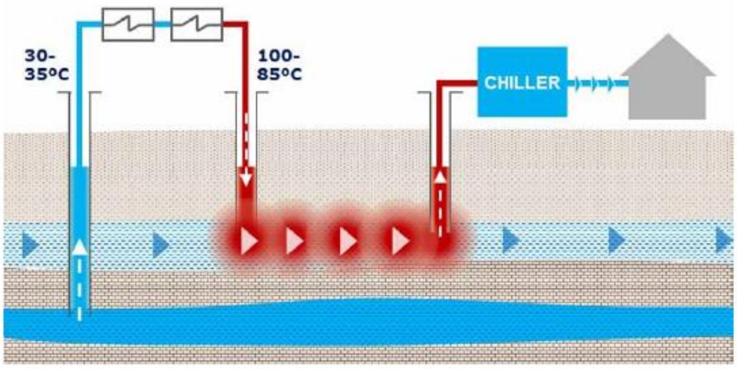
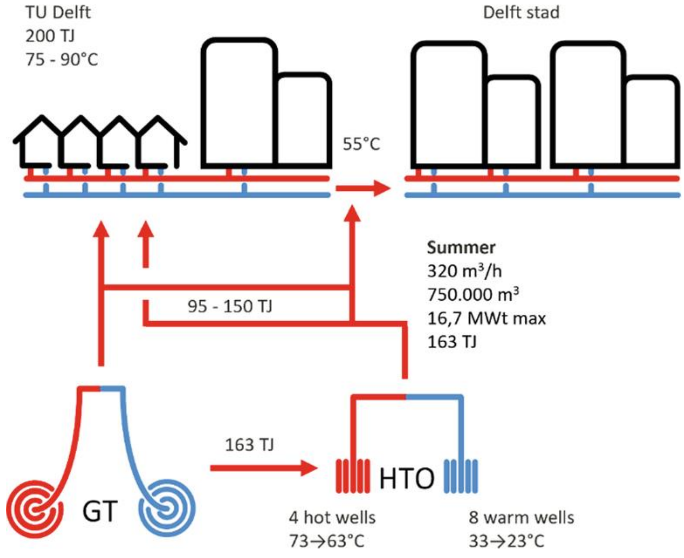
<table>
<tr><td>Examples</td><td>Munich, District Cooling Network, Germany [30, 31, 33]: Hydrogeothermal source with medium temperature, medium temperature netwoirk combined with high tempoerature network.</td></tr>
<tr><td></td><td>


Figure 27: Munich, District Cooling Network, Germany.

A recent example of the integration of deep geothermal energy into a district cooling network can be found in Munich. The SWM is currently installing large-scale absorption chillers with a capacity of several MW at their geothermal project in Sendling. It must be noted that the absorption chillers are technically not directly supplied by the geothermal brine but by the district heating systems. This is due to practical reasons such as migrating the risk of corrosion and scaling at the absorption chiller's heat exchanger and an easier backup heat supply in case of maintenance work at the geothermal wells. Nevertheless, the motivation to install the absorption chiller is the available geothermal heat at this site. Thus, the project can be seen as an example of geothermally driven district cooling systems. The cold will be transported to the central district cooling system in the city centre by a 5 km-long pipeline [30, 31]. The subsequent figure shows that the current district cooling networks in Munich. It can be seen that are several minor island networks around the city. These networks often supply selected local major cold consumers and are feed by groundwater and/or minor underground streams. In the city centre, a central district cooling network with a length of more than 20 km is in operation and under constant expansion. This central network is currently connected to the geothermal site in Sendling [33].</td></tr>
</table>

F 01	Basic + HT-ATES – MT/HT Network					
	T Source [°C]	**T Grid [°C]**	**aquifer / ground**	**storage**	**heating / cooling**	**type**
	90 <<	90	Aquifer	yes	Heating	Complex
Technology	• Possible basic scenarios: ○ Hydrogeothermal Well Doublets • Heat exchanger • District heating network					
Description	Aquifers are used as a storage medium with a stored temperature of about 90 °C (maximum), at depths ranging from 300/400 m to 2/3 km. Well doublets are used to store and extract heat when needed. A heat exchanger transfers the heat directly to the district heating network.  *Figure 28:* Example for a HT-ATES application scheme [34].					
Parameters	• Location of aquifer • Temperature • Volume flux (defined generally by permeability and aquifer thickness) • Hydrochemistry • Storage specific parameters ○ Recovery efficiency • Coefficient of thermal dispersivity					
Limitations	• Nature/water protection • Seismic activity • Nature/water protection • Artesian groundwater condition • Underground structures • Unsuitable hydrochemistry					

Examples	***Delft, The Netherlands*** [35]
	The HT-ATES is proposed to be connected to the existing district heating network of the TU Delft at the university campus. Developments are ongoing, with plans to realize a geothermal system for heating purposes, as well as to extend this network to part of the city of Delft. A Summary of the HT-ATES at the University campus is given in the figure.  *Figure 29:* HT-ATES Scheme of Delft, The Netherlands.
	Several studies and pilot projects exist about the implementation of HT-ATES Applications. See e.g. [26]

F 02 Advanced Geothermal Systems

	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling	type
	90 <<	90	Ground	no	Heating	Future

Technology

Deep Drilling uses the underground as a large heat exchanger.

- EAVOR-Loop
- GreenFire's GreenLoop

Description

AGS refers to a new generation of "closed loop" systems, in which no fluids are introduced to or extracted from the Earth; there's no fracking. Instead, fluids circulate underground in sealed pipes and boreholes, picking up the heat by conduction and carrying it to the surface, where it can be used for a adjustable mix of heat and electricity. Their main advantages are

- Heat production can be estimated with relatively high confidence.
- Reservoir stimulation is not required, which limits the risk of induced seismicity and lowers water consumption.
- It can theoretically be applied anywhere.

Currently, two main designs are expected to be developed:

1) The Eavor-Loop is a closed-loop geothermal system within which a proprietary working fluid is contained and circulated [36]. The working fluid is not fluid from a reservoir flowing into our wells, it is a fluid added to the closed-loop Eavor-Loop™ to create an efficient radiator." The deep rock formations accessed by AGS may be sedimentary rocks or, ideally, even deeper and thus hotter crystalline rock formations. The main advantage of Eavor-Loop uses compared to traditional as well as EGS geothermal is scalability. Eavor-Loop plants can be installed near to industrial and residential zones. This includes different solutions:

a) Eavor-Lite (Prototype)

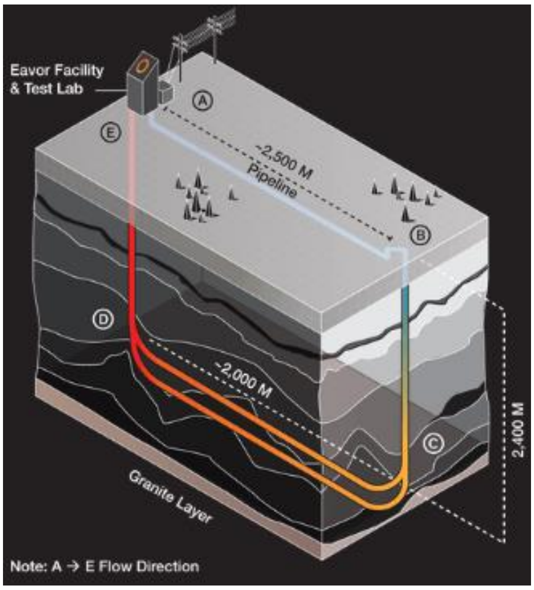


Figure 30 Eavor-Lite (Prototype)

b) Eavor-Loop™ [37]

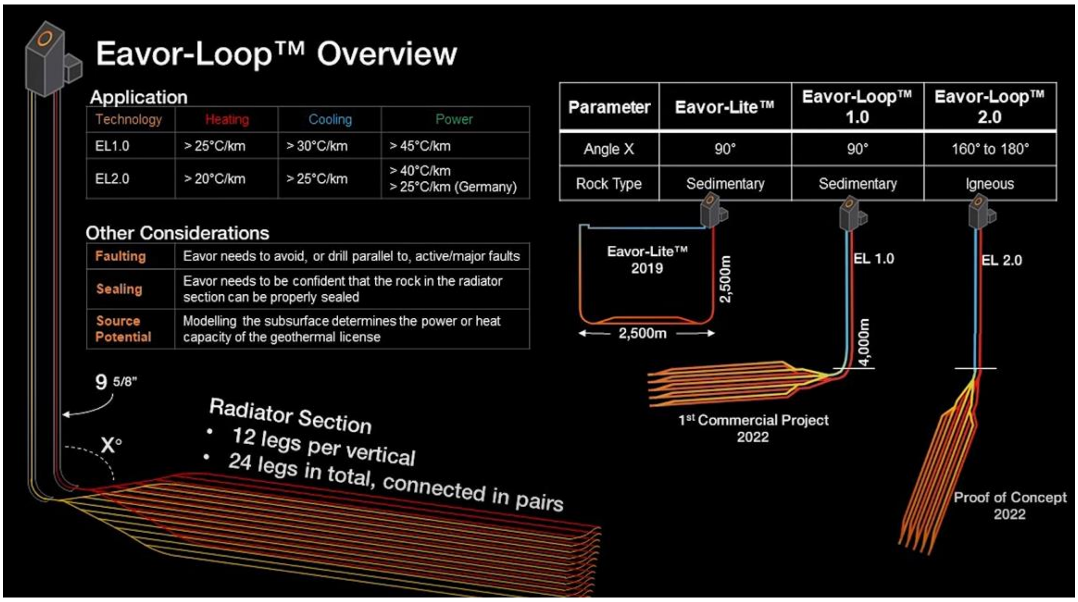


Figure 31: Eavor-Loop™

c) Eavor-Deep™ (next-generation geothermal project run in New Mexico) – drilling a two-leg multilateral well down to 18,000' TVD (ca. 5 500m) and ~250°C. These milestones achieved are a combination of technical and operational measures and markers including depth, temperature, bit-life and rate of penetration in granite rock. [38]

2) **GreenLoop Designs** [39] consist of a closed-loop system that includes a Downbore Heat Exchanger (DBHX), in a specific architecture (e.g., coaxial, multilateral), a working fluid (e.g., sCO_2 [40], water), and other equipment. The DBHX circulates the selected working fluid through a closed loop to absorb heat before returning to the surface. A variety of turbine types can be considered for power generation. Otherwise, the heat can be directly used for heating and cooling or for industrial applications. A Surface Heat (SHX) is also available for removing non-condensable gases. Includes different solutions: Steam GreenLoop, 2-Phase GreenLoop, Liquid GreenLoop, Hot Dry Rock GreenLoop, Hot Springs GreenLoop, Steam GreenLoop and 2-Phase GreenLoop Designs

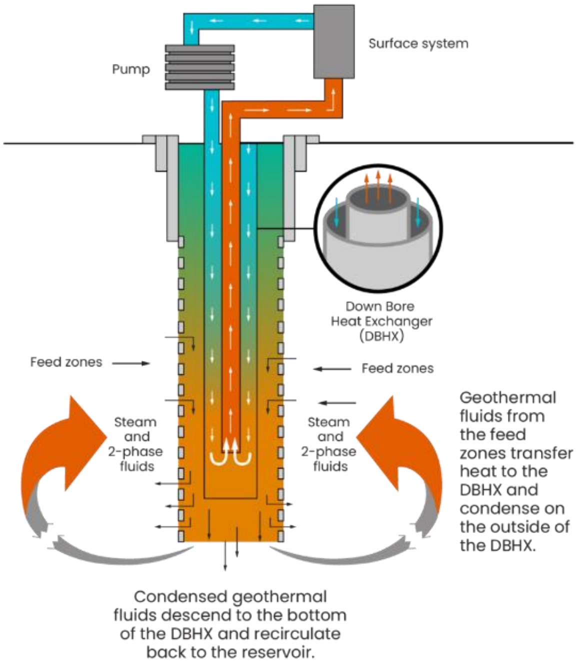


Figure 32 GreenLoop Designs [39].

Parameters	• Reservoir depth (temperature) • Reservoir rock volume • Reservoir rock temperature – >90/100°C • Low initial permeability • Low effective porosity of the rock mass • High TC and high specific heat of reservoir rock • High circulation flow rate
Limitations	• Targeting mainly crystalline bedrock; • Reservoir depth, usually – 4-6 km (depending on geothermal gradient); • High investment cost due to significant borehole depth needed; • Petrophysical rock properties requirements (low: porosity, permeability…); • Projects lifetime and sustainability (no commercial implementation is available).
Examples	1) **Eavor-Loop:** in Geretsried, Germany (under construction) - began in October 2022, and drilling is scheduled to commence in July 2023; 2) **GreenFire Energy:** in Coso geothermal field, California [41]

F 03	Enhanced geothermal system (EGS)					
	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling	type
	90 – 120	90	Ground	no	Heating	future
Technology	• Hot Dry Rock (HDR), Hot Fractured Rock (HFR), Enhanced geothermal system (EGS)					

Description

The Enhanced Geothermal System (EGS), also known as the Hot Dry Rock method (HDR) or Hot Fractured Rock (HFR), harnesses geothermal heat from the Earth's depths, typically between 3 to 6 km, residing within low-permeability rocks or even deeper. This concept is closely related to the petrothermal system. The fundamental approach involves establishing an oversized subterranean heat exchanger connecting at least two boreholes. Through the injection of pressurized water, reaching up to 15 MPa (150 bar), existing cracks in the rock expand while new one's form, despite the immense rock tension. These fractures permanently remain open, with an average width of less than one millimetre. This innovative process effectively creates a vast heat exchange surface area spanning several square kilometres within the rock matrix, interconnecting the boreholes. [42]

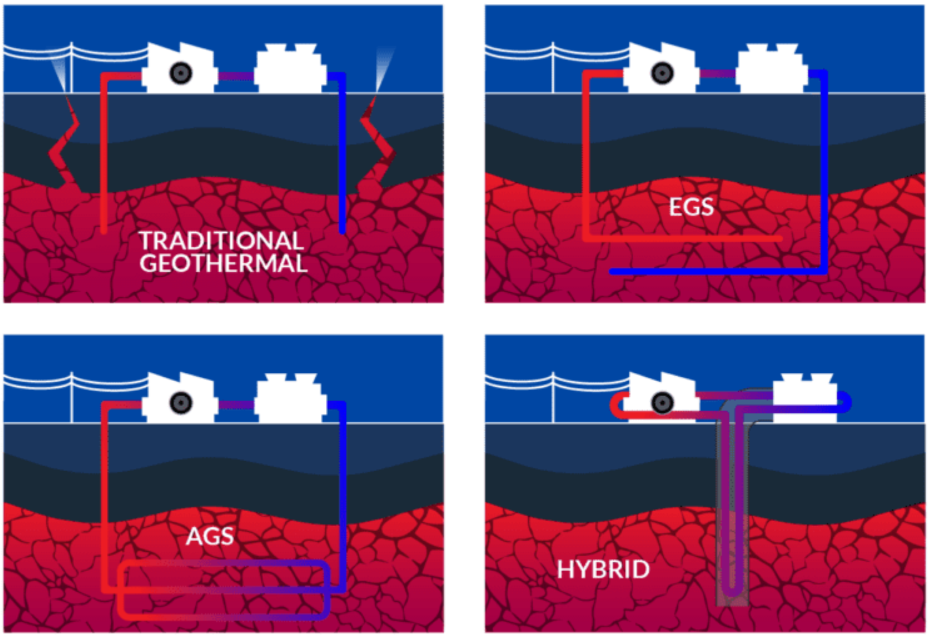


Figure 33: Comparison of traditional geothermal systems to EGS, AGS and Hybrid systems [43]

In theory, there is a clear separation between the initial idea of HDR and the later EGS method. The EGS method focuses on the widening and shearing of already existing natural fractures and faults, whereas the HDR method focuses on the targeted hydraulic connection of boreholes via numerous artificially created fractures (see figure below). The latter involves keeping the newly created flow zones open with the help of proppants. However, due to the complexity of the subsurface, an increase or change in pressure may in principle also simultaneously cause shear movements and new fractures.[44]

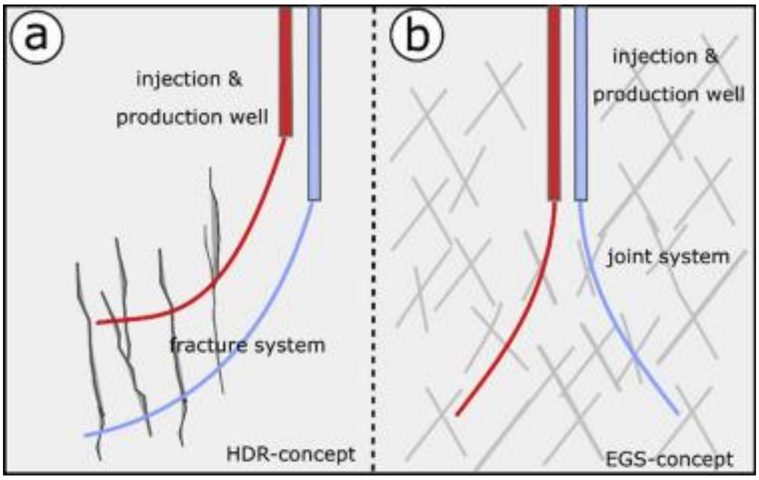


Figure 34: Comparison of HDR-concept vs. EGS-concept [43]

EGS technologies can function as baseload resources that produce power 24 hours a day. Unlike hydrothermal, EGS may be feasible anywhere in the world, depending on the economic limits of drill depth. Good locations are over deep granite covered by a 3–5 kilometres layer of insulating sediments that slow heat loss. Advanced drilling techniques may be able to drill into hard crystalline rock at depths of up to or exceeding 15 km, which would give access to higher-temperature rock (400 °C and above) around the world. An EGS plant is expected to have an economical lifetime of 20–30 years using current technology. EGS systems are currently being developed and tested in Australia, France, Germany, Japan, Switzerland, and the United States. The largest EGS project in the world is a 25 MW demonstration plant currently being developed in Cooper Basin, Australia. Cooper Basin has the potential to generate 5,000–10,000 MW.

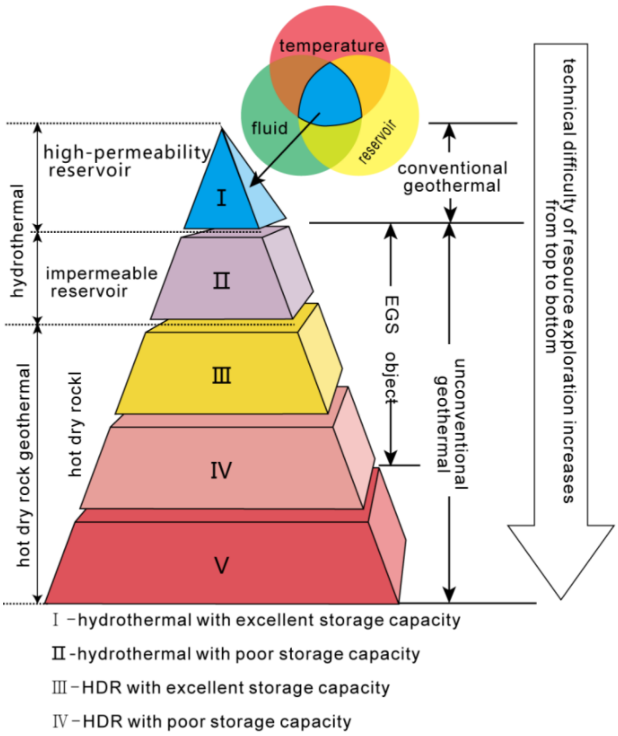


Figure 35: Distribution of geothermal resources and their range of applicability in EGS [45]

Future concept and trends: The use of **supercritical CO_2** instead of water (Hot Dry Rock) to extract heat from a geothermal reservoir has further advantages:

- reducing the circulating pumping power requirements,
- eliminating the scaling in the surface piping, and
- enhance in the exploitation of very high temperature reservoirs (> 350°C) without problems related to silica dissolution (e.g., [46]).

For the conversion of CO_2 to supercritical phase, the reduction of NH_3 concentration below 0.1 ppmV and removal of H_2O is necessary to prevent the formation of solids during compression of the gas [47].

Parameters	• Rock temperature • Rock permeability (lower – better) • Rock thermal conductivity (higher – better) • Depth of prospective orogene
Limitations	• Induced seismic risk (distance to cities etc),

	• Water contamination risk – distance to freshwater reservoirs • Seismic activity (tectonically active regions) • Water availability for operational purposes • Advanced and expensive technologies (reservoir engineering and stimulation)
Examples	• First experimental HDR installation in Los Alamos, New Mexico, USA in 1970 • First commercial EGS plants were deployed in Europe at Soultz-sous-Forêts in France and Landau in Germany • Cooper Basin Enhanced Geothermal Systems (project closed 10 December 2015) • Newberry EGS Demonstration project, Oregon, USA (super-hot EGS) • Cornwall, UK (unclear if launched and/or operational).

f 04 Deep BHE + HTHP – MT/HT Network

	T Source [°C]	T Grid [°C]	aquifer / ground	storage	heating / cooling	type
	20 –50	90	Ground	no	Heating	future

Technology

- Borehole heat exchangers (type: coaxial; depth 500-3,000 m)
- HP
- Distribution grid

Description

Generally, deep BHEs are abandoned/unproductive oil and gas or geothermal wells which are repurposed to save drilling costs that often account for more than 50% of the total project cost of ground-source heat pump systems. Deep BHE are 0.15-0.3 m boreholes made of coaxial heat exchangers with a direct flow pattern (downflow in the annulus and upflow in the centre) with a steel casing and a low-conductive inner pipe (e.g., high-density polyethylene, vacuum insulated tubing). Inlet temperature varies between 7 to 15 °C to provide outlet temperatures in the order of 15-30 °C at flow rates of 1-4 l/s. Outlet temperatures of more than 50 °C can also be reached in specific geological and geothermal settings. Heat extraction rates normally exceed 80 W/m. Heat pumps fed by deep BHE can provide very interesting COP due to high fluid temperatures.

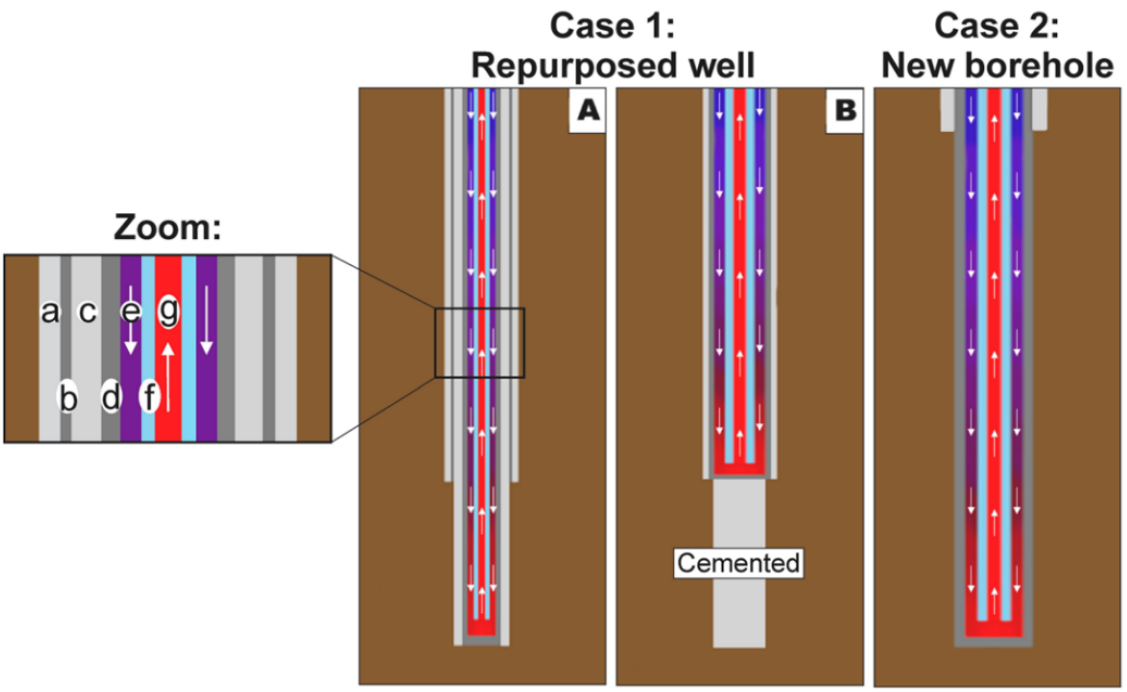


Fig. 2. Coaxial DBHEs installed in a repurposed O&G well (Case 1) and in a new borehole (Case 2). Scenario A: Inserting an outer pipe inside the existing casing in order to cover the lower open section. Scenario B: Using the pre-existing casing as the outer pipe, while its lower open section is cemented. Zoom: a: Pre-existing grout, b: Pre-existing casing, c: New grout, d: Steel outer pipe, e: Annulus space, f: Inner pipe, g: Inner space.

Figure 36: DBHEs Source:[48]

<table>
<tr><td>Parameters</td><td>Subsurface thermal conductivity
Geothermal gradient
Heat flow
BHE depth
Inlet temperature
Pipe and grout thermal conductivity
Flow rate</td></tr>
<tr><td>Limitations</td><td>Small well diameter
Low geothermal gradient (< 20 °C/km)
Low subsurface thermal conductivity
Distance between abandoned wells can limit the possibility having a BHE field able to feed a DH grid</td></tr>
<tr><td rowspan="3">Examples</td><td>Weggis, Weisbad, Switzerland [49]</td></tr>
<tr><td>

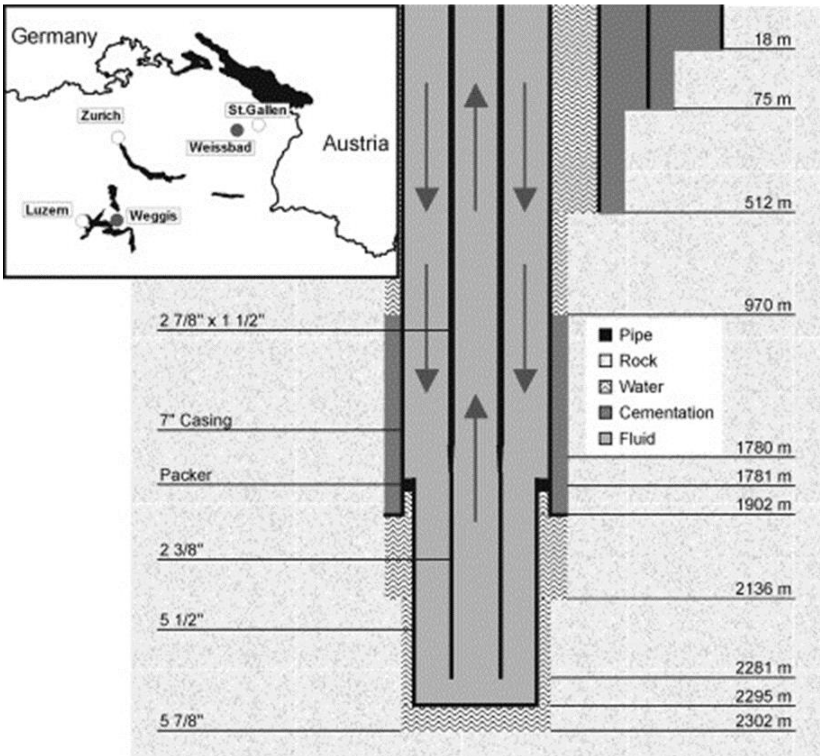


Figure 37: Example of Weggis, Weisbad, Switzerland *Source. [49]*

Two deep BHE have been in operation in Weggis (2.3 km) and Weissbad (1.6 km) in Switzerland since 1994. These are abandoned oil and gas wells that were repurposed with a coaxial heat exchanger to feed a HP and provide heating and DHW to residential dwellings. In the beginning, the deep BHE were significantly underexploited (ca. 20 W/m) due to a very low flow rate and the limited number of operational hours annually. Simulations demonstrated that up to 85 W/m could be extracted in a normal geothermal gradient setting (30 °C/km).

</td></tr>
<tr><td>Prenzlau, Germany: In 1996 in Prenzlau, a 2.7 km deep unproductive geothermal well was repurposed to a coaxial BHE to provide up to 500 kW of heating and DHW to a retirement home.</td></tr>
</table>

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