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Development of a pilot site for high temperature heat pumps, with high temperature mine thermal energy storage as heat source

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ABSTRACT

A pilot plant for high temperature heat pumps (HTHP's) combined with high temperature mine thermal energy storage (HT-MTES) is developed at the Fraunhofer IEG location of Bochum. The aim of the plant is to inject renewable heat into the district heating (DH) grid. The HT-MTES is a seasonal thermal storage: heat is injected during the summer and successively extracted during the cold season. A HTHP, hydraulically connected to the storage, transfers heat to the DH grid.

1. INTRODUCTION

In order to achieve European and German CO_2 reduction targets, the development of sustainable and renewable solutions for the heating sector is of fundamental importance, especially in the populated regions of North-West Europe (NWE) that largely rely on coal.

With this motivation, two European-funded projects were initiated: Geothermica HeatStore and NWE-Interreg DGE-Rollout. Within HeatStore, the development of a seasonal HT-MTES pilot plant is accomplished. During the summer, solar thermal energy increases the temperature of water present in a small shallow flooded coal mine, situated at the premises of Fraunhofer IEG in Bochum. As part of DGE-Rollout, during the cold season, the mine water is the heat source of a HTHP connected to the DH grid.

2. PILOT SYSTEM DESCRIPTION

The individual components of the pilot site, shown in Fig. 1, are described and analyzed to enable design and construction of the overall system.

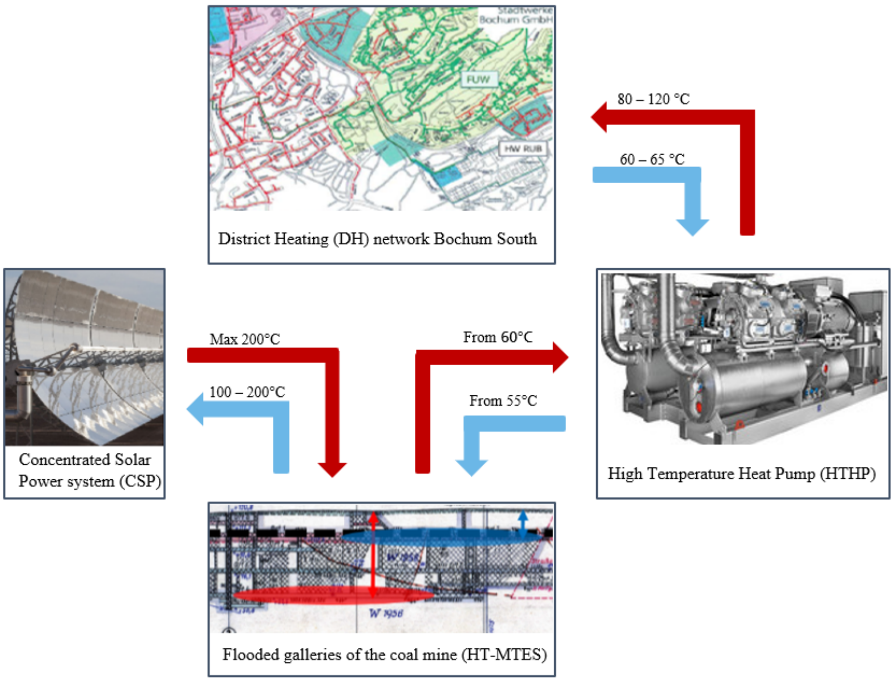

Figure 1: Schematics of the components of the test site (Fritschle et al. 2020).

2.1 Solar thermal collectors

In the summer, the groundwater of the HT-MTES, with an initial temperature of 12°C, is heated up to 60°C by means of parabolic trough concentrated solar power (CSP) technology.
During the initial test phase, concluded in 2021, 6 collectors were hydraulically connected to the HT-MTES and tested. The total number of collectors of the pilot site is 12 with a total peak capacity of 60 kW. Relevant specifications are reported in Table 1.

Table 1: CSP specifications

Collector surface area [m^2]	108
Collector mounting area [m^2]	220
Peak heat capacity [kW]	60
Technology max temperature [°C]	200
Concentration factor	43
Heating fluid	Water

The dimensioning of the CSP collectors is performed within the HeatStore project with the goal of storing a capacity of 165 MWh/y. Additional capacity from waste heat and further heat sources is planned in order to reach 1.000 MWh/y for the DGE-Rollout HTHP implementation.

2.2 Seasonal high temperature mine thermal energy storage

Several research projects concerning the exploitation of water from former collieries to obtain thermal energy are described in literature. Examples are reported in the Netherlands in the city of Heerlen and in Germany in the cities of Essen, Bochum, Berlin and in the state of Saxony (Hahn et al. 2019). The utilization of mine as seasonal storage however, is not documented prior to the currently described pilot plant.

The seasonal HT-MTES, i.e. the HTHP heat source, consists of unemployed shallow flooded coal mine galleries that are situated directly beneath the Fraunhofer IEG office and laboratory buildings in the southern area of Bochum (Fig. 2).

The shallow colliery was used for production between 1954 and 1957 and the total mass of extracted coal is documented to be 37.043 t, which is equivalent to the volume of 27.439 m^3. Relevant characteristic values of the mine are summarized in Table 2 (Hahn et al. 2019).

Table 2: Coal mine galleries specifications

Years of production	1954 - 1957
Mine depth [m b.g.l.]	75
Groundwater level [m b.g.l.]	23
Coal extracted [t]	37.043
Coal extracted [m^3]	27.439

In order to derive the thermal potential of the mine chosen as seasonal storage, the volume of water stored should be evaluated. This assessment can be performed starting from the mass of coal that was extracted.

It can be assumed that approximatively 70% of the extracted volume of coal is currently replaced by water, hence the maximum exploitable volume of water as heat source of the HTHP is 19.207 m^3. This value takes into account the water level that lays at 23 m b.g.l., the presence of shafts and drifts in the mine structure, the backfill of different areas of the mine and the subsidence.

To analyze the HT-MTES seasonal behavior and determine the best drilling locations for injection and production wells, numerical 3D simulations of groundwater flow and heat transport were performed. Thanks to the collaboration with *delta h Ingenieurgesellschaft,* the simulation was carried out with the software SPRING following a stepwise approach considering three different spatial scales with increasing level of complexity (König et al. 2019). Finite element approximation was applied to solve groundwater flow and transport equations.

In addition, for different possible relevant wells configurations, time-dependent simulations were performed with the goal of observing the behavior of the storage over several seasonal cycles of heat

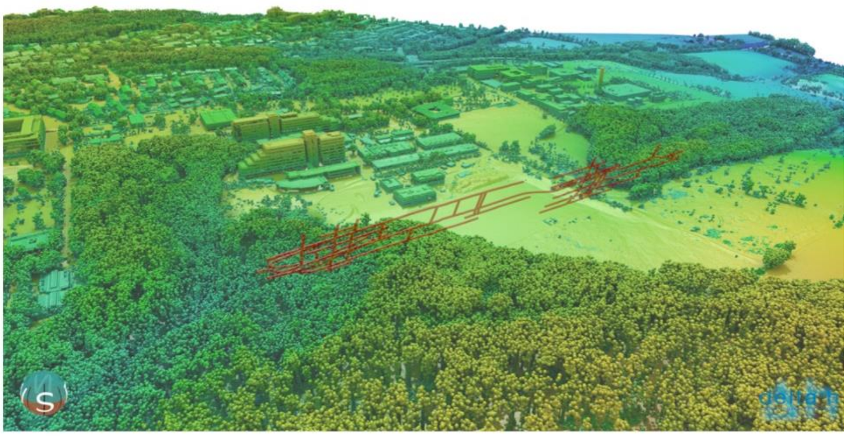

Figure 2: Mine used as HT-MTES for the HTHP.

injection and extraction. The chosen configuration is shown as cross section in Fig. 3.a and Fig. 3.b. In the figures, the yellow vertical lines represent the wells, the black lines are shafts and drifts of the mine. Hot and cold storage side of the mine are also represented. Fig. 3.a shows the HT-MTES behavior after a 2-year period of exploitation, whereas Fig. 3.b represents the behavior after 8 years.

It is possible to observe the increase in heating effect due to the contribution of the rocks that surround the reservoirs that raise the storage performances with the progression of seasonal cycles of exploitation of the HT-MTES.

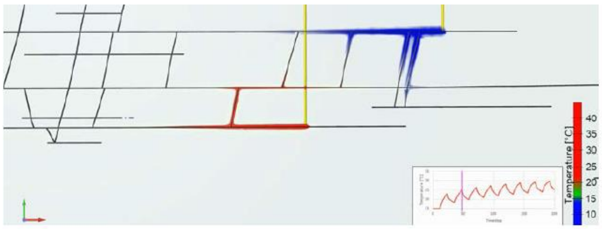

Figure 3.a: HT-MTES behavior after 2 years (König et al. 2019).

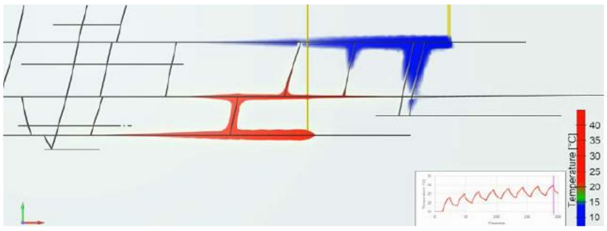

Figure 3.b: HT-MTES behavior after 8 years (König et al. 2019).

2.3 District heating of Bochum south

The Bochum south DH grid, i.e. the HTHP heat sink**,** presents an overall capacity of 115 MW. The grid operates with pressurized water and requires supply temperatures between 80°C and 120°C, function of external ambient air temperature, as shown in Fig. 4. The return water temperature is between 60°C and 65°C.

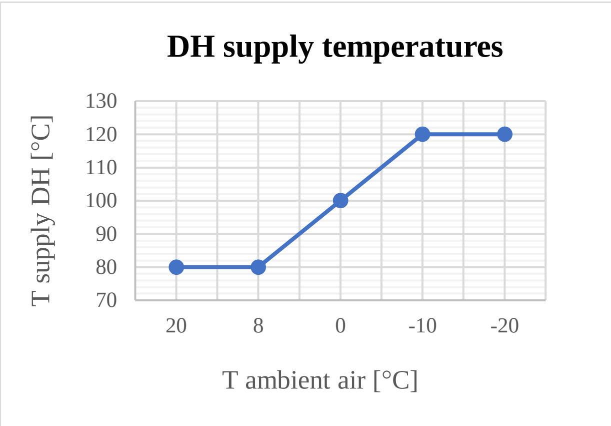

Figure 4: DH supply T vs. ambient air T.

2.4 High temperature heat pump technology

Considering the mine water features and the required HTHP performances, it is possible to define the needed heat pump technology, with a nominal thermal power production of 500 kW. Operating constraints include the supply of water up to 120°C and the ability to follow the HT-MTES seasonal temperature variation. In addition, extreme flexibility in power modulation is required for research purposes. Several technologies were reviewed to select suitable solutions.

3. RESULTS AND DISCUSSION

Results and discussion are described in terms of the different elements of the system.

3.1 Solar thermal collectors

The CSP collectors were delivered to the site and subsequently installed (Fig. 5). Heat injection tests over a week period were performed, with a temperature at the collectors set at 85°C. The temperature variation due to heat injection on the tested well aligned with the predictive models.

Figure 5: CSP collectors installed in Bochum.

3.2 Seasonal high temperature mine thermal energy storage

Considering the HT-MTES, as a result of the simulations performed, the best drilling sites for injection and production wells were determined. In addition, the drilling of a monitoring well was planned. The 3 wells are shown in Fig. 6 in an aerial view (Hahn et al. 2019). In the figure, MP1 is the chosen production well, located at 64 m b.g.l., MI1 is the injection well located at 29 m b.g.l., and MO1 is the monitoring well, also located at 64 m b.g.l..

Figure 6: Location of MP1 (red), MI1 (blue), MO1 (grey).

The drilling of the described wells was performed in 2020 with the Fraunhofer IEG self-owned drilling equipment (Fig. 7).

Figure 7: Drilling operations with BO.REX rig.

Groundwater samples from the wells and pump tests up to 7 m³/h were analyzed. The chemical water content allowed the installation of the planned heat exchanger.

3.3 High temperature heat pump technology

Particularly challenging for the HTHP technology are the required supply temperatures. On the market exist circa 20 models of HTHP that reach supply temperatures higher than 90°C, but only few are able to exceed 120°C. In Fig. 8 are shown the different commercially available HTHP with nominal thermal power ranges, maximum supply temperatures and compressor type (Arpagaus et al. 2018). Also reported in Fig. 8 is the range of interest for the application.

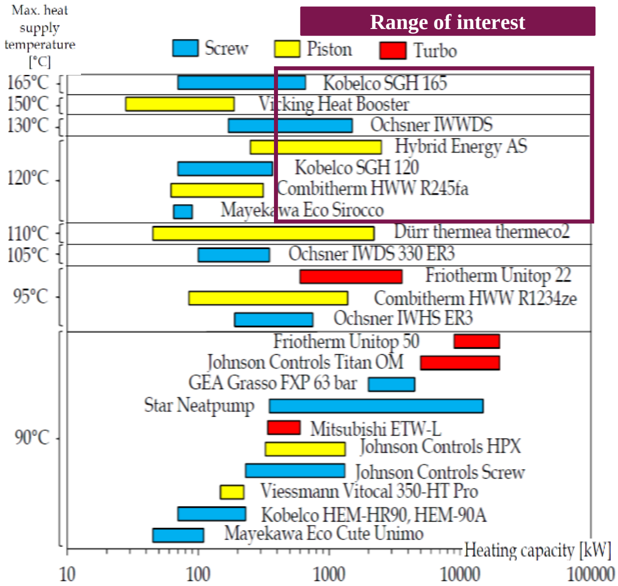

Figure 8: Commercially available HTHP's 2018 (Arpagaus et al. 2018).

Considering the current state of the market of large-scale water to water heat pumps, it is possible to observe 1-stage thermodynamic cycle solutions up to 90°C of supply temperature, with however often minimum source temperatures of circa 35°C. In this case it is also possible to have both subcritical and transcritical solutions. Above 90°C of supply temperature and with an elevated temperature difference between heat sink and heat source (above 90°C), 2-stage heat pumps are the most common. This is confirmed by the heat pumps listed in Fig. 8, with exception of solutions from Kobe Steel in which steam is produced, Hybrid Energy that considers a hybrid cycle between compression and absorption driven heat pump and Mayekawa that presents an air to air heat pump.

The choice of the refrigerants plays a fundamental role on the ability of the heat pump to reach elevated supply temperatures, therefore an analysis on different suitable and commercially available refrigerants was performed. Preferred characteristics of refrigerants include: elevated critical temperature (Tcr), low critical pressure (Pcr), null ozone depletion potential (ODP), low global warming potential (GWP), low toxicity and low flammability, i.e. preferably A1 safety group (SG).

In Table 3 are reported suitable refrigerants for different technical solutions, pertinent to the purposes of the project, combined with the mentioned relevant features. Not shown in Table 3 are the ODP values since these are equal to zero for all considered refrigerants. The green cells of the table show favorable fluids characteristics, whereas red cells are the least preferred ones. It should be noted that in the case of R744 and R1234ze(e), the low critical temperatures allow to perform transcritical cycles.

In addition to what reported in Table 3, an important role is taken by the atmospheric lifetime of the refrigerant, that should preferably be short, as well as the choice between natural or synthetic refrigerants, with a preference for natural in the case of the project.

Table 3: Possible suitable refrigerants for the project application

Refrigerant	Tcr (°C)	Pcr (kPa)	GWP	SG
R134a	101,06	4059	1300	A1
R744	31,04	7380	1	A1
R717	132,40	11280	0	B2L
R718	373,95	22060	0,2±0,2	A1
R245fa	154,05	3640	858	B1
R407c	86,05	4634	1774	A1
R1234ze(e)	109,40	36	6	A2L
R410a	70,17	4770	2088	A1
R600	152,01	3796	4	A3
R1336mzzZ	171,30	2900	2	A1

Examples of relevant refrigerants for the application are R134a and R410a, typically used for conventional heat pump applications, and possibly suitable for the low temperature stage in case of two-stage cycle. Pairs of refrigerants can be used for 2-stage solutions, these include R717 and R600 as well as R134a and R245fa. In addition, applications with water (R718) are currently gaining importance for the heat pump field application (Zühlsdorf et al. 2019).

3. CONCLUSIONS AND NEXT STEPS

With the goal of CO_2 reduction in the heating sector, the European-funded HeatStore and DGE-Rollout projects are developed. The progress of the projects implied the evaluation of **the best drilling locations** for the three needed wells at the Fraunhofer IEG location of Bochum by means of 3D modeling and specific time-dependent modeling. The **drilling was conducted** in the summer of 2020**.**

Solar thermal collectors of **CSP** technology were delivered, installed and tested.

Following the analysis of **market availability** and thanks to the theoretical knowledge **of the HTHP** heat source and sink features, **requirements for the HTHP** technology were drawn.

With the further development of the projects, it will be possible to **prove the exploitation of abandoned mines as heat storage facilities.** Coupling them with heat pumps will enable the energy conversion towards the CO_2 reduction goals.
In particular, seasonal heat injection into flooded unused collieries and their exploitation as heat source for heat pumps can contribute to the substitution of fossil fueled solutions for DH applications. Furthermore, **the heat pump technology is ready for the substitution even in areas in which the DH grid requires elevated supply temperatures.**

Next steps for the projects focus on testing the mine as a storage facility and include the HTHP installation with the hydraulic connection from HT-MTES to HTHP and DH.

NOMENCLATURE

Abbreviations

BO.REX	Bochum Research and Education Drilling Rig
CSP	Concentrated solar power
DGE	Deep geothermal energy
DH	District heating
GWP	Global warming potential
HTHP	High temperature heat pump
HT-MTES	high temperature mine thermal energy storage
MI1	Injection well
MO1	Monitoring well
MP1	Production well
NWE	North-West Europe
ODP	Ozone depletion potential
Pcr	Critical pressure
SG	Safety group
T	Temperature
Tcr	Critical temperature

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