Managing Urban Shallow geothermal Energy
Project number GeoE.171.006

Deliverable 2.2

Catalogue of factsheets of evaluated and characterised SGE concepts of use in urban areas

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General description of the task in the application form

Task 2.4: Identification and characterisation of proven and prospective technical solutions for SGE based heating and cooling supply including seasonal heat storage (ICGC)

Innovative and prospective technical solutions will be assessed and characterised by means of joint evaluation criteria. The assessment itself will be based on internal surveys within the project team, the activities in the selected pilot areas (WP4), communication with external stakeholders (WP5) and on general web and literature research. Operators of identified technical solutions will be contacted and interviewed. In the final stage of this task, a good practice workshop participated in by operators is proposed.

General description of the deliverable in the application form

D 2.2 Catalogue of factsheets of evaluated and characterised SGE concepts of use in urban areas

The identified technologies will be categorised into good existing practice, proven concepts, future concepts and bad practice. The catalogue will cover concepts of open- and closed loop systems as well as Underground Thermal Energy Storage (UTES). For overview purposes, the catalogue will give an overall comparison of specific installation costs (e.g. EUR/MW installed capacity) for shallow geothermal systems in the pilot areas.

Involved MUSE team including preparation of the partner questionnaires

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation, acronym	Full name
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
BHE	Borehole Heat Exchanger
CAPEX	Capital Expenditure (Investment costs)
CL	Closed-Loop System
CTES	(Rock) Cavern Thermal Energy Storage
DHC	District Heating and Cooling (network)
DHW	Domestic Hot Water
EU	European Union
HHE	Helical Heat Exchanger
HorHE	Horizontal Heat Exchanger
HX	Heat Exchanger
HP	Heat Pump
GSHE	Ground Source Heat Exchanger
GSHP	Ground Source Heat Pump
GWHP	Groundwater Heat Pump (water-to-water heat pump)
MTES	Mine Thermal Energy Storage (alternative nomenclature for CTES)
OL	Open-Loop System
OPEX	Operational Expenditure
NSGE	Near Surface Geothermal Energy
PTES	Pit Thermal Energy Storage
SGE	Shallow Geothermal Energy
SHER	Specific Heat Exchange Rate
SWHE	Surface Water Heat Exchanger
TAF	Thermo-Active Foundation
TRL	Technical Readiness Level
TRT	Thermal Response Test
UTES	Underground Thermal Energy Storage
WSHE	Water-Source Heat Exchanger
WWHE	Wastewater Heat Exchanger

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1 INTRODUCTION

Shallow Geothermal Energy (SGE) is a safe modern technology which contributes to mitigation of smog and low emissions [Bayer 2012, Giambastiani 2014], especially when associated with renewable electricity sources. It is a reliable source of thermal energy used for space heating and cooling through application of diverse novel technologies of ground-coupled heat pumps (HPs), including both closed- (CL) [Lucia et al. 2017; Self, Reddy, Rosen 2013; Sarbu, Sebarchievici 2014; Yang, Cui, Fang 2010] and open-loop systems (OL) [Abesser 2007; Banks 2012], respectively. In case of OL systems the main heat carrier in the lower heat source is the surface or groundwater which is extracted via the intake heads or groundwater wells. In case of CL systems, the heat exchangers (HEs) are placed deep into large surface water bodies or the underground in form of submerged/buried pipes, through which a heat carried fluid (water or brine) flows. There are several types of HEs, among which the most common are: horizontal loops, borehole HEs (BHEs), compact forms of ground HEs (e.g. spiral), thermo-active building foundation structures (TAF), etc. All these types are listed in **Error! No s'ha trobat l'origen de la referència.**.

Tab. 1. Different categories of SGE systems and their associated acronyms.

SGE installation	Loop type	Category of heat exchanger employed	Acronym
Ground and water source heat Exchanger (GSHE/WSHE) systems	Closed	Vertical Borehole Heat Exchanger	BHE
		Helical Heat Exchanger	HHE
		Horizontal Heat Exchanger (coiled/linear, flat/trenched)	HorHE
		Thermo-Active Foundation	TAF
		Closed-loop Surface Water Heat Exchanger	SWHE-CL
	Open	Groundwater Heat Exchanger	GWHE
		Open-loop surface Water Heat Exchanger	SWHE-OL
		Waste Water Heat Exchanger	WWHE
UTES	Closed	Vertical Borehole Thermal Energy Storage	BTES
	Open	Aquifer Thermal Energy Storage	ATES
		(Rock) Cavern Thermal Energy Storage	CTES

2 GENERAL DESCRIPTION OF THE DELIVERABLE

The deliverable D.2.2: Catalogue of factsheets of evaluated and characterised SGE concepts of use in urban areas, has been accomplished as one of the results of the Work Package 2 (WP2) entitled Technical aspects of SGE use in urban areas, under the terms of the task T.2.4: *Identification and characterisation of proven and prospective technical solutions for SGE based heating and cooling supply including seasonal heat storage*;

This deliverable has been elaborated mainly by the MUSE partner Institut Cartogràfic i Geològic de Catalunya (ICGC), with specific contributions from the following consortium partners:

- P1 GBA
- P2 NERC-BGS
- P4 HGI-CGS
- P5 CGS
- P6 BRGM (France)
- P7 GSI
- P8 RBINS-GSB (Belgium)
- P9 GeoZS
- P10 IGME (Spain)
- P12 TNO (The Netherlands)
- P14 SGIDS

The information is presented as a collection of 1+8 individual Factsheets (Appendix III):

- Factsheet 0: A general overview of what SGE is and how can be exploited.
- Factsheet 1: Focused on vertical BHEs
- Factsheet 2: Focused on TAFs
- Factsheet 3: Focused on GWHEs
- Factsheet 4: Focused on SWHEs
- Factsheet 5: Focused on BTES
- Factsheet 6: Focused on ATES
- Factsheet 7: Focused on CTES
- Factsheet 8: Focused on SGE within district heating and cooling (DHC) networks

Each of the Factsheets (except Factsheet 0) is structured as a 2-page (2-column) document with a short introductory text describing the main characteristics of the SGE category, followed by 4 sections:

- **1. Proven concepts** → The most outstanding characteristics are emphasized and compared between different SGE categories. Relevant cases are highlighted, and historical context is provided.

- **2. Future concepts** → Selected innovative trends or technologies are presented along with new projects representing a breakthrough in the field. Current technical challenges and prospective solutions are also provided.
- **3. Good existing practices** → Consolidated practices concerning execution and operation of the installations are exposed, as well as the key points in the design and planning phases of a SGE project.
- **4. Lessons learned** → This section gathers important challenges that have been already overcome and important issues that are commonly underestimated. Moreover, good advices are also given in order to aid successful management of SGE.

After these 4 sections, a set of case studies (mainly from the pilot areas) are presented in each Factsheet from 1 to 8.

Additional information to the catalogue is provided in this report, comprising transversal aspects of SGE (technical and defining), and basic information about the capital costs involved in SGE (€/$W_{\text{installed capacity}}$) as part of section 5. Bibliographic references are provided in section 7.

The structure of the deliverable D.2.2 *Catalogue of factsheets of evaluated and characterised SGE concepts of use in urban areas* consists of the following parts:

- **Summary report**: Report covering:
    - Materials and methods employed to carry out task 2.4
    - General and transversal aspects (technical and defining) of SGE as well as its costs.
    - Summary and conclusions
    - References
    - **Appendix I** List of installations considered for CAPEX of SGE installations in Europe
    - **Appendix II** Summary of the replies to the questionnaires
    - **Appendix III** Catalogue of Factsheets (including references)
    - **Appendix IV** Glossary of terms
- **Catalogue of Factsheets** (from 0 to 8)
- **Questionnaire templates** (from 0 to 7)

3 AIM AND SCOPE OF THE REPORT

This summary report aims at offering an overview of the different exploitation schemes of the subsurface, both as an energy resource itself and as an energy storage medium, from a technical perspective. It pursues the dissemination and a better understanding of the potential of SGE as major contributor to (renewable) energy supply and energy efficiency in urban areas.

This overview is basically limited to the European territory level. The main contribution of case studies is from the pilot areas defined in MUSE project (obtained through specific questionnaires distributed among the partners), although examples from other regions have also been used. In the context of recent European initiatives and policies promoting cleaner and sustainable cities (like the **Energy union strategy**[1], the **Urban Agenda for the EU**[2], the **Energy Performance of Buildings directive**[3], the **EU Covenant of Mayors for Climate & Energy**[4] or the **Strategic Energy Technology Plan**[5]), the information presented in this report is oriented to a wide range of stakeholders. On the one hand, it is oriented to the geotechnical industry that is not yet familiarized with SGE or even those companies traditionally involved in mining, surface and groundwater management. On the other hand, it is oriented to those private and public bodies involved in the assessment, provision and management of new energy resources (mainly geoscientists, civil engineers, builders, architects, contractors, installers, planners, and/or decision makers) from small to large scale.

Finally, this report does not aim to provide an in-depth overview on aspects such as drilling or HP technology. It focuses mainly on the heat exchanging media (soil, surface and groundwater) and their associated technologies and concepts.

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[1] COM/2015/080; https://ec.europa.eu/energy/topics/energy-strategy/energy-union_en?redir=1

[2] https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/urban-agenda-eu_en

[3] European Directive 2010/31/EU on the Energy performance of Buildings and Amendment 2018/844/EU.

http://data.europa.eu/eli/dir/2010/31/2018-12-24 ; http://data.europa.eu/eli/dir/2018/844/oj

[4] https://www.covenantofmayors.eu/en/

[5] https://ec.europa.eu/energy/topics/technology-and-innovation/strategic-energy-technology-plan_en

4 MATERIALS AND METHODS

Research activities pursued within the Deliverable D.2.2 focused on studies of the state of the art concerning SGE resource management and exploitation, mostly at European level. This included:

- The outcomes of the relevant EU research and structural projects related to SGE
- Technical aspects of national guides and norms from different European member states
- Trends and technical solutions adopted by the Geotechnical industry concerning SGE
- Trends and technical solutions reported in scientific and technical magazines
- The partner's replies to the questionnaires

4.1 Bibliographic research

The bibliographic search has been carried out entirely through the web. The information concerning SGE present in the web is vast and covers multiple fields such as Earth sciences, Engineering (Civil, Industrial and Energy Engineering) and Technology (HEs, HPs, drilling, fluidics). The present work did not aim to generate a new and redundant state of the art on SGE in the widest sense, but to obtain enough documented case studies in order to **draw a picture of the best ways to deploy SGE successfully**. Indeed, the bibliographic research represents a complementary strategy to the questionnaires.

Concerning the capital expenditure (CAPEX) of SGE installations, the data was gathered from individual detailed cases available online or papers/reports where CAPEX of the SGE installations were reported. Nevertheless, the information provided in most of the cases was very disperse, poorly detailed or including different or unclear items within the investment costs. For this reason, the data shown in this section is in the form of dispersion plots. Basically, the data found correspond to the **cost of HXs** systems (essentially the design and geotechnical previous work, boreholes/well drilling works, intake/outtake installations, piping, etc.) **and the HP equipment** (this might include or not storage tanks, domestic hot water tanks or monitoring systems). However, the CAPEX value often includes the distribution system (radiators, radiant floor), back-up or support units or alternative energy sources in case the installation is hybridised with photovoltaic panels (for instance). These cases have not been included in the comparison. Moreover, the costs data are obtained in terms of the year of installation, so all of them were inflation-corrected (the source for the yearly inflation in the European Union was the World Bank Organization[6]). The installations considered for this analysis are listed in Appendix I.

[6] https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=EU&view=chart

4.2 Partner questionnaire and feedback analysis

A first questionnaire (Q0) was sent to the partners where the identification of a certain number of SGE installations (in operation, under construction or as already-approved projects) was requested in their respective pilot areas. The amount of installations was related to the partners' assigned workload in WP2. The questionnaire was sent also to external companies/experts outside of MUSE.

After the reception of the proposed installations, a selection was made based on the following:

- Singularity of the installations (size, technological challenge, environmental relevance, etc.)
- Type of installations (as many types as possible was desirable)

The next step was to send specific questionnaires (7 different templates, each corresponding to 7 categories of SGE installations) to the contributing partners according to the installations proposed by them.

Tab. 2. General structure of the project partner questionnaires from 1 to 7.

Requested technical details about the following issues:	Q1 (BHE)	Q2 (SWHE-CL)	Q3 (GWHE)	Q4 (SWHE-OL)	Q5 (BTES)	Q6 (ATES)	Q7 (CTES)
Ground	X				X		
Aquifer/groundwater			X			X	X
Surface water		X		X			
Production/injection wells			X			X	X
Water intake/outtake		X		X			
Loop details (direct/indirect)			X	X		X	X
Borehole	X				X		
Thermal energy storage					X	X	X
Piping	X	X			X		
Filling material	X				X		
Brine	X	X			X	X	
Monitoring system	X	X	X	X	X	X	X
Performance	X	X	X	X	X	X	X
CAPEX and OPEX data	X	X	X	X	X	X	X
Relevant features	X	X	X	X	X	X	X

Tab. 3. Feedback received in response to the questionnaires Q1- Q7.

Contributions				Questionnaire # identifications						
ID	Acronym	Country/Region	Country code *	1	2	3	4	5	6	7
P01	GBA	Austria	AT	2		2				
P02	NERC-BGS	United Kingdom	UK	2		1				
P03	ICGC	Spain/ Catalonia	ES	2		1				
P04	HGI-CGS	Croatia	HR			2				
P05	CGS	Czech Republic	CZ	1						
P06	BRGM	France	FR							1
P07	GSI	Ireland	IE			1				
P08	RBINS-GSB	Belgium	BE					1	1	
P09	GeoZS	Slovenia	SI			1				
P10	IGME	Spain	ES			3				
P11	SGU	Sweden	SE							
P12	TNO	The Netherlands	NL	1						
P13	PIG-PIB	Poland	PL	1				1		
P14	SGIDS	Slovakia	SK							
P15	GEOINFORM	Ukraine	UA							
P16	GEUS	Denmark	DK							
-	Groenholland BV	The Netherlands	NL	1						
			Total	10	0	11	0	2	1	1

*ISO 3166 Alpha2code

4.3 Elaboration of Factsheets

The information provided in the questionnaires was filtered and selected to be included as part of the Factsheets along with information from other sources. Notice that there is not a one-to-one correspondence between the questionnaires and the final Factsheets. The reasons for this are the qualitative and quantitative differences between the information obtained by the questionnaires and the information obtained through alternative channels. For instance, no examples of TAFs were identified by the partners in any of the pilot areas, although this is a very well-established type of SGE exploitation scheme. Besides, it was found appropriate to unify both OL- and CL-SWHE systems, since CL-SWHE systems are just testimonial in Europe.

5 TRANSVERSAL ASPECTS OF SGE

5.1 Definition of SGE

Currently there is not an official or internationally accepted and binding definition for Shallow geothermal energy (SGE) [Dilger G., 2017], although it can be said that there is a "common understanding" of what is and what is not. In WP3 of MUSE a partner questionnaire revealed that most participating countries do not have a legally binding definition of SGE [Klonowski, M.R. et al, 2020]. Defining SGE will provide legal certainty [Rupprecht et al, 2018] and will contribute to simplification of the procedures and regulations linked to SGE management which in effect will foster development of the market and technologies. Therefore, the MUSE team proposes the following definition of SGE according to the report D 3.1 [Klonowski, M.R. et al, 2020]:

- *"Generally, SGE is understood as a thermal energy recovered from the subsurface with the use of heat pumps, in both open and closed systems, for heating, cooling (free cooling as well as ground source-based chillers) and thermal energy storage".*
- *"It is also called near-surface geothermal energy or low-temperature (low-enthalpy) geothermal energy into the European energy mix".*

Due to the low temperature level of its source, geothermal energy can furthermore be specified in terms of "ambient geothermal" inside the ambient heat sources, such as air or surface waters (see Figure 4).

The basis of SGE exploitation is the **high thermal inertia of the subsurface** (this includes the ground, large surface water bodies and groundwater). In the case of the ground, this translates into an almost constant temperature throughout the year (ranging between 10 and 20 ºC, depending on the region of the planet) of the heat exchanging medium. In the case of surface water bodies (rivers, lakes, the sea), although the temperature is not constant along the year, it shows a remarkably lower variation with respect to the ambient air, especially at depths below 30 - 40 m (see *Figure* 2). This allows its use for both heating and cooling by means of HPs, although direct use is also possible (i.e.: free-cooling in the case of close-to-0 ºC water bodies, or free-heating in the case of high-temperature (HT) UTES).

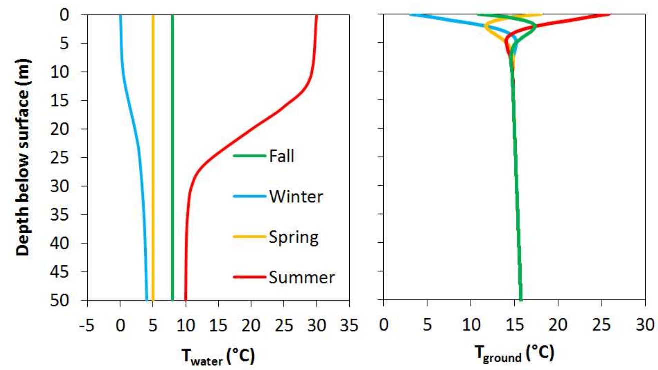

Figure 2. Generic lake and ground temperature depth profile corresponding to a location above 45° northern latitude (left and right plots, respectively). In the ground, temperature is almost constant throughout the year from ~15 m downwards, from where the geothermal gradient (20 - 30 °C/km) prevails. Lakes show a wider range of temperature profiles depending on several parameters like lake size and depth, water balance, turbidity or climatic conditions.

When talking about SGE, the most common mental association is with very-low enthalpy geothermal energy, which involves a thermal energy exchange with the ground by means of HP technology. In fact, this is the most common exploitation scheme, and is usually sub-divided into **open-loop and closed-loop HE** systems (OL-HE and CL-HE, respectively). Alternative binomial classifications exist, like ground/water source HEs (**GSHEs & WSHEs**) **and UTES** systems, or **vertical and horizontal** systems. Moreover, new and interesting typologies add to the existing ones. **Thermo-active foundations (TAFs)** are a well-established type of HE that combines building and energy efficiencies. The direct or HP-aided **use of residual heat** from the urban industries, the subway or the urban **wastewater (WWHEs)** are becoming popular and fall into the category of SGE (as defined above). All SGE categories considered in this document (see Table 1) are presented in a comprehensive scheme in Figure 3.

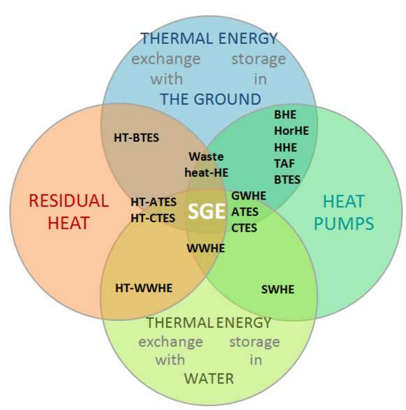

Figure 3. SGE can be an ambiguous concept embracing multiple resource typologies and exploitation schemes.

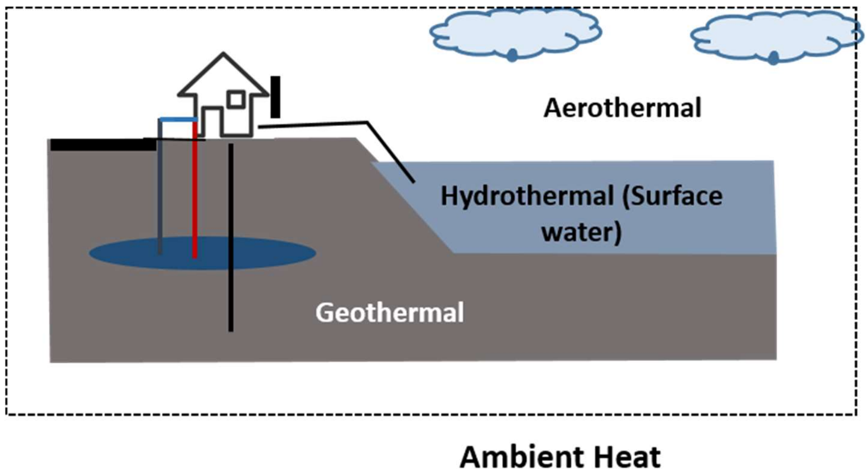

Figure 4: The concept of "ambient geothermal" inside heat pump supported ambient heat sources.

The ultimate origin of SGE (in the sense of an energy resource) is the irradiation of the Sun, not the internal heat of the Earth. In fact, the Sun irradiance absorbed by the Earth's crust and the oceans exceeds three orders of magnitude the Earth's internal heat budget (~**165 W/m^2** of average solar irradiance absorbed at the Earth surface [Stephens G. et al., 2002] compared to ~**0.065 W/m^2** of average estimated heat coming from inside the Earth's crust and below [Turcotte D.L., Schubert G., 2002]). In order to contextualize these numbers, it is good to recall the average **human primary energy consumption in 2019[7], which was 580.5 EJ (0.034 W/m^2 on average)**.

5.2 Why SGE?

The most outstanding conclusion after comparing SGE and deep geothermal energy (DGE) is that SGE represents a far larger market. Currently in Europe, SGE installed capacity (26.9 GW_{th} corresponding to GSHP&WSHP including UTES) exceeds 2.5 times the installed capacity of Geothermal energy (10.6 GW_{th} corresponding to direct heating use) and almost 9 times the Geothermal power generation (3.0 GW_e). Furthermore, SGE is everywhere below our feet and can be easily accessed, even for single family homes, while the access to DEG resources is very location sensitive. If compared to solar energy, SGE offers continuity of supply, 24h per day, 365 days per year, with far less land-use requirements. But make no

[7] British Petroleum (BP), "Statistical Review of World Energy" (2019)

https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html mistake, SGE should not be a competitor of solar energy (in particular, solar thermal energy). On the contrary, SGE is an excellent partner of solar energy, both thermal and photovoltaic, especially in urban environments. Conditioning the space of a building for heating and cooling and the production of domestic hot water contributes to approximately 45-50% of the total energy consumed in buildings in the EU. To achieve a reduction of fossil fuels to zero by 2050 through the provision of 100% renewable heating and cooling in cities, districts, buildings and industrial processes, according to the RHC-ETIP (2019), a smart and efficient combination of the various alternatives will be necessary. existing thermals. In this context, geothermal heat pump technologies will have a high potential to play an important role in the decarbonization of this sector. Finally, it is important to mention that SGE offers cooling and seasonal underground storage of waste heat (e.g. from room chillers) to be used in the subsequent heating season.

Tab. 4. Comparison between deep and shallow geothermal energy (strictly as an energy resource) concerning qualitative potential of deployment.

	Shallow Geothermal Energy	Deep Geothermal	Solar
Risk of investment	Low	High	Low
Level of investment	Low-Moderate	High	Low-Moderate
Weather and seasonal dependence	Almost none	None	High
Availability	Ubiquitous	Location dependent	Ubiquitous
Continuity of supply	Yes	Yes	No
Renewable	Yes	Yes	Yes
Possibility of power generation	No	Under certain conditions	Yes
Possibility of direct use of heat	No	Yes	Yes
Possibility of efficient cooling	Yes	No	No
Use of the technology for energy storage	Yes	Yes	No

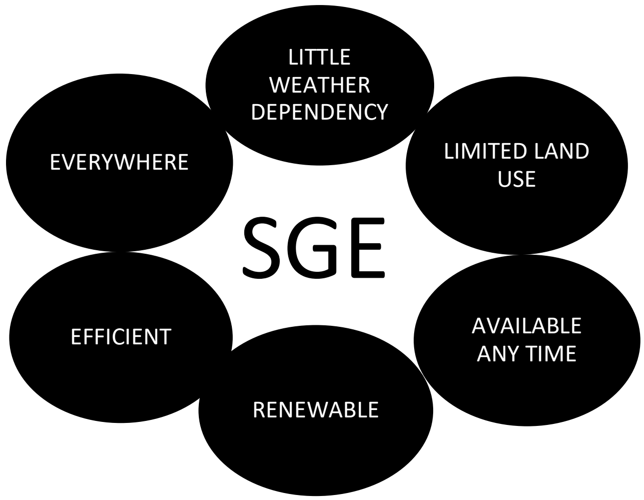

Figure 5. SGE complies with all the requisites of a distributed and renewable energy resource.

Because of all the above-mentioned reasons (Figure 5), SGE technology deployment has been explicitly included (mentioned as ground-source HPs) in the amendment 2018/844 to the European directive 2010/31/EU on Energy performance of Buildings. Therefore, it should be considered as one of the most important contributions to the nearly zero emissions buildings (nZEBs)[8] and to comply with the targets set in the new European directive 2018/2001 (promotion of energy from renewable sources)[9]. Within **UTES** category, it is also possible to find new configurations where the use of HPs in residential applications can be avoided (this is known as "**direct use**" or "**free heating**"). In these cases, the heat exchanging fluid is raised at temperatures above 60ºC (for example in the case of residual heat from the industrial processes or from power generation) [Drijver B., van Aarssen, M., de Zwart B., 2012].

SGE technology has demonstrated over the years to be a solid alternative for both heating and cooling from renewable energy sources in urban areas. Although it can be exploited almost everywhere, it is probably the **best solution in cold climates**, where the efficiency of aerothermal HPs is limited by low air temperatures in winter, and where direct solar irradiation show a very discontinuous profile along the year. This is one of the main technical

[8] European Directive 2010/31/EU on the Energy performance of Buildings and Amendment 2018/844/EU. http://data.europa.eu/eli/dir/2010/31/2018-12-24 ; http://data.europa.eu/eli/dir/2018/844/oj

[9] European Directive 2018/2001 on the promotion of use of energy from renewable sources (recast of 2009/28/EU). https://eur-lex.europa.eu/eli/dir/2018/2001/oj

reasons why the deployment of SGE shows a huge difference from North to South Europe (Figure 6).

Within the EU-28 region, several countries stand out for their contribution to SGE development. Sweden is by far the country with the highest use of SGE with more than 6.5 GW_{th} installed (0.64 kW_{th} per capita) [Sanner B., 2019].

France and The Netherlands pioneered the development of UTES [Kallesøe A.J., Vangkilde-Pedersen T., 2019], and Austria that of thermo-active foundations [Brandl H., 2013].

According to the latest market report of the European Geothermal Energy Council, the number of installed units in Europe surpassed 2 million in 2019 leading to accumulated heat production of around 56 TWh (Garabetian at all, 2020). Still, the market conditions significantly differ between the European countries. We can differ between (1) mature-, (2) emerging and (3) juvenile markets.

Mature markets affected by a high level of diffusion (number of installed units per households) and moderate sales growth rates (less than 5% p.a.). Leading countries in geothermal energy use are Sweden (12% of all households use shallow geothermal energy), followed by Finland, Austria, Switzerland or Denmark at diffusion rates around 5%.

Emerging markets show low levels of diffusion (below 1%) but strong sales growth (more than 5% p.a.). These markets can be observed in many European countries, such as Poland, Netherlands, Slovenia or Spain.

Juvenile markets do not yet offer favorable conditions for the deployment of shallow geothermal energy. These countries, such as Slovakia are marked by low level of diffusion and low growth numbers in annual sales.

Most shallow geothermal energy markets in Europe show similar diffusion behavior at different points in time on a development path. For instance, Poland shows market characteristics, which could have been observed in Denmark 10 to 15 years before. However, the diffusion of shallow geothermal energy is affected by dynamic external boundary conditions, which control the market conditions. These external factors are represented by fluctuating subsidies (stop and go policies), energy prices on fossil fuels and/or electricity as well as the general level of awareness towards the use of shallow geothermal in a society. In countries such as France, which has been among the pioneers of shallow geothermal energy use in Europe, low electricity prices led to a strong dominance of air-based heat pumps, which in turns hampers the market diffusion of shallow geothermal.

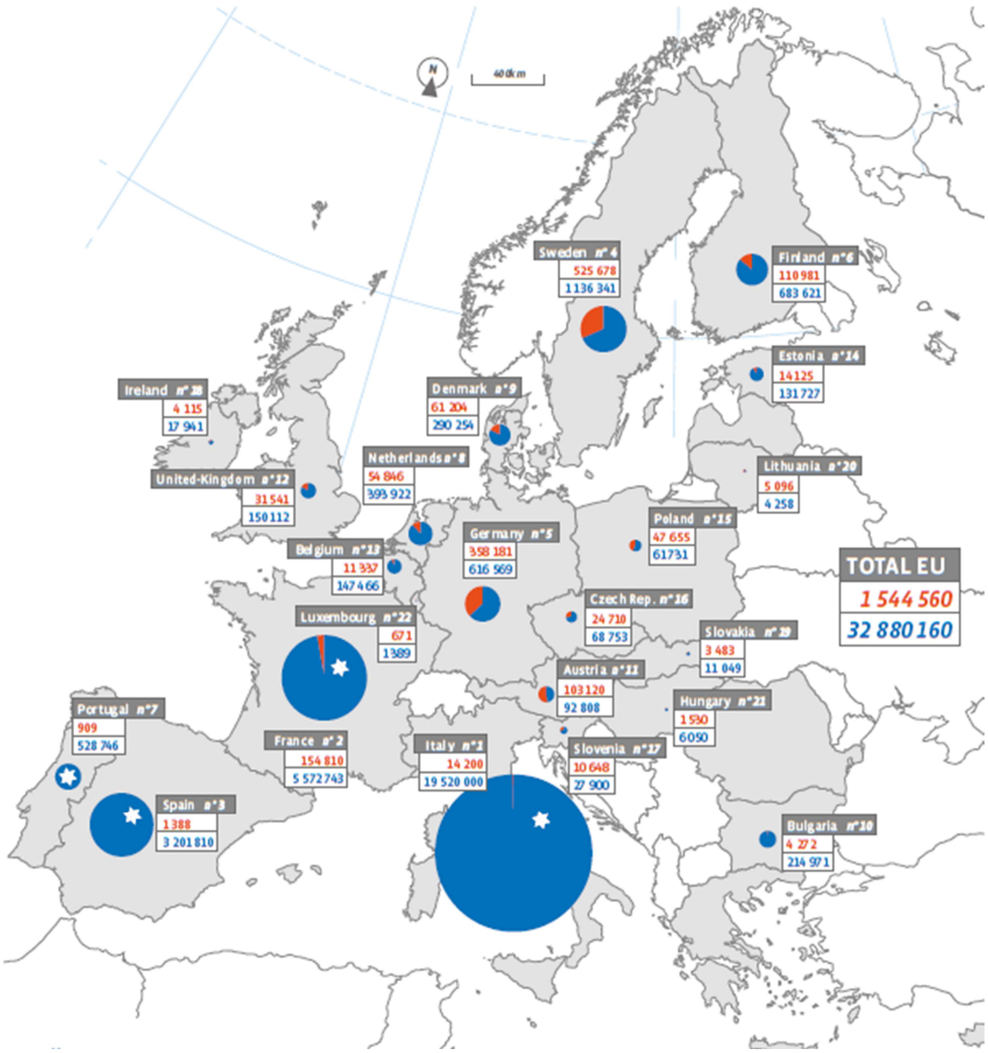

Figure 6. Aerothermal (in blue) and geothermal (in red) HPs operating in 2017 (reprinted from EurObserv'ER 2018[10]). Aerothermal HP data from France, Portugal, Spain and Italy concerning include the only-cooling devices.

5.3 Good practices common to all SGE types

At some point, the active implication/intervention of the public sector becomes essential in order to boost the market or guarantee a sustainable use of the resource. In this sense, it is

[10] EurObserv'ER: Heat pumps barometer 2018. https://www.eurobserv-er.org/heat-pumps-barometer-2018/

mandatory to aid a **meaningful estimation of the SGE resource potential** at local or regional level (Hydrogeological characterization of the underground) [Ostermann V., 2010], [Arola T. et al., 2019].

Currently, several **Pan-European initiatives** have been undertaken aiming to provide information and decision-making tools for the deployment of renewable energy technologies for heating and cooling:

- In project CHEAP-GSHP, a “Decision Support System (DSS) Application” was developed to assist on preliminary economical assessments of GSHP systems[11]. Just a few but easy-to-know data are required to feed the model, accounting for the location, the building typology and its use.
- The HotMaps project defines itself as “The open source mapping and planning tool for heating and cooling”. Its main goal is to provide GIS-based online software that offers multiple information layers covering the entire EU-28[12]. The layers are grouped in 6 blocks: **Buildings** (type of building and energy demand); **Industry** (emissions, excess heat); **Population**; **R.E.S. potential** (Shallow geothermal, solar, wind, waste, etc.); **Climate** (severity, solar radiation) and **Electricity** (associated CO_2 emissions).

Numerical simulations can provide reliable estimations of the ground temperature evolution with time. This information is important to evaluate the influence of unbalanced loads in an early design stage of the project. Commercial software with demonstrated solvency can be found in the market (GLD[13], EED[14] or GLHEPro[15]). For optimization purposes (building dynamics included, or hybrid systems considered), TRNSYS is the most popular option[16].

Regardless of the climatization technology to be implemented in new buildings, the first and most important step in the design process is the **minimization of its energy demand[17]**. This can be done through a bioclimatic conception of its architecture. In the specific case of SGE-

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[11] dss.cheap-gshp.eu/App

[12] hotmaps.hevs.ch/map

[13] Thermal dynamics Inc.: Ground loop design (GLD). https://www.groundloopdesign.com/

[14] Blocon AB: Earth Energy Designer (EED). https://buildingphysics.com/eed-2/

[15] Building & Environmental Thermal Systems Group (Oklahoma State University): Ground loop heat exchanger design software (GLHEPro). https://hvac.okstate.edu/glhepro/overview

[16] Thermal Energy System Specialists LCC.: Transient System Simulation Tool (TRNSYS).

http://www.trnsys.com/

[17] The Passive House Institute. https://passivehouse.com/

based systems, this aspect will result in a lower installed capacity, a lower need for thermal exchange with the subsoil, and therefore a lower environmental impact.

The **contrast between average and peak demands**, and the balance between cooling and heating demands are crucial parameters when sizing SGE installations. Installations with a high peak demand but a low average demand (**low utilization factor**) are perfect examples of oversized installations. Hybridization with other heating sources is an efficient and cost-effective solution where SGE is used as the base heating and cooling production system and the complementary equipment is used to meet the peak demands or the unbalanced heating/cooling loads[18].

As for the **balance between heating and cooling loads**, note that a good insulation envelope will reduce the heating load considerably, but it also will increase the cooling load, since the low heat losses will play against a high degree of occupancy during the warm season. This is especially noticeable in office buildings, and for this reason office building show a remarkable cooling demand in cold climates compared to residential buildings.

As an important reminder, the smart project designer should keep in mind that **well balanced heating and cooling loads** in a building should not mean that they are equal. Instead, it is the yearly balance of the ground-exchanged energy which should be null [Kavanaugh S., Rafferty K., 2014]. As a rule of thumb, heating load should be approximately 50% higher than the cooling load to achieve a neutral heat exchange with the ground.

5.4 Investment costs associated to SGE

CAPEX data can vary largely from one installation to another and from country to country. Additionally, it is expected to observe a descending trend in the €/W indicator as the installed capacity becomes higher. In order to compare significantly these costs, it would be necessary to obtain either a sufficiently large dataset (>50) of case studies per SGE category, or a short dataset of case studies evaluated under the same metrics. The questionnaires pursued the second option, but this specific information has proved to be the most difficult to obtain (Only 3 out of 24 cases of study in the pilot areas were able to provide information about CAPEX).

Data is presented here in the form of a plot of specific CAPEX (€/W) against installed capacity (MW) (see Figure 7). Notice that in the case of UTES systems, the specific CAPEX per unit of installed capacity is not a fully representative cost indicator. When it comes to UTES systems, it is equally important to talk about both specific CAPEX per unit of stored

[18] Vinci Energies, Renewable energy: geothermal energy and biomass combined for an innovative heating network. Online article available at: https://www.vinci-energies.com/en/our-news/newscenter/renewable-energy-geothermal-energy-and-biomass-combined-for-an-innovative-heating-network/

energy (€/kWh) and per unit of installed capacity (€/W). However, not enough data has been obtained under this premise.

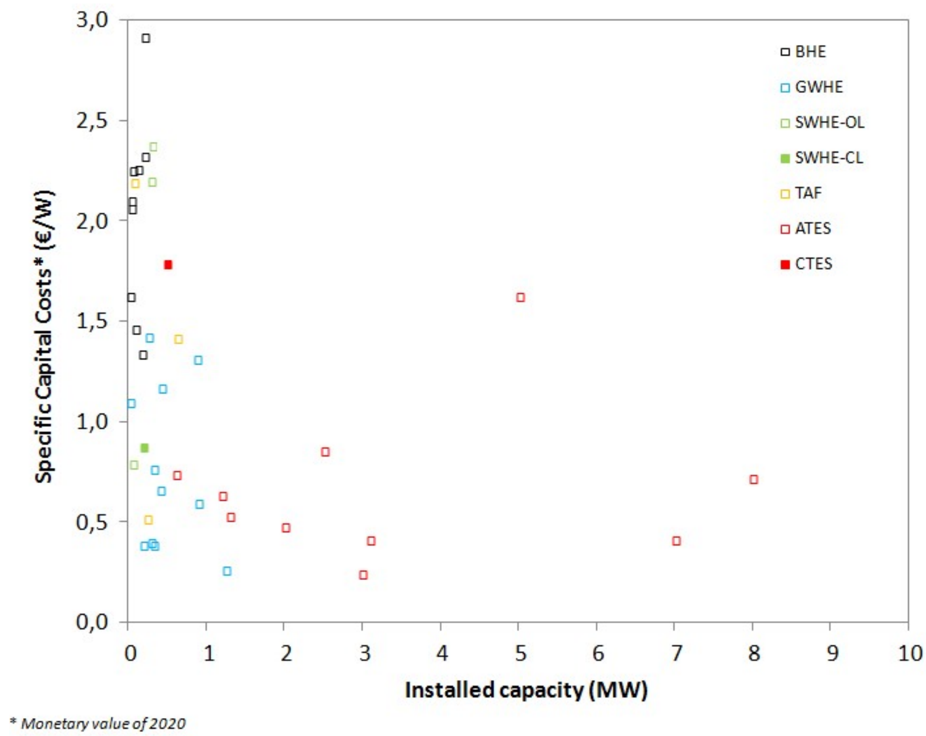

Figure 7. Specific CAPEX of several SGE installations, mainly from Europe (source: see Appendix I).

According to Figure 7 significant differences can be observed between the costs of BHE and GWHE of the SGE installations identified for the study. This is quantified in *Tab. 5.*

Roughly speaking, BHE systems require twice as much investment as GWHE systems. Additionally, a slight lower CAPEX in ATES with respect to GWHE systems is observed. However, the comparison is not fully honest because of the big difference in installed capacity, and because ATES and GWHE systems are not conceptually analogous.

ATES is related to energy storage, while GWHE systems are related to energy exchange, although in practice the difference between certain ATES and GWHE systems is not so clear. Finally, as far as TAF and SWHE systems, it is risky to extract a conclusion on their CAPEX compared to BHE or GWHE systems. It can only be said that they are in the same order of magnitude.

Tab. 5. Statistical analysis of the SGE installations, concerning their specific CAPEX.

SGE concepts	Mean (€/W)	Std. Dev. (€/W)	Cases number
ATES	0,66	0,4	11
BHE	2,03	0,6	10
GWHE	0,8	0,4	11
SWHE-OL	1,8	0,9	3
TAF	1,4	0,8	3

6 SUMMARY AND CONCLUSIONS

6.1 Heat Exchanger systems

Vertical BHEs are the dominant choice for the exploitation of SGE resources, especially at low scale (dwellings). Although CAPEX is high compared to other SGE exploitation schemes, **BHEs can be installed almost everywhere in Europe**. Moreover, the operational costs (OPEX) are lower than for open-loop systems. The dependence on weather conditions are also the lowest, which guarantees continuous operation throughout the year. In countries with a mature degree of implementation, boreholes drilling depths generally vary between 150-200 m.

TAFs are inherently attractive because they require a null extra land use compared to BHEs or GWHEs. TAFs represent an efficient and cost-effective building strategy, since both structural and energy functionalities are given to the same elements (piles, diaphragm walls, etc.). However, because of their much shallower nature (10-40 m), this type of HEs are much more sensitive to climate conditions and to annual variations in the water table level. **TAFs are therefore ideal for temperate climates**, with a **near-to-null yearly heat exchange balance with the ground** (same heat extracted than injected), and a **low ground thermal diffusivity**.

GWHE systems are preferred wherever a suitable aquifer is available. The term s*uitable* should be understood here as missing limitations of use, proper water chemistry (to avoid/minimize corrosion/scaling) and a size (also the extraction rate) large enough for the projected heating/cooling demand. **The unsurpassed volumetric heat capacity of water (4.18 MJ/m^{3}K)** is the most relevant indicator about the amount of sensible heat available per unit volume. Additionally, the groundwater temperature in general favors a more efficient operation of the HPs throughout the seasons, both in heating and cooling modes, compared to BHEs. Another advantage is the possibility of **free cooling** for hospitals or industrial and office buildings, which is even more efficient since no heat pump is necessary.

SWHE systems are probably the most location and climate sensitive type of SGE installations, although they do not require any drilling work, and the implementation works are rather easy. However, conflicts of use deal with marine, river or lake fauna disturbance, temperature influence in biological processes, ship activity (fishing, anchors), but also its chemical composition, since surface water has a high content of dissolved oxygen, which favours fouling. **Closed-loop systems in Europe are hard to identify**, compared to North America. **Free cooling** is also possible for SWHE systems.

A large amount of low-temperature (15-20 ºC) urban excess heat sources is available that can play a fundamental role in the decarbonisation of the heating sector in many cities. Along these lines, new exploitation schemes are being developed, from the SGE point of view, with solutions for recovering excess urban heat, such as extra sensitive heat in wastewater, or residual heat from underground spaces - tunnel air and the tunnel lining- as a geothermal source. Recovering solutions can be using air-to-air HXs directly placed within existing ventilation shafts or secondly using capillary HXs systems – absorber pipes - placed in the metro tunnel lining to absorb the heat in the surrounding rock cooling the tunnel, which can be then re-heated by a HP to provide heat for the above-ground building and domestic hot water.

6.2 Underground thermal energy storage systems

The **UTES** systems store energy for the purpose of later extraction by pumping heat into/from an underground space.

This installations above are used to keep the ground thermal balance in the long run in heating-dominated climates where heating exceeds cooling demand, although cases of cold-water injection into aquifers during winter for summer cooling exists. The most common scenario is the use of UTES as inter-seasonal heat storage but also could be for long-term storage. **UTES systems store the heat** from a certain source during the warm season (usually excess thermal energy from solar collectors, residual heat from CHP plants or industrial processes, the heat rejected by a building itself during cooling, waste heat from data centers, and ultimately also waste heat through flue gases generated by a biomass combustion plants, etc.) for its later use during the cold season. UTES systems show heat losses greatly influenced by the size of the reservoir and groundwater flow characteristics. The suitability of UTES systems usually is justified for large size buildings or DHC networks, but partial recuperation by applying certain UTEs techniques, such as **BTES**, also bring energetic benefits to small scale uses irrespective of heat losses.

While the attention is put mainly on electricity and electrical storage, heat supply and rejection represent by far the largest portion of final energy consumption in the residential sector. **Therefore, UTES offers one of the most cost-effective and efficient solutions to the intermittent supply provided by renewable sources of thermal energy like solar energy**.

UTES systems with both boreholes (**BTES**) and aquifers (**ATES**) are the most developed storage schemes and are mostly used for seasonal storage.

BTES represents analogous advantages as vertical BHEs with respect to open-loop systems concerning versatility and location-dependence. Its implementation is not yet widely deployed, although many examples can be found in the North of Europe (Germany and Scandinavia, mostly), USA and Canada. In Canada, the Drake Landing Solar Community in Okotoks, (Alberta, Canada, commissioned in 2007) has demonstrated that **solar collectors can meet 100% of the heating demand** of a set of dwelling despite intermittence of solar radiation, **thanks to thermal energy storage, and without the need of HPs**.

ATES is a very mature exploitation scheme, although this only applies to a few countries. The Netherlands is nowadays a world-leader in this field and very active in developing this kind of systems. Meanwhile, interest in alternative ATES systems from medium (30º - 60ºC) to high (> 60ºC) temperature (MD - HT) are increasing, as a higher storage temperature allows a greater amount of energy stored in the same volume of soil. MD-UTES would increase the efficiency of GSHP systems in the heating period, while in the case of HT-ATES it would allow the direct use of heat (without the need for HP), which would then not be considered part of the concepts of SGE. In theses cases care in the designs should be taken to avoid environmental concerns.

PTES is a scheme that store hot water in large excavations with an insulated lid. Sides and bottom are normally covered by a polymer-liner or concrete. Temperatures up to approx. 90°C can be stored. PTES offers the same flexibility to seasonal storage for district heating energy systems as BTES but also for short term storage.

CTES or MTES is the least deployed of all UTES typologies, since the economic profit of excavating underground cavities for thermal storage purposes is more than questionable. The existing examples are just testimonials. Instead, the conversion of naturally flooded old mines into hot water reservoirs has a lot of potential, especially in areas with a large mining industry immersed in a dismantling process (or planning it), mostly due to the coal phase-out. The same applies to underground oil storage cavities, although there are far less examples, and most of them are still in use. In any case, **the CTES concept should be considered in all existing mine or oil storage cavities under use**, which have a natural water table level near to the surface and will be facing its closure in the forthcoming years. This would enable a more efficient transition from one exploitation scheme to a new one.

6.3 Cross-cutting conclusions

At first sight, BTES and BHE systems, as well as ATES and GWHEs systems might not seem different from the execution and operation perspectives. On the contrary, the differences are numerous, since **BTES and ATES rely on heat storage, while BHE and GWHE systems rely on heat exchange**.

Groundwater dynamics is one of the most important technical aspects to bear in mind in SGE resource characterisation and management. High groundwater flow favours the implementation of heat exchanging systems such as BHEs, GWHEs and TAFs. Conversely, when groundwater flow is low or very low, advection-driven heat losses are minimised, so heat storage systems (BTES and ATES systems) are more efficient.

Flow direction will influence the allocation of boreholes and wells in BHE and GWHE systems, respectively, and will help quantifying the extraction rate in TAFs. Injection wells should always be located downstream in GWHE systems, while in ATES installations the wells should be in a way that thermal plumes do not interact with each other due to the direction of groundwater flow.

Concerning **ground thermal conductivity**, high values are always pursued in heat exchanging systems, while it is not so clear for storage systems. Low thermal conductivity favours low heat losses by conduction, while high values guarantee high charging/de-charging rates. It depends on the operation scheme which value is more favourable.

In groundwater-based systems (GWHEs, ATES, CTES), a trade-off must be performed between pump flow and HP power consumption in order to find an optimum operation point. Furthermore, the depth of the groundwater table will largely determine the efficiency and cost effectiveness of the projected installation.

One of the main technical barriers of SGE deployment in most of the countries is the lack of detailed knowledge about the subsoil at a local level. This is an essential requirement to reduce the risk of investment. Thermal response test (TRT), pumping tests, water chemistry and temperature tests provides valuable information for sizing purposes, although the decision to carry them out usually relies on whether a previous SGE resource characterisation already exists. In this sense, **the role of public bodies (mainly through their National Geological Surveys) is the base for SGE penetration into the heating/cooling market**. At the same time, the progressive increase of local and detailed tests should contribute to feed back the existing knowledge through the creation of publicly available databases. This would result in the reduction of marginal cost concerning planning and sizing of SGE installations.

Concerning specific CAPEX, **GWHE systems still represent a significantly cheaper option compared to vertical BHE systems**. In particular, the upfront cost of vertical BHE systems are about twice the cost of GWHE systems.

SGE is becoming a central piece in the puzzle of new district heating and cooling (DHC) networks, also known as 5th generation DHC (5GDHC) networks. The transport of heat-carrying fluids at very low temperatures (close to the media where they are transported through, ~10-25ºC) and its use by means of HPs is a new paradigm of energy efficiency applied in urban environments. This new scheme will favour the distributed generation and integration of multiple renewable energy sources. Moreover, the smart management of the heating and cooling demands among the different buildings within the DHC network enables the heat exchange between buildings themselves. So, **management is put at the same level as supply**.

6.4 Maturity and scalability of SGE technologies

Among the different technologies related to SGE, BHEs is by far the most extended in terms of installed power and geographical distribution, followed by GWHEs. Nevertheless, this is not a surprise, since either BHEs can be installed almost everywhere in Europe, and at any scale (see table 6). GWHEs is a simple technology but their use restricted to the presence of groundwater and the characteristics of the aquifer. In terms of maturity, there are several facilities large enough of each type of SGE concepts to be considered mature, except for CTES / MTES. Moreover, technological maturity is remarkably inhomogeneous across the European territory. Again, BHEs and GWHEs are the most established technologies anywhere. However, it can be surprising how well deployed is ATES in The Netherlands compared to the rest of Europe, or how little is SGE (in general) deployed in some southern countries yet, despite the huge potential of it.

Tab. 6. Range of applicability of each SGE exploitation scheme, according to the size.

	BHEs	GWHEs	TAFs	SWHEs	BTES	ATES	CTES/MTES
Single dwellings							
Medium buildings							
Large buildings							
Industry							
DHC networks							

Although SGE is a mature field itself and its economic profitability has been demonstrated for decades, there are still many fronts where innovation can take place. Therefore, the SGE industry is ready to new improvements in performance and to widen its fields of application (see Figure 6).

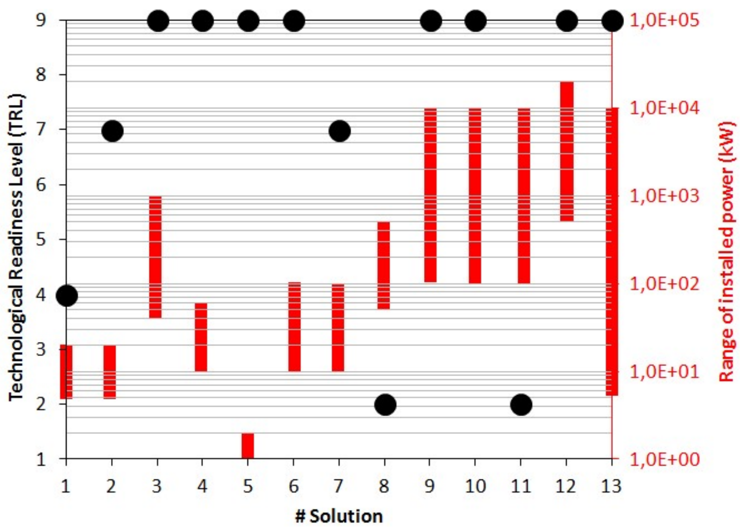

Figure 8. TRL associated to each of the innovative and prospective solutions described in the Factsheets: ***1.-*** *CO_2-based DX-GSHPs;* ***2.-*** *PCM materials embedded in grouts;* ***3.-*** *TAFs in metro tunnels;* ***4.-*** *Dynamic closed loop GWHEs;* ***5.-*** *Energy recovery from sullage;* ***6.-*** *Energy recovery in sewer pipes with embedded heat exchangers;* ***7.-*** *Energy recovery in sewer pipes through heat exchanger stations;* ***8.-*** *Medium-Deep BTES concept;* ***9.-*** *High-temperature ATES;* ***10.-*** *New projects of MTES;* ***11.-*** *CTES in old oil reservoirs;* ***12.-*** *SGE applied to 5th Generation DHC networks;* ***13.-*** *Excess electrical power from renewable stored as thermal energy. The range of installed power associated with each solution is estimated (red bars).*

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APPENDIX I. LIST OF INSTALLATIONS CONSIDERED FOR CAPEX OF SGE INSTALLATIONS IN EUROPE

Tab. 7. List of collected SGE installations. It includes data collected from the questionnaires and from the literature review)

Source	Type	Name and location	Year	Inflation corrected CAPEX (€)	Capacity (MW)	€/W
1	ATES	Brasschaat, Belgium (Klina Hospital)	2011	759853	1,20	0,63
1	ATES	Amersfoot, The Netherlands (Office Building)	2011	962116	2,00	0,48
1	ATES	Oslo, Norway (Airport)	2005	2883564	7,00	0,41
1	ATES	Stockholm, Sweden (Airport)	2009	5732840	8,00	0,72
1	ATES	Copenhagen, Denmark (Airport)	2018	8130442	5,00	1,63
1	ATES	Malle, Belgium (Office building)	2006	444450	0,60	0,74
1	ATES	Frösundavik, Sweden (Office Building)	1994	725952	3,00	0,24
1	ATES	Utrecht, The Netherlands (University)	1991	2141864	2,50	0,86
1	ATES	Mälmo, Sweden (Residential Building)	1992	690826	1,30	0,53
1	ATES	Karlsruhe, Germany (Hospital)	2019	1271000	3,10	0,41
2	CTES	Gardanne, Aix-en-Provence, France ("Pôle Yvon-Morandat")	2019	892000	0,50	1,78
2	BHE	Sant Gregori, Girona, Spain (Dwelling)	2019	17500	0,01	1,59
3	BHE	Flavigny-Sur-Ozerain, France (Religious building)	2000	452433	0,20	2,26
3	BHE	Revel, France (Social Centre)	2010	78106	0,04	1,95
3	BHE	Saint-Malo, France ("La grande pasarelle", Cultural building)	2014	577515	0,21	2,72
4	BHE	Valle d'Aosta Region, Italy (Bar-Restaurant "Pit-Stop", Touristic building)	2014	126003	0,06	2,10
3	BHE	La Courtine, France ("Établissement d'Hébergement pour Personnes Agées Dépendantes, EHPAD Le Chabanou", Accommodation Facility for Dependent Elderly)	2013	208741	0,17	1,23

3	BHE	Beaumont, France ("Hôtel de Ville")	2013	107316	0,08	1,34
3	BHE	Saint-Gilles Croix de Vie, France ("Siège social de Bénétau")	2013	263030	0,13	2,07
3	BHE	Mende, France ("Crèche de Valcroze")	2010	74724	0,04	1,92
2	GWHE	Cardiff, UK (Grangetown Nursery School)	2015	24166	0,02	1,10
3	GWHE	Pantin, France (Multi-dwelling building)	2011	384846	0,27	1,43
3	GWHE	Blois, France (Events and conventions room)	1985	516464	0,44	1,17
3	GWHE	Evreux, France ("Centre Hospitalier de Navarre", Hospital)	2013	1157332	0,88	1,32
3	GWHE	Moulins, France ("Centre aqualudique")	2007	546773	0,91	0,60
3	GWHE	Paris, France ("Collège des Bernadins")	2008	249737	0,33	0,77
3	GWHE	Tourville-la-Rivière, France (IKEA, commercial building)	2020	334000	1,26	0,27
3	GWHE	Entzheim, France ("Hall d'exposition automobile Vodiff")	2012	131415	0,34	0,39
3	GWHE	Cheverny, France ("Serres Coup'Flor", Agriculture)	2008	122556	0,31	0,40
3	GWHE	Baron, France ("Serres Mitton", Bonsais acclimatation)	2005	272513	0,41	0,66
4	GWHE	Tyrol Region, Austria (Factory Euroclima, Industrial Building)	2013	78909	0,20	0,39
3	SWHE-CL	Linguizzetta, Corse, France (Campsite)	2013	173902	0,20	0,87
5	SWHE-OL	Anglesey, UK (Plas Newydd)	2014	711918	0,30	2,37
5	SWHE-OL	Alaska Sea Life Center, USA	2012	631785	0,29	2,19
4	SWHE-OL	Carinthia Region, Austria (Lake-water pool at Hotel Hochschober, Touristic building)	1995	33104	0,04	0,79
6	TAF	Zürich, Switzerland (Airport)	2003	890250	0,63	1,41
3	TAF	Auxerre, France (Concerts room)	2009	123829	0,24	0,52
3	TAF	Tours, France ("Centre de Maintenance des Tramways", Maintenance building)	2013	131515	0,06	2,19

Sources:

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4. Near Surface Geothermal Resources in the Territory of the Alpine Apace (project GRETA; Interreg Alpine Space), 2018. Annex I to Deliverable 3.1.1.: Catalogue of techniques and best practices for the utilization of Near-Surface Geothermal Energy, pp. 1-48, Report available online at: https://www.alpine-space.eu/projects/greta/en/project-results/outputs/deliverables

5 Martin M., 2015. Water source heat pump report. (Aberdeen Heat and Power company ltd., UK), pp. 1-37. Report available online at: https://heatandthecity.org.uk/wp-content/uploads/2017/08/AH_and_P_LECF_feasibility_study_2015_02_19_final.pdf

6 Pahud D., Hubbuch M., 2007. Measured Thermal Performances of the Energy Pile System of the Dock Midfield at Zürich Airport. European Geotherma Congress, pp. 1-7.

7 Klonowski M.R., Lipinska O., Zerun M., Kocyla J., Konieczynska M., Ryzynski G., Garcia-Gil A., Goetzl G., 2020. Deliverable 3.1 – Report on the current legal framework, procedures and policies on SGE use in selected European cities. GeoERA project MUSE, project number GeoE.171.006.

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APPENDIX II SUMMARY OF THE REPLIES TO THE QUESTIONNAIRES

Tab. 8. Level of completion of the questionnaires corresponding to vertical BHE systems.

		1	2	3	4	5	6	7	8	9
Information block	Numer of fields to be filled	P01-GBA VIERTEL ZWEI (closed loop part)	P01-GBA Austria Campus	P02-NERC-BGS Undeterm. (Cardiff)	P02-NERC-BGS Undeterm. (Cardiff)	P03-ICGC Stand-Alone House (Sant Gregori-Girona)	P03-ICGC Stand-Alone House (Salt-Girona)	P05-CGS Lida Barova Villa (Prague)	P12-TNO Multiple dwellings (Etten Leur)	P13-PIG-PIB Student Dormitory (Warsaw)
1. Ground characteristics	6	50%	67%	0%	0%	0%	0%	83%	83%	100%
2. Borehole characteristics	8	88%	88%	0%	0%	75%	63%	88%	88%	88%
3. Pipe characteristics	2	100%	100%	0%	0%	100%	50%	100%	75%	100%
4. Filling material	1	100%	100%	0%	0%	50%	50%	100%	100%	100%
5. Brine	5	60%	0%	0%	0%	80%	40%	100%	40%	100%
6. Monitoring system	5	80%	0%	0%	0%	80%	80%	80%	20%	60%
7. Peformance Characteristics	15	73%	33%	0%	0%	73%	53%	47%	87%	53%
8. CAPEX and OPEX	5	0%	0%	0%	0%	80%	0%	0%	0%	0%
9. Additional information	1	100%	100%	0%	0%	100%	100%	100%	0%	0%

Tab. 9. Level of completion of the questionnaires corresponding to GWHE systems.

		1	2	3	4	5	6	7	8	9	10	11
Information block	Numer of fields to be filled	P01-GBA VIERTEL ZWEI (open loop part)	P01-GBA WU Campus (Wien)	P02-NERC-BGS Kndrgardn. (Cardiff)	P04-HGI-CGS Stand-Alone House (Zagreb)	P04-HGI-CGS IKEA (Zagreb)	P07-GSI Glucksman Art Museum (Cork)	P09-GeoZS Primary School (Polje)	P10-IGME Clinic Hospital (Zaragoza)	P10-IGME CS-Inocencio Jiménez (Zaragoza)	P10-IGME Hospital Provincial (Zaragoza)	P03-ICGC Spa Center (Girona)
1. Aquifer / Groundwater characteristics	13	15%	69%	77%	62%	0%	54%	92%	100%	100%	100%	69%
2. Production well characteristics	12	42%	42%	100%	92%	0%	25%	92%	100%	100%	100%	75%
3. Injection well characteristics	12	33%	42%	100%	92%	0%	25%	92%	100%	100%	100%	75%
4. Loop information	5	50%	60%	100%	40%	0%	50%	100%	100%	100%	100%	100%
5. Specific information for IL systems	6	33%	0%	0%	0%	0%	50%	0%	83%	50%	50%	50%
6. Pipe characteristics	3	0%	100%	67%	0%	0%	0%	67%	100%	0%	100%	33%
7. Monitoring system	6	50%	50%	100%	33%	0%	0%	50%	83%	33%	83%	86%
8. Peformance Characteristics	13	85%	46%	77%	8%	0%	77%	54%	100%	31%	31%	15%
9. CAPEX and OPEX	4	0%	0%	100%	0%	0%	50%	6%	50%	0%	0%	0%
10. Additional information	1	100%	100%	100%	0%	0%	0%	100%	100%	0%	0%	100%

Tab. 10. Level of completion of the questionnaires corresponding to ATES systems.

ATES		1
Information block	Numer of fields to be filled	P08-RBINS-GSB Herman Teirlinck Building (Brussels)
1. Aquifer / Groundwater characteristics	13	0%
2.Thermal Energy Storage charactersitics	2	0%
3. Production well characteristics	12	0%
4. Injection well characteristics	12	0%
5. Loop information	7	0%
6. Specific information for IL systems	7	0%
7. Pipe characteristics (ATES)	3	0%
8. Monitoring system (ATES)	13	0%
9. Performance Characteristics	19	0%
10. CAPEX and OPEX (ATES)	4	0%
11. Additional information	1	0%

Tab. 11. Level of completion of the questionnaires corresponding to BTES systems.

BTES		1	2
Information block	Numer of fields to be filled	P08-RBINS-GSB DELTA-CHIRAC Hospital (Brussels)	P13-PIG-PIB Cosmetics Plant Bell 2 (Warsaw)
1. Ground characteristics	6	50%	80%
2. Thermal Energy Storage charactersitics	2	100%	100%
3. Borehole characteristics	7	86%	86%
4. Pipe characteristics (BTES)	2	100%	100%
5. Filling material	1	100%	100%
6. Brine	5	20%	100%
7. Monitoring system (BTES)	5	0%	60%
8. Peformance Characteristics	17	53%	35%
9. CAPEX and OPEX	5	0%	0%
10. Additional information	1	0%	0%

Tab. 12. Level of completion of the questionnaires corresponding to CTES systems.

CTES		1
Information block	Numer of fields to be filled	P06-BRGM Old coal & lignite mine (Gardanne)
1. Cavity and ground characteristics	8	50%
2. Thermal energy storage characteristics	2	100%
3. Production well characteristics	4	100%
4. Injection well characteristics	4	100%
5. Loop information	8	100%
6. Specific Info for IL systesms	4	88%
7. Pipe characteristics	3	100%
8. Monitoring system	13	62%
9. Performance Characteristics	19	68%
10. CAPEX and OPEX	4	88%
11. Additional information	1	0%

APPENDIX III CATALOGUE OF FACTSHEETS (INCLUDING REFERENCES)

Factsheets from number 0 to 8 can be found as individual documents accompanying this report, as well as examples of SGE installations. Here, an extended version of Factsheets from number 0 to 8 are presented together, which means that bibliographic references are included and can be found at the end of each Factsheet.

FACTSHEET0

OVERVIEW OF SHALLOW GEOTHERMAL ENERGY SYSTEMS IN AREAS

SGE is ubiquitous, available any time, weather independent, efficient and renewable

64 % of World **primary energy** is consumed in urban areas [1]

72% of EU **population** lives in urban areas [2]

70 % of World CO_2 **emissions** are concentrated in cities [1]

17% of EU **land** is considered as **"urban"** [2]

From 0 to 200 m under the surface (exceptionally up to 400 m) **SHALLOW**

Stored/exchanged in/with the subsurface **GEOTHERMAL**

Heat extracted/injected from/to the subsurface with (or without) HEAT PUMPS **ENERGY**

1. IAE, "Energy Technology Perspectives" (2016)
2. PBL Netherlands Environmental Assessment Agency, "Facts and Figures on Cities and Urban Areas" (2016)
3. Nature Geoscience 5, 671-696 (2012)
4. BP, "Statistical Review of World Energy" (2019)
5. Turcotte D.L. & Schubert G., "Geodynamics" (2nd ed. 2002)

The Sun is the true main source of SGE

Average solar radiation absorbed at the Earth's surface [3]
165 W/m²

World human average power consumption [4]
→ 34 mW/m²

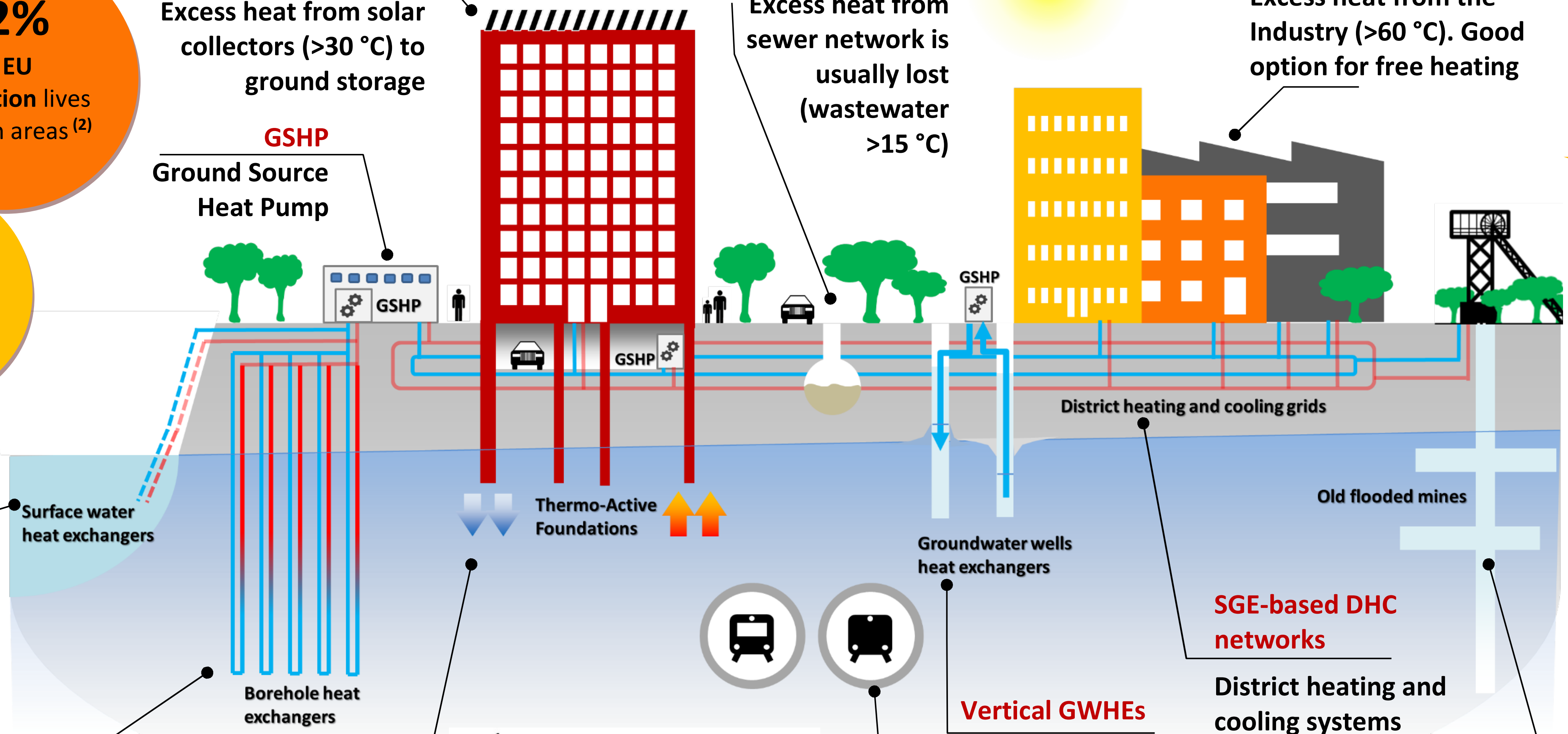
Average power reaching the Earth crust from its internal heat budget [5]
40 - 90 mW/m²
Average value in continental areas
~ 65 mW/m²

CTES, BTES, ATES
Excess heat from solar collectors (>30 °C) to ground storage

GSHP
Ground Source Heat Pump

Excess heat from sewer network is usually lost (wastewater >15 °C)

Excess heat from the Industry (>60 °C). Good option for free heating



OL-SWHEs, CL-SWHEs

Large water bodies like rivers, lakes and the sea show a reduced yearly temperature variation compared to air. Good option for free cooling

SGE-based DHC networks

District heating and cooling systems powered with SGE technologies or combined with other RES or waste heat sources

CTES, GWHEs

Abandoned and naturally flooded mines with groundwater

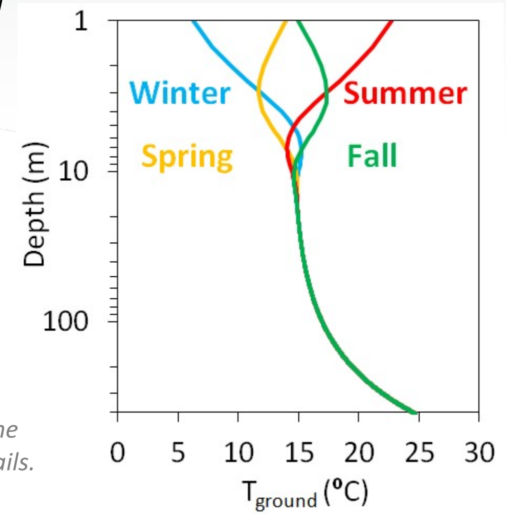
Vertical BHEs, BTES

The geo-exchange within the ground using close loop systems (CL).

Almost constant temperature along the year (10 - 18 °C) below 10m depth to 100 - 200 m

TAFs

Heat exchanger can be embedded in deep foundations (>10 m)



T_{ground} is dominated by solar irradiation close to the surface. Afterwards, the geothermal gradient prevails.

Vertical GWHEs

The groundwater exchange abstracting and injecting groundwater from the aquifers

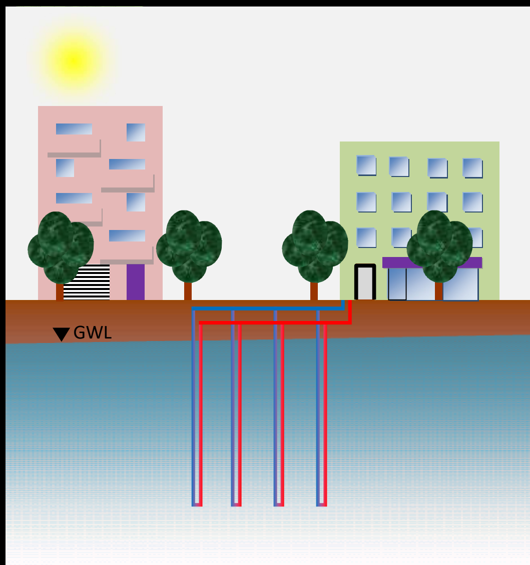
Excess heat from underground infrastructures causes cumulative ground warming and warm air at tunnels (>25 °C)

MUSE GeoERA GEO-ENERGY
Managing Urban Shallow Geothermal Energy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

OL and CL: open and closed-loop / SW and GW: surface- and groundwater / B: Borehole; C: Cavern; A: Aquifer / HE: heat exchanger; TES: thermal energy storage / TAF: Thermo-active foundation / DHC: District heating and cooling

CLOSE-LOOP VERTICAL BOREHOLE HEAT EXCHANGER SYSTEMS



In closed-loop Borehole Heat Exchangers (BHE), heat is exchanged with the ground by means of a brine flow (mainly water or water mixed with a portion of antifreeze) circulating through a set of probes buried in vertically drilled boreholes ranging between 50 and 200 m typically.

1 PROVEN CONCEPTS

SCALING-UP

Very large BHE fields (> 1 MW_{th}) offer the well-known advantages of the economies of scale. The aggregation of a distributed energy resource such as shallow geothermal energy (SGE) allows a more efficient management of it (including the ground and the system monitoring, and the processing of permits).

Three different typologies of very large installations can be identified:

- **Large buildings** (Hospital de Sant Pau, Barcelona, Spain, 3.6 MW_{th})
- **District heating and cooling networks** (Viertel Zwei and Austria Campus, Wien, Austria, 0.45 MW_{th} and 1.2 MW_{th} for heating and cooling, respectively)
- **Residential areas with individualised BHE systems** (Neighbourhood in Etten Leur, The Netherlands, 5 MW_{th} and 6.7 MW_{th} for heating and cooling, respectively)

DEEP SHALLOW or SHALLOW DEEP?

In areas where the use of SGE is a mature practice, there is a **growing need for drilling deeper**. This strategy partly overcomes possible thermal interaction with neighbouring installations. In addition, **deeper BHEs favour heat pump heating efficiency** thanks to the geothermal gradient (20 - 30 °C/km). In Sweden, the average borehole depth has doubled since 1995, from 100 to 200 m. In Sipoo (Finland), there is one of the largest SGE installations in Europe, with 319 boreholes 300 m deep each to supply a logistics centre.

2 FUTURE CONCEPTS

SMART GROUTS ENHANCE EFFICENCY

A new strategy for borehole grouting consists of embedding into the grout a high content of micro or macro-encapsulated phase-changing materials (PCMs) with melting temperatures in the range 10 - 60 °C. The idea is to **use latent heat instead of sensible heat within the boreholes**, so the minimum brine temperature could be raised in cold climates and the maximum brine temperature could be lowered in warm climates (figure 1), leading to an increase in heat pump efficiency.

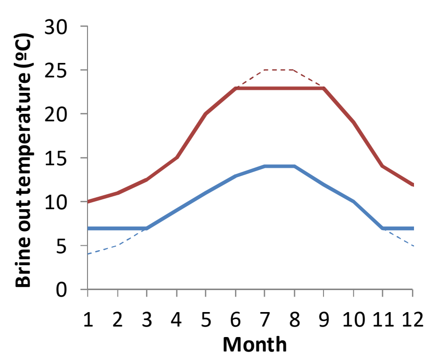


Figure 1. Hypothetic brine out temperature profiles corresponding to a cold climate (blue lines) and a warm climate (red lines). Dashed lines represent the temperature values achieved without PCMs in the in the borehole. Solid lines represent the ideal temperature profiles achieved thanks to PCMs.

CARBON SEQUESTRATION IN HEAT PUMPS

Most common refrigerant fluids in geothermal heat pumps show global warming potential values about 2000 times higher than CO_2. But what if CO_2 itself was a good alternative as a refrigerant? In fact... it is! Active research is being carried out to use CO_2 in **direct-expansion ground source heat pumps** (DX-GSHPs). In DX-GSHPs, CO_2 can act both as the ground heat exchanging fluid and the refrigerant fluid in the heat pump.

3 GOOD EXISTING PRACTICES

INTERVIEW WITH THE GROUND

Thermal properties of the ground can be estimated from existing geological data, as e.g. geological surveys provide it, or it can be accurately measured by a thermal response test (TRT). The convenience of performing such tests increases with the projected capacity to be installed. **In small installations, uncertainty is usually compensated through oversizing**. However, the drilling costs and the TRT cost itself must be considered when taking the final decision, even for small-scale installations.

ROAD TO OPTIMUM DESIGN

An efficient design of a closed-loop BHE field must focus on (see Figure 2):

- **minimise total borehole length** (L_b)
- **minimise circulation pump power** (Q_{pump})
- **maximise heating and cooling seasonal performance factors** (SPF_h and SPF_c, respectively)

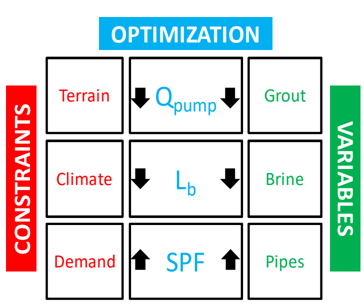


Figure2. Design aspects of a BHE

A trade-off must be carried out between the main variables of the system: the grouting of the BHE, the pipe material, geometry and the brine composition. On the side of the constraints, the ground characteristics, the climate and the demand of the building will impose their limits to the final design through the thermal ground conductivity (λ_g), the undisturbed ground temperature (T_{g0}) and the minimum and maximum brine temperatures (ELT_{min}; ELT_{max}), respectively. L_b impacts directly on the investment cost (and to a lower extent on the feasibility), while Q_{pump} and SPF impact on the operation cost, and therefore on the energy savings and the payback period.

4 LESSONS LEARNED

USE HIGH QUALITY GEO-SERVICES

Not considering existing and **readily available hydrogeological information** can lead to unexpected drilling problems involving environmental hazards, building/ infrastructure damage or inadequate SGE exploitation schemes. Most frequent omitted aspects are:

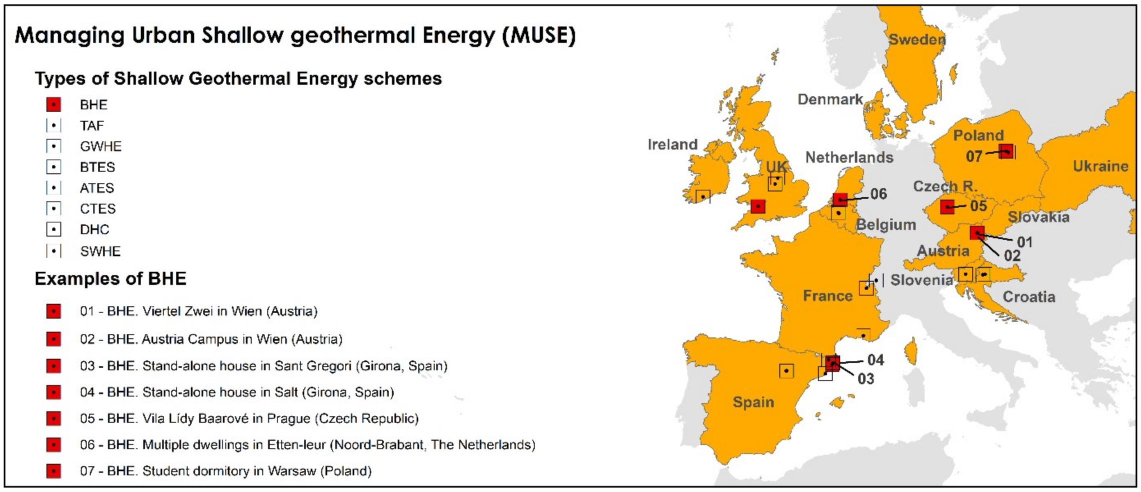
- The existence of artesian aquifers.
- Areas with high groundwater flow.
- Existence of contaminated soils.
- Presence of karstified rocks.
- Presence of thermal anomalies.

It is also important to consider **access of drilling** machinery in densely packed urban areas, as well as limitations imposed by the building **structural stability** or by **the architecture itself**.

BOREHOLES NEED THEIR SPACE

Especially in urban areas, the possible **thermal interference between adjacent installations** must be considered, since the addition of a new installation can create “lose-lose” scenarios between existing and forthcoming customers. Therefore, public databases of existing boreholes and their characteristics are extremely helpful.

5 EXAMPLES



BHE-1. Viertel Zwei in Wien (Austria)

WIEN PILOT AREA

Location (WGS84 coordinates): N 48.212830 E 16.415016

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2377	229

Undisturbed T_{ground} [ºC]: 12.1

Minimum T_{brine} [ºC]: 5.4 (simul.)

Maximum T_{brine} [ºC]: 22 (simul.)

Number of Boreholes: 165

Total length [m]: 23100

	Heating	Cooling
Capacity installed [kW]	450	1200
Demand [MWh]	5.6	2.4
Seasonal performance (SPF_{H2})	4.5	5.5

This shallow geothermal energy installation is part of a smart anergy grid, which combines borehole and groundwater heat exchangers, as well as wastewater and waste heat utilization, providing space heating, domestic hot water and cooling (with floor heating system and concrete core activation) to a complex of residential and office buildings (District Heating). Shallow geothermal energy alone meets 70% and 95% of the heating and cooling demands in the complex, respectively.

BHE-2. Austria Campus in Wien (Austria)

WIEN PILOT AREA

Location (WGS84 coordinates): N 48.223196 E 16.394030

	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	2377	229

Undisturbed T_{ground} [ºC]: 12.8
Minimum T_{brine} [ºC]: no data
Maximum T_{brine} [ºC]: no data

Number of Boreholes: 207
Total length [m]: 30593

	Heating	Cooling
Capacity installed [kW]	918	569
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	No data	No data

The Austria Campus is a business district consisting of offices, underground parking, a hotel, health and conference centre, and areas for restaurants and retail (Rental space: 20 hectares). Apart from the borehole heat exchanger (BHE) field (what this factsheet is about), thermo-active foundations (TAFs) were implemented: slurry (diaphragm) walls, auger piles and parts of the base plate are geothermally activated through absorber pipes for the purpose of heating and cooling in the building complex. As an innovation, the installation of geothermal energy cycles into unreinforced piles was realized by means of a specially developed distribution system. Combined it is one of the largest geothermal projects in Austria.

BHE-3. Stand-alone house in Sant Gregori (Girona, Spain)

GIRONA PILOT AREA

Location (WGS84 coordinates): N 41.90693 E 2.761794

	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	1718	219

Undisturbed T_{ground} [ºC]: 16.5
Minimum T_{brine} [ºC]: no data
Maximum T_{brine} [ºC]: no data

Number of Boreholes: 3
Total length [m]: 300

	Heating	Cooling
Capacity installed [kW]	11	11
Demand [MWh]	1.52	1.05
Seasonal performance (SPF_2)	7.1*	

The SGE installation consists of an oversized BHE field (300m for 9kW installed capacity), since it is expected to meet additional demand from adjacent dwellings in the near future. The electricity production is aided by a rooftop photovoltaic installation (3 kW_p) and a set of Li-ion batteries (6 kWh of storage capacity). The electricity surplus activates the ground source heat pump (GSHP) automatically to produce domestic hot water (DHW) at 65ºC (this represents a thermal energy battery). During the warm season, the heat rejected from the building is profited to produce DHW, which enhances the overall efficiency of the SGE installation. The hybrid installation generates >100% of the dwelling total demand.
The total CAPEX (including PV and batteries) is 31000€, and the estimated pay-back period is 11 years.

** This value accounts for (E_h+E_{DHW}+E_c)/E_e, from April to September 2019. E_{DHW} and E_c are produced simultaneously most of the time, where E - energy, h - heating, c-ccoling, and DHW - domestic hot water*

BHE-4. Stand-alone house in Salt (Girona, Spain)

GIRONA PILOT AREA

Location (WGS84 coordinates): N 41.968048 E 2.788189

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	1718	219

Undisturbed T_{ground} [ºC]: 16.5
Minimum T_{brine} [ºC]: no data
Maximum T_{brine} [ºC]: no data
Number of Boreholes: 2
Total length [m]: 200

	Heating	Cooling
Capacity installed [kW]	12	12
Demand [MWh]	31.8	no data
Seasonal performance (SPF_{H2})	4.2	no data

This is a retrofitted building. The shallow geothermal energy installation consists of a 12 kW ground source heat pump coupled to a 2-borehole heat exchanger field. The installation meets entirely the cooling, heating and domestic hot water demand. It substitutes a previous gas-fired boiler system.

BHE-5. Vila Lídy Baarové in Prague (Czech Republic)

PRAGUE PILOT AREA

Location (WGS84 coordinates): N 50.1091636 E 14.3816253

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2855	77

Undisturbed T_{ground} [ºC]: 12.8
Minimum T_{brine} [ºC]: -7
Maximum T_{brine} [ºC]: 20
Number of Boreholes: 3
Total length [m]: 240

	Heating	Cooling
Capacity installed [kW]	25.6	6.7
Demand [MWh]	51.8	no data
Seasonal performance (SPF_{H2})	no data	no data

Refurbished building. A new SGE installation was implemented to meet the entire demand of heating, domestic hot water production and cooling. The distribution system consist of radiant floor combined with existing cast iron radiators. A fan-coil unit is used for cooling.
Vila Lídy Baarové is a well-known building in an exposed and historically protected area. The reconstruction took place under the strict supervision of the Heritage department.

BHE-6. Multiple dwellings in Etten-leur (Noord-Brabant, The Netherlands)

ETTEN-LEUR AREA

Location (WGS84 coordinates): N 51.590329 E 4.659573

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2435	25

Undisturbed T_{ground} [ºC]: 11.0
Minimum T_{brine} [ºC]: 0
Maximum T_{brine} [ºC]: 15

Number of Boreholes: >2000
Total length [m]: >180000

	Heating	Cooling
Capacity installed [kW]*	5	6.7
Demand [MWh] *	8-12	1-2
Seasonal performance (SPF_{H2})*	3.5-4.0	25

2005-2015 new housing development of 1500 homes in the municipality of Etten-Leur. All electric infrastructure (no gas) with individual vertical closed-loop systems for heating and domestic hot water production. In summertime free cooling potential of ground loop is used to provide cooling to the homes. Prior to the start of the development a feasibility study was carried out and over the last 8 years the soil temperature has been monitored at various depth's in 30 observation wells.

** Average values per dwelling unit*

BHE-7. Student dormitory in Warsaw (Poland)

WARSAW PILOT AREA

Location (WGS84 coordinates): N 52.251829 E 21.032445

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	3254	30

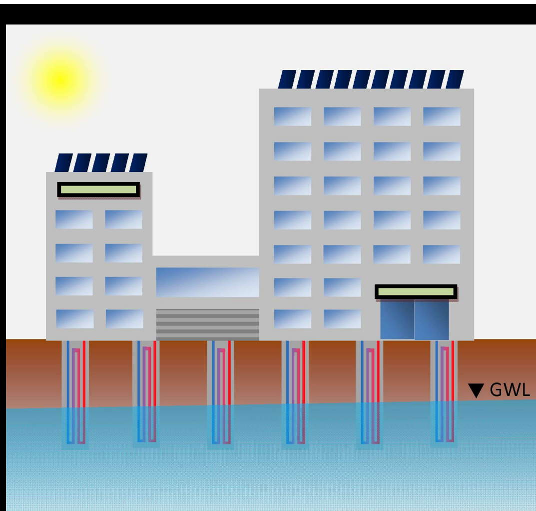
Undisturbed T_{ground} [ºC]: 11.8
Minimum T_{brine} [ºC]: 6
Maximum T_{brine} [ºC]: 16

Number of Boreholes: 100
Total length [m]: 2300

	Heating	Cooling
Capacity installed [kW]	190	250
Demand [MWh]	60	6
Seasonal performance (SPF_{H2})	no data	no data

The student dormitory (public building) is a new building constructed in 2015 and is integrated into an historic urban area of the city. Due to the lack of space all the borehole heat exchangers (BHEs) were drilled and installed within the building perimeter, so the access to them is done at the basement (parking). The system of active space heating and cooling of this multi-storey hotel building uses a cascade of ground source heat pumps achieving a total capacity of 200 kW. Additional 100 kW of heating are available from the existing district heating. The building is equipped with a building management system to control and monitor ventilation as well as water and electric energy use.

THERMO-ACTIVE FOUNDATION SYSTEMS



Thermo-active foundations (TAFs) embed heat exchanging probes into the subsurface concrete structures, which act as the foundations of a building, like piles and/or diaphragm walls. They are also known as thermally activated building structures/systems (TABSs), although the latter refers not only to foundations. Some commercial solutions exist like the Building-Integrated GEOexchangers (BiGEOs).

1 PROVEN CONCEPTS

LITTLE INVESTMENT, GREAT SAVINGS

As an energy solution, TAFs represent the attribution of **a new functionality to the structural elements of a building without incurring a proportional increase in costs** (no additional drilling works and no further land use). In fact, using TAF solutions allows up to 40% in investment cost savings compared to vertical borehole heat exchangers (BHEs). Additionally, the payback period can be as low as 4 years.

NOT SUITABLE FOR THE SMALLEST ONES

TAFs are rarely found in small residential buildings. Conversely, **large buildings (office, commercial and arena buildings, hospitals) are the main beneficiaries of this option**. District heating and cooling networks are neither among the main targets, by now.

Austria is a pioneer in this field, although other regions are following in its footsteps. A recent and remarkable example is the renovation of the *Sant Antoni* market in Barcelona (Spain). The installed capacity corresponding to TAFs is 600 kW_{th}, which fully covers the heating demand, and > 65% of the cooling. PE-X probes are embedded in 40 m deep diaphragm walls (Figure 1), with a total area of 16500 m^2, and a specific heat extraction rate of 40 W/m^2.

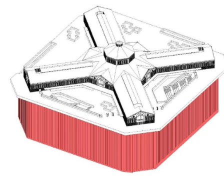


Figure 1. Thermally activated diaphragm walls in red at Sant Antoni market in Barcelona (Spain).

2 FUTURE CONCEPTS

TAFs IN METRO INFRASTRUCTURE

Austria is also the first country where TAFs have been applied in new metro stations. Within the scope of the extension works in the metro line U2 (Wien, 2008 - 2013), the metro stations were constructed by the “cut and cover” method. Diaphragm walls and bottom slabs were used to install the geothermal probes. The new and massive project “Grand Paris” (Paris, France) is taking over with more than 200 km of new metro tunnels and 68 new stations planned. The first feasibility studies have been undertaken for the application of TAFs in the stations.

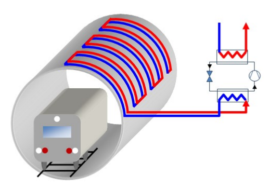


Figure 2. Illustrative scheme of an energy tunnel.

However, **the true big potential remains in excavated metro tunnels** (as for urban scenarios), which are usually too deep to be made by the “cut and cover” method, and therefore different types of heat exchangers (Figure 2) are installed during tunnel construction. Specific energy tubbing segments can be implemented in tunnels excavated by tunnel drilling machines. Nevertheless, depth is an advantage in terms of the specific heat extraction rate.

Moreover, it is well known that **trains are an inherent source of heat** contributing to ground warming in the long run (like in the famous case of London). Hence, the application of TAFs or any other alternative heat exchanger technology could be welcome in existing and future underground infrastructure for cooling and of course heating, if necessary.

3 GOOD EXISTING PRACTICES

A good indicator of maturity in the construction industry is the level of integration of environmental and energy efficiency aspects into the draft projects. This applies to both the private and public sector. **Any new infrastructure or building should have TAFs in mind.**

SHALLOW... BUT THE DEEPER, THE BETTER

TAFs are a shallow geothermal energy solution between horizontal and vertical ground-source heat exchangers. Usually, seasonal ground temperature variations are low after the first 5 m and nearly suppressed from 15 m depth downwards. **Minimum depth of piles or diaphragm walls should be at least 10 m to be used as TAFs**. Two main aspects **impact feasibility and profitability**:

- **Ground thermal diffusivity (α)**. Concerning seasonal ground temperature (T_{gr}) variation, low α values and temperate climates are favourable for the implementation of TAFs (Figure 3).

  However, the relationship between α and the ground thermal conductivity λ_{gr} should not be forgotten:

  $$\alpha = \frac{\lambda_{gr}}{\rho \cdot c_p}$$

  A low α should not be at the expense of a low λ_{gr}. Conversely, high values of ground density (ρ) and specific heat capacity (c_p) are those that should minimise α.

- **Groundwater dynamics.** A comprehensive knowledge of groundwater occurrence before, during and after the execution of TAFs is required. **Monitoring of the water table variations along the year** is crucial not only for construction purposes, but also for the performance of the TAFs, since λ_{gr} will be largely affected by groundwater flows surrounding them.

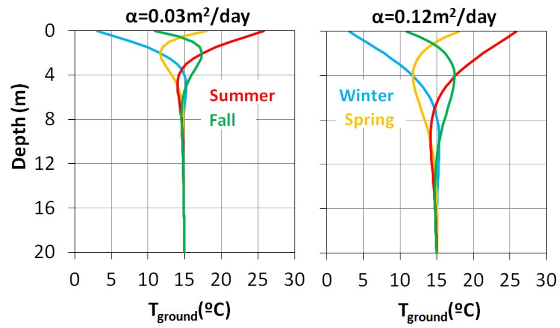


Figure 3. Typical ground temperature depth profile of a warm climate location for two different values of α.

4 LESSONS LEARNED

BEWARE OF THE UNDERGROUND

Given the shallow nature of TAFs, a local characterization of groundwater flows is needed because of the **multiple subsurface structures that can deviate or block the groundwater flow** with respect to its natural path.

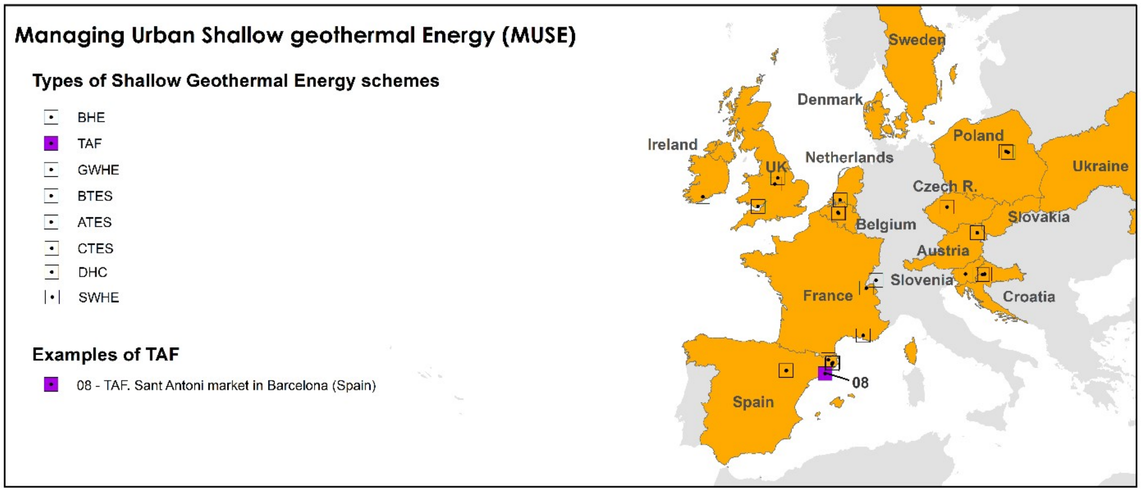
In this sense, operation managers should **keep an eye also on nearby construction works**, and general urban infrastructure management.

It is of special relevance for the mid and long term to achieve **a close-to-null balance with the ground** (same heat extracted and rejected). Notice that for this to happen, the building heating load should be, as a rule of thumb, approximately 50% higher than the cooling load.

BEST THINGS ARE NEVER FREE OR EASY

It has been demonstrated in extreme cases that **seasonal temperature cycling of the fluid within TAFs can induce stresses** on the reinforced concrete structures (expansion and contraction). This will eventually affect the settlement process of the entire building, so thermal loads and structural loads should be correlated in the design phase. It is recommended also to monitor the phenomena by the installation of displacement gauges on the TAFs.

5 EXAMPLES FROM PILOT AREAS



TAF-1. Sant Antoni market in Barcelona (Spain)

BARCELONA

Location (WGS84 coordinates): N 41.3786048 E 2.1620784

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	1754	187

Undisturbed T_{ground} [ºC]: 19.8
Minimum T_{brine} [ºC]: no data
Maximum T_{brine} [ºC]: no data

Depth of foundations [m]: 40
Area exposed to ground [m^2]: 16530
Total probe length [m]: 43970

	Heating	Cooling
Capacity installed [kW]	600	450
Demand [MWh]	2700	850
Seasonal performance (SPF_{H2})	> 4	>5

The old market of Sant Antoni was refurbished, and new floors were gained in the underground. During excavating work, old city walls were encountered and extra work was planned to preserve this valuable heritage. 40 m deep diaphragm walls were constructed following the perimeter of the block where the market is located. These walls were used as thermo-activated foundations (TAFs). The total surface of the resulting heat exchanger allowed the full coverage of heating demand by means of heat pumps (HPs), and more than 65 % of the cooling demand. Additionally, the HPs operate very efficiently during summer, since the heat rejected by the building is re-used for domestic hot water (DHW) production.

TAF-2. Austria Campus in Wien (Austria)

WIEN PILOT AREA

Location (WGS84 coordinates): N 48.212830 E 16.415016

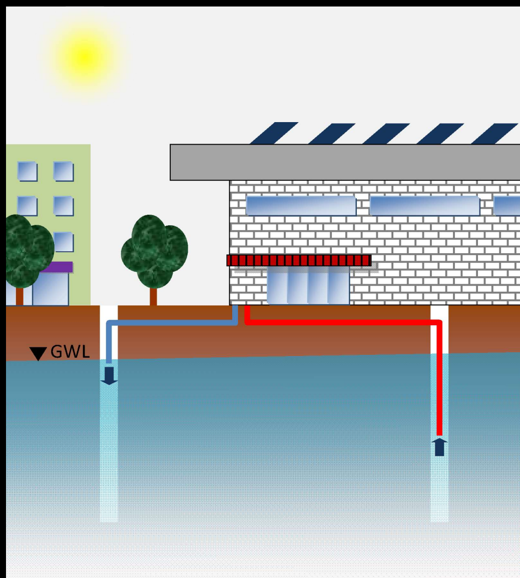
	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	2377	229

Undisturbed T_{ground} [ºC]: 12.8
Minimum T_{brine} [ºC]: no data
Maximum T_{brine} [ºC]: no data
Depth of foundations [m]: 14
Area exposed to ground [m^2]: No data
Total probe length [m]: 250000

	Heating	Cooling
Capacity installed [kW]	3000	No data
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	No data	No data

The Austria Campus is a business district consisting of offices, underground parking, a hotel, health and conference centre, and areas for restaurants and retail (Rental space: 20 hectares). Apart from the borehole heat exchanger (BHE) field, thermo-active foundations (TAFs) were implemented (what this factsheet is about): slurry (diaphragm) walls, auger piles and parts of the base plate are geothermally activated through absorber pipes for the purpose of heating and cooling in the building complex. As an innovation, the installation of geothermal energy cycles into unreinforced piles was realized by means of a specially developed distribution system. Combined it is one of the largest geothermal projects in Austria.

OPEN-LOOP GROUNDWATER HEAT EXCHANGER SYSTEMS



In an open-loop groundwater heat exchanger (GWHE), water is pumped from the ground and circulated through a heat pump – potentially with an additional intermediate heat exchanger – to exchange its sensible heat. The same flow is usually re-injected into the ground again. Free cooling without heat pump is generally possible under certain conditions.

1 PROVEN CONCEPTS

A HIDDEN POWER

Liquid water has one of the highest capacities of all available compounds on the Earth's crust to release or absorb sensible heat (c_p = 4180 J/kgK). For this reason, groundwater heat exchangers (GWHEs) are the best option over borehole heat exchangers (BHEs) (Figure 1), **when its exploitation is feasible**. Groundwater resources are not ubiquitous, and its use demands the most careful risk assessment among all non-storage SGE systems. However, there are several urban areas where a successful profit has been demonstrated with good aquifers, like in Zaragoza (Spain), with more than 100 MW_{th} of installed cooling capacity.

GWHE		BHE
1 l/s @ ΔT = 1 °C	=	105 m @ 40 W/m

Figure 1. Equivalent GWHE and BHE systems in terms of heat exchanging potential.

VERTICAL LIMITATIONS? GO HORIZONTAL

Horizontal injection wells are a good solution when there is a low hydraulic conductivity and limitations related to maximum drilling depth of the wells or a high extraction rate is wanted. A good example of its application can be found in the **Wirtschaftsuniversität Campus (Wien, Austria)**, where a set of 10 horizontal extraction wells provide a pumped flow of 150 l/s with a maximum drilled depth of 12 m (>3 MW_{th} installed).

WHY CHOOSING IF YOU CAN HAVE IT ALL?

Viertel Zwei district heating (Wien, Austria) has demonstrated that **GWHEs and BHEs can coexist successfully** in the same installation (210 kW_{th} and 450 kW_{th} installed, respectively). Moreover, additional heat sources/sinks are used, as wastewater and the Danube River itself using a surface water heat exchanger.

2 FUTURE CONCEPTS

"CLOSED-LOOP" GWHE

A recent new approach developed in Japan consists on installing **double U-Tube probes in artesian wells**. This is actually a closed-loop vertical BHE system, although it shows important differences. This scheme exploits the high upward flow of groundwater towards the surface, increasing the specific heat exchanging rate dramatically with respect to that of the soil surrounding the borehole (Figure 2).

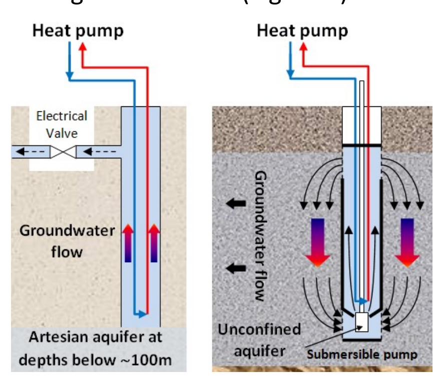


Figure 2. Left: BHEs in artesian wells (adapted from Shrestha et al., Energies 11 (2018) 1178). Right: Dynamic closed-loop solution.

In parallel, a Spanish company (DCL Geoenergia S.L.) is already implementing an **analogous**

solution called "Dynamic closed-loop" (DCL) designed for unconfined aquifers. In this case, a submersible circulating pump is installed in the borehole under the U-Tube probes (more than one loop per borehole), forcing a convective flow, which enhances the specific heat exchanging rate (more than 300 W/m is claimed for a single borehole).

3 GOOD EXISTING PRACTICES

SENSIBLE HEAT IN A SENSITITVE RESOURCE

A municipal measuring/testing point network is the key for an efficient management of groundwater as an energy resource:

- **Groundwater quality** (pH, hardness, alkalinity, calcium content). Water chemistry influences corrosion, scaling, fouling and potentially clogging of pipes and/or heat exchangers. It must be a guide for materials selection and **impacts feasibility, CAPEX and OPEX**. Contaminants and subsoil biological activity are also important aspects.
- **Groundwater temperature**. Below 10 °C free cooling is possible. Above 15 °C, HPs work efficiently in heating mode, **concerning efficiency and pay-back time**.
- **Piezometric level**. A smart network of measured values determines the flow direction of groundwater. Extraction wells should be located upstream. Neighbouring installations should be along the perpendicular direction to groundwater flow to minimise thermal interferences. **This must be considered in the design**.

OPTIMUM FLOW - MAXIMUM EFFICIENCY

The thermal energy exchange rate with groundwater (Q_{gw}) can be estimated by the well-known expression:

$$Q_{gw} = c_p \cdot \rho \cdot q_{gw} \cdot \Delta T_{gw}$$

Where c_p and ρ are, respectively, the specific heat capacity and density of water. q_{gw} is the groundwater flow and ΔT_{gw} is the difference between entering and leaving groundwater.

Compressors in heat pumps require less power consumption when ΔT_{gw} is low. But this implies an increase of q_{gw} to keep the same value of Q_{gw}. The higher q_{gw}, the higher the power consumption of well pumps. Hence **a smart design should find an optimum value for q_{gw}** that minimises the combined power consumption of heat pumps and well pumps (Figure 3).

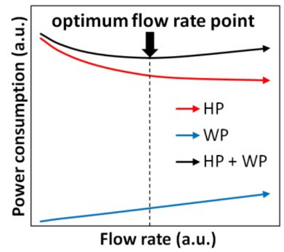


Figure 3. The flow rate is ideal when combined electrical power consumption of heat pump (HP) and well pump (WP) is at its minimum.

4 LESSONS LEARNED

A BUNCH OF GOOD ADVICES

The groundwater loop is often isolated from the building loop by means of **an intermediate heat exchanger** to keep corrosion/scaling problems away from the most expensive equipment and building pipes. Non-metallic pipes are then preferred for the groundwater loop.

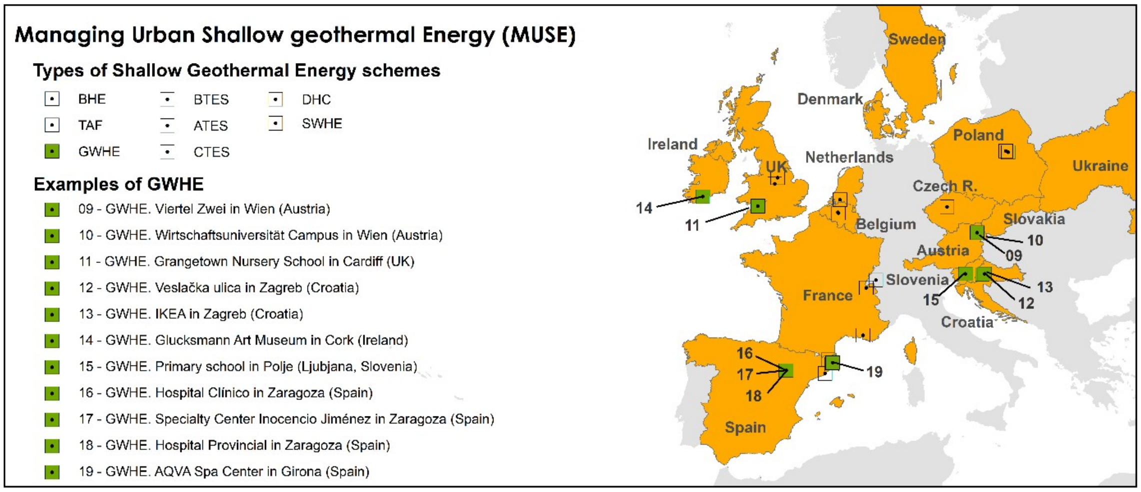
Injection temperature should be always above a safe threshold to avoid excessive condensation or even freezing and below the admissible temperature value for drinking water (5 - 20 °C).

Injection of used groundwater back to the aquifer is (and should be) the predominant option. It **avoids aquifer depletion** over time, **prevents subsidence** and contributes to a sustainable use of the resource.

Open water tanks for groundwater storage in surface must be **totally disregarded**. This could promote the entrance of oxygen (fouling ↑) and let dissolved CO_2 to escape (pH ↓, corrosion↑).

Hydrodynamics and water chemistry may change over time. **Favourable groundwater** analysis at the beginning of the project might **not be enough to guarantee a trouble-free operation** during the predicted lifetime of an installation.

5 EXAMPLES



GWHE-1. Viertel Zwei in Wien (Austria)

WIEN PILOT AREA

Location (WGS84 coordinates): N 48.212830 E 16.415016

	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	2377	229

Maximum flow [m^3/h]: 36
Minimum T_{gw} [ºC]: 5
Maximum T_{gw} [ºC]: 18

Depth of extraction [m]: 10 (2 wells)
Depth of injection [m]: 10 (2 wells)

	Heating	Cooling
Capacity installed [kW]	210	210
Demand [MWh]	5.6	2.4
Seasonal performance (SPF_{H2})	4.5	5.5

This shallow geothermal energy installation is part of a smart anergy grid, which combines borehole and groundwater heat exchangers, as well as wastewater and waste heat utilization, providing space heating, domestic hot water and cooling (with floor heating system and concrete core activation) to a complex of residential and office buildings (District Heating). Shallow geothermal energy alone meets 70% and 95% of the heating and cooling demands in the complex, respectively.

GWHE-2. Wirtschaftsuniversität Campus in Wien (Austria)

WIEN PILOT AREA

Location (WGS84 coordinates): N 48.213532 E 16.408565

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2377	229

Maximum flow [m^3/h]: 540
Minimum T_{gw} [ºC]: unknown
Maximum T_{gw} [ºC]: unknown
Depth of extraction [m]: 12
Depth of injection [m]: 10

	Heating	Cooling
Capacity installed [kW]	3000	3000
Demand [MWh]	unknown	unknown
Seasonal performance (SPF$_{H2}$)	unknown	unknown

Over 70 percent of the required energy in the WU campus is generated by shallow geothermal energy from the groundwater and it is one of the largest installations of its kind in Austria. Up to 150 liters per second are pumped from a set of 10 of horizontal filter wells. Heating is produced mainly with heat pumps, while cooling is carried out mainly as "free cooling". Peak loads and high temperature-heating is provided by a district heating network. Peak loads of the cooling demand are covered by heating/cooling machines and conventional heat exchangers.

GWHE-3. Grangetown Nursery School in Cardiff (UK)

CARDIFF PILOT AREA

Location (WGS84 coordinates): N 51.463459 W 3.179977

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2329	4

Maximum flow [m^3/h]: 1.52
Minimum T_{gw} [ºC]: 8
Maximum T_{gw} [ºC]: 10
Depth of extraction [m]: 22
Depth of injection [m]: 18.6

	Heating	Cooling
Capacity installed [kW]	22	na
Demand [MWh]	93.3	na
Seasonal performance (SPF$_{H2}$)	6.0	na

This groundwater heat exchanger installation used for active heating of a school building. The well doublet has a 20m spacing between extration and injection wells. Groundwater pertains to a confined shallow gravel aquifer, where water is pumped from a depth of 15 m and reinjected at a depth of 10m.

Overall heating output capacity is 22kW using two 11kW Dimplex heat pumps. The distribution system is based on wall mounted radiators. Additional back-up heating unit is an old gas boiler.

It is an example of public installation where performance and long term environmental impact on aquifer is being actively monitored and analysed.

GWHE-4. Residential building in Zagreb (Croatia)

ZAGREB PILOT AREA

Location (WGS84 coordinates): N 45.788304 E 15.956723

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2348	157

Maximum flow [m^3/h]: Unknown
Minimum T$_{gw}$ [ºC]: unknown
Maximum T$_{gw}$ [ºC]: unknown
Depth of extraction [m]: 9
Depth of injection [m]: 9

	Heating	Cooling
Capacity installed [kW]	Unknown	Unknown
Demand [MWh]	unknown	unknown
Seasonal performance (SPF$_{H2}$)	unknown	unknown

This is a new residential building with 119 dwellings with individualised heating systems based on heat pumps. The heat source is the groundwater from a shallow aquifer. 2 wells are used for the extraction and 3 wells for injection.

GWHE-5. Glucksmann Art Museum in Cork (Ireland)

CORK PILOT AREA

Location (WGS84 coordinates): N 51.894827 W 8.490414

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2537	0

Maximum flow [m^3/h]: 36
Minimum T$_{gw}$ [ºC]: unknown
Maximum T$_{gw}$ [ºC]: unknown
Depth of extraction [m]: 12
Depth of injection [m]: 12

	Heating	Cooling
Capacity installed [kW]	200	170
Demand [MWh]	384.5	112
Seasonal performance (SPF$_{H2}$)	4	3

Shallow geothermal energy installation used for simultaneous heating and cooling. The building has an area of 2350 m^2. The heat source is the underlying Sand and Gravel aquifer with elevated temperatures (~15 ºC) associated with the urban heat island effect. A groundwater heat exchanger system pumps water from a depth of 20 m. The open loop system is rated 170 kW and 200 kW for cooling and heating respectively against corresponding loads of 130 kW and 190 kW. Groundwater is used alternatively for toilet flushing and garden irrigation. Excess water is discharged to the nearby River Lee. Additional systems are: air handling units, an ancillary plant (two equally rated cold and hot loop circulating submersible pumps set at a depth of 12 m), ventilation and air circulation units, two gas boilers, and underfloor heating. Pay-back period was 6 years.

GWHE-6. Primary school in Polje (Ljubjana, Slovenia)

LJUBJANA PILOT AREA

Location (WGS84 coordinates): N 46.055133 E 14. 587578

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2649	93

Maximum flow [m^3/h]: 60
Minimum T_{gw} [ºC]: 11.3
Maximum T_{gw} [ºC]: 12.5
Depth of extraction [m]: 7.4
Depth of injection [m]: 7.4

	Heating	Cooling
Capacity installed [kW]	195.5	N.A.
Demand [MWh]	434.9	N.A.
Seasonal performance (SPF_{H2})	No data	N.A.

This is a very recent shallow geothermal energy installation (operated since 2019), which is used for heating (radiators with T_{in}=55 ºC) and domestic water production in the building (5202 m^2). Groundwater level is on average 10.9 m below the surface and the estimated thickness of saturated zone is 20 m. Water is reinjected into the same aquifer. Additional heating unit is a gas boiler (200 kW). 70% of the heating demand is met by the groundwater heat exchanger system.

GWHE-7. Hospital Clínico in Zaragoza (Spain)

ZARAGOZA PILOT AREA

Location (WGS84 coordinates): N 41.643574 W 0,903282

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	1790	269

Average flow [m^3/h]: 161.8
Minimum T_{gw} [ºC]: 25.0/19.2/8.4*
Maximum T_{gw} [ºC]: 35.5/29.0/35.0*
Depth of extraction [m]: 28
Depth of injection [m]: 24.3

	Heating	Cooling
Capacity installed [kW]	NA	8589
Demand [MWh]	NA	13290
Seasonal performance (SPF_{H2})	NA	2.9-3.6/3.5**

There are 4 production wells (3 in operation) and 2 discharge wells. The mean (undisturbed) temperature is 19ºC. There are two circuits in operation (cooling only): one for continuous operation (hospital) and one for discontinuous operation (external offices). The total installed power is 8.6 MW, although the maximum cooling capacity achieved so far has been 4.7 MW (oversized heat pump units).

The current groundwater heat pump was installed to replace the previous air-to-air unit. Other factors apart from the economic one were considered for the feasibility of the project. For example, the new configuration guarantees a null risk of legionella proliferation.

** The three values correspond to each of the 3 production wells / ** Hospital circuit and External offices circui, respectively*

GWHE-8. Specialty Center Inocencio Jiménez in Zaragoza (Spain)

ZARAGOZA PILOT AREA

Location (WGS84 coordinates): N 41.656434 W 0.909370

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	1790	269

Maximum flow [m^3/h]: 39.5/26.3*
Minimum T_{gw} [ºC]: unknown
Maximum T_{gw} [ºC]: unknown
Depth of extraction [m]: 10
Depth of injection [m]: 5

	Heating	Cooling
Capacity installed [kW]	1454	1306
Demand [MWh]	740	640
Seasonal performance (SPF_{H2})	unknown	unknown

This installation comprises two wells for extraction (35 m) and two more for injection (20 m). In Zaragoza there is an important deployment of grounwater heat exchanger systems, but mostly for cooling, which poses a risk of an excessive temperature rise of the groundwater. Installations like this help to equilibrate the heat exchanged with the groundwater through a well balanced heating and cooling loads.

**Heating and cooling flow rates, respectively*

GWHE-9. Hospital Provincial in Zaragoza (Spain)

ZARAGOZA PILOT AREA

Location (WGS84 coordinates): N 41.652275 W 0.887119

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	1790	269

Average flow [m^3/h]: 38.3
Minimum T_{gw} [ºC]: 18.5**
Maximum T_{gw} [ºC]: unknown
Depth of extraction [m]: 30 / 33*
Depth of injection [m]: 34.8

	Heating	Cooling
Capacity installed [kW]	NA	1400
Demand [MWh]	NA	1200
Seasonal performance (SPF_{H2})	NA	No data

In Hospital Provincial 2 production wells and 2 injection wells are used in the groundwater heat exchanger installation. A wellhead siphon is used to prevent air entry into the groundwater circuit.

**Injection 1 and 2, respectively / ** Value at the beggining of the exploitation, in 2011*

GWHE-10. AQVA Spa Center in Girona (Spain)

GIRONA PILOT AREA

Location (WGS84 coordinates): N 41.989106 E 2.825784

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	1718	219

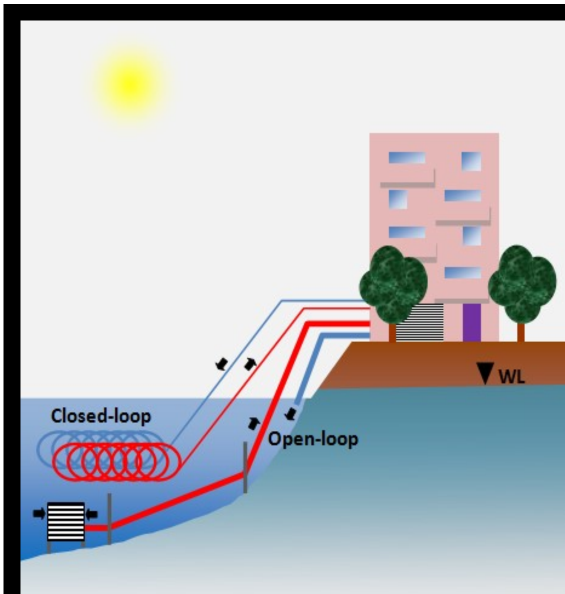
Maximum flow [m^3/h]: 8
Minimum T_{gw} [ºC]: 14.4
Maximum T_{gw} [ºC]: 15.4
Depth of extraction [m]: 18 / 20*
Depth of injection [m]: 18

	Heating	Cooling
Capacity installed [kW]	80	80
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	No data	No data

This a very unique groundwater heat exchanger system for several reasons. There are 4 wells (2+1 for production and 1 for injection) drilled in a very reduced space (8x25m^2). The Spa center was built from the remains of a ancient building located in the historic part of Girona city (it dates from Roman times). Simultaneous cooling, heating (dehumification) and domestic hot water is carried out by the installation (6-pipe system). The system is capable of meeting the entire demand, although it has a gas-boiler as a back-up unit. Two storage tanks (cool and warm water, 2500 liters each) and the air-treatment unit adds to heating/cooling infrastructure. Nevertheless, the system is totally integrated within the building boundaries, with no visible parts from outside. The extraction zone of the wells are not cased, since the soil is a consolidated rock formation (Limestone).

**Values correspondingto the 2 wells used for extraction (there is an additional well but it is currently unused with extraction depth at 18m)*

SURFACE WATER HEAT EXCHANGER SYSTEMS



In surface water heat exchanger (SWHE) systems, thermal energy is exchanged with large water bodies like rivers, lakes or the sea. Heat pumps are necessary mainly for heating. Both open- and closed-loop (OL & CL, respectively) options are possible. Upfront costs are lower than in groundwater heat exchangers (GWHEs), although surface water temperature is more variable.

1 PROVEN CONCEPTS

THE FIRST IN EUROPE

The first documented European project that could be considered as a shallow hydrothermal energy installation **was an OL-SWHE system** that used the water from Limmat River and a heat pump to meet the heating demand of the City Council in Zürich (Switzerland, 1938). **A modern example** can be found in a district cooling network in Tartu (Estonia, 13 MW_{th}).

TAPPING HEAT FROM SEA WATER

Seawater is a natural brine with its freezing point around -2 °C. This makes **OL-SWHEs at seaports a feasible option for heating in cold climates.** Värta Ropsten plant in Stockholm (Sweden) is the biggest of its class (180 MW_{th}). It provides hot water (80 °C), heating and cooling through a district heating network since 1988.

In Drammen (Norway) **the water of the fjord is used as the heat source**. This 60 MW_{th} district heating network was retrofitted in 2011 with new heat pump equipment (15 MW_{th}) that produces hot water at 90 °C (Fjord water is 8 °C). The refrigerant in the heat pump is ammonia. Thanks to the high outlet temperature, the old buildings did not have to replace their existing radiators.

IT LAYS DEEP IN THE LAKES

OL-SWHEs are the most common option in Europe when the water from lakes is used as the heat source/sink. Geneva (Switzerland) uses cool water from Lake Léman for "free cooling" (23.5 MW_{th}) and heating (3 MW_{th}).

Although **CL-SWHEs are far more common in North America**, in Europe a few examples can be found. Possibly the biggest one is King's Mill Hospital in Mansfield (UK, 5 MW_{th}).

2 FUTURE CONCEPTS

SEWAGE IS NASTY. HEAT IS NICE

Waste heat from the urban sewer network is **a yet little exploited resource,** although its recovery is not a novel concept. Average sewage temperature can be easily above 15 °C, and compared with surface water bodies, sewage temperature variations along the year is lower. Hence, **it is an ideal source for efficient heating**. Three exploitation schemes are identified:

- **In-place heat recovery**. The residual heat contained in wash water (grey water or sullage) from households can be recovered and upgraded by heat pumps before being thrown into the sewer. It is the most efficient option at small scale from the nearly zero energy building (nZEB) perspective.
- **Embedded heat exchangers in sewer pipes.** There are commercial solutions already available consisting of large concrete sewage pipes with embedded heat exchanger probes in their lower part of the wall. However, it means that an additional water flow is required to recover the residual heat. It is the best solution for new constructions or retrofitting old sewer pipes. Oriented to district heating networks.

- **Advanced heat exchangers.** They consist of intake stations at the desired location, where part of the sewage flows via a bye-pass to a heat exchanger. Heat exchangers operating with sewage are challenging, since sludge must be filtered first. Oriented to large buildings or district heating networks.

3 GOOD EXISTING PRACTICES

SENSIBLE HEAT IN A SENSITIVE RESOURCE

Leaving aside regulatory aspects, managers and project planners must be concerned about the following aspects (quantity and quality of the resource **influencing feasibility, profitability and limitations of use**):

- **Water balance:** Water inflows and outflows (rainfall, groundwater connections) and yearly volumetric variations in lakes (surface evaporation) and rivers.
- **Water temperature:** In-depth profiles of average temperatures along the year in lakes, rivers and the sea. This also influences the most suitable location for intake and outtake. In lakes also solar irradiation, night sky radiation, surface freezing and heat exchange with the ground influence the temperature.
- **Water quality** (pH, hardness, alkalinity, calcium content) is a bigger concern in OL-SWHE (more in seawater) than in groundwater heat exchangers (GWHE), due to dissolved oxygen and biological activity. Non-metallic CL-SWHEs avoid most of water-related problems except for fouling.
- **Biological activity** gains extra importance in SWHEs. Interaction with living creatures should cause minimal or no damage to them and keep equipment deterioration under an admissible level.

DESIGN PARALLELISMS

Conceptually, the **methodology involved in the design of an OL-SWHE and a GWHE are analogous**. Pumping power (Q_{pump}) and water temperature “jump” (ΔT_w) are the main drivers of optimization (see Factsheet 3). In contrast, the **design of CL-SWHEs (coiled pipes) has many points in common with borehole heat exchangers (BHE)** (see Factsheet 1). The main conceptual difference is in the heat exchange mechanism. Convection dominates in CL-SWHEs while conduction does in BHEs.

4 LESSONS LEARNED

LAKES ARE “PICKY”

Lakes require a deeper characterization than any other water body, mainly because it is a very static system, compared to rivers and the sea, and because water is a unique liquid. Its solid phase is lighter than the liquid one, and maximum density is achieved at about 4 °C. These two features drive water thermal patterns (Figure 1). As a result, **the intake should be placed at the bottom regardless of the season**.

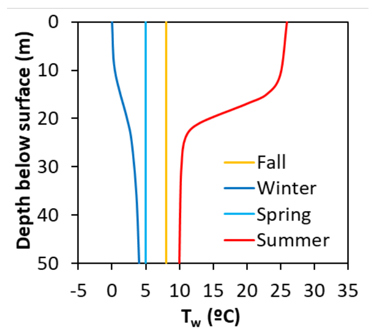


Figure 1. Ideal T_w depth profiles in a European lake.

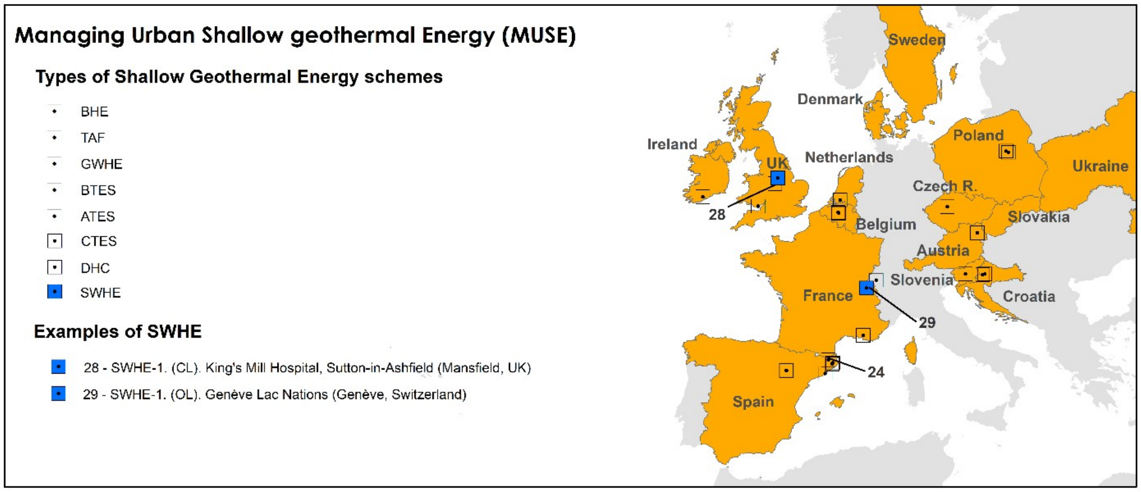
CL-SWHEs SHOULD BE THE CHOICE, BUT...

CL-SWHEs have a clear edge over OL-SWHEs. **The heat pump loop is isolated from the heat source/sink** (like in BHEs), so:

- Water chemistry becomes a minor concern.
- A lower temperature of operation under heating mode is permitted (even 0 °C).

Nevertheless, CL-SWHE systems should be discarded in rivers, mainly due to complex installation and maintenance (water inherent thrust and dragging of multiple objects). Only plate heat exchangers instead of coiled pipes could be a feasible option. **In seawater, CL-SWHEs are not recommended in locations with a high human activity**, like seaports or bays, since installation and maintenance would be tricky again due to the continuous operation of boats, ships and ferries.

5 EXAMPLES



SWHE-1 (CL). King's Mill Hospital in Sutton-in-Ashfield (Mansfield, United Kindom)

MANSFIELD

Location (WGS84 coordinates): N 53.135924 W -1.234571

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2539	2

Minimum T_{brine} [ºC]: unknown
Maximum T_{brine} [ºC]: unknown
Max./Min. $T_{reservoir}$ [ºC]: 21 / 3*

Depth of exchangers [m]: 4
Surface of exchangers [m^2]: 1560
Volume of the reservoir [Hm^3]: 8.3

	Heating	Cooling
Capacity installed [kW]	5000	5400
Demand [MWh]	unknown	unknown
Seasonal performance (SPF$_{H2}$)	unknown	unknown

This is the largest closed-loop surface water heat exchanger system in Europe. The heat source is the old King's Mill reservoir, which is an artificial lake close to the Hospital. 42 heat pumps are operated for space heating (45 ºC) and cooling (6 ºC). The brine exchanges heat with the water reservoir by means of plate heat exchangers (Slim Jim™ type) located at the bottom of the water reservoir.

** Surface temperature (2013)*

SWHE-2 (OL). Genève Lac Nations in Genève (Switzerland)

GENÈVE

Location (WGS84 coordinates): N 46.2277 E 6.1388

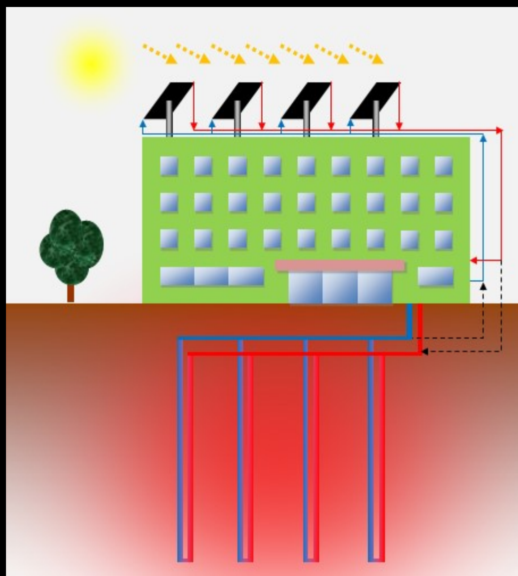
	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	3000	156

Maximum flow [m^3/h]: 2700
Minimum $T_{lake\ water}$ [ºC]: 6
Maximum $T_{lake\ water}$ [ºC]: 10
Depth of intake [m]: 37
Depth of outtake [m^2]: 4.5
Volume of the reservoir [km^3]: 89

	Heating	Cooling
Capacity installed [kW]	2900	16200
Demand [MWh]	5000	20000
Seasonal performance (SPF_{H2})	2.5	8.8

The bottom water of the lake Léman is pumped (open loop) to provide heating and cooling to a district heating and cooling network, with emblematic buildings like those of United Nations or the Red Cross. The pipes are made of stainless steel. Cooling is "free cooling" (no heat pumps involved). Compared to other shallow geothermal energy typologies, power consumed by circulating pumps is remarkable (the water is pumped through 6 km of stainless pipes from the lake to the different buildings). However, the low seasonal performance factor under heating mode is compensated by the high value obtained under cooling mode. The overall coefficient of performance is approximately 6.5 (considering heat produced + heat rejected divided by electricity consumed).

BOREHOLE THERMAL ENERGY STORAGE



In borehole thermal energy storage (BTES) systems, excess heat (e.g. from solar collectors, heat rejection from cooling in buildings, industrial processes, deep geothermal, etc.) is exchanged with the ground by means of a borehole heat exchanger (BHE) array. This causes a localised and sustained-over-time temperature raise in the surroundings. Thus, the stored heat can be used later during the cold season. The same principle is applicable to cooling, although it is less common.

1 PROVEN CONCEPTS

HEAT STORAGE WORKS!

The main advantage of BTES compared to aquifer thermal energy storage (ATES) is the much **larger availability of locations**. Investment costs are higher, mostly due to borehole drilling, but **flexibility does pay the difference**. BTES is also versatile in size, being a feasible and profitable solution from large buildings to very large installations and district-heating networks (E_{stored} = 0.5 to 10 GWh/year and more).

The first commercial BTES system worldwide was implemented at the campus of the University of Luleå (Sweden, 1983 - 1989). Heat source was the residual heat from a steel plant (maximum T_{in} = 82 °C). Since then, **BTES systems have gained popularity mostly in Northern Europe**, but also in the US and Canada. Most of the large systems **store residual heat from industrial processes and solar thermal collectors (STCs)** (T_{in} = 60-90 °C). However, there are also BTES systems with low temperature heat sources (T_{in} = 15-30 °C), like the heat rejected by buildings during the warm season (cooling). In this case, heat pumps are used.

SUN AND SOIL: NATURAL PARTNERS

In most climates the thermal loads are not balanced over the year and consequently the continued use of a ground source heat pumps for heating can decreased ground temperature in the long term and therefore lose efficiency. An option to tackle with this problem might be to increase the borehole depth, but this leads to an increase in the cost. The easiest alternative is storing heat in the ground with solar heat energy. In some cases, it is even possible to avoid the use of heat pumps (**"free heating")**. Maybe the most outstanding example is the **Drake Landing Solar Community in Okotoks (Canada, 2007)**. This installation meets more than 90% (100% in 2015-2016) of space heating with solar energy in a cold climate location, with no heat pumps involved ($T_{gr} \sim$ 55 °C after the first 5 years of operation).

2 FUTURE CONCEPTS

DEEP STORAGE AGAINST SHALLOW LOSSES

The presence of shallow aquifers can be an important limiting factor for BTES projects. **Advection thermal losses and conflicts of use (like drinking water use) are inherent risks**. The solution usually adopted is to drill a larger number of boreholes at a greater depth in order to avoid interaction with the shallow aquifer (Figure 1). However, this implies a larger land use, which poses a new challenge in densely populated urban areas.

A new concept is yet to be developed, called **medium-deep borehole thermal energy storage (MD-BTES)**. This will translate soon into a **pilot plant at the campus of the Technische Universität Darmstadt (Germany)**. The project will drill just 4 boreholes (~750 m) through the aquifer in order to reach the rock formation underneath. This way, the actual storage volume will be located beneath the **aquifer, which is expected to act as a top insulator layer**.

Theoretically, this solution minimises aquifer interaction, reduces thermal losses and reduces drastically the land surface required.

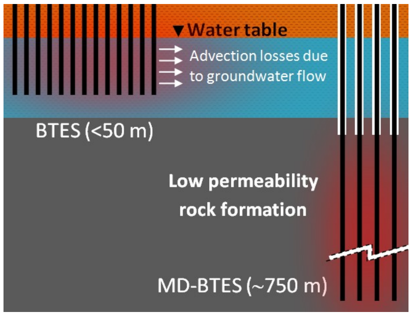


Figure 1. Schematic not to scale representation comparing shallow BTES (left) and MD-BTES (right). Adapted from Schulte D. O. et al., EGC 2019.

3 GOOD EXISTING PRACTICES

NOT STOPPED, BUT SLOWED

Thermal losses are inevitable in UTES systems, since they are **"open systems" from a heat transfer perspective**. Therefore, minimisation of heat losses is a crucial factor in the design, construction and operation of such infrastructures. In BTES, this translates into the **following requirements**:

- **Almost no groundwater flow** to avoid or minimise advection losses.
- **Maximised volume-to-surface ratio** of the storage volume. The ideal shape resembles a cylinder with equal height and diameter.
- **Optimised borehole distribution layout**. Hexagonal patterns perform better than quadratic ones (same borehole-spacing in less surface area), although the latter can be advantageous from the construction and operation perspective (see Figure 2).

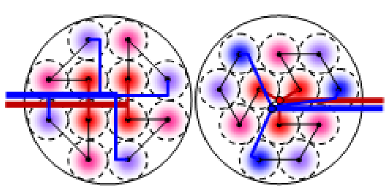


Figure 2. Quadratic and hexagonal layouts and proposed interconnections for a set of 12 boreholes. The position of the boreholes and their series connections are represented by black dots and lines. Red and blue lines represent the parallel connections.

- **Optimised borehole connection**. Radially symmetric grouped boreholes connected in series from the centre to the periphery favours heat concentration at the centre.
- **High volumetric thermal capacity (C_V) and low-moderate ground thermal conductivity (λ_{gr})**. By definition, a ground with high C_V is a "must" (>2 MJ/m^{3}K). Low-to-moderate λ_{gr} (1 - 2.5 W/mK) implies slow heat transfer rates, but also minimum conduction losses. However, high λ_{gr} (>3 W/mK) are preferred when high heat transfer rate is prioritised over low losses.

4 LESSONS LEARNED

NOT JUST A BUNCH OF BOREHOLES

A **warm-up or cool-down period of 3 to 6 years** is necessary for a BTES system in order to reach the new operating temperature in the ground.

It is highly recommended to **drill extra boreholes to implement an environmental monitoring** system (e.g.: ground temperature distribution and evolution).

A **buffer water tank** is the most reliable solution to be used on surface to **compensate for the slow response** in heat charging and de-charging.

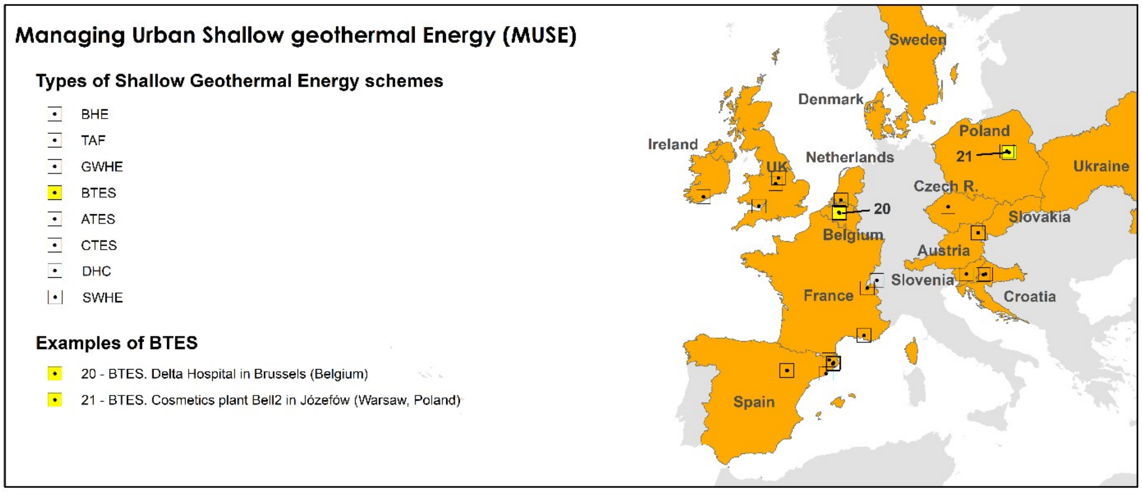
Regardless of λ_{gr} of the ground, **borehole thermal resistance should be minimised**. In locations with hard rock formations (Scandinavia), the water can flow in contact with the borehole walls in a coaxial configuration, but in many other cases, this is not possible and high thermal conductivity grouts are required around the probes. In U-tube probe configurations "shank-spacing" must be maximised.

The top part of the BTES is the most sensitive to ambient temperature variations. Insulation layers like hard extruded polystyrene (XPS), foam glass gravel for instance (as a cost-effective approach) should be implemented.

Cross-linked high density polyethylene (PEX) probes are preferred for BTES for its better performance at high pressure and temperature.

In practice, drift from the targeted drilling trajectory can easily reach more than 1cm/m, so **the risk of overlapping boreholes must be an input in borehole layout design**.

5 EXAMPLES



BTES-1. Delta Hospital in Brussels (Belgium)

BRUSSELS PILOT AREA

Location (WGS84 coordinates): N 50.816377 E 4.399962

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	2411	28

Initial $T_{brine\text{-}cool\ season}$: unknown
Initial $T_{brine\text{-}warm\ season}$: unknown
Undisturbed T_{ground} [ºC]: 12.2

Number of Boreholes: 176
Total length [m]: 15840

	Heating	Cooling
Capacity installed [kW]	600	450
Demand [MWh]	4.5	4.4
Seasonal performance (SPF_{H2})	4.5	4.5

The Chirec-Delta Hospital in Brussels is equipped with an oversized heating and cooling capacity. It has 7 MW$_t$ of condensing boilers (only 4 MW$_t$ are used by the hospital building), 0.6 MW$_e$ + 0.8 MW$_t$ from a cogeneration plant, a set of solar thermal collectors (100 m^2) plus the ground source heat pumps for heating and cooling. The excess heat is stored at the borehole thermal energy storage field or supplied to a district heating network that covers a commercial area.

BTES-2. Cosmetics plant Bell2 in Józefów (Warsaw, Poland)

WARSAW PILOT AREA

Location (WGS84 coordinates): N 52.141219 E 21.196917

source: Internet, M Kwadrat

	heating (15/18)	cooling (21/24)
Degree-days$_{2017-18}$ [ºC·days/year]	3254	30

Initial $T_{brine-cool\ season}$: 16

Initial $T_{brine-warm\ season}$: 22

Undisturbed T_{ground} [ºC]: No data

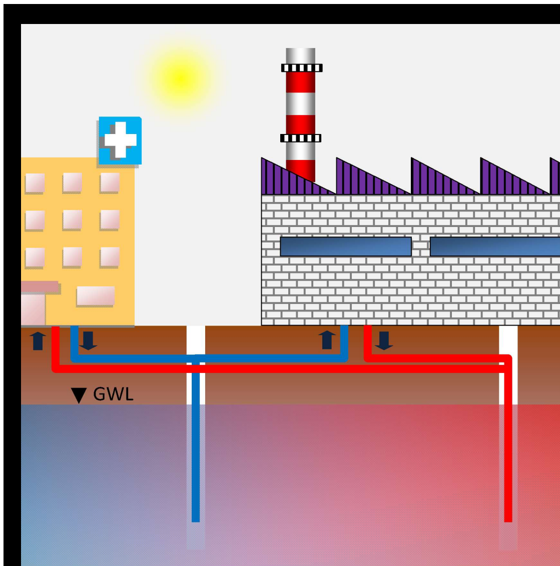
Number of Boreholes: 35

Total length [m]: 3500

	Heating	Cooling
Capacity installed [kW]	315	390
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	No data	No data

The main goal of the applied installation is the ability to recover the excess heat from the production machinery, store it in the ground and use seasonally for active heating and cooling of the facility. The heating and cooling system uses a cascade of ground source heat pumps of ~60 kW_t each. The system is also equipped with a “free cooling” solution, which enables operation in the cooling mode without using the GSHPs, so based only on the ambient temperature of underground. The local geological conditions are quite beneficial in the context of the GSHPs efficiency due to presence of a 40 m thick Pleistocene aquifer characterised by high values of thermal conductivity (>2 W/mK) and volumetric heat capacity (2.3 MJ/m^3K).

AQUIFER THERMAL ENERGY STORAGE



In aquifer thermal energy storage (ATES) systems, excess heat produced/rejected during summer (from solar collectors, building heat rejection, industrial processes, deep geothermal, etc.) is exchanged with groundwater, causing a localised temperature to raise in the water body. This allows a more efficient use of heat during winter (eventually "free heating") compared to groundwater heat exchangers (GWHEs).

1 PROVEN CONCEPTS

IF THERE IS WATER, USE IT!

Water is characterised by an outstanding energy storage capacity (per unit volume) compared to soils (Figure 1). This represents **an inherent advantage of ATES** over borehole thermal energy storage (BTES) **whenever an aquifer is present, and its exploitation is feasible.**

ATES		BTES
4.18 MJ/m^{3}K	↔	1.3-2.7 MJ/m^{3}K

Figure 1. Heat storage capacity of water (ATES) vs. soil (BTES).

First ATES systems were conceived in the 1960's in Shangai (China), although The Netherlands is currently a world leader in the deployment of ATES (> 2500 systems). They can follow different configurations, typically bi-directional systems, with a mono-well or a well doublet, allowing heat injection during summer for its use during winter and inject cold water during the wintertime for efficient cooling during summer.

SIZE MATTERS

ATES is oriented mostly to large **systems (> 100 kW$_{th}$ of installed power)**. The **minimum stored volume** to consider an economically viable ATES system is **around 0.1 hm^3**. Depending on its thermal losses, which are greatly determined by the **temperature** of the injected water and **ground flow characteristics**, this volume can oscillate. Besides, three exploitation schemes related to the storage water temperature (T_{in}) are commonly accepted:

- Low temperature **(LT)-ATES: < 30 ºC** (Example: **Klina Hospital, Brasschaat, Belgium)**. Heat source: Building excess heat.
- Medium temperature **(MT)-ATES: 30 – 60 ºC** (Example: **Dolfinarium Harderwijk, The Netherlands)**. Heat source: Residual heat from the combined heat and power (CHP) plant in the same building.
- High temperature **(HT)-ATES: > 60 ºC** (Example: **Reichstag building in Berlin, Germany)**. Heat source: Residual heat from a CHP plant nearby.

2 FUTURE CONCEPTS

GREATER POTENTIAL, GREATER CHALLENGE

Although nowadays there are few active HT-ATES systems worldwide**, the potential is clear**: given a certain amount of thermal energy required, the higher the temperature, the smaller the HP requirements. Furthermore, high temperature water implies **high quality heat**, which means that **"free heating" without heat pumps** is possible and the **range of applications is wider**. However, the list of challenges and potential risks also grow with T_{in}:

- Thermally induced chemical changes in groundwater composition favour the **precipitation of minerals and scaling**. This poses a greater restriction on groundwater chemistry (low carbonate content) or implies the **use of acids (HCl) for water treatment** to minimise scaling.
- Higher **distance between extraction and injection wells** is needed in order to minimise thermal losses. Alternatively, the

combination of a shallow (< 50 - 100 m; cold well) and a deep aquifer (> 100 - 150 m; warm well), reduces drastically the problem of land use, although the water mixing **between different aquifers** adds additional risks and has to be avoided.

- HT-ATES can affect the **microbiological activity** in groundwater severely.

3 GOOD EXISTING PRACTICES

DESIGN CONSIDERATIONS

Confined aquifers show advantages concerning **thermal isolation** and **temperature stability** along the year over unconfined ones. On the contrary, a **higher depth implies higher drilling costs** and generally higher pumping power, which depends on the piezometric level. In any case, the main technical requirements for an aquifer to admit feasible ATES projects are:

- Low groundwater flow velocity ($\mathbf{v_{gw}} \lesssim 25$ m/y).
- High hydraulic conductivity ($\boldsymbol{k} \gtrsim 10^{-5}$m/s) (sands, gravels, limestone). Note that high values of *k* also favour buoyancy flow and thermal losses. Hence, a trade-off is required.
- Favourable water chemistry at high temperatures.
- Minimum aquifer thickness of 20 m.

Distance between warm and cold wells (d_{W-C}) should be at least **three times the thermal radius (r_{th})** of the thermally affected volume:

$$r_{th} = \sqrt{c_w V / c_{aq} \pi L}$$

Where $\mathbf{c_w}$ and $\mathbf{c_{aq}}$ are water and aquifer volumetric heat capacity [J/m^{3}K], **V** is the volume of the injected water [m^3] and **L** is the length of the well screen [m]. Besides, **too long d_{W-C}** could cause large differences in hydraulic head, favouring **subsidence / differential settlement. Extra monitoring wells adjacent to injection and extraction wells** are necessary to monitor the temperature of the reservoir without the perturbations caused by the water flow as well as to control groundwater levels.

HEAT STORAGE vs. HEAT EXCHANGE

Some authors refer to GWHEs as "recirculation" systems within the ATES category, although there is a crucial difference: **GWHEs do not rely on underground heat storage.**

In ATES systems, the orientation of warm and cold wells with respect to the groundwater flow should avoid or minimise a thermal **short-circuit** between them. In GWHE systems, it is advised to place the extraction well upstream (Figure 2.).

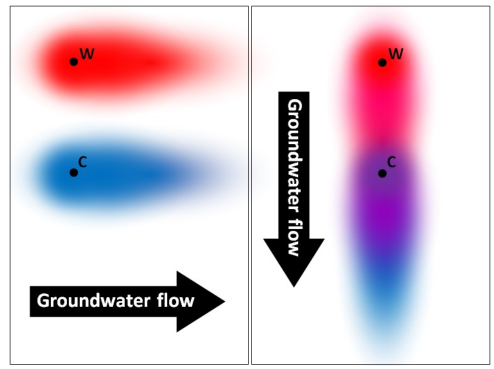


Figure 2. Illustrative representation of thermal plume evolution around the warm (W) and cold (C) wells, depending on the groundwater flow direction with respect to the well position. Left side scheme represents the ideal configuration in ATES systems. Right side scheme represents an ideal configuration for GWHE systems.

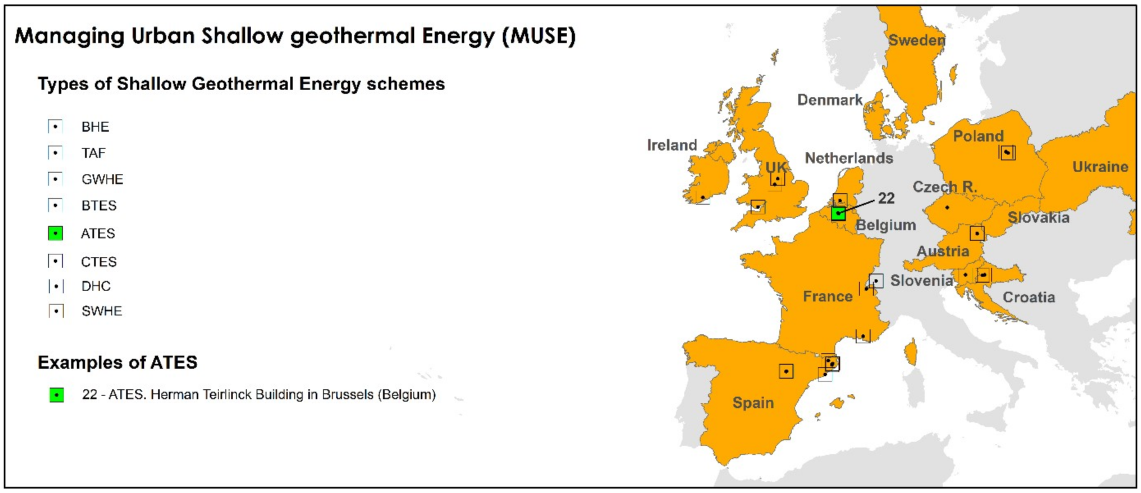
4 LESSONS LEARNED

RECOVERY EFFICIENCY IS THE KEY

Recovery efficiency η_{rec} (ratio of heat extracted to heat injected) and $\mathbf{T_{in}}$ are the most comprehensive **figures of merit that define ATES systems** and its performance (η_{rec} oscillates mainly between 40 and 60%). The minimum admissible value of η_{rec} to consider a project as viable depends mainly on the **cost of the injected heat** (e.g. heat from solar collectors vs. industrial processes), and the **value of the recovered heat** (low temperature water might require the use of heat pumps, high temperature water may not). The higher the cost, the higher the expected η_{rec} will be.

η_{rec} is not only driven by thermal losses in the aquifer, but a **good match between heat injection and heat demand**. Moreover, the minimum temperature at which groundwater is still usable (**cut-off temperature**) should be as low as possible. **This issue must be tackled in the planning phase**.

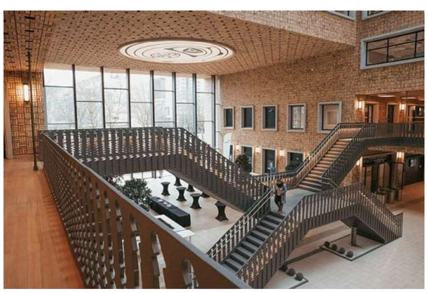
5 EXAMPLES FROM PILOT AREAS



ATES-1. Herman Teirlinck Building in Brussels (Belgium)

BRUSSELS PILOT AREA

Location (WGS84 coordinates): N 50.866171 E 4.350024



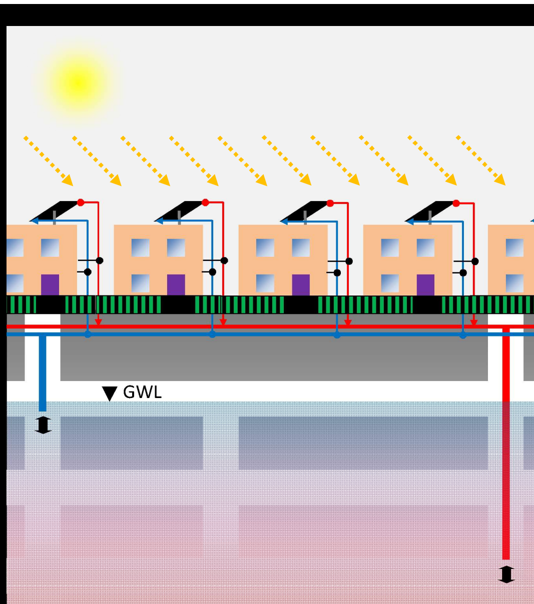
	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	2411	28

Maximum flow [m^3/h]:
Minimum T_{gw} [ºC]: No data
Maximum T_{gw} [ºC]: No data
Depth of extraction [m]: No data
Depth of injection [m]: No data

	Heating	Cooling
Capacity installed [kW]	No data	No data
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	No data	No data

The Herman Teirlinck Building was recently built for the Flemish Environment Ministry at Brussels (area called Tour& Taxis). The ATES system comprises 4 injection wells and 4 production wells.

(ROCK) CAVERN THERMAL ENERGY STORAGE



For rock cavern thermal energy storage (CTES) systems, the most common scenario is the use of an abandoned, naturally flooded mine as a heat sink for the excess heat produced during summer (e.g. from solar collectors, industrial processes, deep geothermal, etc.). A thermal gradient is induced into the water contained in the cavity network. The stored heat is extracted during winter.

1 PROVEN CONCEPTS

FREELY CONFINED WATER

Although CTES is the least common one among underground thermal energy storage (UTES) systems, it represents the most appealing option from an operational perspective. In the end, it is “nothing more” than a large mass of water contained in a medium with low thermal loss (the underground), so the **heat exchanging rates are the highest compared to aquifer or borehole thermal energy storage (ATES and BTES, respectively) systems**. However, **the occurrence of sufficiently large cavities** (> 0.01 hm³) is **neither common** (in the case of natural caves with no specific use restrictions), **nor economically feasible** (the cost of cavities excavated on purpose is one order of magnitude higher than that of an equivalent BTES system).

Therefore, CTES projects can only prosper in existing, human-made cavities, like **flooded old mines**. Not in vain CTES is also known as mine-thermal energy storage (MTES).

Besides thermal energy storage applications, mine water in flooded mines is used in many cases as **a low enthalpy geothermal resource**, given the large depth of extraction (500 - 1000 m), which provides between 10 and 30 °C extra degrees only due to the geothermal gradient (20 - 30 °C/km). **This should not be confused with a storage concept**.

A RESOURCE DIFFICULT TO SPOT

The **Lyckebo project** (Uppsala, Sweden) can be identified as the only operating CTES system based on an artificial cave that was specifically excavated for thermal energy storage purposes. In contrast, several old mines have been already reconverted in Germany, The Netherlands or Canada, most of them **oriented to district heating (DH) networks**.

The Lyckebo CTES system is based on an excavated volume of 0.1 hm³, allowing an energy storage of up to 5.5 GWh/year with a storage temperature T_{in} between 60 and 90 °C. The heat source was originally a field of solar collectors, but now is the residual heat from a combined heat and power plant. The cost was about 45 €/m³.

The project **Minewater 2.0 in Heerlen** (The Netherlands) is a representative example of an old mine re-utilisation. It started as a pilot plant back in 2008 for cool (16 °C, 250 m depth) and warm (28 °C, 700 m depth) mine water extraction from a flooded abandoned mine. In 2013, the pilot plant was upgraded to a cool and warm CTES system, combined with an intelligent DH network, where heat can be exchanged directly between buildings. The old mine is used in case of excess or shortage of heat and cold.

2 FUTURE CONCEPTS

FUTURE CONCEPTS: FUTURE PROJECTS

As seen in the previous paragraphs, the use of flooded old mines for CTES is not a new concept, but a concept yet to be exploited. Therefore, future concepts here mean “future projects”. In the current context of coal phase-out, many coal-mining areas across Europe represent a vast potential. Some examples with an historic mining activity and comprising notorious urban areas are the Central England (UK) and the Ruhr region (Germany).

OIL RESERVOIRS WITH A GREEN FUTURE

In Kruunuvuorenranta, or Kronobergsstranden (Helsinki, Finland), it is projected to re-use **two caverns formerly used as oil reservoirs** (excavated in the 1970's) to store seawater during the summer and use it during winter as a heat source for a heat pump-based DH network. The total volume is 0.3 hm^3 and it is located between 20 and 50 m below the sea level. The idea is simple but powerful: **storing seawater when it is warmest into the underground (>20 °C in August)** is a straight way to store solar thermal energy, indeed.

3 GOOD EXISTING PRACTICES

In contrast to excavated caves, old abandoned mines consist of a 3D intricate network with tunnels and wells, which is **far from an optimised shape to minimise thermal losses**. Hence, a relatively low temperature difference (10 - 20 °C) compared to the undisturbed ground temperature will favour a low thermal loss scenario. Since the optimum temperature depends on many factors (hydrogeology of the location, volume of stored water and its 3D distribution), simulation becomes an essential tool to assess the actual storing potential.

Also because of the specific configuration of a mine, it might be justified to **allocate the warm reservoir at the deepest part of the mine**:

- **Buoyancy flow is limited** due to the twisted path that water must follow through the tunnel network.
- In cases where deep mine levels already exist (>500 m), significantly better conditions for heat storage will be achieved at the bottom **thanks to the geothermal gradient**.
- **Lower environmental risks** (temperature driven biological processes or thermal interaction with shallower aquifers).

The mine water level should not be excessively deep (< 100 m). An excessively high hydraulic head implies a too high pump power, reducing overall coefficient of performance and endangering economic profitability. However, there are several variables driving this decision. Given a certain heat-exchanging rate, different configurations of pumping flow and temperature difference (ΔT) leads to large differences in efficiency (see Figure 1).

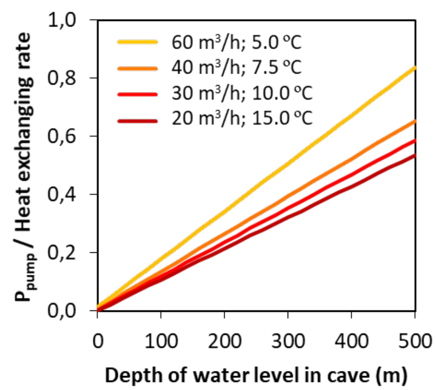


Figure 1. Ratio between pumping power and heat exchanging rate vs. depth of water level below the surface. Different pump flow and ΔT configurations are compared. Heat exchanging rate is ~350 kW_{th} in all cases. Pump power is calculated for pure water flowing through $Ø_{ID}$=6" steel pipes and $\eta_{e\text{-}m}$=40%.

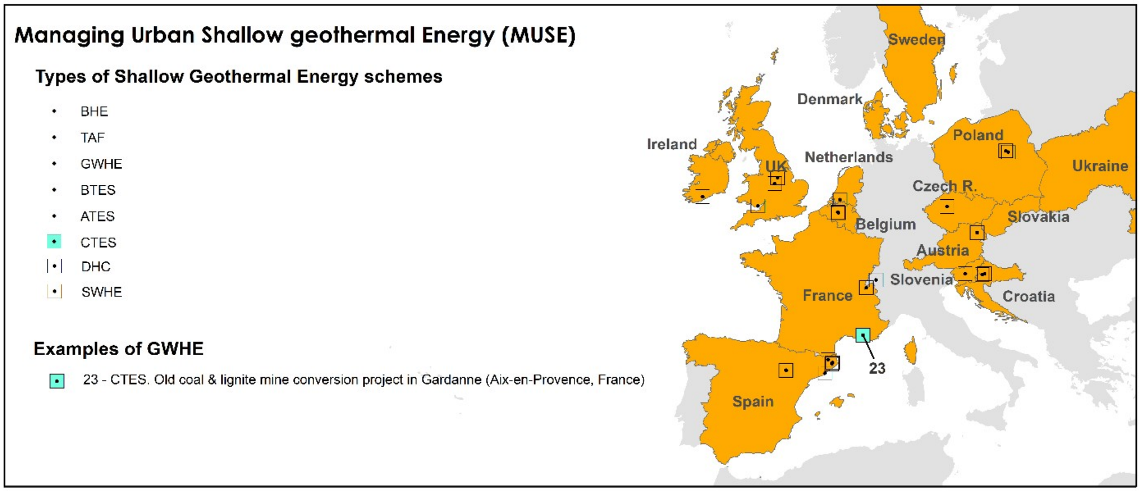
4 LESSONS LEARNED

When new UTES are conceived, subsidence events related to old mining areas must be considered. Hence, **geotechnical studies and further ground monitoring installations should be implemented**.

Those abandoned mines where a water pumping infrastructure remains active for environmental reasons (for example, in order to avoid mineralised mine water mixing with shallower aquifers) should receive special attention. The cost of this pumping is an externality, so it makes sense at least to **compensate this energy expenditure by the energy that could be stored or extracted in/from the mine water**.

Existing operative mines should receive probably as much attention as old ones. The exploitation of many of these caverns across Europe might get to an end in the next 5-10 years. From a practical point of view, an **early resource assessment** when the mines are still accessible will surely help to a smarter and more efficient transition in its use.

5 EXAMPLES



CTES-1. Old coal & lignite mine conversion project in Gardanne (Aix-en-Provence, France)

GARDANNE PILOT AREA

Location (WGS84 coordinates): N 43.451893 E 5.448345

	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	1476	272

Maximum flow [m^3/h]: 50

Initial $T_{gw\text{-}cool\ season}$ [ºC]: No data

Initial $T_{gw\text{-}warm\ season}$ [ºC]: No data

Depth of extraction [m]: 330

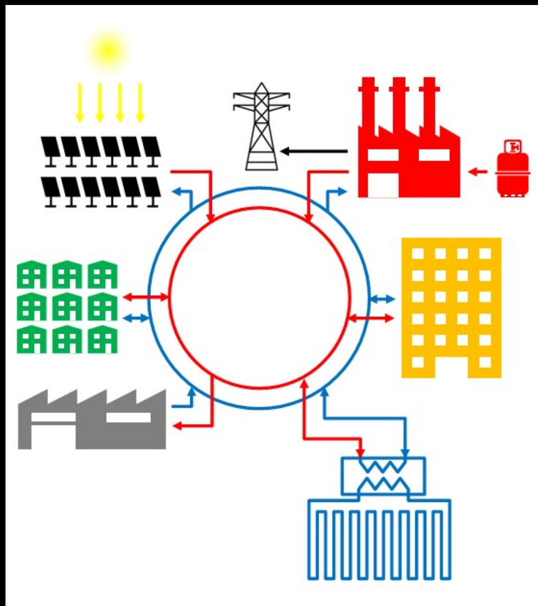
Depth of injection [m]: 1100

Reservoir volume [m^3]: 65000

	Heating	Cooling
Capacity installed [kW]	500 (simul.)	500 (simul.)
Demand [MWh]	2.1 (calculated)	1.3
Seasonal performance (SPF_{H2})	no data available	no data available

The utilization of the minewater from the old mine is part of a large project for the conversion of this obsolete installation within the project "Pôle Yvon-Morandat". The minewater is pumped at 330 m of depth and re-injected at 1100 m, creating a loop where heat is exchanged in a titanium heat exchanger. At the other side of the heat exchanger, water is circulated and deposited in 2x50 m^3 storage tanks, from where a temperated water network will be used for heating and cooling (depending of the season) multiple buildings by using heat pumps. Photovoltaic solar panels will provide 100% renewable electricity to the buildings, and excess power will be used to pump the water from the extraction well. The storage tanks favours low thermal losses and an optimized utilization of photovoltaic solar panels. The balance between extracted and injected heat into the minewater reservoir is expected to be null.

SGE IN DISTRICT HEATING AND COOLING NETWORKS



District heating and cooling (DHC) grids are large projects (1 - 100 MW_{th}) where thermal power sources/sinks of different types are shared by a network of nearby buildings (office buildings, dwellings, hospitals, factories, etc.). Heat can be supplied and rejected to and from the buildings, but also between them (smart grids). In this context, shallow geothermal energy (SGE) can play a major role due to the versatility and high efficiency of its different exploitation schemes.

1 PROVEN CONCEPTS

The concept of district heating (DH) has evolved since the nineteenth century, always obeying the same principle: **the economy of scale applied to efficiency**. 4 different generations (G) of systems are identified throughout history:

- **1st GDH: Pressurised water steam at temperatures < 200 °C**. The most famous and largest example is in Manhattan (New York, USA), operative since 1882.
- **2nd GDH: Pressurised water at temperatures 100 - 200 °C**. Mostly deployed in Eastern Europe. Combined heat and power (CHP) plants (Fossil fuel-fired) were the most common heat source.
- **3rd GDH: Hot water at temperatures 80 - 100 °C**. Renewable sources such as geothermal (direct heating or driven by large heat pumps) or solar energy.
- **4th GDH: Hot water at temperatures 50 - 70 °C**. Fancoils, modern radiators and radiant floors allowed reducing significantly the minimum temperature needed for the heat carrier fluid. Consequently, transport losses were greatly reduced, more renewable energy sources and other heat sources present in urban environments could be incorporated (waste heat from a wider range of industries and CHP plants burning waste). Absorption chillers were also used to create the first DHC networks. **Centralised SGE installations such as large heat pumps as well as underground thermal energy storage (UTES) systems** for seasonal energy storage are among the many possibilities of conceiving a modern DHC.

2 FUTURE CONCEPTS

5th GENERATION DHCs

In the current energy transition context, a growing complexity is observed due to:

- Increase in renewable energy generation
- Distributed generation of energy
- Energy efficiency pushed to its very limits

All these issues converge in a recent category: **the 5th generation of DHC (5GDCH) networks**. 5GDHC networks are those where the heat exchanger fluid is water at a neutral temperature (close to that of the medium through which is transported, between 10 and 25 °C), and small-to-medium size water-to-water heat pumps are installed at each building of the network. The changes with respect to previous schemes are remarkable:

- **Change from centralised generation to distributed generation**. Easier extension of the network, although at a higher investment cost per connection point.
- **Almost null heat losses due to transport** in cost-effective pipe circuits.
- **Buildings both provide and consume heat** as so called **"prosumers"**. A recent example is the project Minewater 2.0, in Heerlen (The Netherlands).

SGE IN DISTRICT HEATING AND COOLING NETWORKS

- **Heating and cooling to different eras of buildings** (old/retrofitted or new) can be done in the same network through heat pump tailored solutions.

POWER TO HEAT

It is well-known that **100% renewable-based power systems are non-viable without a large storage infrastructure** supporting them, due to the intermittence of important sources like wind and solar energy. SGE facilities combined with UTES offer an efficient and cost effective alternative for managing district heating and cooling grids. **Heat pumps in DHC can be driven by the surplus electricity** from intermittent wind and solar photovoltaics with the use of batteries (essentially during low-price hours), which **stores the heat or cold generated in the UTES** system for its later use.

3 GOOD EXISTING PRACTICES

A PLAYGROUND FOR ENERGY PLANNERS

SGE in any of its application schemes as a heat source and/or sink has the potential to be implemented almost everywhere in Europe for DHC purposes:

- **Groundwater heat exchangers (GWHEs):** Bound to large aquifers with low hydraulic head (< 50 m) in inland areas.
- **Surface water heat exchangers (SWHEs)**: Ideal heat sources/sinks close to large water bodies (rivers or lakes) or close to the coast areas.
- **Vertical borehole heat exchangers (BHEs)**: Feasible almost everywhere. When water is not present or not exploitable, BHEs still have an opportunity if thermal conductivity shows a minimum reasonable value (1.5 - 2 W/mK).

Concerning **UTES**, DHC networks can benefit mainly from two perspectives:

- Regardless of the heat source or sink of the DHC network, an efficient **seasonal storage allows an effective increase in usable energy with the same installed capacity**.
- When different and **complementary building demands coexist** in the same network (office buildings, households, industries, commercial areas, hospitals or data centres), **cold and warm reservoirs in thermal storage systems of any kind act as large buffer tanks**. This allows an effective heat exchange between the buildings themselves. In this sense, **fast heat charge and discharge systems as ATES and CTES** are the best option from the operational perspective.

4 LESSONS LEARNED

FROM BUILDING TO BUILDING

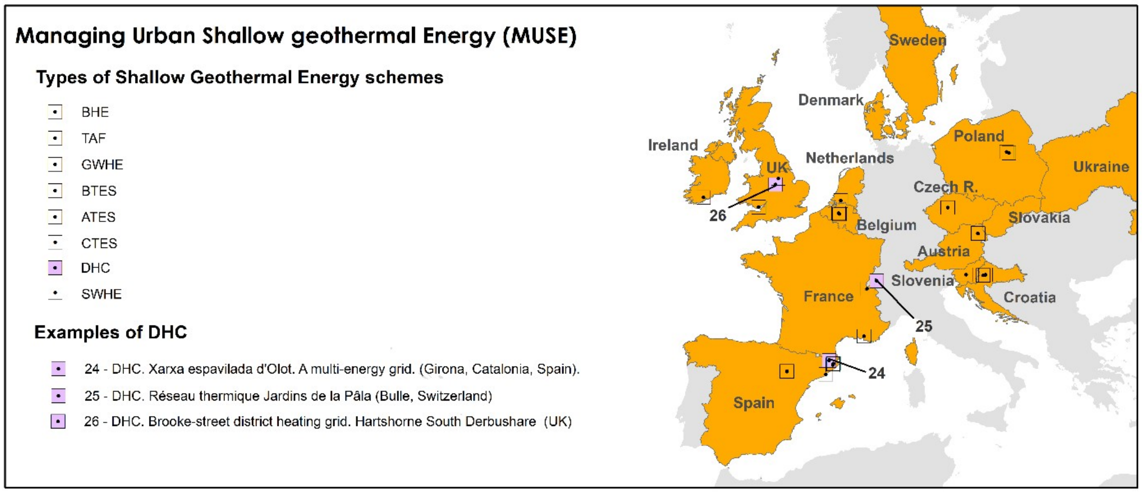
The ideal DHC network should require a minimum heating/cooling infrastructure, favoured by:

- **A smart management of the urban energy metabolism**. At a local scale, it is more efficient to transport heat between different buildings than to produce or reject it from or towards a heat source or sink.
- **Non-simultaneous peak demand patterns among the different buildings**. Peak loads of different buildings taking place at different moments of the day will minimise the required overall installed capacity in centralised DHC networks.

ENERGY AND URBANISATION

Mostly during the second half of the past twentieth century, energy infrastructure planning was characterized by a growing disconnection with urbanisation, due to the centralised production of electrical energy and the reliance on fossil fuels. In other words, **energy infrastructure adapted to urbanisation**. However, in the present context where a circular and de-carbonised economy is pursued, **energy infrastructure planning must be considered an essential piece in future urbanisation patterns**. In this sense, DHC networks will surely gain prominence in the forthcoming years. In particular, **SGE and UTES** systems are postulated as modern and renewable **energy sources and tools**.

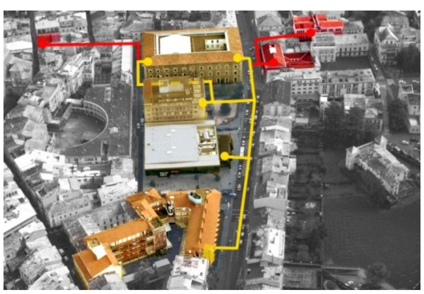
5 EXAMPLES



DHC-1. Xarxa Espavilada (Smart Grid) in Olot (Girona, Spain)

GIRONA PILOT AREA

Location (WGS84 coordinates): N 42.180841 E 2.487193



	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	1718	219

SGE contribution: multi-grid energy DHC (geothermal, biomassa and PV)

Number of Boreholes: 24

Total length [m]: 2400

T_{gr0} [ºC]: 15

T_{flow}/T_{return} [ºC]: 90/60 (heating), 5/15 (cooling)

	Heating	Cooling
Capacity installed [kW]	180	180
Demand [MWh]	~3400	No data
Seasonal performance (SPF_{H2})	No data	No data

The "Xarxa Espavilada d'Olot" is a District Heating and Cooling (DHC) multienergy grid located in the town of Olot (Girona, Spain) that combines: Shallow geothermal energy (60 kW_{th} ground source heat pumps x 3 = 180 kW_{th}) + Biomass boilers (600 kW_{th}) + Solar PV panels (28.8 kW_p), i.e. it is a trigenaration thermal energy grid based on three renewable energy sources. It is the first of its class in Catalonia and has a very important side-objective in promoting the use of renewable energy sources in the city of Olot and beyond. There are two storage tanks of 8 m^3 each and has back-up unit is a gas boiler of 700 kW_{th}, that at the moment never has been used. The DHC supplies simultaneusly heating and cooling to several public buildings in the city centre (a market, a hospital and a regional museum, among others).

DHC-2. Jardins de la Pâla in Bulle (Switzerland)

BULLE

Location (WGS84 coordinates): N 46.6151 E 7.0393

	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	4000	50

SGE contribution: De-centralised GWHEs (3+3 prod. and inj. wells)

T_{gw} [ºC]: 8-12 Depth of extr./inj. [m]: 50-65

T_{flow} [ºC]: 35-40 (heating), 60 (Domestic Hot Water)

	Heating	Cooling
Capacity installed [kW]	2000	NA
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	No data	No data

According to Buffa et al (2012*), this is an example of the new concept 5th Generation District Heating and Cooling (5GDHC) network comprising a set of new residential, industrial and commercial buildings. Groundwater is used as the only heat source/sink by means of individualised heat pumps. While heating is carried out by heat pumps, cooling is passive (de-centralised heat exchangers separating groundwater flow from building brine flows). Up to 240 m^3/h can be extracted from the 3 extraction wells, in total.

(*) Buffa et al 2012. 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews 104 (2019) 504–522. https://doi.org/10.1016/j.rser.2018.12.059

DHC-3. Brooke Street - South Derbyshire (UK)

Hartshorne South DERBYSHARE

Location (WGS84 coordinates): N 52.7888 W - 1.524723

	heating (15/18)	cooling (21/24)
Degree-days$_{2017\text{-}18}$ [ºC·days/year]	3077	0

SGE contribution: Centralised ground source heat pumps (GSHPs)

T_{ground} [ºC]: 6-12 Number of Boreholes: 28

$T_{condenser}$ [ºC]: 60 Total length [m]: 2800

	Heating	Cooling
Capacity installed [kW]	120	NA
Demand [MWh]	No data	No data
Seasonal performance (SPF_{H2})	3.2. (design)	No data

Brooke Street is an off-gas grid area on the edge of a rural village: Hartshorne, in South Derbyshire. A small heat pump in district heating installation was implemented in 2012 to serve 18 existing local authority flats (built in 1982). The previous heating strategy had been carried out by all-electric storage heaters. Due to numerous complaints about the high running cost of these systems and the low level of control, it was decided to explore renewable energy solutions and obtained an RHPP grant to cover part of the cost of the heat pump in district heating installation. The system provides space heating and domestic hot water (DHW) to each flat. The flats were all retrofitted with low temperature radiators so that the space heating supply temperature can be kept as low as 55 °C. The system temperature is raised to 60 °C for a period every night to heat the DHW cylinder to mitigate Legionella risks. Two plant rooms have been installed, one serving six flats and the other serving twelve flats. Each heat pump also has a 100 l thermal store. Three blocks of six flats (18 falts in total) are served from three ground source heat pumps (40 kW$_{th}$ each) coupled to a common ground loop served by 28 boreholes, each 100 m deep.

APPENDIX IV GLOSSARY OF TERMS

Aquifer Thermal Energy Storage (ATES)

It is the seasonal heat storage in either a natural- or an artificial aquifer based on open loop systems. For heat storage (warm season), the groundwater is extracted from a cold reservoir and injected into a hot reservoir after it is heated up by an external source (solar collectors, residual heat from industry, etc.). During the cold season, the direction of groundwater flow is reversed, flowing from the warm reservoir to the cold reservoir.

Borehole Thermal Energy Storage (BTES)

It is the seasonal heat storage in a certain ground volume. Heat is injected and released into/from the ground through a set of borehole heat exchangers located closely together. The geometry of the borehole heat exchanger field and the pattern of brine/water circulation is devoted for achieving the highest temperature possible at the inner core of the ground volume and to keep it if possible, in order to minimise thermal energy losses.

Borehole Heat Exchanger (BHE)

It is a type of ground source heat exchanger where a borehole is drilled at depths ranging typically between 50 and 200 m (although they can be deeper). It consists of a heat transfer fluid (brine or water) that circulates through a probe embedded within the borehole (buried, grouted or in direct contact with groundwater). The probes can be usually a simple or double U tube, but also two coaxial pipes

Capital Expenditure (Investment costs) (CAPEX)

It is one-off expenditure that results in the acquisition, construction or enhancement of significant fixed assets including land, buildings and equipment that will be of use or benefit for more than one financial year.

(Rock) Cavern Thermal Energy Storage (CTES)

It is the seasonal heat storage in free water contained in naturally or artificially excavated underground volumes. The operation is analogous as in aquifer thermal energy storage systems. Most of the existing systems of this type are based in abandoned old mines that have been naturally flooded.

Alternative nomenclature: **Mine Thermal Energy Storage (MTES)**

Closed-Loop (CL) System

Closed loop systems are those where the heat transfer fluid is isolated with the heat source/sink medium. Borehole heat exchangers, thermo-active foundations and closed-loop surface water heat exchangers fall within this category.

District Heating and Cooling (DHC) network

Traditionally, it is the centralised production of heat and cold which, through a system of networks that transport thermalized fluids, satisfies the demand for heating, cooling and DHW for the users connected to the network. District heating and cooling networks comprise areas typically smaller than 10 km2. In modern DHC networks, the heat exchanging fluid is close to ambient temperature, so heat and cold is produced in-place (at each building or dwelling) by means of heat pumps. A smart management of these networks allows the exchange of heat between building themselves.

Domestic Hot Water (DHW)

It is water intended for human consumption (drinking, cooking, hygiene and sanitary purposes) that has been heated, in any type of building. Normally the water comes from the building's water installation. This definition does not include space heating or swimming pool heating.

Helical Heat Exchanger (HHE)

It is a subtype of borehole heat exchangers where the probe configuration consists of a helicoid buried/grouted with a depth typically between 10 and 30 m. In this case, the borehole internal diameter is between 30 and 50 cm. In practice, it behaves like a mixture between a horizontal and a vertical borehole heat exchanger.

Horizontal Heat Exchanger (HorHE)

It is a type ground source heat exchanger system where a heat carrying fluid circulates through a set of buried probes to a depth usually between 1 and 2 m and comprises a piece of land usually from several hundreds of m^2 to a few hm^2. Compared to vertical borehole heat exchangers, horizontal heat exchangers require lower upfront costs, although their main limitations are related to the use of land and the efficiency, which is more affected by meteorological conditions.

Ground Source Heat Exchanger (GSHE)

It is a heat exchanger system where generally a liquid-phase fluid circulates in direct (open-loop) or indirect (closed-loop) contact with the subsurface. The heat exchanged with the medium (saturated/unsaturated soil, groundwater or surface water, mostly) is used for heating (heat extraction) and cooling (heat dissipation) purposes.

Ground Source Heat Pump (GSHP)

Heat pump device that uses the subsurface as an energy source or sink. The most common types are brine-to-water and water-to-water units, although it is also common brine-to-air and water-to-air devices. Direct expansion ground source heat pumps are a case where the heat transfer fluid coincides with the internal refrigerant fluid of the heat pump.

Groundwater Heat Exchanger (GWHE)

It is a type of ground source heat exchanger where heat is exchanged with the water extracted from an excavated well in a confined or unconfined aquifer. This water is circulated directly or indirectly (via an intermediate heat exchanger) through the heat pump unit. Afterwards, the water is injected back into the aquifer, usually at a different well located downstream.

Leaving Liquid Temperature (LLT)

In the context of ground-source heat pumps (GSHPs) operation, it is temperature of the fluid leaving the heat pump device before exchanging heat with the ground, either at its evaporator stage (heating mode) or at its condenser stage (cooling mode).

Open-Loop (OL) System

A type of shallow geothermal system which uses the heat stored in groundwater bodies. An extraction well pumps water to the surface; this passes a heat exchanger and is returned to the aquifer via an injection well. If designed accordingly, the system can provide heating and/or cooling.

Operational Expenditure (OPEX)

Those costs which are necessary for the operation of an installation throughout its lifespan. It comprises mainly the cost of fuels (electricity, gas, etc.), insurance, maintenance/repair, management and monitoring costs. It does not include the replacement of entire equipment like buffer tanks or heat pumps or decommissioning.

Shallow Geothermal Energy (SGE)

SGE is understood as a thermal energy recovered from the subsurface with the use of heat pumps, in both open and closed systems, for heating, cooling (free cooling as well as ground source-based chillers) and thermal energy storage. It is also called near surface geothermal energy or low-temperature (low-enthalpy) geothermal energy into the European energy mix

Specific Heat Exchange Rate (SHER)

In closed-loop systems, it is the linear/surface density of heat transfer rate between the ground source and the heat carrying fluid that circulates through the heat exchanger. It is expressed in units of energy per unit length in BHEs (W/m), where the length to consider is its depth, not the length of the probes embedded within. The same applies to energy piles. In TAFs based on diaphragm walls, SHER is expressed in units of energy per unit surface (W/m^2), where the surface to consider is just one face of the TAF structure. In HorHE and closed loop SHWEs the utility of this concept can be blurred due to the multiple configurations of the probes (slinky, coiled, straight tubes or plate heat exchangers).

Surface Water Heat Exchanger (SWHE)

It is a type of ground source heat exchanger that consists of exchanging heat with the water contained in large bodies like rivers, lakes or the sea. There exists both open- and closed-loop configurations. In the case of open-loop systems, water can be circulated directly through the heat pump unit or indirectly by means of an intermediate Heat exchanger (IHE). This is especially necessary when the water chemistry can potentially obstruct or deteriorate the heat exchanger stages (Evaporator/Condenser) within the heat pump, like in the case of sea water. In the case of closed-loop systems, the heat exchanger structure (slinky coils or plate heat exchangers) is submerged into the water body.

Thermo-Active Foundation (TAF)

It is a type of ground source heat exchanger that consists of embedding heat exchanging probes into the subsurface concrete structures that act as the foundations of a building, like piles and/or diaphragm walls. Therefore, the same elements present a double function: structural as well as energetic.

Synonyms: “Thermo-Active Buildings Systems (TABS)”; “Thermo-active Ground-Source Structures for Heating and Cooling”; “Thermal piles”; “Energy-piles”, “Building Integrated Geo-exchangers (BiGEO)”.

Technology readiness levels (TRL)

Technology readiness levels (TRLs) are a method for understanding the technical maturity of a technology during its acquisition phase.

Thermal Response Test (TRT)

A thermal response test is applied to borehole heat exchangers (closed loop system) to determine the effective thermal conductivity and the quality of borehole grouting. A TRT considers a line heat source injecting heat at a defined level for a specific observation time. The thermal response of the subsurface is simultaneously measured at the inlet and outlet of the borehole heat exchanger.

Underground Thermal Energy Storage (UTES)

Temporary (seasonal) storage of excess heat by means of shallow geothermal energy methods. UTES can be applied on shallow aquifers (ATES), boreholes (BTES), caverns (CTES) or mines (MTES) and on water insulated reservoirs lined with a plastic lining and covered with an isolating lid named as Pit Thermal Energy Storage (PTES).

Water-Source Heat Exchanger (WSHE)

It is a sub-category of ground source heat exchangers that comprises all heat exchangers involving water as the heat exchanging medium or fluid: groundwater, surface water and wastewater heat exchangers (both open and closed loop)

Wastewater Heat Exchanger (WWHE)

It is a type of ground source heat exchanger that consists of exchanging heat with the wastewater circulating through the sewer network. The interest of these systems relies on the fact that wastewater can easily achieve temperature values between 5 and 10 °C above groundwater.