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Shallow geothermal energy systems for district heating and cooling networks: Review and technological progression through case studies

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ABSTRACT

Heating and Cooling constitute a major part of society's final energy use and a significant contributor to greenhouse gas emissions. The world society ought to mitigate climate change through decarbonisation, which must include the transition to low-temperature, sustainable and renewable heating and cooling technologies. Shallow Geothermal Energy is one of the most energy efficient and least greenhouse gas emitting available alternatives to provide space heating and cooling. The decarbonisation of the heating and cooling sector may have to comprise both individual systems and shared electrified heating and cooling systems from renewable sources of energy, where economies of scale and synergies between different types of consumers can be exploited. To this end, the focus of this paper is on the integration of shallow geothermal energy technologies into district heating and cooling systems. A key contribution of this work is the illustration of a number of practical case studies, highlighting the potential of existing shallow geothermal systems for DHC networks, which, as front runners in adopting such technologies, serve as paradigms for future development. Follows a discussion providing an outlook over the next 25 years. All in all, the future of utilizing shallow geothermal energy for district heating and cooling seems to be promising to play a pivotal role in sustainable urban development and decarbonizing the heating and cooling sector.

1. Introduction

Heating and cooling (H&C) are a major part of society's final energy use and a significant contributor to greenhouse gas emissions. In recent years, systems to extract thermal energy from the environment (including from the soil, water or air) have been commonly used, usually including a heat pump to enable the supply of thermal energy at the required temperatures. Extracting thermal energy from the air is one of the most straightforward types of systems to install, as there are no site-

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specific constraints, except outside air temperature and available space. However, they aim to provide heating when the outside air is very cold and supply cooling when the outside air is warm, therefore often suffer from low thermal efficiency. On the contrary, systems which extract thermal energy from water or the ground (i.e. Shallow Geothermal Energy (SGE) systems) buffer the external air temperatures due to their significant heat capacities and can therefore improve efficiencies. However, site specific factors must be considered in their design and installation. Frequently, such systems are installed to serve the heating and/or cooling needs of individual buildings, yet it is proposed that this can be scaled by connecting these systems to collective distribution systems, i.e. District Heating and Cooling (DHC) systems.

Glossary

ATES	*Aquifer Thermal Energy Storage.* A heating and cooling storage installation, usually with a heat pump, connected to a geothermal heat exchanger under an open-loop configuration which exchanges mass (groundwater) and thermal energy with the ground/aquifer
BHE	*Borehole Heat Exchanger*. A type of geothermal heat exchanger comprised by closed loop pipe circuit inside a borehole
BTES	*Borehole Thermal Energy Storage.* A heating and cooling storage installation, usually with a heat pump, connected to a set of geothermal heat exchangers under a closed-loop configuration which exchanges thermal energy with the ground
DCN	*District Cooling Networks*. Energy infrastructure which integrates cooling technologies at a district-scale
DHC	*District Heating and Cooling.* Energy infrastructure which integrates heating and cooling technologies at a district-scale
DHN	*District Heating Networks*. Energy infrastructure which integrates heating technologies at a district-scale
EG	*Energy Geostructures*. Structural elements in which geothermal heat exchangers are integrated
GCHP	*Ground Coupled Heat Pump.* A heating and cooling installation, usually with a heat pump, connected to a geothermal heat exchanger under a closed-loop configuration which exchanges thermal energy with the ground
GHE	*Ground heat exchanger*. Underground heat exchanger that can capture heat from and/or dissipate heat to the ground
GHG	*Greenhouse Gas.* Any gas in the atmosphere capable of absorbing and/or storing infrared radiation
GSHP	*Ground Source Heat Pump*. A heating and cooling installation with a heat pump connected to a geothermal heat exchanger under any type of loop configuration which exchanges thermal energy with the ground or shallow/surface water bodies
GWHP	*Ground Water Heat Pump*. A heating and cooling installation, usually with a heat pump, connected to geothermal heat exchanger under an open-loop configuration which exchanges mass (groundwater) and thermal energy with the underground water body
H&C	*Heating and cooling*
HVAC	*Heating, Ventilation, and Air-Conditioning.* Set of technologies to control the temperature, humidity, renewal of air and its treatment, in interior spaces in order to provide healthy and comfortable conditions
RES	*Renewable Energy Sources*
SGE	*Shallow Geothermal Energy*. Internal low-enthalpy thermal energy stored in rocks, sediment and groundwater in the shallow subsurface
SPF	*Seasonal Performance Factor*. Energy performance indicator of a heat pump system throughout a specific operation season
SWHP	*Surface Water Heat Pump.* A heating and cooling installation, usually with a heat pump, connected to a geothermal heat exchanger under an open-loop configuration which exchanges mass (surface water) and thermal energy with a surface water body

Hence using SGE systems in DHC networks contributes to reducing carbon emissions and reduce the needs for primary energy due to their higher efficiency. They help to provide a consistent and continuous energy supply, unlike some renewable sources, which are intermittent. SGE systems have also a low environmental impact, generating negligible levels of greenhouse gases and pollutants when compared to traditional fossil fuel-based systems, contributing to the global efforts to tackle climate change.

DHC systems are a well-established option for space heating and cooling in high-demand density areas because they are more efficient than individual systems and are recognized as a critical technology for the energy transition [1,2]. These criteria make them suited for places with high heating demand, which explains why they have been installed mostly in Central and Northern Europe and North America, while they are much less common, if present at all, in milder climates such as Mediterranean Europe or Australia [3]. Other distinguishing features of classic District Heating Networks (DHN) include their reliance on fossil energy sources and their high operating temperatures, which increase the energy density yet result in significant thermal losses. The high operating temperatures eliminate the option of incorporating low-temperature renewable sources and low-grade waste heat, both of which may meet a large fraction of total demand [4]. Furthermore, even in Europe, climate change and improved building energy efficiency are predicted to reduce overall heating demand and needed temperatures, but energy usage for space cooling is anticipated to climb quickly and overtake space heating by the end of the century, owing primarily to rising income levels in developing nations. As a result, new (4th and 5th) generation district energy systems should be able to operate in moderate climates with reduced heat demand density, while also delivering both heating and cooling and incorporating high percentages of Renewable Energy Sources (RES) (Gjoka, 2023). Potential benefits, drawbacks and further prospects of 5th generation DHC can be found in Pellegrini and Bianchini [5], while relevant technology strengths, weaknesses and opportunities are addressed in Buffa et al. [6]. Further, a number of recent works provide overviews of the main features of DHC grids coupled with closed- and open-loop geothermal systems [7–9].

The objective of this paper is to present an overview of the application/integration of SGE systems in DHC networks, by presenting the state-of-the-art on such matters, as well as looking into the future with regard to sustainability, technology and social impact. In particular, this article makes a significant contribution by illustrating a variety of real-life case studies that show the potential of current SGE systems for DHC networks, which, as early adopters of such technologies, can serve as paradigms for future developments. In conjunction with this, the present study offers a series of suggestions in relation to the implementation of SGE in DHC systems.

The rest of the paper is organized as follows. In Section 2, the SGE technologies to extract or store thermal energy from the soil and water shallow environment are first outlined. In Section 3, the state-of-the-art regarding SGE technologies within DHC systems is extensively overviewed. Then, in Section 4, a series of case studies are presented, serving as examples of conditions where such systems are feasible and showing the potential of utilizing SGE for collective heating and cooling. A discussion that includes suggestions and facts on the advantages and barriers in relation to the adoption of such systems, with a look into the future is given in Section 5. We conclude with Section 6.

2. Technological overview

The shallow underground, hereafter defined as (approximately) the first 200 m of depth below ground surface (bgs), constitutes a thermal energy reservoir characterized by a reasonably initial stable temperature throughout the year. It offers an immense potential, for Heating, Ventilation, and Air-Conditioning (HVAC) of buildings and other heating and cooling needs. The thermal energy retained in shallow underground reservoirs is known as SGE [10]. The depth limit of a couple hundred meters is constrained by the depth limits of the currently existing drilling technologies used to achieve an economically viable heat exchanger. This is different depending on the geological conditions in each location. SGE is also known as low or very low temperature geothermal energy since the vast majority of the shallow underground, of the continental domain, is in thermal equilibrium with the long-term atmospheric conditions and the solar radiation [11]. Under these conditions, shallow geothermal reservoirs present stable temperatures of approximately 2 °C above the annual average local air temperatures, which are globally within the range of -5 °C to 28 °C, depending on the existent local climatology [12]. Recent studies show that the underground temperature in urban areas is significantly increasing due to climate change and urbanization effects, like a rising sealing [13,14]. This further improves conditions for SGE use, especially as concurrently a high heat demand exist in urban areas. Shallow geothermal reservoirs are constituted by rocks, soils and groundwater with favourable thermal potential - meaning that all shallow geothermal reservoirs are energetically exploitable. Therefore, shallow geothermal energy can be considered as an ubiquitous resource. Different geological and hydrogeological characteristics, and especially hydraulic and thermal parameters, determine the selection and design of the appropriate geothermal application.

The continuous development of heat pump technology has improved efficiencies and reduced costs. When highly efficient heat pumps are coupled with ground heat exchangers in shallow geothermal reservoirs, the resulting technology, known as GSHPs, becomes an energy-efficient technology for building heating, cooling and domestic hot water production [15]. Heat pumps utilise external (usually electrical) energy to run a vapor compression cycle using a refrigerant. This is most of the external energy used in GSHPs, significantly higher than the energy consumed for the operation of the hydraulic circulation pumps. The energy performance of geothermal heat pumps is about 50–70 % higher than that of conventional (gas-fired) heating systems, and 20–40 % better than available air-to-air heat pumps [16], resulting in lower demand of primary energy without further emissions (noise and other air pollution). Recent developments are also motivated by the political and social response to global warming. The Greenhouse Gas (GHG) emission reduction impact of these systems has also been proven. For example, in 2008, the use of around 879,000 GSHP systems in 19 European countries saved 3.7×10^6 tCO_2 (eq.) in comparison to conventional heating practices [17], which is equivalent to approximately the annual emissions of 804,000 cars (typical passenger car emits about 4,6 tCO_2 per year). The external energy use of these systems still means that GHG emissions and atmospheric particle pollution are produced indirectly from the electrical energy consumption, which is about 1 kWh electric per 4–8 kWh of thermal energy being transferred [18]. Therefore, emissions of these systems will depend on the emissions caused during the production of the electrical energy mix, reaching zero emissions when the electrical energy consumed by the system is provided entirely from renewables. The substantial reduction in electrical energy consumption and consequential low GHG emissions, alongside the individual building scale, are key reasons why SGE is increasingly discussed, promoted, and implemented as a promising technology to reduce fossil fuel consumption and, therefore, mitigate climate change [19].

For all these reasons, the use of SGE systems for heating or cooling purposes is experiencing explosive growth worldwide. Between 2015 and 2019, the world's total capacity of SGE systems installed increased at an annual rate of 10.86 %, up to 77,547 MWt total capacity, with an annual energy use of 599,981 TJ/year. The equivalent number of installed 12 kW units is approximately 6.46 million, which represents a 54 % increase over the number of installed units in 2015 [20].

Two main categories of shallow geothermal systems can be found depending on the geothermal heat exchanger connected to the water-to-water heat pump (Fig. 1): GCHP systems (closed systems) and GWHP systems (open systems). These are described in the Sections below. Most shallow geothermal systems utilise heat pumps, but depending on the exact circumstances, if a sufficient temperature difference is available without a heat pump, then a similar system without a heat pump can be installed.

2.1. GCHP systems (closed systems)

Closed-loop SGE systems, also known as GCHP (Ground Coupled Heat Pumps), are a subset of GSHP, consisting of closed-loop piping systems buried in the ground connected to a heating/cooling delivery system (Fig. 2), usually via a heat pump [21,22]. GSHPs may take a number of different forms according to ground heat exchanger type and design [23,24].

Traditional forms of GCHP include Borehole Heat Exchangers (BHE), in which pipes for the circulation of a heat transfer fluid are embedded into vertical boreholes, and shallower horizontal systems in which the pipes are arranged in trenches near the ground surface [21]. BHEs are the most widespread technology to utilise shallow geothermal resources.

In GCHP systems with BHEs, it is common to use single or double U-tube heat exchangers separated by longitudinal spacers. In addition, a helical-shaped pipe configuration requires lower drilling lengths, but it is less used. The tubes are thermally fused at the bottom of the bore to a close return U-bend. The heat exchanger in the borehole is backfilled with grout, or other material (i.e. soil), to ensure a good thermal connection with the surrounding soil [21,25] and to ensure integrity of the underground piping circuit. The energy is conducted from the soil into the BHE by conduction, no exchange of fluid occurs between the BHE and the ground.

The depth of the boreholes is set according to the heating and cooling loads, the ground conditions, underground constraints and available land area. For example, when the available land area for BHEs is not enough to satisfy the loads with regular borehole depths, higher depths

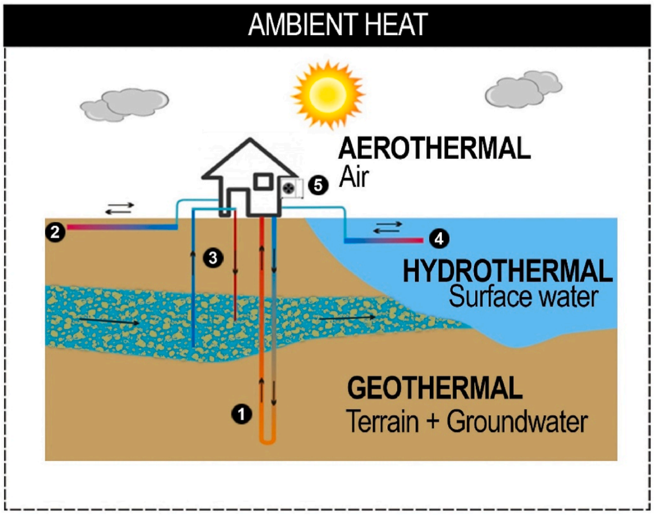

Fig. 1. Shallow Geothermal energy systems: closed-loop (1,2) and open-loop (3,4).

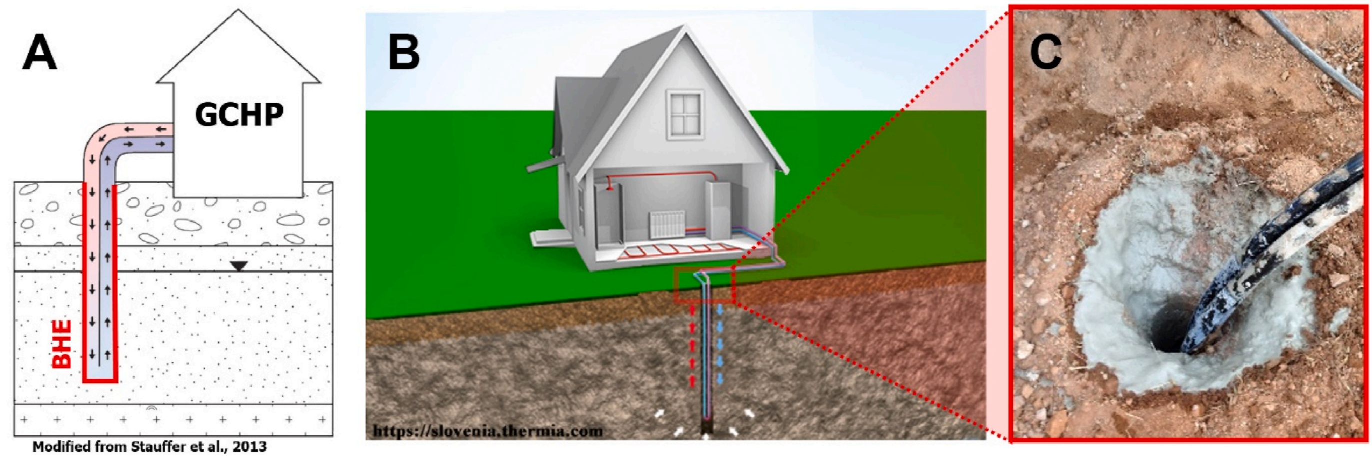

Fig. 2. Individual GCHP (A) configured with one closed-loop geothermal heat exchanger (B) with a BHE configuration (C). Figure A modified from Stauffer et al. [19].

can be the solution. Caution is required to off-set deep-bore conditions and added pipe head losses even when the largest standard-sized U-tubes are applied. In Kavanaugh and Rafferty [21], theory is available to predict external pressures (or borehole depths) that would cause pipe collapse when the stresses due to the external material are greater than that of the strength of the pipe.

The advantages of vertical GCHPs are that they require relatively small plots of ground, are in contact with the soil that varies naturally very little in temperature, the thermal properties are stable throughout the year, require the smallest number of pipes of all GSHPs and the least circulation pump energy, and can yield the most efficient GCHP system performance. The disadvantage is that they are typically higher in cost than other GSHP, which is partially due to the limited availability of appropriate equipment and skilled labour.

Horizontal GCHPs can be divided into three subgroups: single, multiple, and coiled pipes. The advantages of horizontal GCHPs are that they are typically less expensive than vertical systems, mainly because appropriate installation equipment is often more widely available. In addition, these systems are suitable for both heating and cooling only applications, as well as both. They are typically relevant in residential and small commercial building applications due to the availability of adequate ground area. Disadvantages of these shallower systems include greater adverse variations in performance due to the seasonal fluctuation of thermal properties (due to the variation of saturation ratios) and ground temperatures, the impact of rainfall, less seasonal energy storage due to energy exchange with the atmosphere, slightly higher pumping energy requirements (due to longer pipes needed) and lower system efficiencies.

Energy Geostructures (EG) or thermoactive foundations are now being constructed and developed in several countries (e.g., Ref. [26–29]). These novel types of GCHPs make dual use of civil engineering structures such as piled foundations, tunnel linings, retaining walls, diaphragm walls and basement slabs or walls, augmented with heat exchanger pipes which form the primary circuit of a geothermal energy system, so that they serve as heat exchangers in addition to providing structural support [30]. The essential difference from conventional earth-collector systems or ground heat exchanger boreholes is that the earth-contact concrete elements that serve as heat exchangers are already required for structural reasons and do not need to be constructed separately. Furthermore, they take advantage of the concrete thermal conductivity which is generally higher than soil. The main disadvantage is that their design is mainly performed with structural/geotechnical criteria, such that the thermal design flexibility is restricted, as is typically the depth.

Combinations with near-surface earth collectors or retaining structures are also possible. Energy foundations can be used for heating and/or cooling buildings of all sizes, as well as for de-icing of road pavements, bridge decks etc. [30–33].

Typically, the efficiency of GCHP systems is closely related to the efficiency of the exchange of thermal energy between the ground and the heat exchanger, and it increases with an increase on the thermal conductivity of the ground. In all cases, recharge of the systems by also using them to provide cooling when heating is the primary use, or vice versa, improves efficiency and reduces impact on nearby systems. When the thermal properties of the ground are not suitable for high efficiency extraction of thermal energy, the ground can be used as a seasonal thermal energy storage medium. Similar to the vertical GCHP, when the purpose is to exploit the storage capacity of the ground, a Borehole Thermal Energy Storage (BTES) system can be installed, comprising a set of closely spaced BHEs. These are generally supplied by an external thermal energy supplier, such as solar collectors or waste heat.

2.2. *GWHP systems (open systems)*

Ground Water Heat Pump (GWHP) systems are commonly known as open loop systems. In an open loop system, water from a ground or surface (aquifer, lake, sea, etc.) reservoir is directly used as a thermal source or sink medium (Fig. 3). GWHP systems were the oldest and most widely installed systems until the development of other GSHP systems. GWHP systems can function as a direct use system, indirect use system, or a standing column well system.

In direct use systems, wells are typically drilled in pairs, in which the first well is used to extract groundwater from the aquifer/reservoir (called the production well) and the second is for water discharge back to the aquifer/reservoir (called the injection or reinjection well). In general, the wells should be located in the same aquifer and placed in a proper distance taking into consideration the conditions of the water body in order to avoid mixing water of different geo-chemical compositions, which can cause environmental and operational difficulties. In some cases, a reinjection well may not be necessary with water being discharged into a surface water body, as long as it is permitted by its water characteristics and the environmental regulations of that specific site area.

Indirect use GWHP systems have similar configurations as direct use systems with the addition that the extracted water passes through an intermediate heat exchanger and exchanges heat with a secondary water loop, which can then be supplied to a heat pump. This system is mainly used in order to minimize the corrosion and fouling phenomena in the evaporator/condenser of the heat pump and other mechanical components and is driven by the water geochemistry.

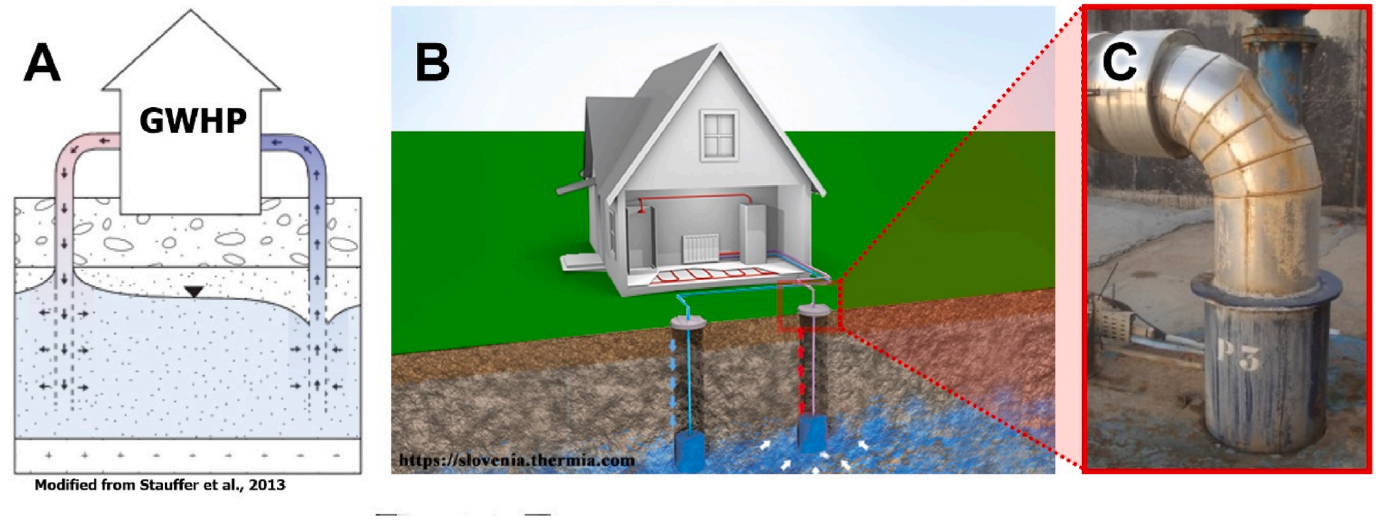

Fig. 3. Individual GWHP (A) configured with one open-loop geothermal heat exchanger (B). A real production well is shown (C). Figure A modified form Stauffer et al. [19].

In a standing column well system, only one well is installed and used for both the extraction and reinjection of the water. Typically, a submersible pump is placed in the bottom of the well, while the return water is injected in the top of the aquifer. Due to the fact that both points are placed in the same well, specific care is required to avoid short circuit phenomena that lead to thermal interference between the injected and pumped water.

The advantages of GWHP systems include the amount of energy which can be extracted per system of well drilled (due to the use of advection as the main heat transfer mechanism), the consequential lower capital cost (per unit of energy) and the use of more mature technology than the closed loop systems. However, the major disadvantages of these systems compared to closed systems are the resource availability (a productive aquifer is required), and also potential environmental issues including thermal and chemical pollution due to the extraction and discharge of water from a natural reservoir, and the increased risk for maintenance because of corrosion, scaling, and/or fouling phenomena.

The use of a single GWHP system for both heating and cooling offers higher system efficiencies, as energy is not continuously extracted and is replenished, usually on a seasonal basis. This type of system in known as an Aquifer Thermal Energy Storage system (ATES). These can be installed similarly to the main types of GWHP system, with the main difference that wells operate bi-directionally, i.e. both (sets of) wells must operate as both injection and extraction wells. ATES has additional advantages of lower thermal and chemical impacts on the aquifer and no depletion of the resource. However, the energy demand must be approximately equal for both heating and cooling, or recharging using outside energy supply must be made.

When the water reservoir that is used for thermal extraction and injection is a surface reservoir, the system is called Surface Water Heat Pump system (SWHP) which has the same working principles as GWHP. However, there are only two basic configurations, the direct and indirect use. In-line with the GWHP systems, the main difference between direct and indirect open loop SWHP systems is the use of the intermediate heat exchanger in the latter one. This is to minimize again the corrosion and fouling phenomena, as well as the maintenance cost of the heat pump due to the adverse dissolved agents on the water, e.g. salts, oxides, hydroxides, etc. In comparison to the GWHP systems, open loop SWHP are characterized by lower initial installation cost under equal quality of the water reservoir, while their efficiency controlled by the open water conditions which, for shallow water bodies, typically react faster to the atmospheric conditions. The applicability of these systems is less general that for ground-based systems, due to the limited availability of open water when thermal energy is required. More information about the open loop systems can be found in the following studies [21,34,35].

3. State of the art regarding the use in DHC systems

DHC systems are depicted as efficient systems for distributing heat and cold at a district- or city-scale level, and they are seen as an important part of future energy systems [36]. Throughout five different development stages [37], DHC systems have been evolving towards higher efficiencies and lower distributing temperatures, greatly increasing the potential integration of renewable energy sources and waste heat. The most recent development stage portrays a paradigm change towards more flexibility, exploiting the synergies between different energy sources and consumers in a bi-directional network simultaneously supplying heat and cold, making use of smart technologies.

The recent implementation of 5th Generation DHC (5GDHC) networks paves the way for the use of SGE (in particular EGs) as ground-coupled low-temperature energy sources and storage to meet the energy needs of a broader range of energy users in districts rather than single buildings. SGE technologies can be integrated in both DHN and District Cooling Networks (DCN) networks, and these are used as thermal energy sources or balancing units (compensating for network energy imbalances with its seasonal thermal energy storage capabilities) in multivalent networks. Historically, the integration of geothermal technologies into DHC depended on the location of geothermal resources. Following the trend towards low-temperature distribution networks, the integration of geothermal resources into DHC systems can no longer be limited to medium and high enthalpy resources in specific zones with considerable geothermal gradient. Additionally, besides the use of SGE technologies not being limited to specific locations, they can also provide cooling.

These technologies resort to heat pumps to provide a temperature lift or downgrade to provide space heating and cooling, respectively. Both GSHP and GWHP systems are commonly used for buildings when heating and cooling loads simultaneously occur [38]. The heat pump can be placed before or after the distribution network, depending on the distribution supply temperature, taking into consideration that lower distribution temperatures increase the energy efficiency of the whole system [6].

3.1. GCHP systems integrated into DHC networks

Whereas the use of closed loop GSHP systems are common in heating and cooling systems of individual buildings, the same cannot be said for their use in DHC systems. In fact, De Carli et al. [39] went as far as saying that no paper on the use of GCHP in district systems was present in literature at the time. However, since then there seems to be an increased interest in integrating SGE technologies into DHC systems and there are some successful examples now.

Over the years, several numerical studies on the subject have been conducted, including some testing done to validate the results. These studies include research done by De Carli et al. [39] who studied the energetic and economic aspects of a heating and cooling district system in a mild climate based on a closed loop GSHP system using numerical software TRNSYS; Dehghan [40] who studied the effectiveness of using spiral ground heat exchangers in a ground source heat pump system integrated in a district heating and cooling system using COMSOL numerical simulation, based on optimized parameters from Dehghan et al. [41]; and Huang et al. [42] who studied a solar supplied DHC with GSHP in China, using TRNSYS, motivated by European demonstrated applications (e.g. Ref. [43]).

Related to DHC research and development that leads to thermal networks with decentralized substations exchanging the energy quantities for a price is a business process called 'Transactive Energy' [44]. When analysing the market of GSHP integrated in DHC grids, Buffa et al. [6] highlight the fact that there is still some confusion over the difference between traditional thermal networks, which are often supplied by a centralised power station, and the use of GSHP in district networks. This is also a key issue in the definition of the type of thermal network, with the more traditional (higher temperature) networks being defined as District Heating Networks (DHN), whereas lower temperature systems using GSHP may additionally supply cooling and so are typically called DHC. Buffa et al. [6] highlighted that with the use of the term '5th generation district heating and cooling'. In fact, they consider this '5th generation district heating and cooling' as an extension of GSHPs used in individual buildings, but on a district level. Based on this definition, the authors list 15 case studies of systems utilizing GSHPs in the district system either on their own or in conjunction with other energy sources, such as air, solar or fossil fuels. Some of these include horizontal ground heat exchangers in Wüstenrot, Germany [45] and vertical ground heat exchangers in “Küferweg" district system in Mainz, Germany [46], combined solar/horizontal ground heat exchange in the “Sohnius-Weide” system district in Nümbrech, Germany [47], and combined air/vertical ground heat exchange in the “Sedrun” district system in Tujetsch, Switzerland [48]. Buffa et al. [6] presented 40 5th generation DHC systems in Europe, while Wirtz et al. [49] made a survey of 53 5th generation DHC systems in Germany, including some case studies with SGE technologies as heat sources.

Recent work to reduce the cost of ground source heat has focused on the use of foundation structures, or other buried civil engineering infrastructure as novel ground heat exchangers (e.g. Ref. [50–52]). While some examples, either in terms of case study or numerical analysis, exist regarding the integration of BHEs into DHC networks, no extensive comprehensive research work appears to have been published to date involving the integration of EG within district networks. In fact, EG are still less established than BHEs for building heating/cooling, but they have been increasingly and successfully employed in recent years, especially in central-northern European areas. However, EG do not always get constructed with readily connected heat users, but often can be connected to nearby medium-to-large heat users (e.g. subway stations, shopping malls, among others). This is especially true for metro tunnels and other buried infrastructure projects. For example, the energy piles and walls constructed at Crossrail have an uncertain future since they were built without definitive end use [52]. Connection to heat users therefore remains a barrier to implementation of energy geostructures, but it is a barrier that could be removed through integration of these heat sources within DHN. There is very little precedent and no literature on the integration of energy geostructures into DHN, despite the needed step to fully take advantage of EG. Reasons for this could be a lack of coordination between infrastructure designers, constructors and owners with heat providers and users, an absence of appropriate business models, and an absence of design guidelines and standards. Nonetheless, the capability and feasibility of the concept of integrating EGs into 5GDHC networks are assessed in Meibodi and Loveridge (2021) by analysing various elements of thermal performance of operational energy geostructures and 5GDHC networks.

Given their peculiarities, in terms of different geometry and their dual (structural and thermal) function [30], they are likely to require bespoke tools to assess the feasibility of integrating them in DHC. Some district- or city-scale studies exist regarding the use of EG, with particular reference to thermo-active tunnels, which are mainly aimed at evaluating their overall geothermal potential. However, the need to consider thermal interactions between neighbouring installations is also discussed, as well as attempts to calculate district-scale thermal balances, which can foster further research towards DHC integration. Examples of such studies include thermo-active tunnels in the European cities of Warsaw, Poland [53], Turin, Italy [54] and Basel, Switzerland [55]. Depending on the type of tunnel (highway or railroad) and its location in relation to the geological and hydrogeological conditions, different solutions for near-surface geothermal energy systems can be applied, including heat-transferring segments built into the tunnel lining and the thermal utilization of water circulating in culvert systems. First results suggest that thermal activation of railway tunnels is most efficient when they are located within groundwater-saturated zones of unconsolidated rock deposits. SGE within culverts reveals to be favourable in heating mode only and for sections where motorway tunnels run perpendicular to regional groundwater flow fields and where ambient groundwater temperatures are high.

3.2. GWHP systems integrated into DHC networks

Open loop systems have been used for some time now to supply heat to collective distribution systems. Historically, the direct use of hot groundwater has been used for several purposes over the history of mankind, since Roman times [56]. Either natural or drilled hot springs have been used for space heating. The first documented geothermal DHN is in operation since 1332 in Chaudes-Aigues, France. These geothermal resources have been used in direct use open loop systems with considerable temperatures (60–90 °C), which falls out of the scope of the present document regarding SGE technologies.

GWHP systems have been introduced recently following the DHC trend towards lower distribution temperatures, which resorts to a heat pump to increase the temperature of the extracted groundwater to provide space heating or, in reverse, to provide space cooling. These systems are no longer limited to specific areas with considerable geothermal gradient, but still limited to the availability of surface or underground water bodies. According to Schmidt et al. [57], currently approximately 100 large scale ATES systems are integrated in DHC networks.

4. Collection of case studies

In order to highlight the potential of existing shallow geothermal systems for DHC networks, six case studies across Europe are described in the following. The systems are all constructed and operational. Fig. 4 shows the geographical location of the case studies.

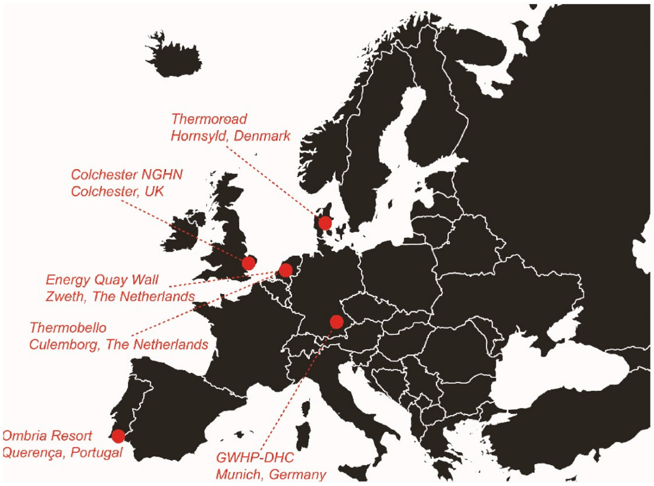

Fig. 4. Location of the case studies of SGE based DHC systems.

4.1. GCHP-DHC

4.1.1. Ombria Resort

4.1.1.1. Location: Querença, Portugal. Project Description: The Ombria Resort is one of the flagship projects of shallow geothermal energy in Portugal, being the largest closed-loop geothermal system and the only DHC system using SGE technology. It is located in the South region of the country with a clear commitment to sustainability with the intent of having nearly-zero energy buildings. With the aim of starting its operation in spring 2023, the resort features a hotel, a golf course, several individual residences, a clubhouse, and a spa. The construction concepts involve bioclimatic architecture, harmonized with the surrounding nature, rainwater collection and water management, LED lighting, electric charging of vehicles, and the use of renewable sources of energy.

The whole resort accounts for a total need for space heating and cooling of about 2370 kW and 1100 kW, respectively, also considering DHW and swimming pool heating needs. These needs are going to be supplied by a highly efficient HVAC system, here considered as a DHC system, supplied by a shallow geothermal energy system and solar thermal collectors.

The GSHP system was designed having considered the results of six TRT's (Thermal Response Test) performed throughout the case study location (Fig. 5). The average temperature of the shallow subsurface was found to be 17.2 °C with average thermal conductivity of 2.14 $Wm^{-1}K^{-1}$. It is comprised by 4 main loops made of: i) 40 BHEs of 100 m depth, ii) 60 BHE of 125 m depth, iii) 72 BHE of 115 m depth, and iv) 72 BHE of 115 m depth. Also, 156 solar thermal collectors were installed to provide H&C and solar regeneration of the ground temperature (or to be stored in the ground for seasonal thermal energy storage).

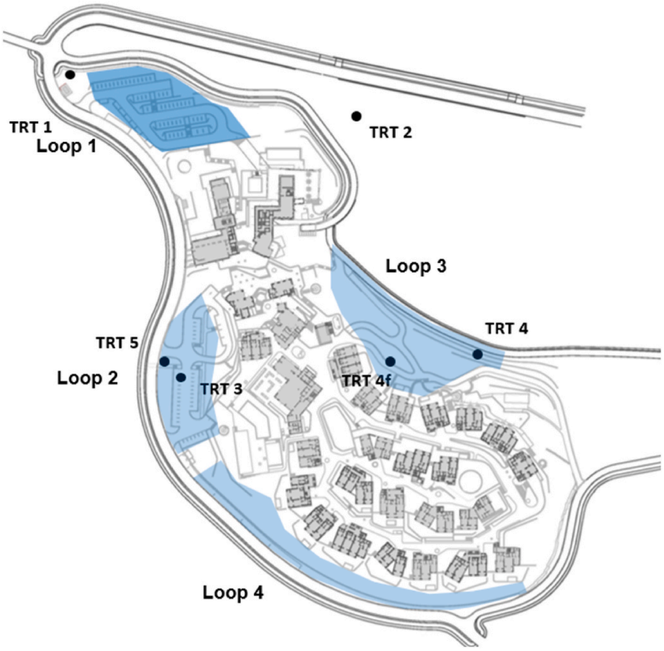

Fig. 5. Ombria Resort with the location of the four loops of BHE (blue zones) and the location of the TRTs performed.

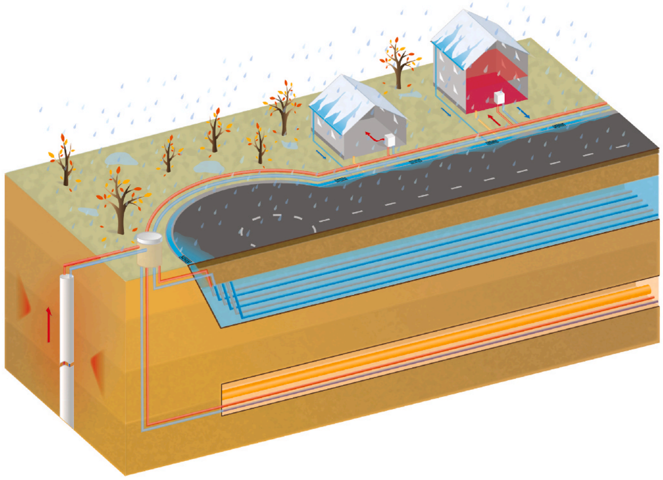

Fig. 6. Thermoroad 5th generation district heating and cooling grid concept.

4.1.2. Thermoroad project

4.1.2.1. Location: Hornsyld, Denmark. Project Description: The Thermoroad is a novel concept of a decentralized, energy efficient, GSHP-based, 5th generation DHC grid combined with local surface water drainage and retardation using the porous roadbed (Fig. 6). The Thermoroad was constructed in 2021 and the surrounding houses will be built during 2023/24. When operational, six dwellings with individual brine to water heat pumps will be fully supplied with domestic hot water, space heating and space cooling with a renewable thermal energy supply.

The Thermoroad uses 1.2 km of horizontal geothermal piping embedded in the roadbed, three 85 m long borehole heat exchangers and 200 m of geothermal piping along the central wastewater pipe to reclaim waste heat. It is a combined energy supply and local surface water management system that utilizes the porosity in the gravel roadbed as a rainwater retarding basin with embedded uninsulated geothermal pipes that exchange energy with their surroundings. In waterlogged areas, the Thermoroad is hydraulically disconnected from the surrounding soil, to prevent seepage of groundwater to the roadbed.

The Thermoroad has been constructed in full scale but is yet to be commissioned as the land parcels have not yet been occupied by buildings and energy consumers. However, a predecessor to the Thermoroad has been in operation for some years and the potential for water management and heating and cooling have been investigated in Poulsen et al. [58] and Andersen et al. [59].

4.1.3. Energy quay wall case study

4.1.3.1. Location: Zweth, The Netherlands. Project Description: Experimental installation in de Zweth, Netherlands, of a ~10m quay wall based on sheet piles extending to a depth of 16m, thermally activated by integrated heat exchangers. Several deep and shallow heat exchangers are connected to a small-scale heating and cooling grid, including a heat pump. Heat exchanger fluid temperatures on the primary circuit side are those typical of shallow geothermal installations, in the range 0–25 °C. An experimental programme has measured the system performance during 2020/2021, supported by numerical modelling (e.g. Refs. [60, 61]), with the results indicating that natural and forced convection in the open water allows a high heat extraction or injection per meter of close-loop pipe (up to 500 Wm^{-1}), with a lower output from the pipe in the soil. The pipe in the soil may play an important role in peak heating or cooling demand due to the substantial buffering behaviour of the soil.

In the Netherlands, several hundred kilometers of quay walls must be refurbished in the next few years and decades, especially those in historic city centres such as Amsterdam. There are two typical arrangements of quay walls: (i) constructed from sheet piles; (ii) constructed from concrete piles, including an ‘L’ wall sitting above the piles. The installation of new piles offers the opportunity to install heat exchangers for a minimal additional cost and the close proximity offers an adjacent heat demand. For this project heat exchangers installed attached to sheet piles walls [62] are used to create energy quay walls [63] - see Fig. 7 for a photograph of installed sheet piles with the heat exchanger pipes visible.

The intention of this type of system is to connect into a DHC network that will supply close by buildings. The system can be a modular system supplying few houses or part of a larger (low temperature) DHC network with additional heat/cold sources. This choice partially depends on the length of quay wall that is installed and the proximity to an appropriate demand. The system is now being scaled up in several pilot tests that will be connected to DHC networks (https://energie-damwanden.nl/).

Fig. 7. Energy quay wall sheet pile installation. Heat exchanger pipes are observed above the ground surface attached to the sheet piles ready to be connected. Vertical pipes are part of the instrumentation system.

4.2. GWHP-DHC

4.2.1. Munich Groundwater cooling GRID

4.2.1.1. Location: Munich, Germany. Project Description: The Munich City Cooling Grid, operated by the City Energy supplier (SWM Services GmbH), is implemented to cover the cooling purposes mainly for data centres, office buildings and industry. For this purpose, SWM Services GmbH set up an inner-city cooling grid using different source components, turbo compressor and hybrid cooling units, ice storage, at newest also adsorption cooling with deep geothermal wells is planned. But the main source in the grid is surface water and groundwater. The grid is in general designed as several island units. One of those is a surface water driven grid, which is combined with an ice storage and a turbo compressor unit, covering 13 MWth cooling demand. At present six groundwater plants with several wells are in operation producing also about 13 MWth. Two additional groundwater plants with about 4 MWth are under construction. To tap the groundwater source, different types of wells are in operation: i) normal vertical groundwater wells (with a general abstraction rate of 20–40 l/s), ii) horizontal wells to increase the volume flux productivity if the groundwater thickness is too low to abstract enough water for covering the energy demand within the water regulations, and iii) culvert wells, which are built in the frame of a subway construction to avoid the retaining of the groundwater. By just installing a pump into the culvert well the abstraction of the collected water is possible. Using culvert wells for direct cooling has the advantage, on one hand, of saving the cost for drilling wells, and, on the other hand, of having a large amount of water available for the system collected by the culvert. The permitted temperature range for the groundwater use is 5–6 °C by a maximum reinjection temperature of 20 °C, which is normally not reached. In some cases, where a demand request exists, a seasonal utilization covering a heating demand by using the waste heat of the cooling by GWHPs are integrated in the Grids. One example of an island cooling grid using culvert wells is the installation for the research data centre of the BMW Group, called “BMW-FIZ” (Fig. 8). Eight culvert wells for the production and seven for the injection are used and combined with two vertical production and injection wells. Altogether they have a production capacity of 255 l/s. With a temperature spreading of 5–6 °C the plant covers with 5.34 MWth the cooling base load of the data centres and office building climatization. The peak load is covered by a conventional cooling unit. 4.6 km of uninsulated pipes of DA 500 PE were placed in a depth of 1–1.5 m to connect the source with the customer. The comparison with covering the cooling demand totally by conventional cooling techniques shows that using direct cooling with groundwater save in this case 90 % of the primary energy, which means about 10 Gwh/year of electricity. There are also some challenges for a successful implementation of such a culvert well system. One important limitation is the cost for burying the pipes, hence, the distance between the customer site and the culvert wells as source should not be too far, so that the system can be cost-efficient. Another challenge is the monitoring and assessment of a temperature increase in the groundwater, seen as an environmental impact by the water administration if the plant is used just for cooling. Due to that, it is highly recommended now to also integrate a heating demand covering by GWHPs to equalize the injected temperature in the groundwater over the year.

4.2.2. Thermobello case study

4.2.2.1. Location: ***Culemborg, The Netherlands***. *Project Description:* Thermobello DHN supplies heat to 210 households and seven commercial buildings by means of an industrial heat pump. The heat pump extracts its heat from the local drinking water reservoir. Thermobello is run by the inhabitants themselves.

Thermal energy recovery from (drinking, surface, sewage) water has large potential for supplying sustainable heating/cooling to the built environment, often together with an ATES to overcome the temporal mismatch in availability and demand for heat. Some first pilot projects have been installed to individual buildings and small-scale heating grids, one of them is Thermobello in Culemborg.

The local drinking water reservoir is used for heat extraction as a source for a heat pump. Because in this case the drinking water comes from groundwater, the water has a constant temperature throughout the year, which is why no seasonal buffer is needed in this case, see Fig. 9. The buffer in the scheme is a small tank, to prevent high frequency switching of the Heat pump.

KWR [64] carried out an extensive evaluation of the energy system. Since only heat is extracted, the water in the drinking water reservoir is cooled down, resulting in a decrease in biological activity, which is positive for the water quality. Also, the energy performance was

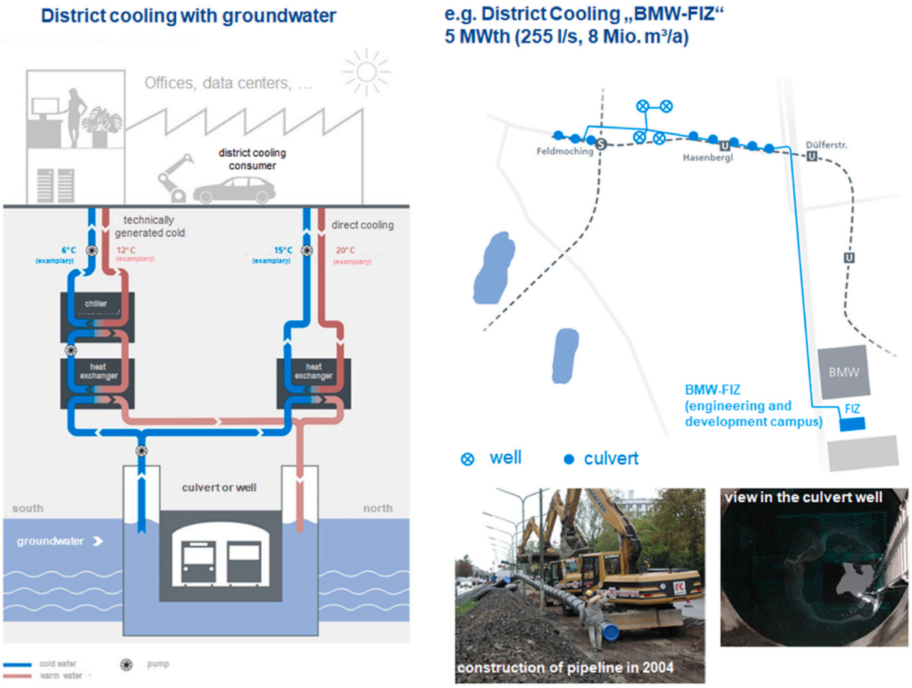

Fig. 8. Example for a part of the Munich Cooling Grid using culvert wells for direct cooling to cover a large cooling demand of data centres and office buildings (source: SWM Services GmbH).

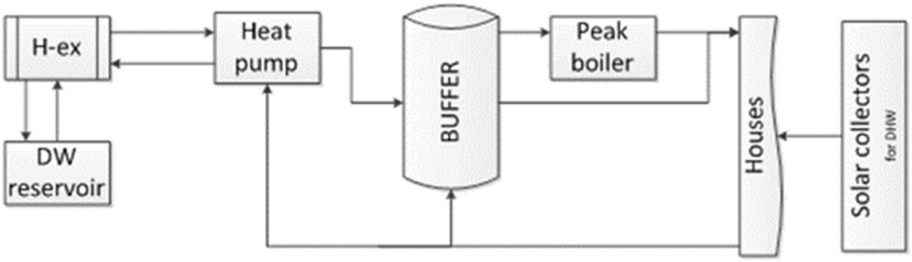

Fig. 9. Schematic overview of system components.

assessed, Table 1. These results show that despite the reasonable heat price the energy performance can be improved. Mainly due to the relatively low drinking water temperature heat pump performance is not optimal, resulting in large electricity consumption. Also, relatively much pump energy is needed to push the drinking water through the heat exchanger.

To assess how the system can be improved, the energy flows were simulated to be delivered by an ATES system. This resulted in a reduction of boiler usage, heat pump electricity and total cost (capex + opex) of 50 %, 10 % and 10 % respectively. Also, a life cycle analysis (LCA, [65]) was carried out, the total eco points for conventional, drinking water and ATES systems are: 101, 97, 78. Also considering the environmental impact of the materials and installation needed indicates that ATES would be a more efficient option in this specific case.

Table 1
Performance of the energy system.

Heat SPF heat pump	3.4
SPF drinking water + heat pump	1.8
SPF overall (including losses in DHN and peak boiler)	1.1
Costs for heat (Eur/GJ)	11
GHG emission reduction power from the grid (compared to conventional boiler)	20 %
GHG emission reduction power from solar/wind	90 %

4.2.3. *Colchester NGHN case study*

4.2.3.1. *__Location__: Colchester, United Kingdom. __Project__ __Description__*: Colchester Northern Gateway Heat Network case study (NGHN). A DHN currently in development that will primarily be heated by an 800 kW open loop groundwater heat pump with 100 m^3 thermal store, with gas boiler for peak load and back up, which when built will provide heating and domestic hot water to 200 houses, 450 apartments, 30,000 m^2 of Offices and a healthcare area including a small hospital via a low temperature distribution network at 65 °C.

Five boreholes have been installed between 135 and 200 m deep into a confined Cretaceous chalk aquifer to supply water to the heat pump. The scheme will mainly abstract groundwater from the Newhaven Chalk, Seaford Chalk and Lewis Chalk Formations (Upper Chalk), and possibly the Thanet Formation sands above [66]. After testing the boreholes individually, a configuration of two abstraction boreholes with a minimum separation of 550 m to three re-inject boreholes were tested for a 1-week system resulting in an abstraction rate of 18 l/s when re-pressurisation effects developed. During the installation and testing, one borehole produced significantly lower yield than the other boreholes which resulted in the odd number of boreholes being installed. The geophysical surveys shed light on the geological reasons behind the variability in yield to improve the conceptual hydrogeological model for the site. It is expected to abstract water at 13 °C and return water to the aquifer at 5 °C (non-consumptive). Borehole geophysical surveys were run to characterise the wells and aquifer condition during the construction stage, before the start of the operational phase, providing an environmental baseline for long-term source-side monitoring. The surveys also provide new geological data which enhances the regional understanding of the geology and stratigraphy, creating knowledge that will benefit the siting and design of future schemes. The bottom hole fluid temperature at 200 m is around 14.2 °C and the geothermal gradient at the site is annual air temperature plus 2.4 °C per 100 m.

Construction of the Energy Centre and heat distribution network is planned for 2026. When fully operational and the development built out, the current modelling shows the heat pump is expected to generate approximately 5.5 GWh of heat a year with 4.1 GWh coming from the chalk aquifer abstracting 486,429 m^3 of water per year. This will see the heat pump deliver 75 % of the development heating and domestic hot water with a low carbon source.

5. Discussion: Outlook towards 2050

The current context of the energy sector is characterized by a paradigm change, where sustainability is becoming more and more significant in the decision-making process. Energy provision, security and sustainability is an essential resource and asset for social progress and economic development, but its generation, management and storage, along with the increasing world population and rapidly increasing energy consumption, are becoming a major challenge to sustain life as it is. The energy transition has to focus on the H&C sector, because it is one of the major energy consuming sectors [67], and for that, SGE is one of the most energy efficient and least GHG emitting available alternatives to provide space H&C, especially when both heating and cooling are needed in the same location [68,69]. In [70], the newly proposed EU strategy for energy system integration, it foresees that 40 % of all residential and 65 % of all commercial buildings will be heated with electrically driven systems by 2030.

The decarbonisation of the H&C sector may have to comprise both individual systems and shared electrified H&C systems from renewable sources of energy, where economies of scale and synergies between different types of consumers and energy systems can be exploited. Individual GSHP systems have been highly successfully deployed, due to several reasons, including: simplicity of operation, low cost, governmental incentives and regulations, and possibly fewer stakeholders in the decision making. Collective systems require more complex engineering and decision making, but offer several potential advantages, including:

- More cost effective use of sources;
- More efficient installations;
- Lower capital investment (per person);
- Multiple sources/storage systems can be combined;
- Improved resilience, as back-up systems can be more easily included;
- High-density housing can be supplied;
- Sources/storage systems can be located centrally, not on the property to be heated/cooled;
- Potential to store waste or excess energy more efficiently;
- Potential business models/opportunities to manage larger systems, invest as a company and supply energy as a commodity.

Traditionally, heating systems have been running with high temperatures to supply high heating demands of poorly insulated systems. Current trends towards more energy-efficient buildings allow the deployment of low-temperature renewable thermal sources such as SGE, waste heat or solar thermal, and the opportunities to reduce the size of installations as the energy demand is lower. Therefore, it is expected that SGE deployment for both individual and shared H&C systems will increase significantly until 2050, if the current trend of decarbonisation continues, mainly due to its renewable, clean, 24/7 and ubiquitous characteristics. Mathiesen et al. [71] define a roadmap for the decarbonisation of the H&C sector in Europe where it is pointed that district heating networks with low-temperature energy sources can play a significant role. However, this roadmap involves several questions that are perceived as barriers for its current deployment. The following are the main barriers envisaged by Bertelsen et al. [72]:

- Lack of available data for project development;
- Insufficient knowledge and awareness about low-temperature available technologies and their advantages;
- Structural disconnection with building renovation strategies, policy makers and the different stakeholders;
- Competition with other technologies, mostly individual fossil-based heating systems and electric cooling systems;
- High upfront costs confronted with lack of appropriate incentives to bridge the gap towards low operational costs;
- Budgetary constraints at the municipal level;
- Absence or inadequate regulation and complex authorisation procedures;
- Absence of appropriate business models and organizational structures;
- Absence of design guides and standards.

Major technological, social and political developments are expected to take place in the following years to increase the deployment of SGE in both individual and district scale solutions for H&C purposes. As the social and environmental pressure to find renewable and clean alternatives for sustaining living conditions for all increases, more focus has been taken into low-temperature solutions for space H&C along with energy efficiency measures in buildings. As an example, Cheap-GSHPs project [73] has been focusing on cutting the upfront costs of installing SGE technology to improve its economic feasibility. Several developments are being made by some pilot projects such as the ones presented in this document that help to realise the nature of possible contract arrangements, business models, design procedures and future legal framework.

6. Conclusions

Further decarbonising our societies unavoidably means to decarbonise the space H&C sector, which is responsible for significant energy consumption and GHG emissions. Sustainable built environment requires clean H&C technologies and energy-efficient buildings allow the deployment of low-temperature renewable thermal sources such as SGE. SGE technologies are one of the most energy efficient and least GHG emitting available alternatives to provide space H&C in both individual and collective thermal systems. The future of utilizing SGE for DHC seems to be promising so as to play a pivotal role in sustainable urban development. Several key directions are anticipated to shape the evolution of such technologies and applications:

- Technological progression, by research and development of more efficient and cost-effective SGE systems (e.g. HP technology, improved materials, improved drilling techniques).
- Enhanced reliability through designing resilient systems with regards to extreme weather and energy interruptions.
- Use of Hybrid systems with other RES (e.g., solar) for improved efficiency and steady energy supply.
- Integration in smart grids for better monitoring, management, and optimization.
- Urban planning for clusters of “geothermal districts” with multiple buildings for higher efficiency and economies of scale.
- Government relevant policies for giving incentives and support to stakeholders and citizens.
- Cascadic interlinking of conventional DH systems and low temperature DHC systems to reduce backflow temperatures in the

conventional system and store excess heat during the summer inside the low temperature DHCs.

As can be seen by the case studies presented, a variety of technological solutions are currently being used or developed at real scale. These are front-runners in the adoption of such technologies and serve as demonstration projects for future expansion. Still, it is true that several barriers could limit such expansion, such as: insufficient data for project development; competition with other technologies; high upfront costs and insufficient incentives to bridge the gap; lack of knowledge and awareness about low-temperature technologies and their benefits by policy makers and stakeholders. However, the potential advantages envisaged, following the examples of the case studies, include: business models for investing and managing larger systems; energy- and cost-efficient systems; multiple and centrally located sources and storage systems; efficient waste/excess energy storage. One would further enhance the advantages of the discussed applications, by looking towards the improvement of optimization and design methodologies, as well as technologies, which will lead to lower costs and lower environmental impact (especially compared to conventional systems).

CRediT authorship contribution statement

João S. Figueira: Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Alejandro García Gil:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Ana Vieira:** Writing – review & editing, Writing – original draft. **Apostolos K. Michopoulos:** Writing – review & editing, Writing – original draft. **David P. Boon:** Writing – review & editing, Writing – original draft. **Fleur Loveridge:** Writing – review & editing. **Francesco Cecinato:** Writing – review & editing, Writing – original draft. **Gregor Götzl:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Jannis Epting:** Writing – review & editing, Writing – original draft. **Kai Zosseder:** Writing – review & editing, Writing – original draft. **Martin Bloemendal:** Writing – review & editing, Writing – original draft. **Michael Woods:** Writing – review & editing, Writing – original draft. **Paul Christodoulides:** Writing – review & editing, Writing – original draft. **Philip J. Vardon:** Writing – review & editing, Writing – original draft. **Simon Paul Borg:** Writing – review & editing, Writing – original draft. **Søren Erbs Poulsen:** Writing – review & editing, Writing – original draft. **Theis Raaschou Andersen:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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