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Improving the Efficiency of District Heating and Cooling Using a Geothermal Technology: Underground Thermal Energy Storage (UTES)

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Abstract. For efficient operation of heating and cooling grids, underground thermal energy storage (UTES) can be a key element. This is due to its ability to seasonally store heat or cold addressing the large mismatch between supply and demand. This technology is already available and there are many operational examples, both within and outside a district heating network. Given the range of available UTES technologies, they are feasible to install almost everywhere. Compared to other storage systems, UTES have the advantage of being able to manage large quantities and fluxes of heat without occupying much surface area, although the storage characteristics are always site specific and depend on the geological and geothermal characteristics of the subsoil. UTES can manage fluctuating production from renewable energy sources, both in the short and long term, and fluctuating demand. It can be used as an instrument to exploit heat available

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from various sources, e.g., solar, waste heat from industry, geothermal, within the same district heating system. The optimization of energy production, the reduction in consumption of primary energy and the reduction in emission of greenhouse gases are guaranteed with UTES, especially when coupled with district heating and cooling networks.

Keywords: Geothermal · UTES · District heating/cooling · Energy transition · Buildings energy retrofitting

1 Introduction

Europe is entering a decade of decarbonization. Referring to the latest policies of the EU commission, such as the "Clean Energy for all European" and the "European Green Deal" [1], Europe is aiming towards the decarbonization of the energy sector. Energy production by renewable energy sources (RES) and improved energy efficiency of buildings are considered key drivers in the pathway from a fossil fuel-based to a carbon neutral society and economy.

A substantial effort and focus are currently placed on electricity, industry and traffic, but half of the energy consumption in the EU is spent on heating and cooling in total [2]. Direct delivery of heating/cooling to consumers via district heating/cooling is seen as an important option to allow the decarbonization of our heating/cooling systems. Optimizing the performance of a sustainable and renewable district heating/cooling grid is becoming an increasingly important topic to both reduce greenhouse gas (GHG) emissions and ensure affordable heating/cooling.

Societal dependence upon energy has increased significantly in the last few decades. Air conditioning systems have increased worldwide from about 4 TW in 1990 to 11 TW (and more) in 2016, and the energy consumption for space heating and cooling is expected to more than triple by 2050 [3]. Since global energy demand for heating and cooling is growing rapidly, good economic and environmental performance are extremely important. Global energy demand is set to grow by more than a quarter to 2040 and the share of generation from renewables is projected to rise from 25% today to around 40%. This is expected to be achieved by promoting the accelerated development of clean and low carbon renewable energy sources and improving energy efficiency. At present, buildings in Europe account for 41% of the final energy consumption, more than transport (32%), and industry (25%), hence the integration of renewable energy technologies is extremely necessary [4]. In addition, cooling needs for warm climates such as Mediterranean areas are increasing. As incomes rise and populations grow, the use of air conditioners is becoming increasingly common, especially in commercial buildings and high-density residences of the hottest world regions. They currently account for about a fifth of the total electricity in buildings around the world [3].

The pressure is high for finding solutions to reduce energy imports, enable low carbon sources and fight against critical heat waves due to climate change. An already feasible and sustainable solution is geothermal energy. It has been used for decades in Europe, and its range of technological solutions can provide electricity, heating and cooling.

As proposed by the Heat Roadmap Europe project [5], heating and cooling grids are crucial for reaching the decarbonization of the heating and cooling sector covering at least 25% of the future end user supply. "Geothermal-DHC", a research network for including geothermal technologies into decarbonized heating and cooling grids, is addressing these topics [6].

Renewable heat can come from many sources, each of which exhibit different characteristics. However, none can be typically generated on-demand and they are often available either continuously or at different times than the demand. To overcome the temporal mismatch in supply and demand of thermal energy, storage facilities are needed.

Therefore, in this paper, the potential of a particular technology concerning geothermal energy and district heating and cooling is depicted: Underground Thermal Energy Storage (UTES). It can serve as seasonal storage or help overcoming short-term peaks of energy requests.

2 UTES in the Energy Transition of District Heating/Cooling Grids

Approximately 1.4 million GWh could be saved and 400 million tons of GHG could be reduced annually by the application of thermal energy storage (TES) in Europe [7].

One of the major sources of renewable heat is solar thermal energy, which harnesses energy from the sun using solar thermal collectors. Most of the solar thermal energy is produced in small-scale systems for domestic space and water heating, but large-scale solar thermal systems for district heating are also common. The supply of solar thermal energy varies seasonally resulting in more energy being available in the summer and less in winter. However, the peak space heating demand is during the winter months, thus creating a seasonal mismatch between the supply and demand. A solution can be to collect energy in the summer, store it seasonally, and use it to cover demand in the winter. One of the methods for seasonal storage of energy is UTES. It includes several different technologies, each one with its specific characteristics. For instance, UTES systems based on sensible heat storage, typically offer a storage capacity of 10–50 kWh/t and storage efficiencies between 50–90%, depending on the specific heat of the storage medium, storage size and thermal insulation technologies [7, 8].

Various UTES systems can be easily integrated into a district heating system in a centralized (large capacity units for neighbourhoods) or decentralized (usually smaller scale units in public and office buildings or households) manner. The utilization of UTES for coupling and the integration of decentralized renewable heat sources contribute to the overall efficiency, flexibility, and response time of a district heating system. The coupling of local renewable energy subsystems and installations to an onsite thermal energy storage system reduces the overall heat consumption of the district heating system. In the case of combined district heating and cooling systems, cold storage is also used. Cold storage may have common storage units with heat storage (operating in seasonal modes) or be designed separately as, for example, cold-water storage or ice storage.

This paper addresses the integration of geothermal energy into multivalent decarbonized district heating and cooling (DHC) networks operating at temperature levels between less than 30 °C (5th generation DHC) and approximately 100 °C (3rd generation DHC). Currently, Geothermal energy (Fig. 1) can be used for baseload supply due to its low operational costs (OPEX). Typically, peak load systems are designed to have a low capital expenditure (CAPEX) with higher OPEX as they are designed to run for only a limited time. UTES can be used to reduce the amount of time peak load systems operate by using low OPEX energy (e.g., from geothermal or other local available renewable or recyclable heat sources). UTES can therefore be used to both fill peak demand loads as well as provide backup supply.

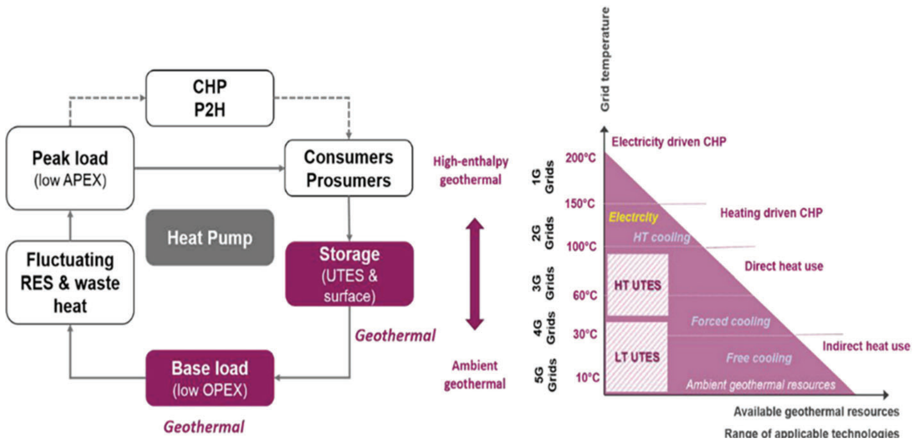

Fig. 1. Sketch of geothermal uses in district heating and cooling networks, from [6].

UTES can provide large-scale seasonal storage of cold and heat in the underground in different ranges of temperature. Commonly, literature refers to Low Temperature (LT) and High Temperature (HT) UTES. The main technical differences between them are:

- LT-UTES uses fluids at temperatures lower than ~25–30 °C; it is usually coupled with geothermal heat pump systems and improves the overall efficiency. It is the most widespread UTES application.
- HT-UTES uses higher temperatures, up to >90 °C, and typically deeper reservoirs; it can be easily coupled with traditional (higher temperature) and innovative district heating, with or without heat pumps to increase temperature.

Moreover, heat pumps at various temperature levels and positions inside the network can also help to modulate and stabilize the DHC network, and waste heat from providing cooling could be recycled through storage. These concepts could be applied to new networks but permit also upgrading existing heating only networks, increasing their overall efficiency.

3 UTES State of the Art in a DHC Context

3.1 Different Types of UTES

UTES falls in the family of technologies based on sensible heat, which is dependent on the mass, specific heat and temperature. The available UTES technologies (Fig. 2, a-f)

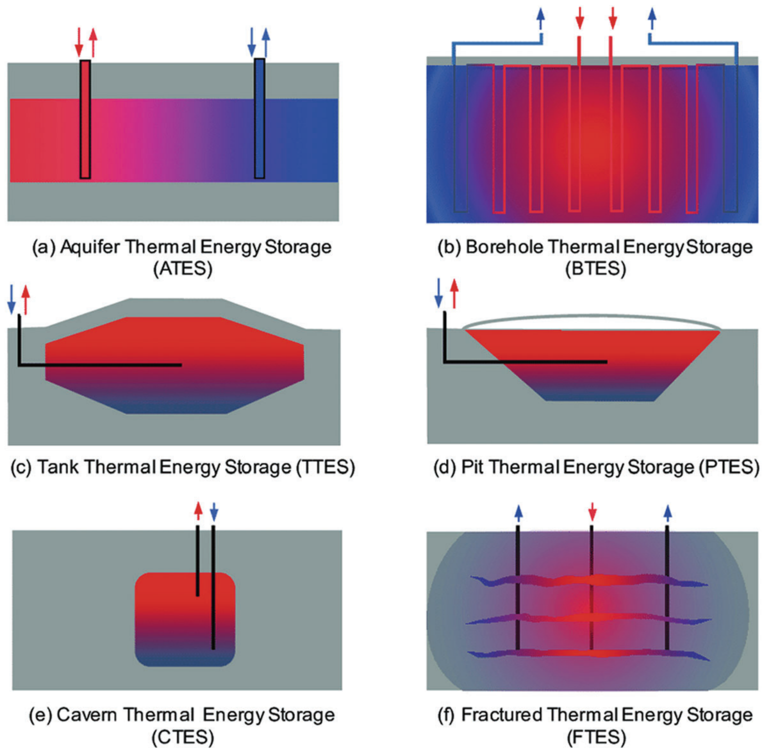

Fig. 2. Sketch of most common UTES technologies, from [12].

include: Aquifer (ATES), Borehole (BTES), Tank (TTES), Pit (PTES), Cavern (CTES), and Fractured (FTES) thermal energy storage [9–11].

ATES uses naturally occurring groundwater bodies at depth between <30 m and up to 2–3 kms. In general, all ATES concepts are based on at least two wells (well doublet) for the extraction and injection of groundwater. These wells are connected to a heat exchanger to transfer the heat between the geofluid circuit and the DHC circuit. For technical, physical and legislative/environmental reasons, the maximum storage temperatures of ATES systems are usually limited to around 90 °C.

BTES can be considered as an improvement on conventional closed-loop Ground Source Heat Pump (GSHP) systems. They consist of an array of vertical borehole heat exchangers (BHE) installed in wells drilled at certain distances and depths depending on geological, hydrogeological and thermo-physical conditions of the underground. BHEs are designed in a way such that heat or cold energy are stored or extracted seasonally from a cylindrical volume of soil or rock (typical distance of heat exchangers: 2–3 m) while GSHPs typically provide dissipation of thermal energy into the subsurface (typical distance of heat exchangers: 6–8 m). Due to their closed-loop technology, they can be installed in almost all locations, but can store less heat for the same CAPEX than ATES systems.

Tank and Pit TES were already used in the 1950s and 1960s, especially in Denmark. They use water containing tanks and pits and operate similarly to ATES systems. Cavern and Fractured systems, again operate similarly, but use natural caverns or fractured formations to store heat, although so far have not been commonly used and their use is restricted to specific sites where the geological and mining conditions allow it.

Currently, ATES and BTES seem to be solutions that guarantee large-scale use and modularity, ranging from storage for small complexes to integration with district heating and cooling networks of large cities.

3.2 UTES Operating Examples

In DHC networks, geothermal energy technology will be a key energy source both in smart cities and smart rural communities, in addition to supplying energy for industry, services and agricultural sectors. This is due to its ability to supply not only heating, cooling and water heating, but also to be a key balancing technology for smart thermal grids via UTES systems. This technology is already on the market and there are several examples of its use, both within and outside a district heating network. The Technology Readiness Level (TRL) provides a useful metric to be used which ranges from technology validated in relevant environment (4–5) to actual system proven in operational environment (9) and ready for the market (Table 1).

Table 1. UTES systems at a glance and their Technology Readiness Level.

Item	Tank	Pit	Borehole	Aquifer
TRL	8–9	Up to 2 GWh: 7–9 above: 3–4	8–9	5–6 (HT) 7–8 (LT)
Storage depth	Surface	Surface to 30 m	30–1,000 m	10–1,000 m
Temperature range	Atmospheric: <100 °C pressurized: >100 °C	<100 °C	Up to 30 °C for shallow and 100 °C for deep systems	Up to 20 °C for shallow and 100 °C for deep systems
Thermal storage capacity	30–80 kWh/m^3	30–50 kWh/m^3	15–30 kWh/m^3	30–40 kWh/m^3
Strengths	Applicable in any place; low development risk	Applicable in any place; low development risk	Low development risk; small surface footprint	High efficiency rate; small surface footprint
Weaknesses	High investment cost; visible landmark	High surface footprint; low efficiency rate	High investment costs; lower efficiency of thermal output	Only applicable in aquifers; development risks

ATES systems provide sustainable heating and cooling energy for different building typologies and can be integrated at a district/urban level. They require a suitable subsurface which allows water to flow easily and can store water (i.e. an aquifer). In [13] is reported that there were around 3,000 ATES applications worldwide by 2017, mostly concentrated in Europe. They are mostly applied for single buildings and small building complexes in the Netherlands with over 2,500 sites, and Nordic Countries such as Sweden and Denmark with 220 and 55 examples, respectively. A more limited number of examples are in Great Britain, China, Japan, Germany, North America and Turkey. The total amount of heat and cold produced by ATES is currently estimated to be 2.5 TWh per year.

The growing number of systems are mainly focused on LT-ATES systems, probably due to market incentive programs and the authorities supporting these kinds of systems. Most of the LT-ATES are in the Netherlands, are shallow and operate with well depths ranging between 25 and 250 m, with temperatures lower than 25 °C, while in Germany the current temperature threshold for these depths is at a maximum of 20 °C for heating and 5 °C for cooling. The TRL of LT-ATES can range between 7 and 8. The applicability of LT-ATES in other European countries is high based on the characteristics of the subsurface. Despite this, the current level of implementation outside the Netherlands lags at the European and worldwide levels [13]. Some large-scale ATES systems are integrated into district heating and cooling networks [14]. The low-temperature range has caused some problems with the integration of ATES systems, as the majority of DHC networks operate at higher temperatures.

A good example of the HT-ATES concept has been developed in Delft, NL (Fig. 3) [15].

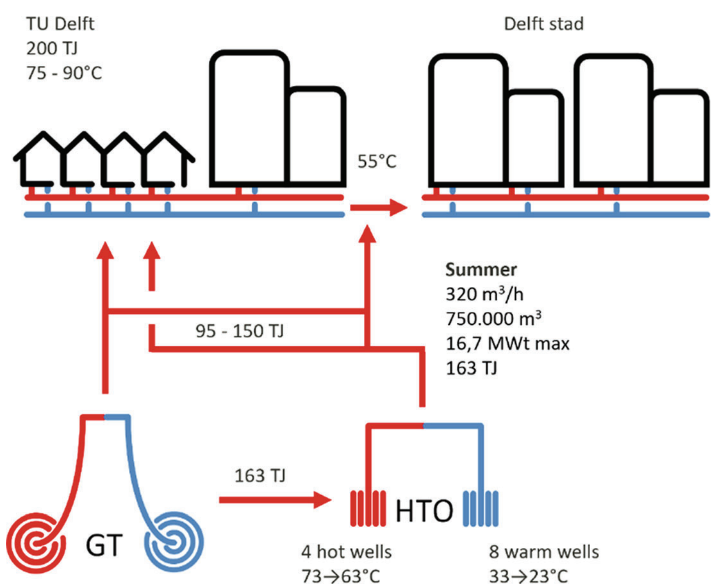

Fig. 3. Delft, the Netherlands: a summary of the HT-ATES at University campus.

The HT-ATES system is proposed to be connected to the existing district heating network of the TU Delft university campus. Developments are ongoing, with plans to realize a geothermal system to supply the heat, and the network will be extended to part of the city of Delft.

Currently, there is a significantly lower implementation of HT-ATES systems, partly due to lack of regulation and partially due to poor technology recognition. In fact, according to [13], only 5 HT-ATES systems are in operation worldwide. The TRL is considered to be between 5 and 7. Generally, several market barriers in the energy market are often preventing the development of such a system in specific countries, where this technology is not yet developed.

BTES applications can be considered to range between a TRL of 7 and 9. They are becoming popular because of their suitability for seasonal storage thanks to slow thermal response and large storage capacities. In recent years, experimental facilities have been used to better understand the underground thermal behavior using these systems, where for example various charging and discharging strategies have been tested [16].

BTES require only a small amount of space to tap into a large volume of subsurface rocks at a relatively low cost. There is no exchange of groundwater like in ATES systems, which increases the geographical applicability. Moreover, a literature review [17] reveals that the energy efficiency of BTES is best when diurnal and seasonal storage are used in conjunction.

An example of this technology can be seen at Crailsheim Hirtenwiesen, Germany (Fig. 4) [18], where 7,300 m^2 of solar thermal collectors provide 50% of the heat for a housing area with 260 units. Heat is stored in two water tanks (100 and 480 m^3) and a seasonal 37,500 m^3 borehole storage. A collector area of 9,700 m^2 (6.8 MWth) and a 75,800 m^3 borehole storage were foreseen. A 489 kWth high-temperature heat pump transfers heat from the larger buffer storage to the smaller one, when necessary, to ensure there is always hot water at 70 °C available.

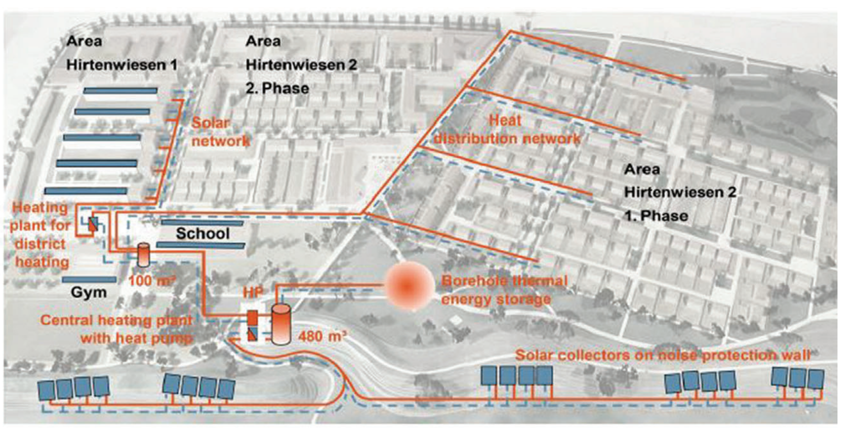

Fig. 4. BTES in Crailsheim Hirtenwiesen, Germany (after [18]).

CTES plants have reached a TRL between 5 and 7. CTES systems require a suitable natural or man-made cavern. Abandoned mines with stable caverns can provide such a facility, especially when located near urban areas (there are over one million abandoned mines worldwide). Depending on the geology and local groundwater conditions, polluted mine water may have to be perpetually treated, becoming a long-term economic burden on current and future generations [19]. Hence, environmental remediation costs could be potentially compensated by exploiting mine water for CTES.

One of the few pilot examples is at Fraunhofer IEG Bochum, Germany [20] (Fig. 5). It is a fully functional high-temperature mine thermal energy storage (HT-MTES) pilot plant, for the energetic reuse of an abandoned coal mine. The seasonal surplus heat available during the summer from solar thermal collectors is stored within the mine workings and is used during the winter season for heating the institute buildings of the "Fraunhofer Institut für Energieinfrastruktur und Geothermie" (IEG).

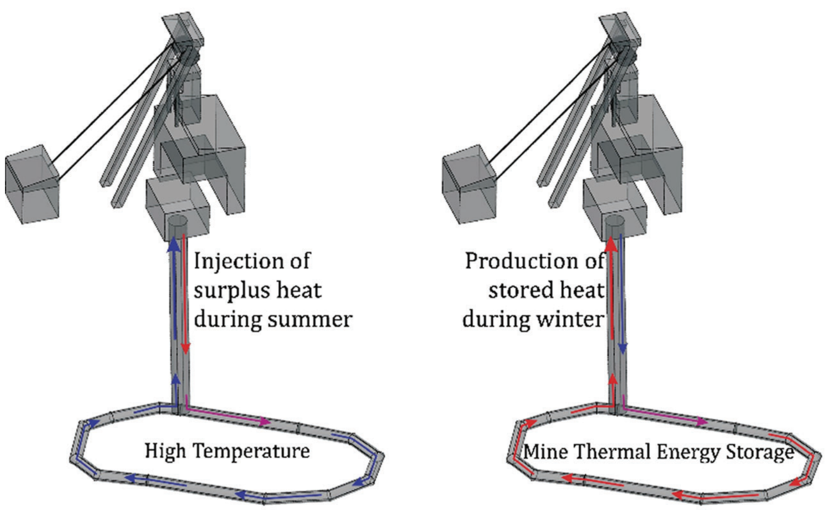

Fig. 5. CTES at Fraunhofer IEG Bochum [20].

4 Discussion

Existing housing infrastructure represents a considerable share of the heating and cooling demand, that can be efficiently and sustainably supplied by geothermal heat pumps and geothermal district heating systems. New materials and designs of the system have also produced promising results to reduce costs and to increase efficiency, but here further work is needed.

Furthermore, geothermal district heating will be increasingly targeted at existing buildings and old inner cities in dense urban areas. At the same time, the concept of UTES is attracting increasing interest from industries, research institutions, and public authorities. It is expected to gain acceptance and market uptake as it will provide a solution to partially replace the use of fossil fuels and to reduce the costs of heating and cooling. It will deliver the combination of geothermal energy with underground storage which will constitute a powerful tool in the context of sector coupling. Geothermal energy combined with small thermal grid systems offers one of the most effective options for this market, both in terms of carbon footprint and economics.

The European Parliament approved an Own Initiative Report on energy storage. The report highlights the role of geothermal as a provider of energy storage and flexibility services, including seasonal thermal energy storage in the underground, batteries and generation of electricity from flexible renewable sources such as geothermal [21].

Stakeholders in district heating and cooling projects such as developers, local authorities, utilities, consumers, and housing associations can be disheartened in investing in UTES technologies, due to non-technical aspects, despite that their technical feasibility has been widely proven. Investment mechanisms, clear guidelines and regulations for planning, building standards and environmental protection, can contribute to accelerate the deployment of UTES projects in the district heating and cooling context [22]. Policy makers should work on removing unnecessary barriers to project progress by ensuring robust planning procedures and assisting potential stakeholders. This stresses the need to implement the current EU Strategy [23] that aims to have flexible procedures in the district heating and cooling market, but still requires special planning for UTES technologies.

The important work of policy makers in this field can be also linked to funding R&D and demonstrations in order to prove the system benefits as well as to promote media campaigns encouraging consumer uptakes. Price support mechanisms are one of the important pillars between the main outlook until 2050; they can help drive the competitiveness of decarbonizing district heating and cooling on the whole, helping to increase demand for thermal storage. Increases in reliability given by thermal storage, and the ability to improve flexibility of using multiple sources, could also be included in such mechanisms.

5 Conclusions

The environmental objectives of the European Green Deal represent an innovation-driven development strategy for Europe, making sustainable development a priority. The new strategy raises several multilevel governance challenges involving not only prosperous cities or capitals but also suburban and rural areas. Energy production by RES and improved energy efficiency of buildings are considered key drivers in the pathway from a fossil fuel-based to a carbon neutral society and economy. Investment decisions taken by agents involved in energy retrofitting of buildings and the development of energy systems, alongside the value of related investments, can determine the success or failure of a fast energy transition.

One of the major challenges for this future energy systems is to overcome the mismatch between supply and demand through the development of energy management tools achieved thanks to new information and communication technologies and a new smart energy system approach.

Underground Thermal Energy Storage enables the utilisation of various sources of heating and cooling and the integration of such renewable energy sources in urban areas.

It is a ready-to-market technology, extensively tested in labs, in numerical models and real scale test sites, with many already operating systems, although some versions of the technology require further development. Compared to other storage systems it has the advantage of being able to store large quantities of heat without occupying a significant surface area, although the storage characteristics are always site-specific and depend on the geological and geothermal characteristics of the subsoil.

Between the most important outlooks until 2050, the International Renewable Energy Agency shows the key attributes of UTES technologies [22], identifying priorities for ongoing research and development such as:

- investment to drive technological development and measures are needed to enhance a market pull, together with well-defined and favourable energy policies aimed at scaling up the use of geothermal energy in the district heating and cooling sector also combined with other renewables;
- UTES systems can contribute to the energy transition investment package available to Countries for post-COVID recovery; this can strengthen health and economic infrastructure and align the energy development with global climate and sustainability goals.

Furthermore, the RHC and EGEC Agenda [23] sets forth certain technologies showing how the well-established, low temperature heat pump supported applications, energy produced from low temperature air source, water source and solar thermal energy could be stored underground and used for heating and cooling purposes. Based on the findings and conclusions reported in this agenda, these systems could become an important provider for heating and cooling for individual houses, industry and utility buildings, as well as for district heating and cooling.

UTES applications reveal an effective technology to bridge the gap between energy demand and supply, seasonally for both district heating and cooling networks. This improves efficiency, techno-economic feasibility and reduces the impact on the environment. Storage is currently the only way to use volatile renewables, such as solar-thermal, and make use of waste heat to enhance the overall energy efficiency of the heating and cooling market, which is an EU goal.

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References

1. European Commission: A European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. accessed 16 Dec 2021
2. European Commission: Heating and cooling (2020). https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en. Update 25 Oct 2021, Accessed 16 Dec 2021
3. IEA: Global Energy Review 2019, Report Extract Electricity (2019). https://www.iea.org/reports/global-energy-review-2019/electricity. Accessed 16 Dec 2021

4. Todorov, O., Alanne, K., Virtanen, M., Kosonen, R.: A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: a case study in Finland. Sustain. Cities Soc. **53**, 101977 (2020)
5. Heat Roadmap Europe. https://heatroadmap.eu. Accessed 16 Dec 2021
6. Goetzl, G., Milenic, D., Schifflechner C.: Geothermal-DHC, European research network on geothermal energy in heating and cooling networks. In: Proceedings World Geothermal Congress 2020+1. IGA, Reykjavik, Iceland (2021)
7. IEA ETSAP & IRENA: Thermal Energy Storage, Technology Brief **E17**, 1–20 (2013)
8. Wild, M., Lüönd, L., Steinfeld, A.: Experimental investigation of a thermochemical reactor for high-temperature heat storage via carbonation-calcination based cycles. Front. Energy Res. **9**, 748665 (2021)
9. Hellström, G., Larson, S.: Seasonal thermal energy storage – the HYDROCK concept. Bull. Eng. Geol. Environ. **60**, 145–156 (2001)
10. Novo, A.V., Bayon, J.R., Castro-Fresno, D., Rodriguez-Hernandez, J.: Review of seasonal heat storage in large basins: water tanks and gravel-water pits. Appl. Energy **87**(2), 390–397 (2010)
11. Pavlov, G.K., Olesen, B.W.: Thermal energy storage - a review of concepts and systems for heating and cooling applications in buildings: Part 1. Seasonal Storage Ground **18**(3), 515–538 (2012)
12. Janiszewsky, M.: Techno-economic aspects OD seasonal underground storage of solar thermal energy in hard crystalline rocks. Doctoral dissertation, Aalto University (2019)
13. Fleuchaus, P., Godschalk, B., Stober, I., Blum, P.: Worldwide application of aquifer thermal energy storage. A review. Renew. Sustain. Energy Rev. **94**, 861–876 (2018)
14. Schmidt, T., Pauschinger, T., Sørensen, P.A., Snijders, A., Thornton, J.: Design aspects for large-scale pit and aquifer thermal energy storage for district heating and cooling. Energy Procedia **149**, 585–594 (2018)
15. Bloemendal, M., et al.: Feasibility study: HT-ATES at the TU Delft campus. TU Delft/ENGIE (2020). https://www.warmingup.info/documenten/window-fase-1---a1---verkenning-hto-tud---feasibilityht_ates_tudelft.pdf
16. Nilsson, E., Rohdin, P.: Empirical validation and numerical predictions of an industrial borehole thermal energy storage system. Energies **12**(12), 2263 (2019)
17. Lanahan, M., Tabares-Velasco, P.C.: Seasonal thermal-energy storage: a critical review on BTES systems, modeling, and system design for higher system efficiency. Energies **10**(6), 743 (2017)
18. Miedaner, O., Mangold, D., Sørensen, P.A.: Borehole thermal energy storage systems in Germany and Denmark – construction and operation experiences. In: Greenstock Beijing 2015, Sensible TES, vol. C-1, pp. 1–8 (2015)
19. Menéndez, J., Ordóñez, A., Álvarez, R., Loredo, J.: Energy from closed mines: underground energy storage and geothermal applications. Renew. Sustain. Energy Rev. **108**, 498–512 (2019)
20. Hahn, F., et al.: The reuse of the former Markgraf II Colliery as a mine thermal energy storage. In: European Geothermal Congress 2019. EGEC, Den Haag, The Netherlands (2019)
21. European Parliament: On a comprehensive European approach to energy storage (2019/2189(INI)) (2019). https://www.europarl.europa.eu/doceo/document/A-9-2020-0130_EN.html
22. IRENA: Innovation Outlook: Thermal Energy Storage. International Renewable Energy Agency, Abu Dhabi (2020). ISBN 978-9260-279-6, www.irena.org/publications
23. European Commission: Towards a smart, efficient and sustainable heating and cooling sector. EU to fight energy waste with the first Heating and Cooling Strategy (2016). https://ec.europa.eu/commission/presscorner/detail/en/MEMO_16_311