Interreg

EUROPEAN UNION

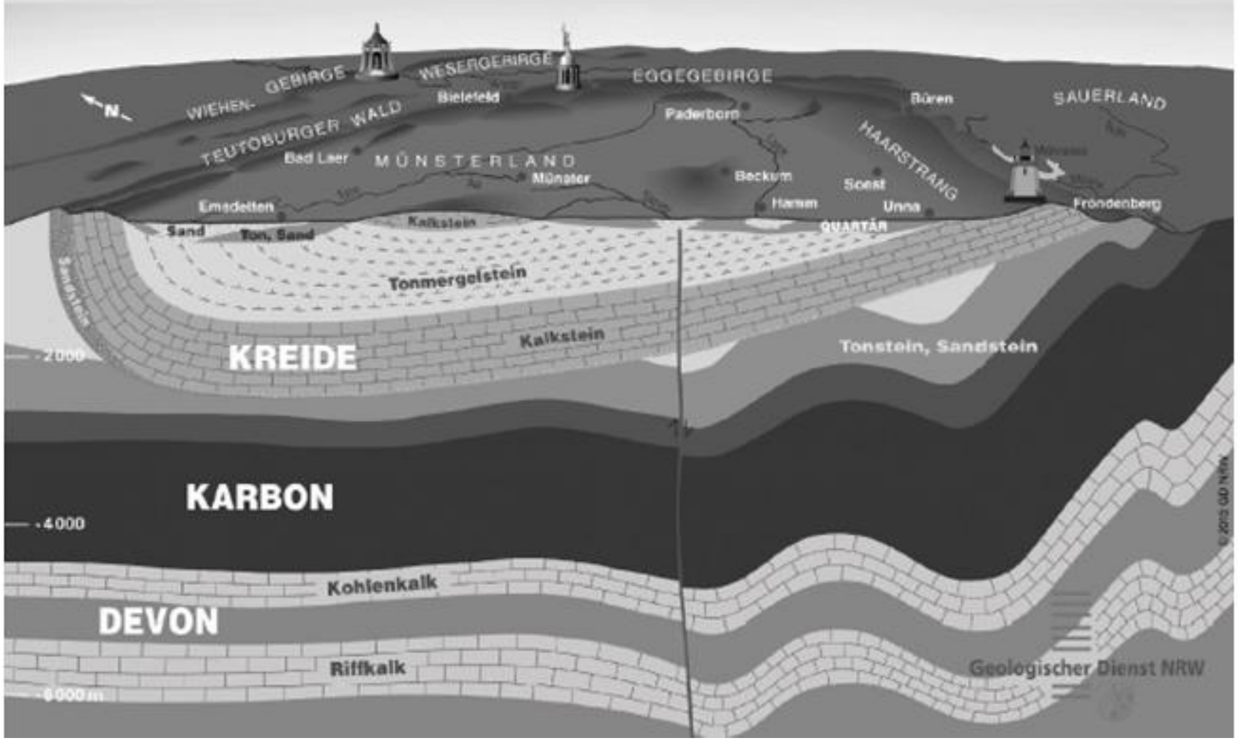
North-West Europe

DGE-ROLLOUT

European Regional Development Fund

Application form

Heat pump system



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Extended summary

i. Introduction

WP I1 of the DGE-Rollout, “Invest Heat Pump Technology: Usability and Upscaling for “NWE” ”, has the goal of developing a high temperature heat pump (HTHP) of large power output that will be connected to the district heating (DH) grid. As source, dismissed flooded mine galleries situated in Bochum under the GZB, will be employed. Possible requirements for the system will be proposed within the document, as well as the state of the activities and next steps.

ii. Methods

In *Section 1*, an analysis on the state of the art and literature review of the most suitable technology has been performed. Required background information are in particular: geothermal heat pump technology, district heating, large scale and high temperature heat pumps, refrigerants, costs estimations, and practical heat pump (HP) examples.

In *Section 2*, considerations about the desired characteristics of the WP I1 HP are derived with support of MATLAB simulations and energy balance calculations. The resulting needed technology should be able to produce pressurized water at temperatures between 120°C and 80°C. It also needs to deal with the temperature difference of the source over the heating period from 60°C to ca. 10°C, without significant decrease in performances. The nominal power is expected to be slightly less than half a MW.

Additional information on the conditions and settings of the heat source are necessary. These will be available shortly after drilling towards the mine galleries and with testing of flow rates in late 2019/early 2020. The data will be of high importance for further specification of the HP system requirements, and may allow for final adjustments in the investment.

In *Section 3* are listed the activities that have been carried out including the making of models, conference attendances and visits. Focus is made on the search for the best fitting technology through the contact of different companies. Current status and next steps cover: examination for the most promising HP suppliers, preparation work for the installment of the HP system, and setting up and run a number of additional computing models to describe a wider range of application scenarios.

iii. Conclusions

Ochsner, Hybrid Energy and Johnson Controls have on the market HP models that could possibly fit the project both in terms of power and temperatures. Additional investigation is undergoing.

Further products available on the market, for the vast majority, do not reach the required temperatures, in other cases, powers might not be fitting.

The main technical challenge is to obtain the high supply temperatures. This obstacle can be overcome by possible collaborations and developments with companies.

If this will result not possible, other options are to directly purchase one of the most fitting existing HP’s or consider different power outputs. For the latter option, there could be few companies on the market.

Introduction

WP I1 of the DGE-Rollout, "Invest Heat Pump Technology: Usability and Upscaling for "NWE" ", has the goal of developing a high temperature heat pump (HTHP) of large power output that will be connected to the district heating (DH) grid of Bochum South. The exploitation and utilization of the heat source is part of the "HeatStore" (Geothermica) project by GZB. Key target of "HeatStore" is the site development of flooded mining galleries situated ca. 70 m below the GZB. The groundwater contained in the mine will be used for seasonal storage of up to 60°C of temperature, heated up by a solar power plant during the summer. Drilling of injection and production wells, that will be eventually connected to the heat pump (HP) system, are scheduled for late 2019.

This application form is divided into 3 *Sections*:

- ***Section 1:*** state of the art for the required technology. The background information necessary to understand the innovative project of WP I1 is described.
- ***Section 2:*** the specific case of the HTHP that will be installed in Bochum, through an analysis on source, sink and powers. A summary on the needed technology is provided.
- ***Section 3:*** the current WP I1 activity status, with a list of the activities and attention drown on possible collaborations with HP suppliers, and an outlook.

1. State of the art

In this *Section,* the general concept of geothermal heat pump technology, district heating, large scale heat pump examples, as well as high temperature heat pumps, refrigerants, prices estimations, and practical heat pump examples are presented.

1.1. Heat pumps and geothermal energy

By definition, a heat pump is a heat engine that is able to transfer thermal energy from a heat source at low temperature to a heat sink at a higher temperature, exploiting different forms of energy, typically the mechanical one.
Heat pumps can be both used for heating and cooling. With a reversing valve it is possible to invert the flow of the refrigerant according to the useful effect that is needed. For heating the goal is to deliver heat to the hot source, for cooling it is to cool down the cold source.

Heat pumps can be classified according to the medium in primary and secondary loop as follows:

- Air-to-Water
- Air-to-Air
- Water-to-Water
- Water-to-Air

The 1st term of each category represents the source circuit. The heat pump can work with external air or water. Water-to-Water (or -to-Air) heat pumps include geothermal heat pumps and in particular ground source heat pumps and water source heat pump (e.g. aquifer, lake, or sea).
The 2nd term of each category represents the sink circuit: air if direct expansion, water if hydronic.
The most common heat pump technologies are vapor compression and absorption heat pump.

1.1.1. Vapor compression heat pumps

The main components of a vapor compression heat pump are: compressor, condenser, expansion valve and evaporator, as shown in *Figure 1*.

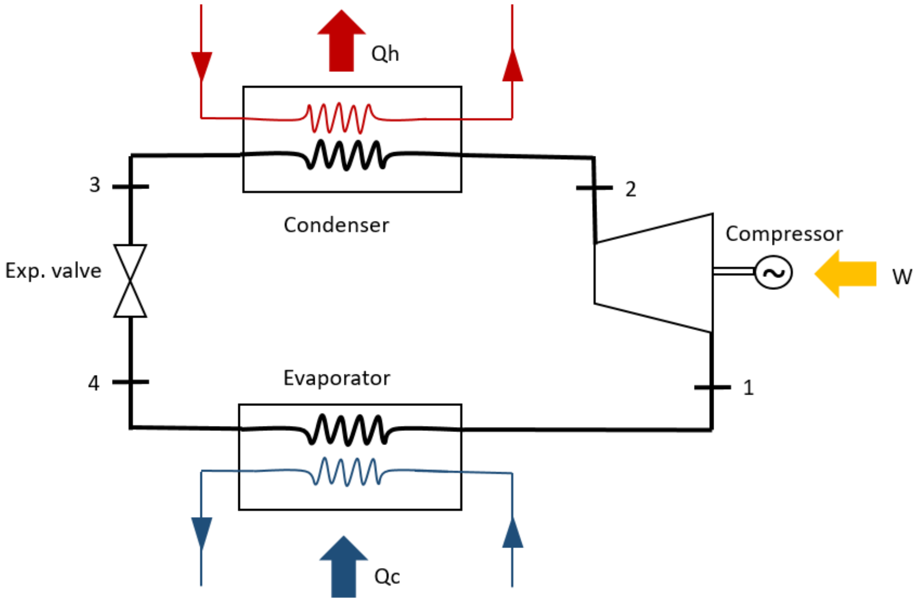


Figure 1. Vapor compression heat pump cycle and main components

This technology is based on the reverse Carnot cycle. The simplified ideal thermodynamic cycle consists of 4 transformations: an adiabatic compression (1-2), two isobaric heat exchange processes (2-3 and 4-1) and an isenthalpic lamination (*Figure 2*).

The energy balance made by the 1st law of thermodynamics is shown in *Figure 1*. Absorbing heat (*Qc*) at the evaporator from a low temperature energy source, it is possible to transfer heat (*Qh*) at a higher temperature sink through the condenser, exploiting the work of the compressor (*W*) generated by electrical energy. Performances are evaluated with the coefficient of performance (*COP*) for heating, and the energy efficiency ratio (*EER*) for cooling as:

$$COP = \frac{Qh}{W} \quad (1)$$

$$EER = \frac{Qc}{W} \quad (2)$$

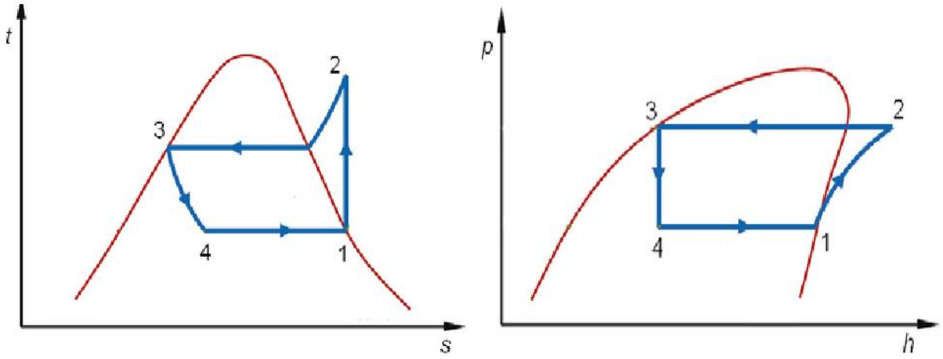


Figure 2. Temperature-entropy and pressure-enthalpy diagram of ideal thermodynamic cycle

1.1.2. Absorption heat pumps

Absorption heat pumps, as opposite to vapor compression heat pumps, are not electrically driven but they need a further heat source (e.g. natural gas, geothermal heat, or solar). Instead of the compression process there are the absorption and generation processes. And the refrigerant solutions used are usually LiBr-H_2O and NH_3-H_2O.

Considering the lithium bromide-water heat pump, water is the refrigerant, whereas with an ammonia-water heat pump. In *Figure 3* the cycle with the latter refrigerants is shown [1].
In particular, at point 1, ammonia vapor goes from the evaporator to the absorber. It is then mixed with the weak solution (low ammonia content) of water and ammonia in point *c*. Mixing the weak solution with pure ammonia from the evaporator, heat ($Q_{out,2}$) is produced through an exothermic reaction. The strong solution (high ammonia content) from point *a* is then pumped to *b* at a higher pressure. Continuing the cycle, it then enters the generator where heat (Q_G) is supplied to evaporate the ammonia. The heat used at this point (plus the work from the pump) is equivalent to the compressor in the vapor compression heat pumps. The ammonia vapor then enters the condenser, releasing $Q_{out,1}$, and continues through the expansion valve and through the evaporator where heat is injected from the source, like for the vapor compression cycles. The weak solution leaving the generator in *c* is then returned to the absorber to repeat the cycle.

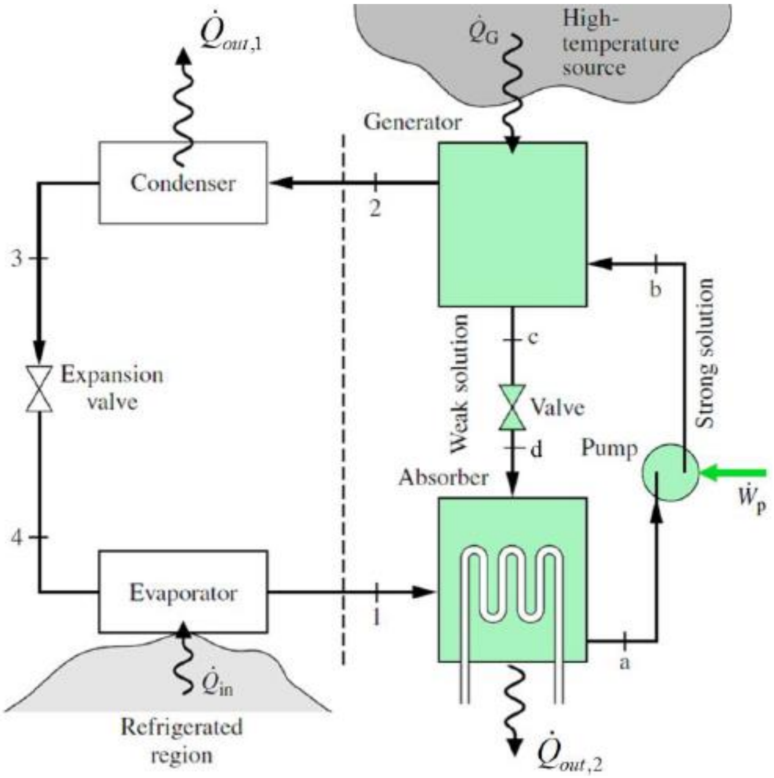


Figure 3. Ammonia-water absorption heat pump cycle and main components [1]

In *Figure 4* an example of simple cycle with weak and strong solutions is shown on a p-T diagram. It can be noted that the high temperature source (Q_G) it needs to be higher than the temperature of point *c*. Minimum Q_G temperatures are reported to be of 60°C for LiBr-H2O absorption heat pumps and 80°C for the NH_3-H_2O ones [2].

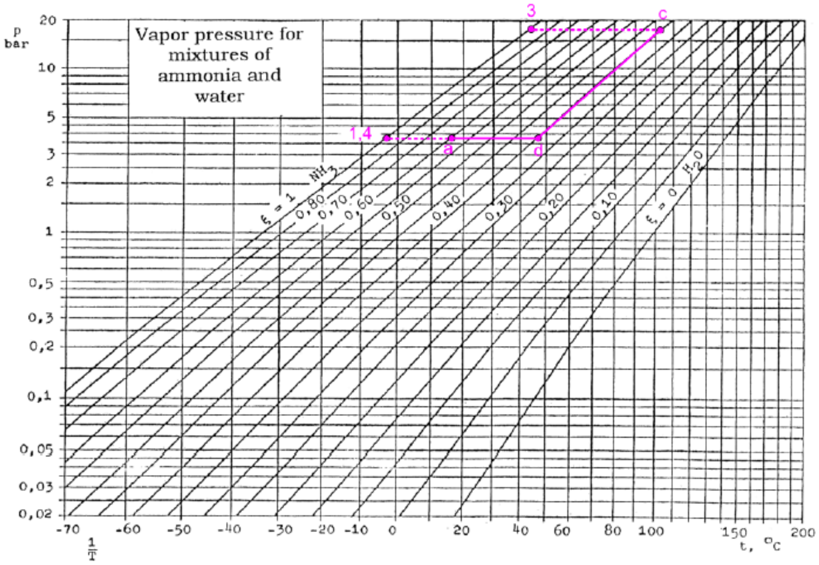


Figure 4. Pressure-temperature diagram of ammonia-water cycle [2]

In this case the performances are evaluated with the gas utilization efficiency (*GUE*) as**:**

$$GUE = \frac{Qh}{Qgas} = \frac{Qcond+Qabs}{Qgas} \qquad (3)$$

Advantages of this technology include the possibility of using different heat sources without the need of mechanical energy, apart from the solution pump. Furthermore, the performances do not degrade as much as for the vapor compression heat pumps at different evaporation conditions. The performances are however overall worse and low temperatures cannot be reached due to the presence of water. There also are limitations in the choice of the refrigerant and the most efficient systems run on fossil fuel burners. Usually in fact, high power and high temperature heat sources are needed.

1.1.3. Geothermal heat pump applications

Scope of the project is to develop a geothermal heat pump (GHP), therefore main solutions for this application are presented in this *Section*.

In general, heat from the Earth can be exploited in different ways according to the different temperature of the geothermal source. In particular, from higher to lower source temperatures, geothermal energy can be used to produce electricity, directly employed to produce heat, or finally, heat pumps can be adopted to increase the temperature of the source for heating purposes.

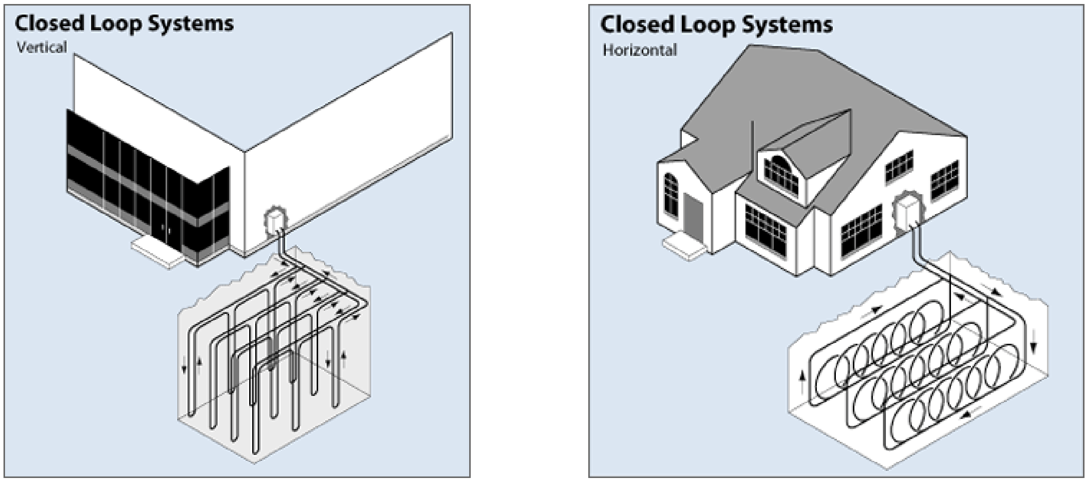
Geothermal heat pumps use the heat that is stored in the ground or in water basins. They furthermore, represent the most diffused type of geothermal applications since they do not ask for particular geological requirements.

For this application, the most common technology is vapor compression water source heat pumps. Making an exemption for the direct exchange geothermal heat pump, there is in fact water running through the evaporator.

GHP’S can be divided in three categories: closed loop, open loop, direct exchange [3].

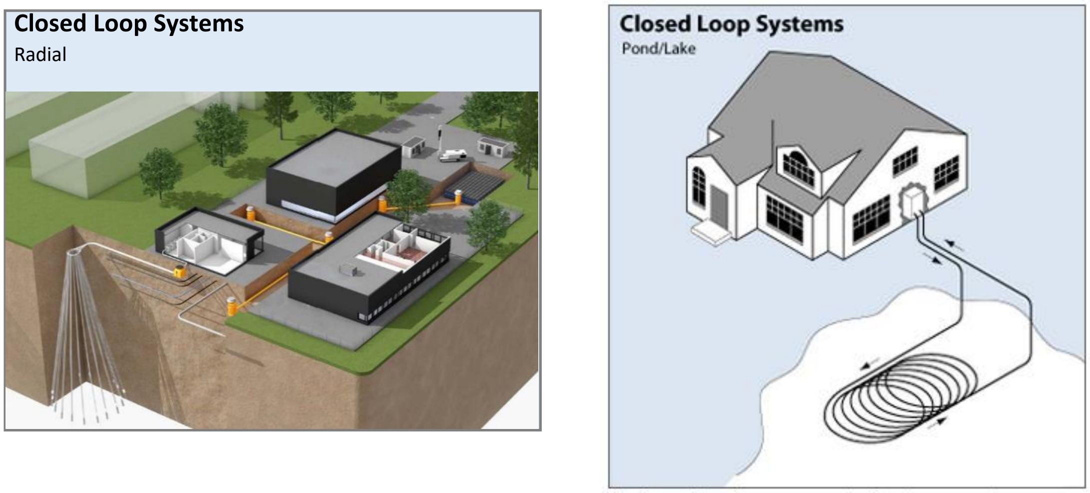
Closed loop systems are characterized by a closed water loop as secondary circuit. Water and antifreeze circulates in polyethylene pipes that are buried underground. There is a heat exchanger between the refrigerant and the water from the closed loop.
Closed loop tubing can be installed in 4 different configurations, as reported in *Figure 5*:

- **Vertical**: the pipes run vertically in the ground.
- **Horizontal**: the pipes run horizontally in the ground.
- **Radial** or directional: the pipes run radially from a single point on the surface.
- **Pond**: the pipes run on surface water of ponds, lakes, rivers, sea, or other solutions. This is not a common solution for this type of applications but it is useful in case of low water quality.



Vertical configuration of a ground-coupled heat pump system

Horizontal configuration of a ground-coupled heat pump system



Configuration of a source water heat pump system

Figure 5. Geothermal heat pump closed loop configurations [3] [4]

In **open loop systems** (or groundwater heat pumps) the water from the body of water is pumped directly into the heat pump heat exchanger. Injection and extraction wells are present, as shown in *Figure 6*. The composition of water must be taken into account (e.g. salinity, bacteria). Of this kind of system of particular importance is the following, shown in *Figure 6*:

- **Standing column well**: a particular type of open loop system where water is pumped from the bottom of the well and reinjected at the top of it.

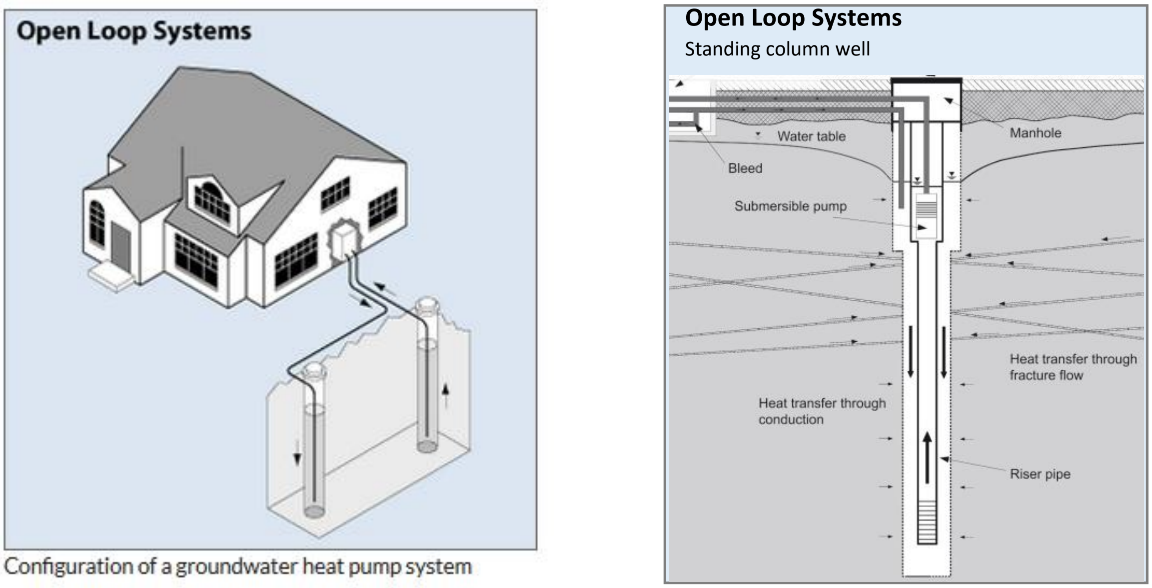


Figure 6. Geothermal heat pump open loop configurations [3]

Finally, in **direct exchange systems**, the refrigerant loop is directly buried underground. The heat exchange between refrigerant and ground happens directly through copper pipes. These heat pumps are one of the oldest technology for ground source heat pump but not very diffused anymore due to environmental leakage issues and cost.

1.2. District heating insights

One of the goals of WP I1 is to connect the heat pump to the district heating. Two aspects of the DH make this project particularly interesting and of a high potential. On the one hand, the district heating in Europe and in Germany is for the vast majority fired by fossil fuels, on the other hand, the temperatures currently required in Germany are in many case elevated.

1.2.1. District heating from geothermal energy in Europe

The district heating in Europe shows big room for development towards renewables. Geothermal use for DH is not new, it dates back to the Roman period. Historically, the areas where geothermal district heating developed first are the ones with higher hydrothermal potential. With the current connotation and with modern technologies, geothermal resources with temperatures above 60°C have been used from the ‘70s after the oil crises. Finally, in the last 5 to 10 years, geothermal district heating is seeing a new strong development due to the concerns about sustainability and CO_2 emissions, as well as the rise of newer technologies, such as large heat pumps or deep geothermal technologies.

As stated by the report of the EU project GEODH: “Developing Geothermal District Heating in Europe” [5], with low temperature geothermal sources it could be advantageous to develop hybrid systems such as heat pump connected with conventional boilers. It is also expected more coupling of heat pumps with solar and biomass. The coupling of HP with concentrated solar is also scope of the WP I1.

1.2.2. District heating development in Germany

According to Euroheat&Power and Der Energieeffizienzverband für Wärme, Kälte und KWK e. V., the total installed district heating capacity in Germany in 2017 was of approximately 57 000 MW [6].

In the 2018 EGEC Geothermal Market Report, the European Geothermal Energy Council reports 343 MW as the installed capacity of geothermal DH in Germany (*Figure 7*). This accounts then for about the 0,6% of the overall DH capacity.

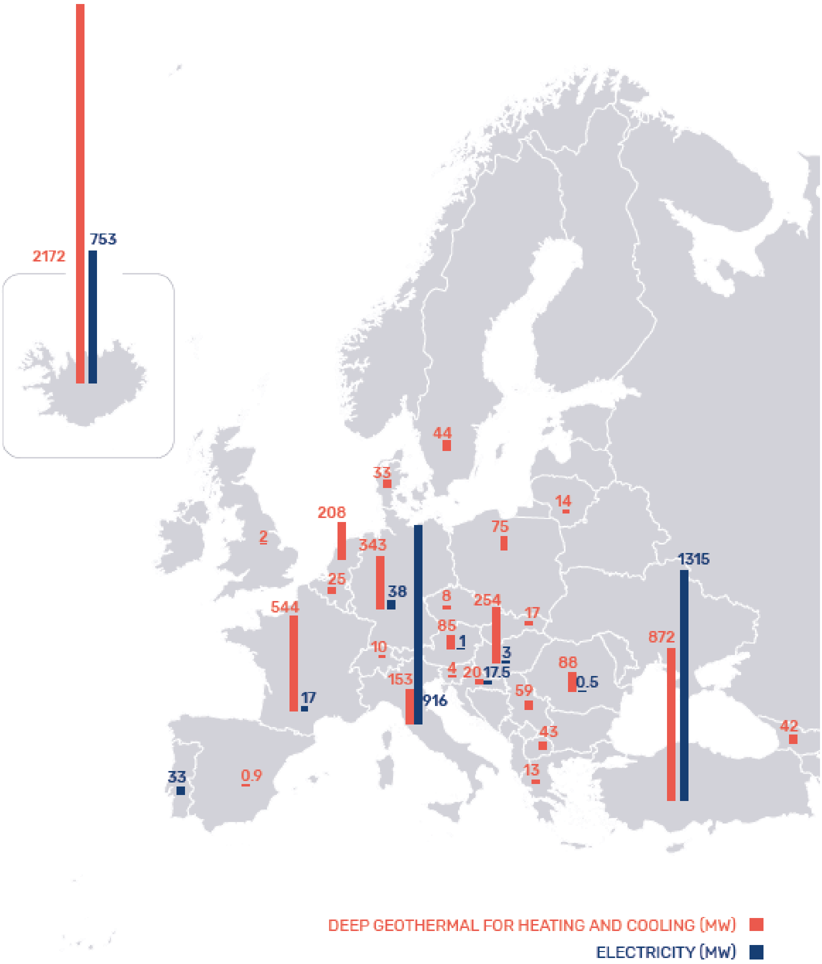


Figure 7. Installed capacity of geothermal electricity and DH by country in 2018 (MW) [7]

Germany represents the 2nd European country after France for number of geothermal heating plants, with almost 30 active plants in 2018 and more than 30 under development (*Figure 8*). The amount of the ton of oil equivalent (toe) from installed DH capacity is the highest in Europe, but it currently represents only the 12% of the National Renewable Energy Action Plan (*Figure 9*). Big room for development is therefore foreseen in this sector.

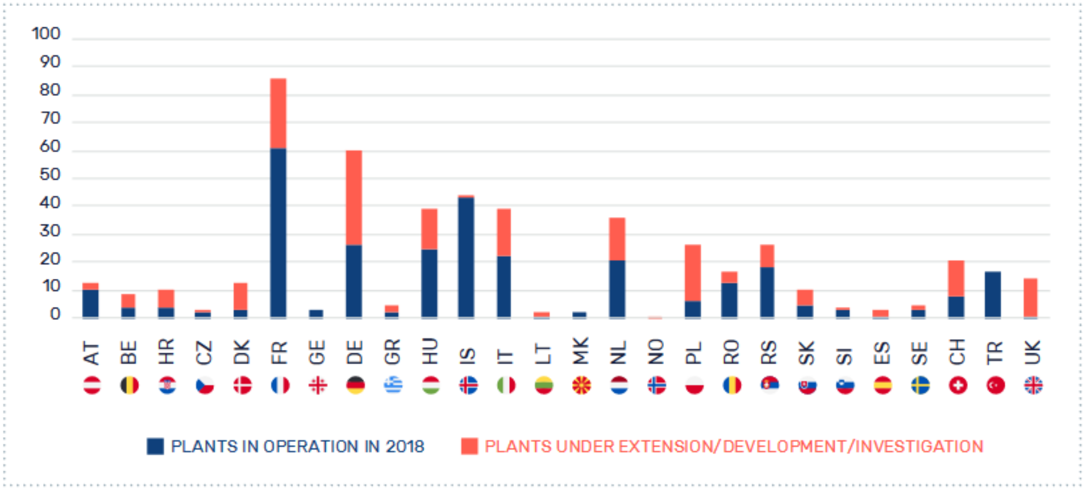


Figure 8. Number of geothermal heating plants in the EU [7]

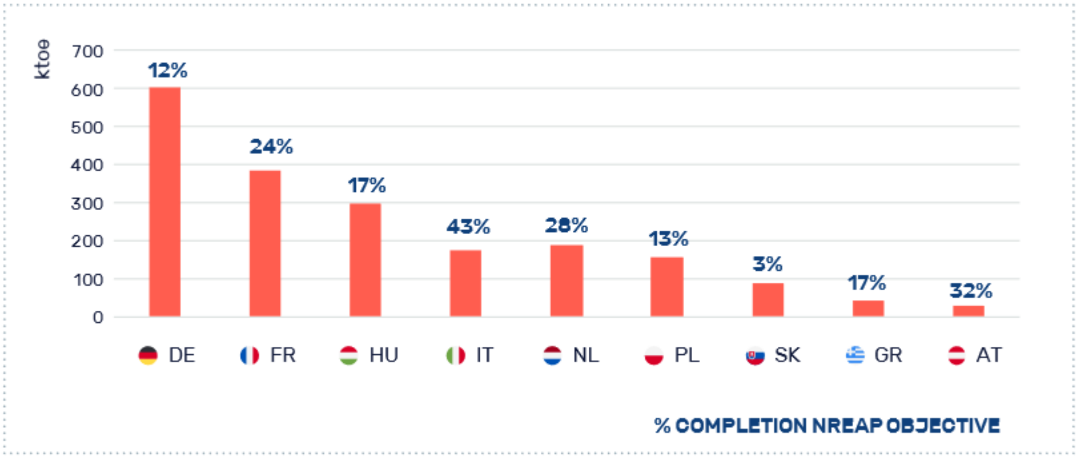


Figure 9. Installed geothermal DH capacity per country. (NREAP = National Renewable Energy Action Plan) [7]

The supply temperatures of district heating networks vary mainly according to the period in which they were built, as shown in *Figure 10*. The period of construction of the DH plants is wide and dates back to the beginning of 1900. As shown in *Figure 11*, there has been a peak of plants built around the 70's and the years 2000. It is then reasonable to assume that there is a high presence of district heating grids with temperatures between 80°C and 100°C or higher.

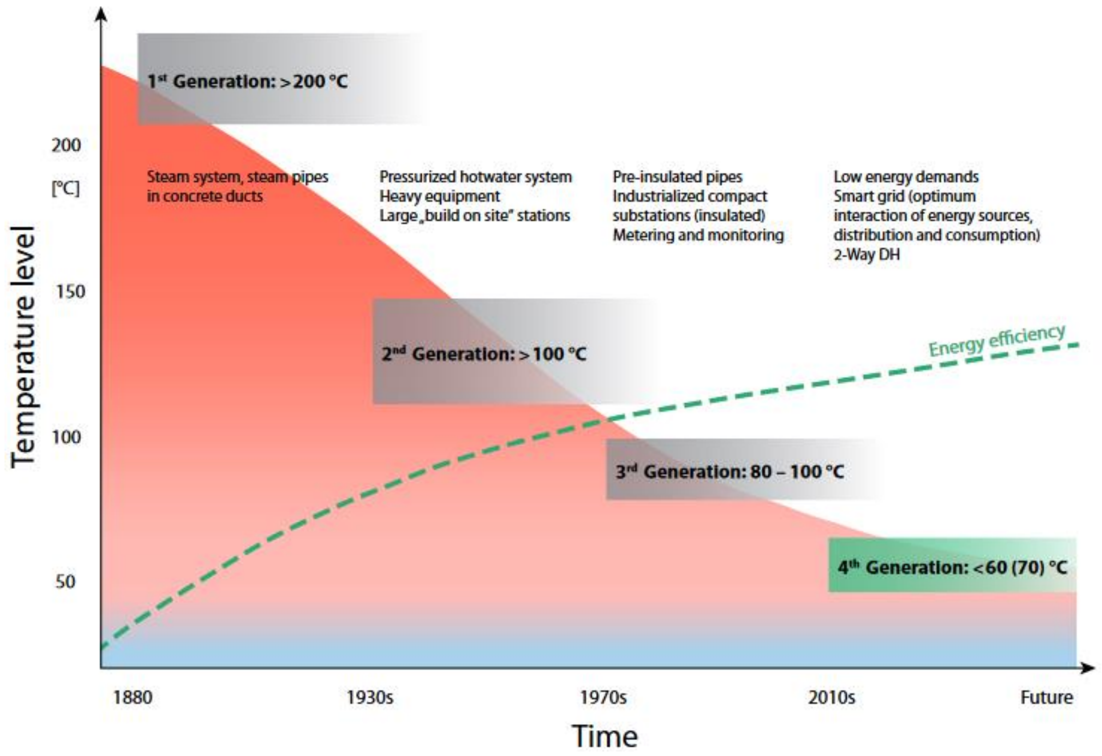


Figure 10. Development of DH technology [8]

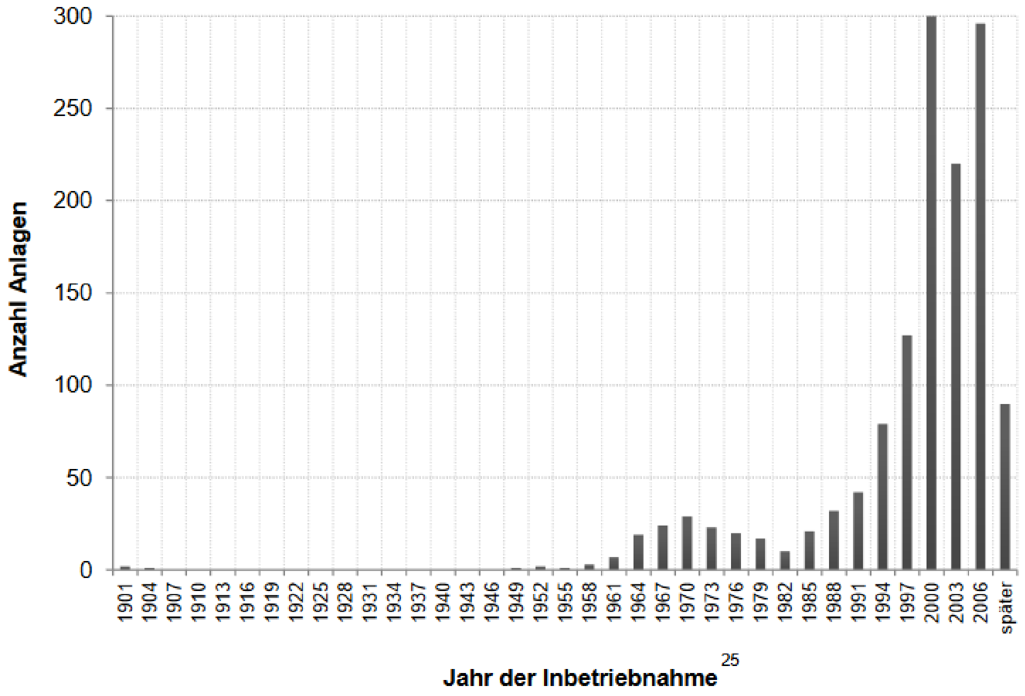


Figure 11. Number of plant commissioning vs. Year of commissioning [9] (2012)

1.3. Large scale heat pumps in Europe, examples

Examples of existing large scale heat pumps present in Europe are listed in *Table 1* [10] [11] [12] [13] [14]. In the columns are reported the general application, the location, the power produced, the refrigerant, the supply temperature, the available information about the source and the brand.

From this analysis, colored in green in *Table 1*, examples of large HP systems for district heating and their features can be found.

Table 1. Large scale HPs in Europe. Examples

Application	**Location**	**Power (MW)**	**Refrigerant**	**COP**	**T supply (°C)**	**Heating source, T source (°C)**	**Brand**
District heating	Bergheim, DE	0,59	R134a	4,4	70	mine water, 26°C	Viessmann
District heating	Bergheim, DE	0,87	R744	3,1	90	district heating water, N/A	Dürr Thermea
District heating	Drammen, NO	13,20	R717	3,0	90	river water, 8°C	Star Refrigeration
District heating	Skjern, DK	8,00	R717	6,7	70	humid air, 55°C	Johnson Controls
District heating	Vienna, AT	0,26	R245fa	5,3	85	district heating water, 45°C	Ochsner
District heating	Mäntsälä, FI	3,60	R134a	3,4	85	exhaust air, N/A	Calefa
District heating/cooling	Lausanne, CH	4,50	R717	4,8	65	lake water, 7°C	Sulzer
District heating/cooling	Budapest, HU	3,80	R134a	7,3	33	sewage water, 10-20°C	Thermowatt (Carrier)
Building heating	Bavaria, DE	0,20	R407c	4,8	37	seasonal water storage or ground, N/A	Viessmann
District heating	Hamburg, DE	0,72	R134a	5,0	45	water, N/A	Ochsner
District heating	Fornebu, NO	16,00	R1234ze(e)	4,4	75	sea water, N/A	Friotherm&Honeywell
Food processing	CH	0,19	R134a	3,4	>70	water, N/A	Viessmann
District heating	Mänttä, FI	0,16	R245fa	2,0	70-120	district heating water, 45°C	Ochsner
District heating/cooling	Dijon, FR	0,42	R134a + R245fa	2,6	90	water N/A	Ochsner
Wood drying	N-E DE	10,00	R717	4,5	78	Ethylene glycol, N/A	GEA
Distict heating	Lempäälä, FI	0,13	R134a	4,5	55-75	ground + heat from cooling process, N/A	Calefa
Food processing	Veghel, NL	1,40	R717	5,9	63	ammonia from refrigeration, N/A	GEA
Building heating	DE	0,11	R410a	4,7	70	waste heat, N/A	Viessmann
Food processing	BE	1,00	R717	4,5	78	waste heat, N/A	Mayekawa&Mytcom
District heating	Milan, IT	1,70	R134a	4,6	75	groundwater, N/A	Ochsner
Building heating	DE	0,60	R134a	4,3	65	waste heat, N/A	Viessmann
Building heating	Kauhava, FI	0,60	R134a	4,3	65	waste heat, N/A	Calefa
District heating	Lillle-Skensved, DK	3,00	R717	10,0	85	waste heat, N/A	Mayekawa&Mytcom
District heating/cooling	Budapest, HU	1,70	R134a	3,9	60	sewage water, N/A	Thermowatt (Carrier)
Drying	Pischelsdorf, AT	0,40	R1336mzzZ	N/A	110-160	waste heat (water), N/A	DryF
Drying	Uttendorf, AT	0,40	R1336mzzZ	N/A	110-160	waste heat (water), N/A	DryF
District heating/cooling	Milan, IT	15,00	R134a	3,0	80-95	groundwater, 15°C	Friotherm
Industrial HTHP	N/A	0,66	R134a/R245fa	5,8	165	N/A, 35°C	Kobe Steel
Industrial HTHP	N/A	0,37	R245fa	3,5	120	N/A, 65°C	Kobe Steel
Industrial HTHP	N/A	0,75	R134a + R245fa	4,0	130	N/A, 45°C	Ochsner
Industrial HTHP	N/A	0,75	R245fa	2,7	130	N/A, 50°C	Ochsner
Industrial HTHP	N/A	0,85	R245fa	N/A	95	N/A	Ochsner
Industrial HTHP	N/A	2,50	R717	4,5	120	N/A, 20-75°C	Hybrid Energy
Industrial HTHP	N/A	2,20	R744	4,3	110	N/A, 20°C	Dürr Thermea
Industrial HTHP	N/A	0,30	R245fa	3,4	100	N/A, 50°C	Combitherm
Industrial HTHP	N/A	3,60	R1234ze(e)	3,5	95	N/A, 33,8°C	Friotherm
Industrial HTHP	N/A	20,00	R134a	N/A	90	N/A	Friotherm
Industrial HTHP	N/A	15,00	R717	5,0	90	N/A, 35-50°C	Star Refrigeration

Industrial HTHP	N/A	4,50	R717	5,0	90	N/A, 35°C	GEA
Industrial HTHP	N/A	1,32	R717	4,0	90	N/A, 39°C	Johnson controls
Industrial HTHP	N/A	2,32	R717	N/A	90	N/A	Johnson controls
Industrial HTHP	N/A	20,00	R134a	N/A	90	N/A	Johnson controls
Industrial HTHP	N/A	0,60	R134a	4,1	90	N/A, 50°C	Mitsubishi
Industrial HTHP	N/A	0,39	R1234ze(e)	3,4	90	N/A, 50°C	Viessmann
Industrial HTHP	N/A	1,20	R717	N/A	70	N/A, 40°C	Johnson controls
Industrial HTHP	N/A	1,60	R717	N/A	90	N/A, 40°C	Johnson controls
Industrial HTHP	N/A	3,00	R717	N/A	90	N/A, 40°C	Johnson controls

1.4. High temperature heat pumps

A further point was to make an analysis on the current state of the art for high temperature heat pumps (HTHP's). One of the big challenges of the project is in fact the possibility of achieving high temperatures for the district heating.

According to Arpagaus et al. [15] more than 20 HP models have been identified on the market, able to achieve supply temperatures of at least 90°C. Few suppliers already managed to exceed 120°C. And concerning the powers, in general, those ranges vary from few kW to about 20 MW.

Research is currently strongly focused on achieving better COP's and higher sink temperatures (greater than 160°C). High relevance is the investigation is given to refrigerants, as reported in detail in *Section 1.4.1*.

Application for HTHP's are mainly industrial processes, as shown in the following picture (*Figure 12*):

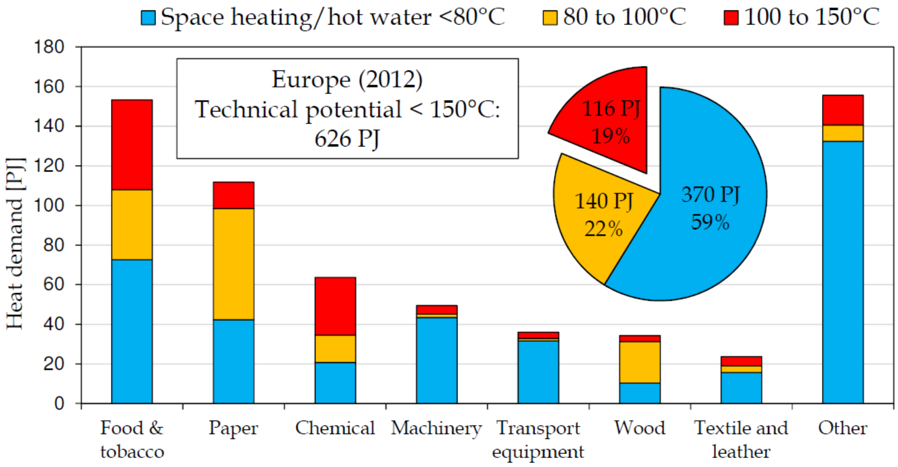


Figure 12. Technical market potential of process heat in Europe accessible with HTHP's [13]

Within these sectors, in *Figure 13* is shown the range of required temperatures and readiness level of HTHP's, where hot water and space heating are shown under "Several sectors" and where they are not considered to reach up to 120°C. This underlines the particularity of the application of the HTHP development within the DGE-Rollout even though, as reported in *Section 1.2.2* several DH applications in Germany currently need elevated temperatures.

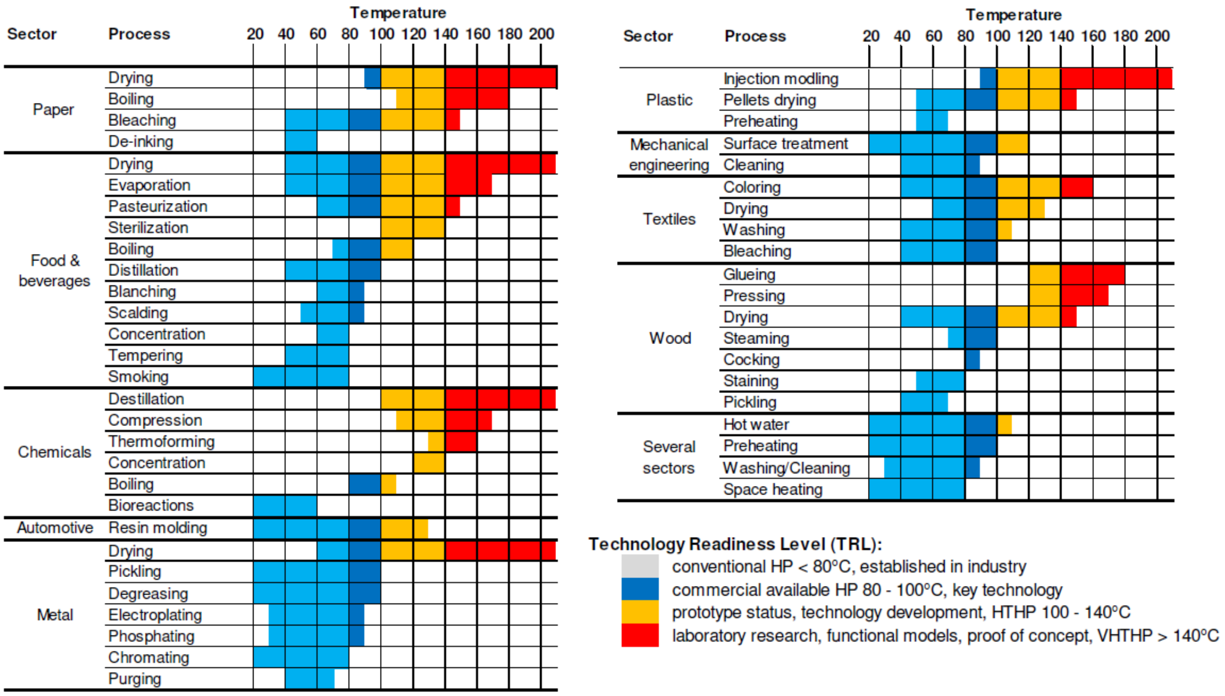


Figure 13. Temperature levels of industrial processes and Heat Pump Technology Readiness [13]

In *Figure 14* are the HTHP models present already on the market. Shown is the maximum achievable supply temperature versus the heating capacity and the compressor type for each model. The models that could already fit the project are the ones at the top right hand corner with relatively high powers and a supply temperature that can be up to 120°C.

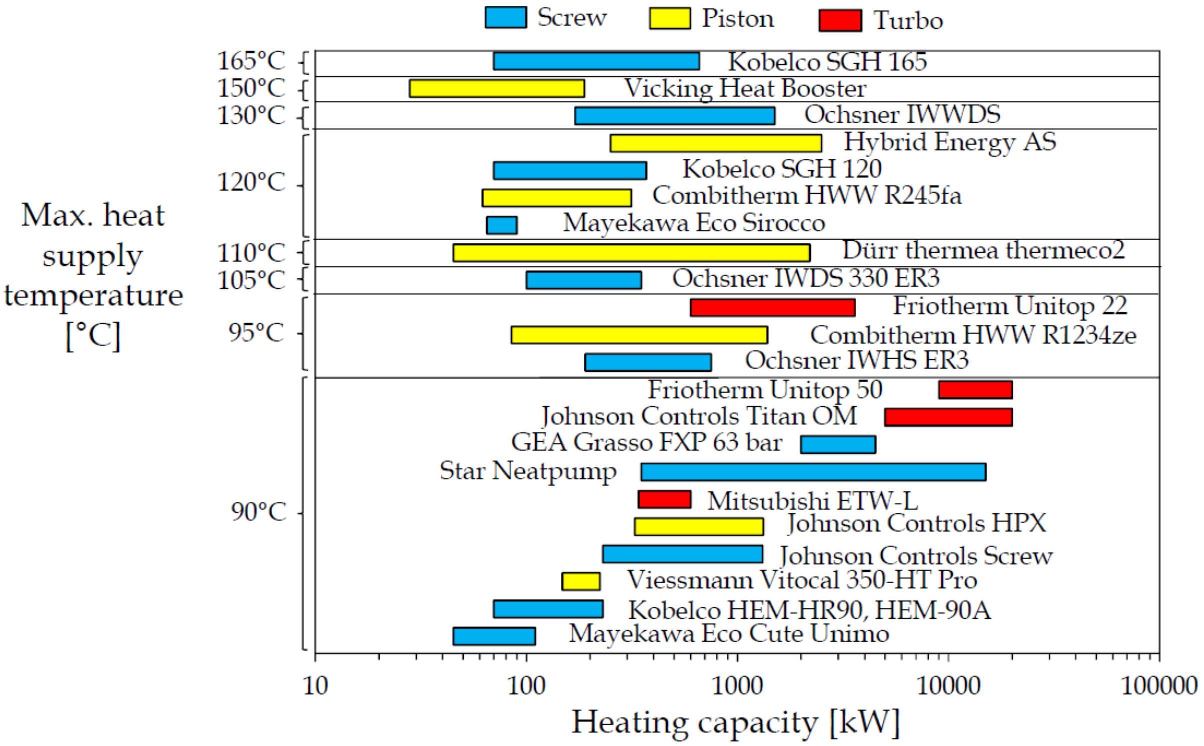


Figure 14. Existing industrial HTHP's with T supply > 90°C [13]

1.4.1. Suitable refrigerants for high temperature heat pumps

For HTHP's the choice of the refrigerant plays a fundamental role in terms of achievable temperatures and to determine the technology that will be used. Since the vast majority of heat pumps present on the market are currently compressor driven, these are here analyzed. Absorption heat pumps in fact do not seem easily applicable for the project since they require vast heat sources and at relatively high temperatures.

The components that can make a difference in compression heat pumps are the heat exchangers, the compressor and the working fluid.
The heat exchangers are for most of the applications shell-and-tube heat exchangers since the heat is transferred between two liquids. The condenser could also be a gas cooler in the case of supercritical cycle. The compressors should be tested to reach high temperatures but few solutions are already available, these are screw or piston or, less frequently, centrifugal compressors. As reported by Guzda and Szmolke [16], piston compressors can be used for HP's with a power up to 200 kW, whereas screw compressors are suitable for powers between 150 kW and 1600 kW. Centrifugal compressors are suitable for heat pumps with powers from 350 kW, they are used rarely. They in fact require high powers, have limited regulation and a big variation of performance with the discharge pressure. They are also expensive.

Since the working fluid, or refrigerant, can be considered as the element that can make the biggest difference in terms of supply temperature, type of thermodynamic cycle and environmental impact, research is currently highly focused on this topic.

General desired characteristics for a refrigerant are:

- High critical temperature (> 150°C)
- Low critical pressure (< 3000 kPa)
- ODP (Ozone depletion potential) = 0
- Low GWP (Global Warming Potential)
- Short atmospheric life
- Non-toxic, non-combustible (safety group = A1, see *Table 2*)
- Other useful qualities include: high COP, low pressure ratio, high volumetric heat capacity, availability on the market.

Table 2. Refrigerants safety group (SG) classification

Flammability	**Higher**	**A3**	**B3**
	Lower	**A2**	**B2**
		A2L	**B2L**
	No flame	**A1**	**B1**
		Lower	**Higher**
		Toxicity	

Analyzing the reported existing solutions from the large scale, high temperature analysis and from advanced stage research activities, the refrigerants in *Table 3* ([17] [13]) appear to be suitable for the application. However, since there is high investigation on refrigerants, other less known solutions could also be possible. The most common refrigerants for conventional heat pumps are R134a and R410a. Even though with these two refrigerants the supply temperature reaches up to only 80°C [14], they have been kept in the analysis because of the possibility of making cascade systems. R717 and R600 are also considered since they could be used as a working pair, as proposed by Johnson Controls. R718 is under observation since chillers with water as working fluid already exist and there could be the possibility of HP implementation. It should also be noted that R744 and R1234ze(e) are suitable for transcritical cycles.

Table 3. Characteristics of possible suitable refrigerants. Negative features are red, positive green

Refrigerant	Tcr (°C)	Pcr (kPa)	ODP	GWP	Life (y)	SG
R134a	101,06	4059	0	1300	14	A1
R744 (CO2)	31,04	7380	0	1	29300-36100	A1
R717 (NH3)	132,40	11280	0	0	< 0,019	B2L
R718 (H2O)	373,95	22060	0	0,2±0,2	0,026	A1
R245fa (ÖKO1)	154,05	3640	0	858	7,6	B1
R407c	86,05	4634	0	1774	15,7	A1
R1234ze(e)	109,40	36	0	6	N/A	A2L
R410a	70,17	4770	0	2088	16,9	A1
R600	152,01	3796	0	4	12±3	A3
R1336mzzZ (Opteon MZ)	171,30	2900	0	2	N/A	A1

1.5. *Heat pump costs estimation*

Having a detailed idea on the pricing of the required heat pump is not trivial. Price lists or other complete information are not easily accessible since these products are sold on commission and many variable parameters are present. To have an estimation on the costs, average values per kW at European and national levels have been found. This represents a general picture on the pricing, and for a more accurate analysis, offers from different suppliers should be evaluated.

The International Renewable Energy Agency (IRENA) reports that in Europe the average cost for large scale heat pumps is around 450 €/kW for heat pumps between 250 kW and 500 kW and around 270 €/kW for heat pumps larger than 1000 kW (*Figure 15.a*) [18]. For heat pumps with powers higher than 40 kW the overall average was of 630 €/kW in 2015 (*Figure 15.b*). They underline the presence of an economy of scale above 100 kW but there is not enough data available [18]. Prices appear to be for the only heat pump with no additional costs.

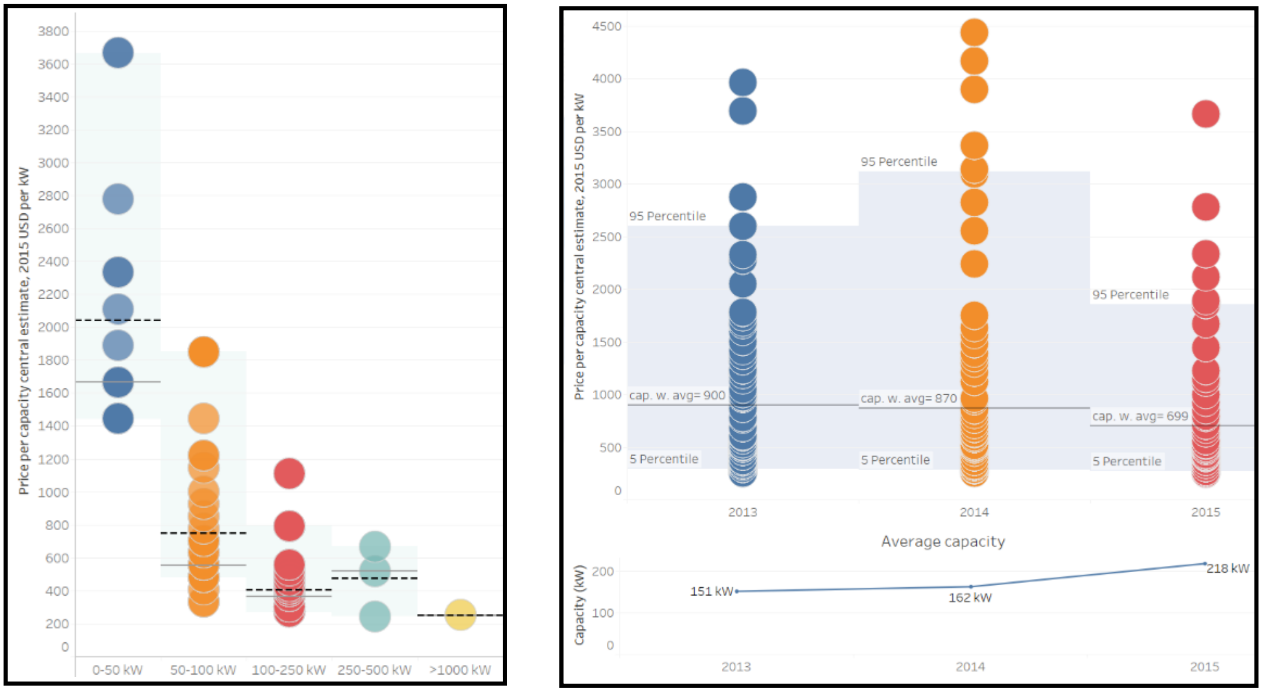
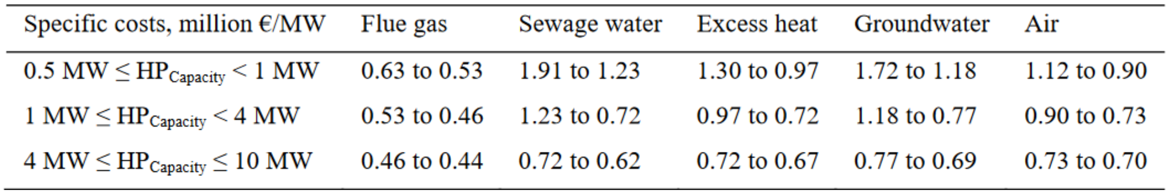


Figure 15. a. Large scale HP prices in Europe (2015) b. Average capacity and prices for HP's with power > 40kW [18]

At a country level, a study done by TU Denmark [19] shows the overall cost for different size ranges of large scale heat pumps for district heating in Denmark (*Figure 16*). These costs refer to the entire project, not only for the heat pump.



Specific costs, million €/MW	Flue gas	Sewage water	Excess heat	Groundwater	Air
0.5 MW $\leq HP_{Capacity} <$ 1 MW	0.63 to 0.53	1.91 to 1.23	1.30 to 0.97	1.72 to 1.18	1.12 to 0.90
1 MW $\leq HP_{Capacity} <$ 4 MW	0.53 to 0.46	1.23 to 0.72	0.97 to 0.72	1.18 to 0.77	0.90 to 0.73
4 MW $\leq HP_{Capacity} \leq$ 10 MW	0.46 to 0.44	0.72 to 0.62	0.72 to 0.67	0.77 to 0.69	0.73 to 0.70

Figure 16. Investment cost of large scale HP's specific to the power

On the same study [19] also reported the breakdown of those costs into heat pump, heat source, construction, electricity and consulting costs (*Figure 17*):

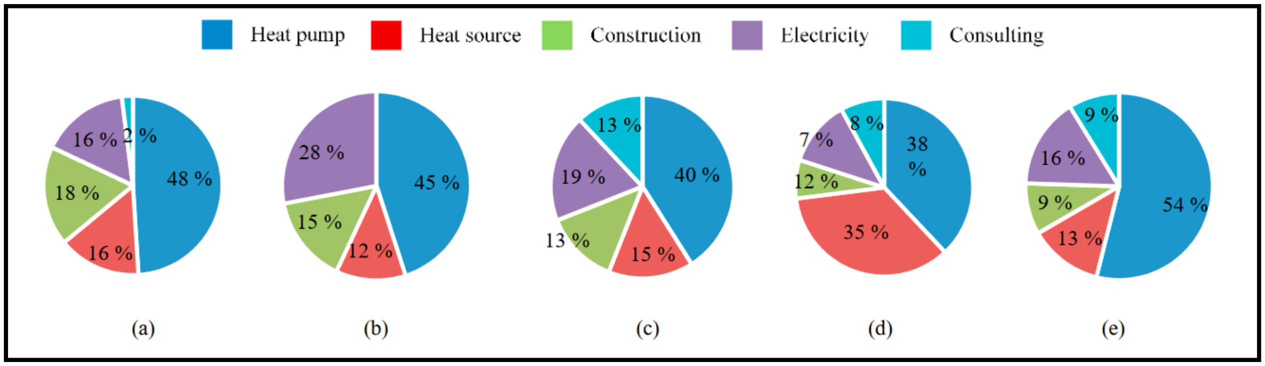


Figure 17. Breakdown of investments costs for different HP's types. (a) air, (b) flue gas, (c) excess heat, (d) groundwater, (e) sewage water [19]

Based on these considerations, the cost of the heat pump itself and the construction cost in Denmark are shown in *Table 4*:

Table 4. Cost of HP systems for DH in Denmark

	Overall cost [€/kW]		**HP cost [€/kW]**	
Power range [MW]	**Max**	**Min**	**Max**	**Min**
0,5-1	1720,00	1180,00	653,60	448,40
1-4	1180,00	770,00	448,40	292,60
4-10	770,00	690,00	292,60	262,20

Another country specific study is done by AFPG (Association Française des Professionnels de la Géothermie). They estimate in France a cost of 1200 €/kW for open loop geothermal HP systems for commercial buildings and 1400 €/kW for collective housing up to 1 MW of power [20].

Finally, for Germany, in a study done by Fraunhofer ISI, TU Wien and DTU to analyze the cost effectiveness of large scale heat pumps in district heating, it is assumed an overall conservative investment cost of 1500 €/kW independent on the HP size [21].

This last value seems therefore a good representative for our case if compared with the other European countries taken as example.

For completeness, absorption heat pumps are reported to usually have double the price of compression HP's [22].

1.6. Available technology as basis for this application, examples

Having described the different technologies and state of the art of high power, high temperature geothermal heat pumps for district heating, 4 representative solutions present on the market have been analyzed. These, even if most of them only partially suitable for the project, can be used as basis for the DGE-Rollout heat pump application.

1.6.1. Friotherm Unitop 50

Friotherm does not currently have a heat pump model that can reach up to the project desired temperature, it is however specialized in large power output HP's and especially in district heating.

The model Unitop 50 achieves up to 15 MW with R134a, a 2-stage compressor and 7000 l of refrigerant. Directly connected to the DH there are 2 heat exchangers: condenser and subcooler. Particularity of this solution is the intermediate vessel in which the vapor fraction of the refrigerant is separated and bled into the 2-stage compressor as shown in *Figure 18b*.

Figure 18. a. Friotherm Unitop 50 at Canavese district heating plant. [23] b. Friotherm Unitop 50 scheme [13]

After the observation of large scale heat pumps made in *Section 1.3* and to better understand how practically the district heating is implemented, a plant where the heat pump of *Figure 18a.* is installed and running has been visited (Canavese power plant in Milan).

1.6.1.1. Canavese plant description

Canavese plant in Milan is run by the local utility company A2A. It is of particular interest because of the similarities with that will be implemented in Bochum. Its visit furthermore, brought awareness to several aspects that should be considered for the project.

The plant is made of several machines that are working in parallel. These are: 3 gas engines for a total of 13,2 MWt, 3 gas boilers of 45 MWt in total and a 15 MWt heat pump. The gas engines also provide for the electricity needed by the heat pump, producing overall 15,2 MWe. The electricity required for the Canavese HP is about 6 MWe and it is convenient to produce it directly on site. Additionally, storage is required, there are tanks for a total of 20 MWt [24]. A simplified scheme of the plant is shown in *Figure 19*.

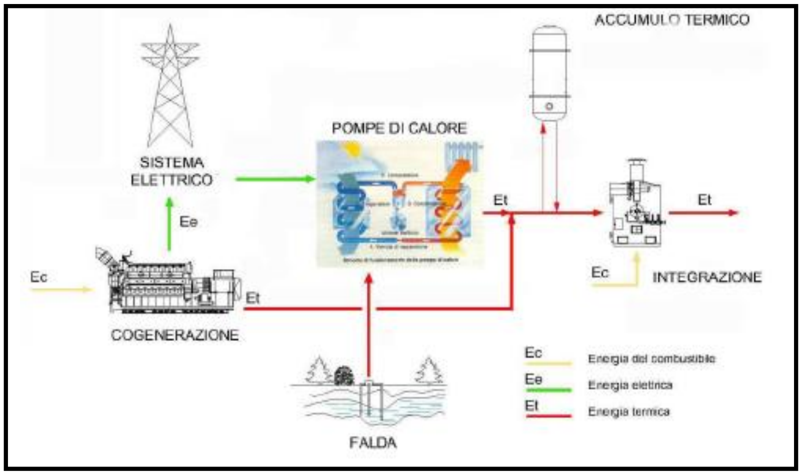


Figure 19. Scheme of Canavese plant in Milan [24]

The sink of the plant is the DH grid shown in *Figure 20*. It requires 3500 m^3/h at 90°C for heating and domestic hot water during winter and 150 m^3/h at 85°C for DHW during summer. The return temperature is in both cases 65°C.

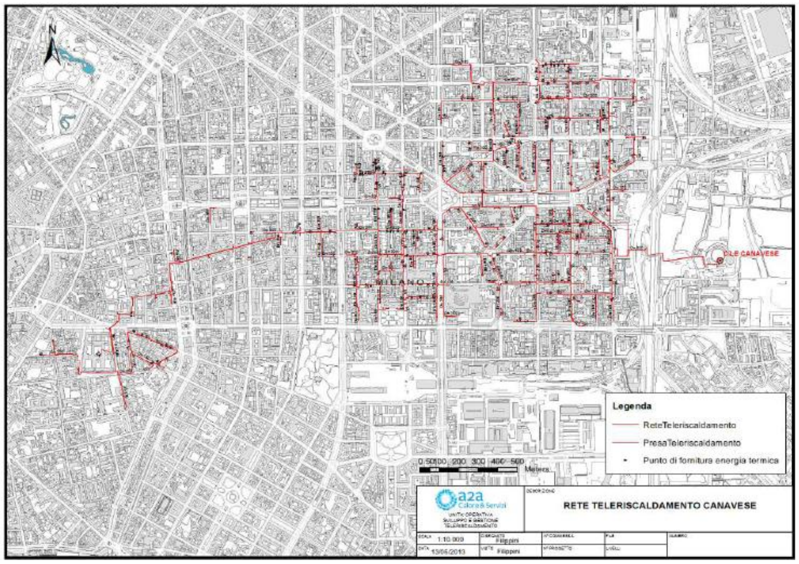


Figure 20. DH grid connected to Canavese plant [24]

The source is an underground aquifer of finite capacity that is connected through an open loop to the heat pump, whose behavior is ideally similar to the mine that is considered for the WP I1.
The overall aquifer power is between 7 MW and 8 MW and it is situated 7 m below the ground of Canavese plant. From the aquifer are extracted 700 m^3/h of water at 15-16°C and reinjected at 5°C. Due to the finite dimension of the aquifer, there is a seasonal temperature difference of the source of a couple of degrees.

For what concerns the heat pump operation, under the specific plant working conditions, the heat pump can reach up to 85°C. Gas boilers are then used to boost the water temperature up to the required 90°C. Additionally, 500 m^3/h of hot water are produced by the HP and the regulation is on/off type. This results in having the machine not running during the summer because the flow required by the DH is much lower. Furthermore, since the heat request during night is lower than in the daytime, the heat pump has been working for 16 h/day for 10 years with daily on/off's. The HP is also limited since it would require 1000 m^3/h of input flow, which is higher than what can usually be extracted from the aquifer.

1.6.2. Ochsner IWWDSS

Ochsner does not reach as high powers as Friotherm with one machine, it arrives however up to 130°C of supply temperatures with the model IWWDSS. This model is characterized by a 2-stage cascading system. In the bottom cycle runs R134a, in the top R245fa. The bottom cycle cannot manage high temperatures but works as an efficient preheating system. Machine and cycle are shown in *Figure 21*. This model could potentially already be a good fit for the project.

Figure 21. a. Ochsner IWWDSS. b. scheme [13]

1.6.3. Dürr Thermea Thermeco 2

Dürr Thermea Thermeco 2 is one of the few example of heat pump using a CO_2 supercritical cycle. Up to more than 1 MW of power and 110°C of supply temperature can be reached with appropriate inlet temperatures. To arrive at even higher power, there is a model with parallel compressors (*Figure 22*).

Despite the interest in this solution, it should be noted that Dürr Thermea just stopped the production of heat pumps.

Figure 22. Thermeco 2 and scheme [13]

1.6.4. Hybrid Energy AS

Hybrid Energy uses ammonia in the cycle but with a technology that is an "hybrid" between absorption and compression heat pump. They can reach 120°C and more than 1 MW of power and are able to work with large temperature differences between source and sink (*Figure 23*). Necessary source temperatures need to be verified.

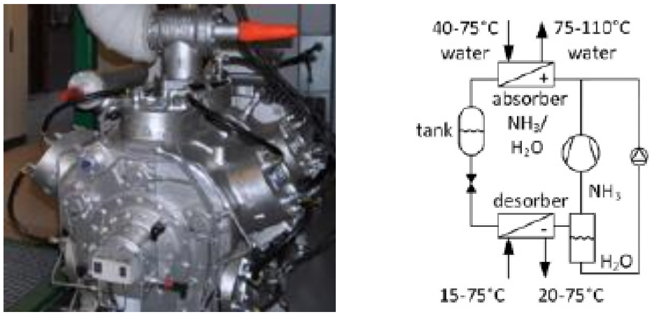


Figure 23. Hybrid energy heat pump and scheme [13]

2. *DGE-Rollout heat pump Bochum, technical specifications*

The technical specifications of the required HP depend on several factors. From sink and source is possible to analyze temperatures and powers, and then choose an adequate technology. Both the heat reservoirs have variable temperatures, and are described in *Section 2.2* and *Section 2.3* respectively.

Figure 24 gives an overview of the system. The source is dismissed mine galleries situated under the GZB buildings. They will be heated using a concentrated solar plant during the summer and will work as seasonal storage for the heat pump during the winter. The aimed sink for the HP is the DH heating grid of Bochum South. This will ideally be possible after a testing phase.

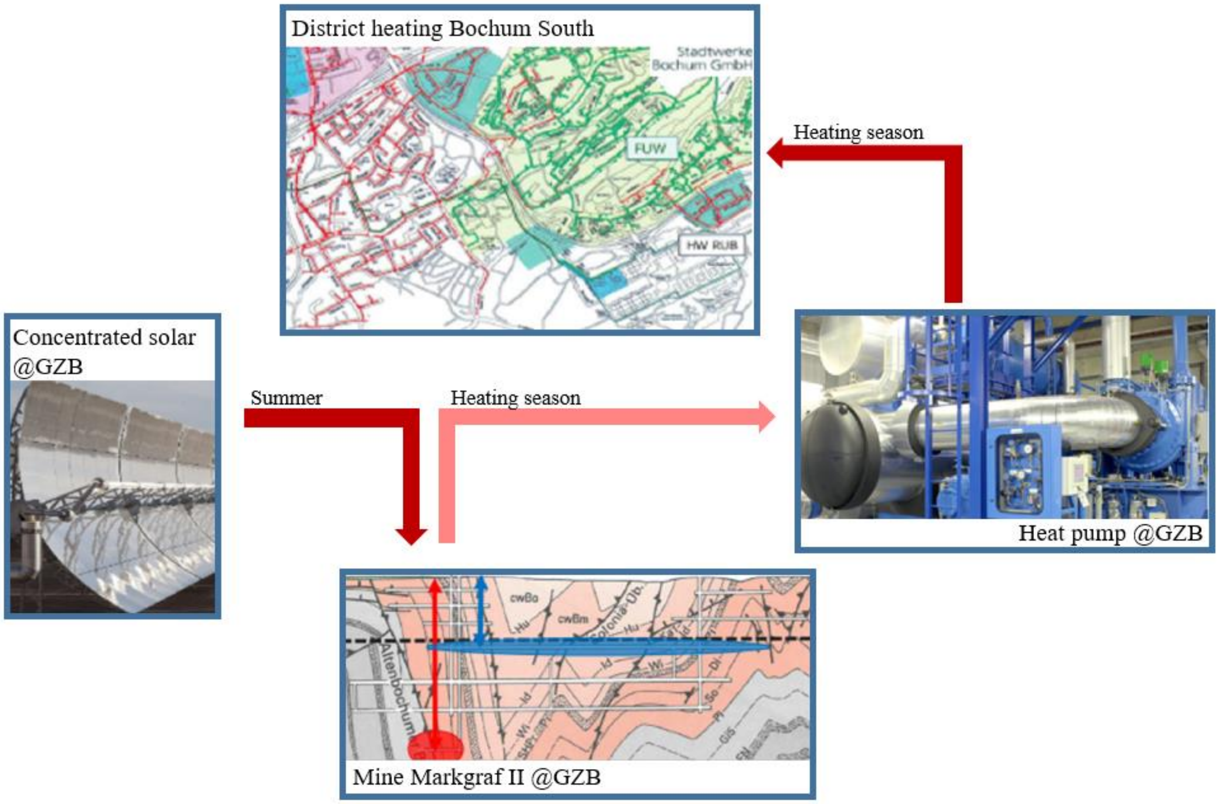


Figure 24. HP system overview [25]

2.1. Sink

After a testing phase, the heat pump will be connected to the Bochum South district heating network. The district heating grid currently has a capacity of 115 MW and it is planned a connection with further areas of the inner city network to provide annual heat of about 270 000 MWh.

Pressurized superheated water runs into the DH grid and the supply temperature varies with the outdoor air temperature. As shown in *Figure 25*, the supply temperature is 80°C for an outdoor temperature higher than 8°C, 120°C for a temperature lower than -10°C and it varies linearly between those 2 threshold outdoor temperatures.

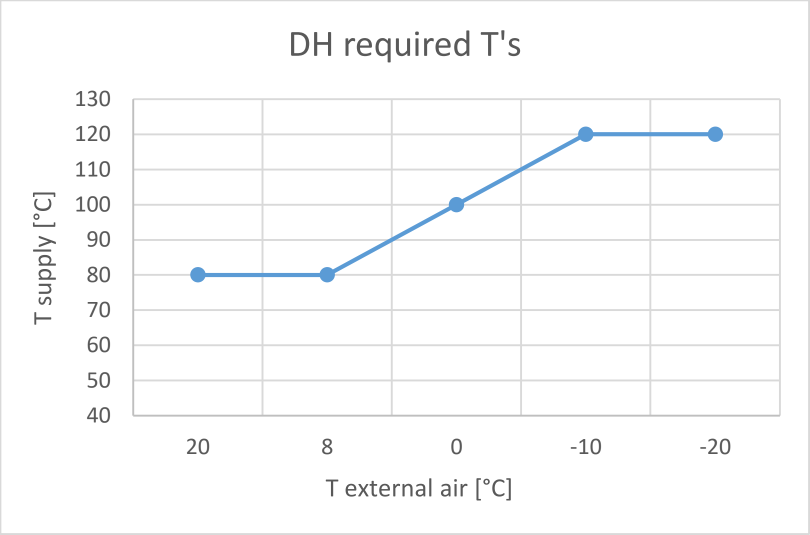


Figure 25. Supply temperatures of Bochum South DH, varying the external air temperature

The heat pump will have to work mainly in the transition phase. Considering for example the year 2018, in Bochum there have been 163 days with minimum temperature above 8°C, and 202 days with minimum temperatures between -10°C and +8°C. This means that for more than half of the days of the year the HP would work in the transition phase. For the solely heating season, 30 days with minimum temperature above 8°C and 182 in transition phase are registered.

Working mainly between 80°C and 120°C, the heat pump needs in to be able to provide 120°C.

Concerning the return temperature of the DH, this is always between 60°C and 65°C since the water is used to cool down 2 CHP (combined heat and power) power plants.

It should be noted that it will be reasonable to connect the heat pump to the district heating grid only once it will be confirmed that the power produced is reasonably large. If it will not be possible to achieve this for technical reasons, a solution would be to use the heat pump to heat up GZB or university buildings.

2.2. Source

The source of the heat pump is studied and will be developed within the project “HeatStore” and as part of the bigger project “TRUDI”.

“TRUDI” project “Tief-runter-unter-die-Ruhr”, is defined as: Ruhr Metropolitan Underground Laboratories. It is a real scale underground laboratory for the exploration of the hydrothermal potentials in the Ruhr area. It is located over a 50 km area in Bochum South and made of different underground infrastructures.

In “TRUDI”, 5 experiments are being carried out at different depths:

- 0 m - 200 m “Geostar”
- 70 m - 120 m “HeatStore”
- 500 m “GECO”
- 300 m - 1000 m “GRUBO”
- 1500 m DGE-Rollout and carbon exploration
- 4000 m - 5000 m Devonian circulation

Without further details on all the projects, as anticipated, the source of the DGE-Rollout HP is within “HeatStore” and made by the flooded mine Markgraf II that is situated under the GZB buildings at a depth of ca. 70 m (*Figure 26*). The galleries expected void volume is of 27 439 m^3 and, as a preliminary evaluation, 70% of this space is filled with water. The temperature of the water, that is currently between 10°C and 12°C will be increased of about 50 K during the summer, hence the expected maximum temperature at the beginning of the heating season is 60°C. This temperature is the goal of the pilot phase of the “HeatStore” project and could be realistically the one that will also be used for the HP. Currently, this is the available knowledge about the source, further information will be available at the end of the year after pumping tests will be performed within the mine. Water properties will also be available and with those it will be determined if it is possible to have an open loop system. In this document, the abovementioned data are taken as assumptions.

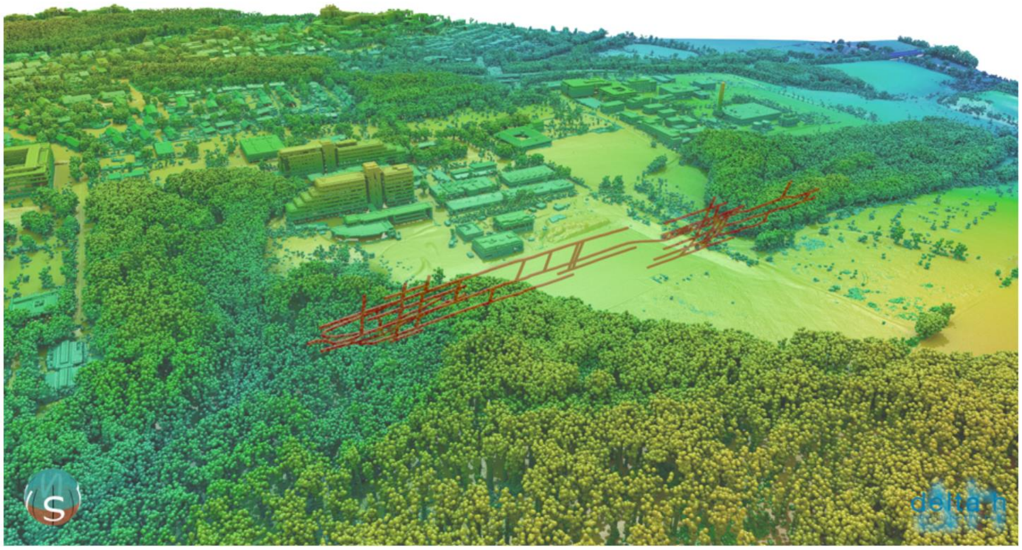


Figure 26. Mine Markgraf II under the GZB. Source: delta h

The particularity of the source lays in the fact that “HeatStore” is a pilot project. It however, also concerns the storage behavior towards the temperatures. Those in fact, vary over the heating season, in contrast to the case of the visited Canavese plant for example.

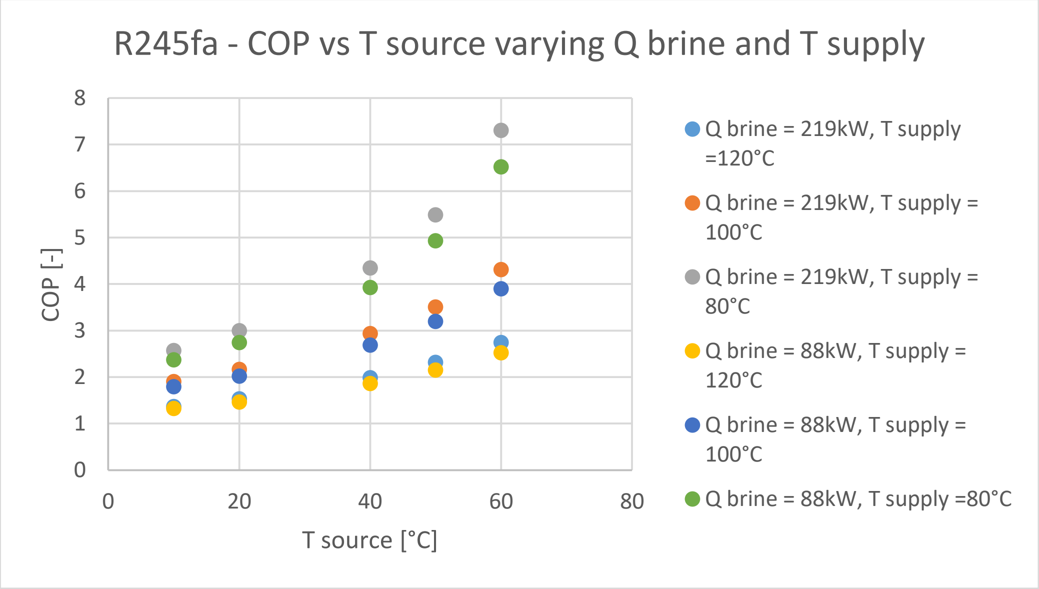
Two different strategies to exploit the source are here considered:

- At the end of the heating season the temperature of the storage is the unheated temperature.
- The temperature at the end of the heating season will be 40°C. This leads to higher performances over the season but will allow lower nominal powers, as explained in the following *Section*. This particular temperature has been chosen since it is a minimum allowed source temperature for different heat pumps on the market.

The powers corresponding to these 2 hypothesis are shown in *Section 2.3.*

Using a developed MATLAB code it has been possible to plot the variation of performance varying the temperature of the source for the different sink temperatures described and for the different powers of the source, because of hypothesis 1 and 2. Refrigerants used for this simulation are R245fa and R717 since they allow a simple subcritical thermodynamic cycle. The MATLAB model accounts only for vapor compression heat pumps since traditional absorption heat pumps are not as widely diffused for this application and it was validated on a pre-existing (at GZB) Excel file.

From *Figure 27 a. and b.* is evident that higher source temperature and lower supply temperature result in higher performances. Having used a simplified model, those COP’s result higher than in the real life case since losses such as pressure losses in the heat exchangers are not considered. The variability of the COP during the heating season appears to be quite high in the considered cases. This is the main reason behind the first strategy: to consider a lower nominal power and a lower storage temperature difference.



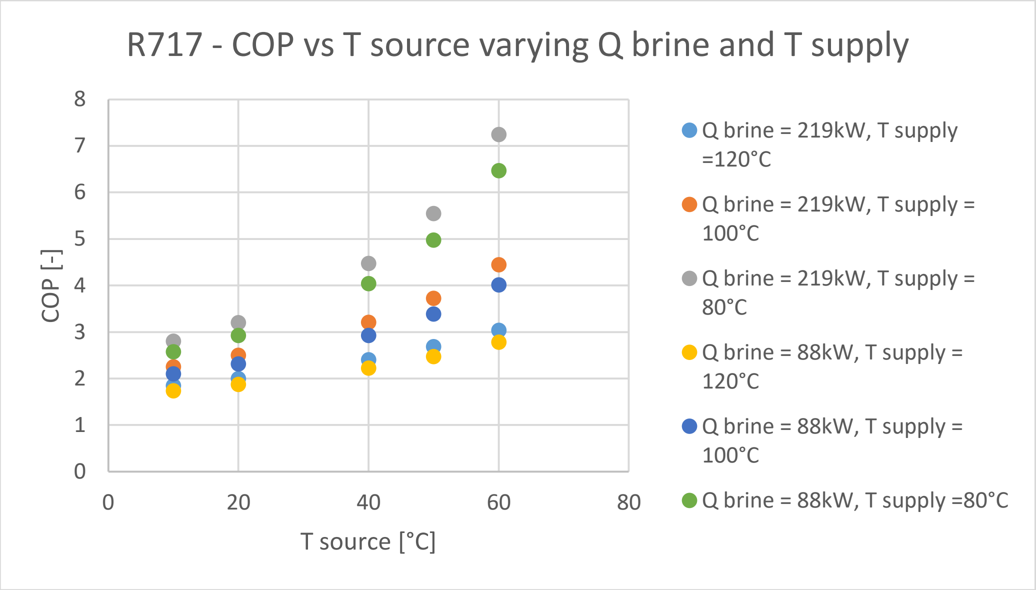


Figure 27. a. R245fa - COP vs T source varying Q brine and T supply. b. R717 - COP vs T source varying Q brine and T supply.

The simplified model used is characterized by the following assumptions:

- Isentropic efficiency of the compressor: 0,8
- Heat exchangers efficiencies: 0,98
- Subcooling T difference = 5K
- Superheating T difference = 5K
- T eva = T source – 10°C
- Tcond = T supply + 10 °C
- Properties of the refrigerants are obtained through the CoolProp library.

2.3. Powers

In this *Section*, sensitivity analysis and hypothesis have been made. With the available information in fact, is not possible yet to determine only one value for the nominal power of the HP. These estimations will therefore need to be confirmed once a more detailed source characterization will be accessible.

At the moment there are no constraints on the amount of power that can be delivered to the utility company, therefore, the power that can be produced is assessed as the maximum that can be extracted from the source.

Overall assumptions to determine hypothetical nominal powers are:

- **HP working hours**: 24 h/day during heating season, that is, in Bochum, from October 1st until April 30th, for a total amount of 212 days. It has been considered that the storage will be heated up by solar during summer and that in this period the heat pump will not be running. Further assumption is that, because of the negative aspect that the on/off processes on the lifetime of the machines, the heat pump works constantly during the winter period.
- **HP performance**: it has been assumed a coefficient of performance (COP) equal to 3 that is a reasonable conservative assumption, considering the temperature variability of the source during the season.

- **Source volume**: The total mine void volume is approximatively 27 439 m^3 based on the amount of coal extracted, as explained in *Section 2.2*. Since the water volume within the mine is expected to be around the 70% of the total volume, the volume of the cold source is: $V_c = 19\ 207$ m^3.
- **Seasonal temperature difference of the source**: this is considered as in *Section 2.2* as 50K and 20K.

The power estimation is based on basic thermodynamic equations. From the total volume of the storage, the seasonal temperature difference of the storage, the working hours of the HP and the performances of the HP, it is in fact possible to estimate the ideal HP nominal power.

The power that can be extracted from the cold heat source during the heating season is the following:

$$\dot{Q}_c = \dot{m}_c\ cp\ \Delta T_c \qquad (4)$$

Where:

- $\dot{m}_c\ \left[\frac{kg}{h}\right]$ is the seasonal mass flow rate of cold fluid that is the water extracted from the cold source. It is function of the source volume V_c, water density ρ, working hours h_w:

$$\dot{m}_c = \frac{\rho V_c}{h_w} = \frac{1000\frac{kg}{m^3}*19207m^3}{212\ day*24\frac{h}{day}} = 1004\,\frac{kg}{h} \qquad (5)$$

- $cp = 0{,}00116\,\frac{kWh}{kgK}$ is the specific heat at constant volume of the water.
- $\Delta T_c\ [K]$ is the seasonal temperature difference of the cold source. This depends on the maximum temperature at which it will be heated during the summer and the temperature at the end of the heating season, different conditions will be simulated as described.

Knowing then the power of the cold source, after estimating the performances of the heat pump, it is possible to derive the power at the hot heat source that is the power at the condenser, or nominal power of the HP: $\dot{Q}_h$.

This can be found from the HP energy balance: $\dot{Q}_c + Pel = \dot{Q}_h$ (6) where $Pel = \frac{\dot{Q}_h}{COP}$ (7), in which COP is the HP coefficient of performance.

Hence, $\dot{Q}_h = \dot{Q}_c\left(\frac{COP}{COP-1}\right)$ (8)

The results are reported in *Table 5.*

Table 5. Results from energy balance

$\Delta T_c\ [K]$	$\dot{Q}_c$ [kW]	Pel[kW]	$\dot{Q}_h$[kW]
20	87,73	43,87	131,60
50	219,33	109,66	328,99

Under these assumptions, in the most optimistic case it is possible to achieve only slightly more than 0,3 MW ($\dot{Q}_h$). This is of course strictly related to the assumptions. And in particular, to the uncertainty about the source and the consideration that it is best for such a HP technology to work without on/off's. It will not however, be of particular interest to install a too over-dimensioned heat pump, that would run few hours per season.

2.4. Needed technology

To summarize, from the analysis and the assumptions on sink, source and powers, what is needed is a technology able to produce pressurized water between 120°C and 80°C, extremes included. It also has to deal with the temperature difference of the source over the heating period from 60°C to ca. 10°C, without high decrease in performances. The nominal power is expected to be slightly less than half a MW.

3. Activities status and further steps

In this *Section*, the list of activities that have been performed so far is described. Key activity is communicating with companies for possible collaborations for the HP development. This is enunciated with higher detail in the separate *Section 3.2*. Finally, an overall outlook on further steps and activities is presented.

3.1. List of activities

In the following, are schematically reported the main undergone activities, conferences and visits.

List of main activities:

- Literature review:
    - Large scale HP's
    - High temperature HP's
    - Refrigerants
    - Components of HP's and DH system components
    - Flow rates for HP's and DH

- Dimensioning:
    - Excel file as basis (already present at GZB)
    - Use of different softwares for HP modelling: geoT*solar, TRNSYS
    - Development of MATLAB code for HP simple compression cycles and simulations with it. MATLAB at the moment resulted the most convenient software.
    - Analysis on existing MATLAB code at GZB for absorption HP's

- Contact with companies

Attendance at conferences/visits:

- 2nd Conference on High Temperature Heat Pumps (HTHP) - Copenhagen
- 15. NRW Geothermiekonferenz - Bochum
- Visit at Canavese HP plant - Milan
- 7th European Geothermal Workshop - Karlsruhe
- European Heat Pump Summit - Nürnberg

3.2. Possible collaborations with companies

One of the significant activities for the development of the project is to find an industrial partner.

As analyzed in *Section 1*, there are on the market possible solutions with different technologies that could already be a good fit for the project. There are also some companies have technologies close to the required one but not fully fitting, and that could be potentially interested in a collaboration for such goal. Finally, there are companies that do not produce HTHP's but could be interested in developing one.

At this stage the idea is to collaborate with a company and not just buy an already available product, in order to be able to develop the product and test it, having complete knowledge on the machine.

Following the idea of these 3 kind of companies, discussion is currently ongoing with possible future suppliers. This is described in S*ection 3.2.1* and S*ection 3.2.2*.

3.2.1. Companies with off-the-shelf products

In this category, companies that have been contacted are Ochsner, Hybrid Energy and Johnson Controls.

Ochsner suggested the model IWWDS that is already described in *Section 1*.

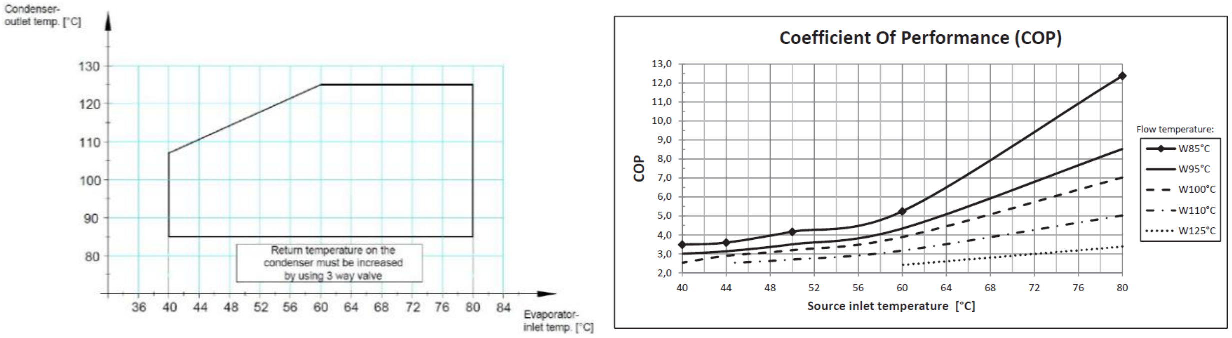


Figure 28. a. temperature range of Ochsner HP. b. Performances of Ochsner proposed HP

In *Figure 28.a.* is shown the range of working temperatures, in the *Figure 28.b.* are presented the performances with the variation of the source temperature. Those could reasonably fit our case. Attention should be put on the lowest evaporation temperature. This heat pump, as previously shown, can reach up to half a MW of nominal power.

Hybrid Energy has available the heat pump shown in *Section 1*. The company is already involved in research projects. The hybrid heat pump could be more expensive since it represents a more complex technology. This will however be verified with the development in the discussion.

Johnson Controls preliminarily proposed two different interesting solutions. As a company, there are interested in making solutions more specific to the customer needs. What could be applied for the project case is either a cascade system with NH3 and R600 or a MVR (Mechanical Vapour Recompression) cycle with water as working fluid. For both these solutions not much literature is available. The second option should be evaluated with a further study since it is usually applied to produce steam and not pressurized water.

All these companies do not seem in this stage interested in developing a completely new product. They could however be in different levels interested in collaborating.

3.2.2. Companies with similar products and interested companies without the technology

Friotherm has high power district heating heat pumps**,** hence a similar technology and large experience in district heating. In this case the discussion is at the first stages but it is not excluded a collaboration.

Turboden mainly develops ORC but showed interest in collaborating for a technology that is completely new for them.

A preliminary discussion is also carried on with **Siemens.**

3.3. Current state & next steps

We are currently checking the most promising HP suppliers and communicate with potential collaboration partners for the best solution of the HP development, which matches the long-term and large-scale heat storage and distribution requirements.

However, additional information on the conditions and settings of the heat source are necessary. These will be available shortly after drilling towards the flooded mine galleries below GZB and testing of flow rates in late 2019/early 2020. The data will be of high importance for further specification of the HP system requirements, and may allow for final adjustments in the investment.

In parallel, preparation work for the installment of the HP systems (building and infrastructure) is designed and implemented in the concept of the GZB facilities (i.e., location of HP system building, locations of wells, location of solar power plant, pipelines, circuit points, etc). Building and installation of the facilities is planned to start in early 2020.

Furthermore, we will set up and run a number of additional MATLAB, and possibly Modelica, models to describe a wider range of application scenarios. These will help to consolidate the HP system requirements on the larger scale and longer term. In this context it will also be useful to test the convenience of only one machine compared to more of smaller power in case of non-matching powers.

Conclusions

From the computational modeling it has been possible to observe the variation in performances of different size HP’s, under the particular source and sink temperature variations. Considerations from these results and from the energy balance on the system, under the presented assumptions, brought to requirements for the desired HP.

The heat pump should produce pressurized water between 120°C and 80°C, extremes included. It also has to deal with the temperature difference of the source over the heating period from 60°C to ca. 10°C, without high decrease in performances. The nominal power is expected to be slightly less than half a MW.

Costs for such technology are roughly estimated as 450 €/kW for the HP and 1500 €/kW for the overall system. It is underlined that very scarce information is available on this topic.

Companies that can be considered for this application are the ones with possible fitting solutions already on the market, those who have technologies similar to the required one, and firms that do not produce HTHP’s but that could be interested in developing one.

Ochsner, Hybrid Energy and Johnson Controls are already producing models that could possibly fit both in terms of power and temperatures. Further attention should be put on the ability of the machines to follow the other requirements.

Further market-ready products, for the vast majority, do not reach the needed temperatures, others, as shown in *Figure 14*, might not have fitting powers.

The main technical challenge to obtain the required HP lays in the high supply temperatures. This obstacle can be overcome by research on different refrigerants and by assuring that all the HP components can stand such high temperatures. For this reason, collaboration with interested companies and the development of the HP is a valid option.

If this will not be possible, it could be evaluated to directly buy one of the most fitting models (i.e. Ochsner, Hybrid Energy, Johnson Controls) or consider different power output HP’s and make some adjustments.

As further developments, additional information on the conditions and settings of the heat source will be available shortly after drilling towards the mine and testing of flow rates in late 2019/early 2020. The data will be of high importance for further specification of the HP system requirements, and may allow for final adjustments in the investment.

Preparation work for the installment of the HP systems is designed and building and installation of the facilities is planned to start in early 2020.

Furthermore, additional computing models will be set up and run to describe a wider range of application scenarios for the HP.

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List of figures

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