Barth *et al. Geothermal Energy* (2026) 14:11
https://doi.org/10.1186/s40517-026-00383-8

Geothermal Energy

RESEARCH **Open Access**

Potential of aquifer thermal energy storage (ATES) for data centres in Germany

Florian Barth[1*], Georg Schefel[1], Philipp Blum[1] and Kathrin Menberg[1]

*Correspondence:
florian.barth@kit.edu

[1] Institute of Applied Geosciences (AGW), Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

Abstract

Data centres (DCs) produce large quantities of waste heat and thus require excessive amounts of cooling, which offers potential for an environmentally friendly space heating supply for nearby areas. However, this coupled supply suffers from a seasonal mismatch, with most space heating being required in winter, while DCs produce heat during the entire year. Aquifer thermal energy storage (ATES) systems are a cost-efficient way to overcome this mismatch and increase the utilisation of DC waste heat. In this study, we quantify the potential waste heat of 19 DCs in Germany, 13 of which are located in areas that are hydrogeologically suited for installing ATES systems. The waste heat of the DCs is quantified based on the installed cooling machines, which are detected on aerial images, their estimated cooling capacity and common DC cooling load factors. Considering typical heat recovery rates of ATES systems, the 13 DCs could supply 707 GWh_{th} of heat. By comparing this amount of potential waste heat with local heating demands, supply areas are delineated, revealing a total of around 20,000 buildings that could be supplied. In Frankfurt, which has one of the largest accumulations of DCs in Europe, six identified DCs located in areas most suitable for ATES could supply 541 GWh_{th}, which is equivalent to 13% of the city's residential and commercial heating demand. Considering all ten DCs in Frankfurt by placing the ATES systems in the most suitable areas, even 819 GWh_{th}, equivalent to 20% of the area's heating demand, could be achieved. This demonstrates the high potential of waste heat storage from DCs for urban areas with suitable subsurface for ATES systems and its importance for current and future municipal heat planning.

Keywords: Data centre, Waste heat, Aquifer thermal energy storage, Geothermal potential

Introduction

With a share of 23%, space heating and domestic hot water production in the residential and commercial sector consumes a large portion of global final energy (International Energy Agency 2019). Simultaneously, data centres, which currently consume about 1.0–1.3% of global electricity (International Energy Agency 2023), require large amounts of cooling, with about 30–50% of their total energy being attributed to the production of cold (Ebrahimi et al. 2014; Li and Kandlikar 2015; Zhang et al. 2021). As a result, they produce large amounts of waste heat, which is usually not utilised, but rejected into the atmosphere (Ebrahimi et al. 2014; Jagdale an Aljbour 2024). In Europe, for example, DCs are estimated to produce 64 TWh of waste heat, which equals 2.3% of the heating demand of buildings in Europe (Lygnerud et al. 2022). Thus, DCs account for 23% of the total urban waste heat potential, second only to sewage water (Lygnerud et al. 2022). The German government has recognised the waste heat potential of DCs and passed a law that makes the examination of waste heat utilisation of future DCs mandatory (Bundesamt für Justiz 2023b). Towards the same goal, newly installed heating systems in German buildings will from 2026 onwards be required to utilise at least 65% heat from renewable sources, such as district heating systems, solar thermal, heat pumps or biomass (Bundesamt für Justiz 2020). Furthermore, German communities have to provide municipal heat plans for the transformation from fossil fuel-based to renewable heat production (Bundesamt für Justiz 2023a). To this end, coupling the production of heat and cold in areas with both heating and cooling demand using low-temperature, 5th generation district heating and cooling (DHC) systems is a promising option, as these systems can increase overall efficiency, as well as decrease CO_2 emissions and cost (Revesz et al. 2020).

As the cooling of DCs contributes significantly to the DCs' energy consumption, efficient cooling strategies are needed to decrease cost (Alkrush et al. 2024). 80% of DCs use cold air to cool their server rooms (Shinde 2024). However, technologies, such as liquid cooling, can significantly decrease the power consumption of the DCs due to higher thermal conductivities of liquids compared to air (Chi et al. 2014) and thus reduce operating cost (Alkrush et al. 2024). Higher thermal conductivities also allow for higher temperatures of the cooling liquid to keep the processors at a constant operating temperature, compared to air-cooled servers (Stahlhut et al. 2025). Thus, waste heat temperatures of liquid cooling are significantly higher (50–60 °C) than from air cooling with computer room air conditioners (15–35 °C) (Wahlroos et al. 2017; Yuan et al. 2023). Conventional 1st to 3rd generation district heating networks (DHN) utilise high-temperature industrial waste heat sources and thus have network temperatures of < 100 to > 200 °C (Lund et al. 2021). 4th generation DHNs supply temperatures as low as 50 °C and 5th generation district heating and cooling systems operate at 10–40 °C (Lund et al. 2021). In this regard, the higher temperatures of liquid cooling offer additional possibilities for waste heat utilisation, making the coupling with district heating systems more straightforward and increasing their economic benefit (Kong et al. 2024; Lu et al. 2024). However, to utilise low-temperature waste heat, e.g. in 5th generation DHNs, heat pumps and thus additional electricity are required to boost temperatures (Gudmundsson et al. 2022). Here, heat pump efficiency depends, e.g., on supply temperature and setpoint temperature. When boosting from a supply temperature of 20 °C to a space heating temperature of 35 °C, water-to-water heat pumps show a coefficient of performance (COP) of up to 10, while for domestic hot water (55 °C) a COP of 5 is observed (Reiners et al. 2021). Additionally, heat losses in the DHNs occur. Low-temperature DHNs are characterised by relatively low network losses due to smaller temperature differences to the environment compared to high-temperature systems (Lund et al. 2014). A 4th generation DHN, e.g., shows a network loss of 3–7% over a distance of 4.5 km, whereas the losses in 5th generation systems can be even lower (Toffanin et al. 2022).

A few examples for direct DC waste heat utilisation in buildings and thermal energy storage (TES) to buffer heat supply and demand already exist (Alkrush et al. 2024). In Odense, Denmark, a DC directly supports the heating of 7,000 homes by boosting

DC waste heat with heat pumps before distributing it in the local DHN (Alley 2020), with plans to extend to 11,000 homes (Hanley 2022). In Dublin, Ireland, DC waste heat directly supplies 32,800 m^2 of public building space (Bryne Wallace Shields LLP 2025). In Stockholm, DCs are supposed to heat 10% of the city by the year 2035 (Biba 2017). In Dresden, Germany, a small DC is directly integrated into a multi-family residential building, providing heating and domestic hot water directly from liquid server cooling (Voss 2016). This coupling allows for particularly efficient operation of the DC, as no conventional cooling is required (Voss 2016). Another system that additionally utilises thermal storage to balance seasonal mismatches in supply and demand is the "Bonner Bogen" complex in Germany. Here, a DC, a hotel and an office building are connected through an energy supply system that uses an aquifer thermal energy storage (ATES) system for thermal storage (Bundesverband Geothermie 2022; Fleuchaus et al. 2021; Stemmle et al. 2021). A larger system is located in Wisconsin (U.S.), where around 40 buildings, including a DC, are connected through a district heating and cooling system utilising geothermal wells for thermal storage (U.S. Department of Energy—Office of Energy Efficiency and Renewable Energy—Geothermal Technologies Office, 2024).

As DCs require cooling all year round and residential and commercial buildings require most heating in winter (Wahlroos et al. 2017), seasonal TES systems, such as ATES systems, are essential to balance seasonal variations in (DC-coupled) low-temperature DHC systems (Revesz et al. 2020). ATES, which is currently mainly utilised in the Netherlands, Belgium and northern Europe (Fleuchaus et al. 2018), uses porous aquifers to seasonally store warm and cold water to decrease the temperature differences between the heat or cold source and the desired indoor or domestic hot water temperature. Thus, heat pump efficiencies in ATES are typically higher than those of air-sourced heat pump (ASHP) or ground-sourced heat pump (GSHP) systems, resulting in overall lower energy consumption (Staffell et al. 2012). ATES systems, which can have capacities up to several MW, can save up to 70% of energy compared to conventional technologies such as gas boilers (Fleuchaus et al. 2018; Vanhoudt et al. 2011), and have significant carbon savings of up to 74% (Stemmle et al. 2021) with payback times of 2–10 years (Bakema et al. 1994; Baxter et al. 2018; Fleuchaus et al. 2018, 2020; Gao et al. 2017; Hoekstra et al. 2020; Midtomme et al. 2017). If used solely for cooling in DCs by storing cooling energy for the summer (without utilisation of the waste heat), ATES can reduce the DC's cooling system's energy consumption by over 20% (Drenkelfort et al. 2015). In Germany, around 50% of the shallow subsurface was shown to be very well or well suited for ATES systems (Stemmle et al. 2022).

Comparing building or district heating demands with the potential heat supply rates of various open and closed geothermal systems demonstrates the large potential of such shallow geothermal energy systems (Miocic and Krecher 2022; Schiel et al. 2016; Tissen et al. 2021). Thereby, it was found that 40% of the buildings in Ludwigsburg (Schiel et al. 2016), 44% of the buildings in the state of Baden-Wuerttemberg (Miocic and Krecher 2022), 63% of the heating demand of Vienna, Austria (Tissen et al. 2021) could theoretically be supplied by GSHP systems. Thus, all of these studies show that decentralised GSHPs on property-scale are not sufficient to meet the high heating demands of dense urban areas (Miocic and Krecher 2022; Schiel et al. 2016; Tissen et al. 2021). However, by coupling multiple GSHPs and managing them on district scale, the useful heating energy produced with GSHPs can be increased by a total of up to 31%, showcasing the potential of district-scale solutions (Walch et al. 2022) It is also shown, that injecting waste heat into GSHPs to recover the subsurface temperature, can increase the power density of the subsurface and thus heating output and efficiency of GSHPs manifold (Walch et al. 2022). Finally, compared to other geothermal systems, such as GSHPs, ATES systems possess significant economic benefits if high system capacities are required, such as for district scale systems (Herrmann et al. 2026).

Hence, the current study aims to quantify the potential of supplying residential and commercial heating demands on district scale by seasonally storing waste heat from DCs using ATES systems (Fig. 1). Therefore, 19 DCs in Germany are selected and classified based on the suitability of the subsurface for ATES at their specific locations. To determine the amount of available waste heat from the DCs, the installed cooling capacities of the DCs are quantified from aerial images, and the annually produced amount of waste heat is estimated based on the DCs' operation. The potential heat supply from seasonal TES is estimated by considering typical heat recovery rates for ATES systems. Finally, comparing this potential heat supply from ATES-coupled DCs to local heating demand data allows delineating potential supply areas.

Methods

ATES suitability and selection of data centres

For efficient long-term operation, ATES systems require specific geological and hydrogeological conditions, which can be spatially evaluated and statistically analysed to map the suitability of the German subsurface for ATES qualitatively (Fig. 2, based on Stemmle et al. 2022). The main factors for ATES operation are significant groundwater resources to provide sufficient storage volume for heat and cold, as well as a low groundwater flow velocity to allow for an efficient recovery of the injected heat and cold (Bloemendal and Olsthoorn 2018; Stemmle et al. 2022). Another factor is the chemical composition of the groundwater, as high concentrations of iron or manganese can lead to well clogging and decrease the life expectancy of the wells (e.g. Lu et al. 2019). Lastly, the ATES suitability map also considers the ratio between heating degree days (HDD) and cooling degree

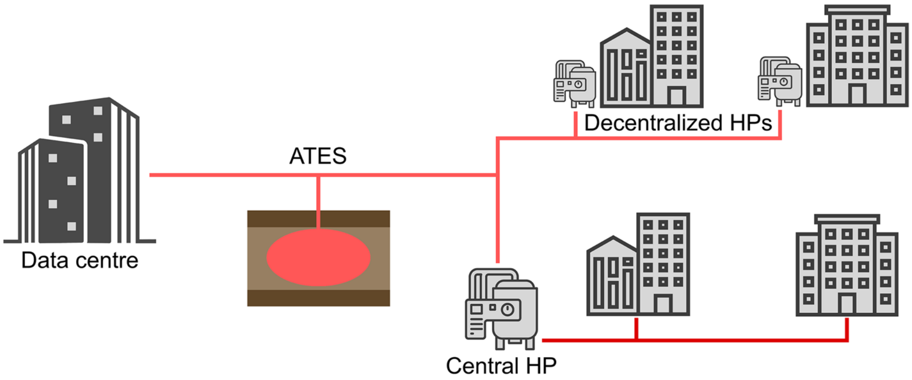

Fig. 1 Systematic scheme for storing data centre waste heat by aquifer thermal energy storage (ATES) systems and distributing heat to customers through DHN. The heat can either be distributed directly to the customers, where decentralised heat pumps are used to boost temperatures, or a large central heat pump boosts the temperature before distribution to the individual customers.

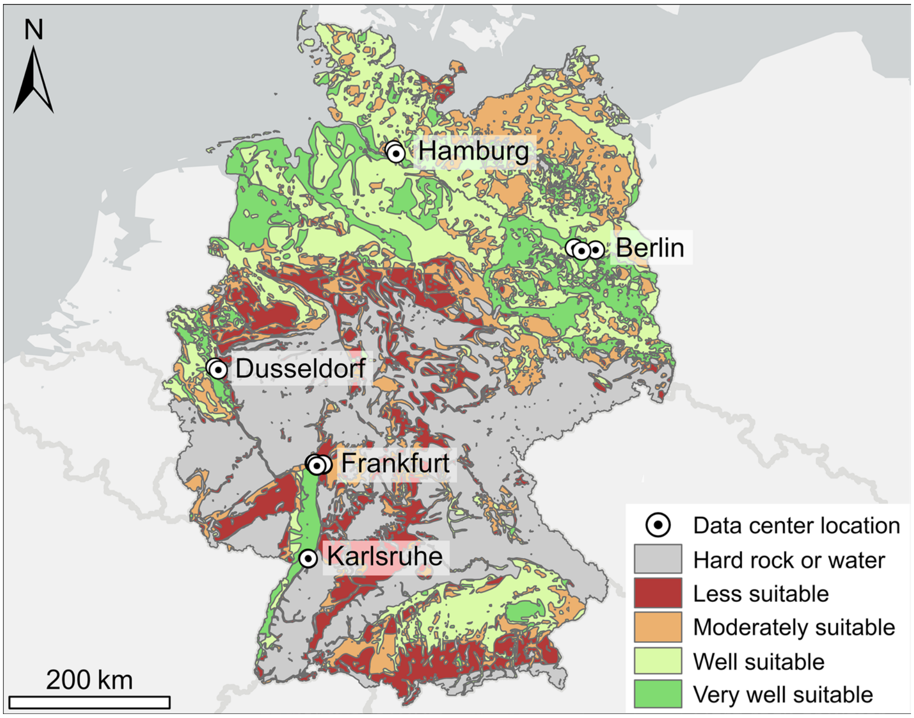

Fig. 2 Location of the cities with the studied 19 data centres on the aquifer thermal energy storage (ATES) suitability map for Germany by Stemmle et al. (2022). Colours indicate the ATES suitability

days (CDD) as a measure of the balance of heating to cooling demand (Stemmle et al. 2022). Thereby, an equal ratio is considered ideal (Stemmle et al. 2022).

DCs are primarily selected based on their location in German cities with generally suitable conditions for ATES in terms of the presence of shallow porous aquifers (Fig. 2). An additional factor is the availability of high-resolution aerial images, such as Google Earth Pro (Google 2023), as these are required for automated detection of the heat rejection units of the cooling systems, which serve as a basis for quantifying installed cooling capacity. Lastly, we specifically focus on cities with available heating demand data to delineate possible supply areas.

Thus, 19 DCs in Hamburg, Berlin, the region around Frankfurt (including Frankfurt am Main and Offenbach), Dusseldorf and Karlsruhe are selected (Fig. 2, Table A.1). Ten of these are located in Frankfurt, which is one of the largest internet hubs in Europe (CollocationIX 2025). If multiple DCs of the same company are situated in a DC park (e.g. Digital Reality FRA29 and Digital Reality FRA30), they are presented as one DC in this study (e.g. Digital Reality FRA29 + 30).

Quantifying potential heat supply from data centres

The cooling capacity of the DCs' installed cooling machines is quantified from aerial images. To do so, heat rejection units of air-cooled chillers, which are visible on aerial images (Fig. 3) (Barth et al. 2023a), are detected from aerial images by applying a trained deep learning algorithm (Barth et al. 2023b, 2025) on aerial images from Google Earth Pro (Google 2023). Heat rejection units used to cool the emergency power generators of the

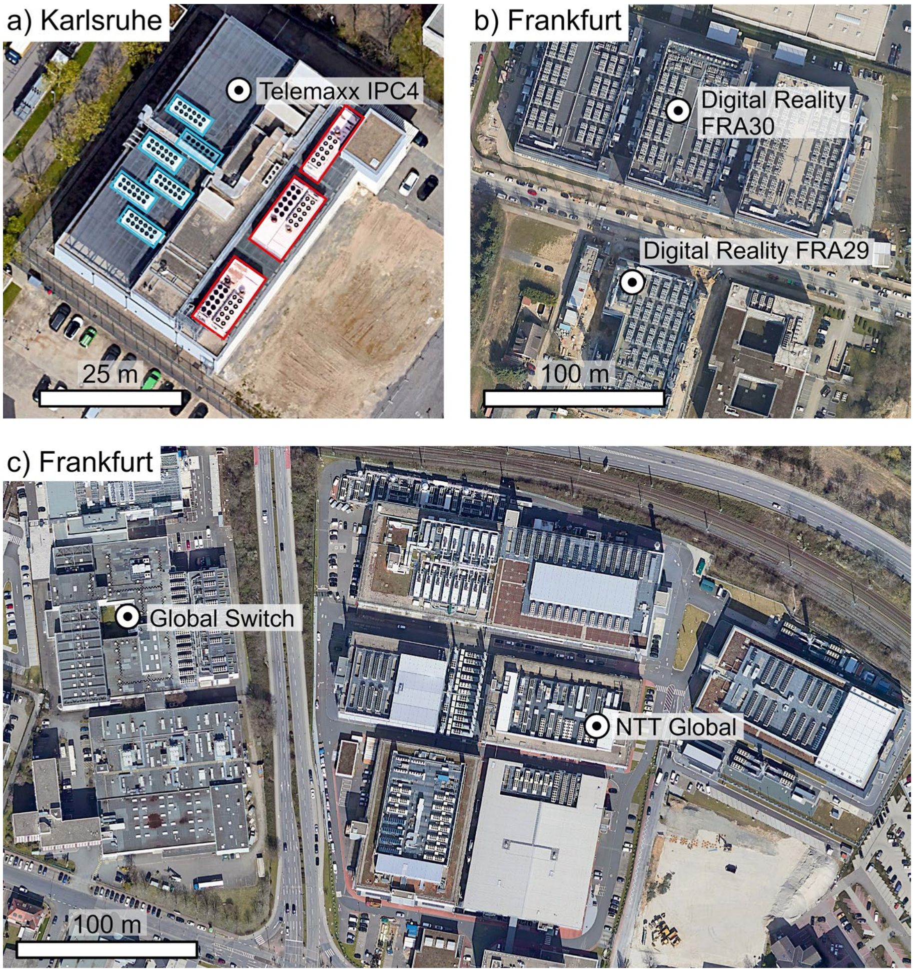

Fig. 3 Exemplary aerial images of data centres in Karlsruhe (**a**) and Frankfurt (**b**, **c**). For the IPC4 in Karlsruhe, heat rejection units for the data centre cooling (blue) and the emergency power generators (red) are highlighted. Aerial images from Google ©

DCs are excluded, as they usually only operate temporarily together with the emergency power generators at high ambient temperatures in summer. The emergency power generators can be identified from their characteristic container-like shape with connected chimneys, with the corresponding heat rejection unit often being installed on top or next to them and connected with ducts (e.g. at the DC Telemaxx IPC4, Fig. 3a).

Heat rejection units (condensers) that are utilised by air-cooled chillers typically induce an airflow by fans to directly cool the condenser coils and the refrigerant with ambient air (Barth et al. 2023a; Naik and Muthukumar 2017). Based on their appearance in aerial images, the condensers can be categorised into two classes, with the main optical difference being the size of the axial fans (Barth et al. 2023b). The nominal cooling capacity of air-cooled chillers utilising condensers with small fans (< 1 m) is quantified according to the following equation, which was obtained from regression analysis using data on nominal cooling capacities from 527 air-cooled chillers (Barth et al. 2025):

$$Q_{th} = 53.3 \times n \tag{1}$$

with Q_{th} being the nominal cooling capacity in kW and n being the number of condenser fans. The regression is based on the principle that the nominal cooling capacity is proportional to the airflow of the condenser (Bracco et al. 2009). For a research campus in Germany, evaluation shows that the highest accuracies are achieved for systems that utilise condensers with over four fans, as they are also typical for most of the DCs of our study (Barth et al. 2025). Here, the total capacity of the cooling systems is overestimated by 6% with a relative average deviation of 13% (Barth et al. 2025). The DC "CyrusOne" in Frankfurt additionally utilises air-cooled condensers with larger fans (1.6 m), compared to the others. The nominal cooling capacity of units with condensers with large fans is quantified according to the following equation, which was derived based on the analysis of 51 chillers (Barth et al. 2023b):

$$Q_{th} = 69.8 \times A - 68.0 \times n - 80.4 \tag{2}$$

with A being the footprint of the condenser in m^2 and n being the number of condenser fans. To quantify the amount of annually generated waste heat of each DC, load factors and the operating time of the utilised chillers have to be considered. The annual waste heat produced by the DCs which is available for seasonal TES can be quantified with the following equation:

$$E_{th} = Q_{th} \times F_{load} \times \left(1 - F_{free}\right) \times (1 - F_{down}) \tag{3}$$

with E_{th} being the annual waste heat in kWh/a, F_{load} being the annual load factor, F_{free} being the share of free cooling and F_{down} being the share of annual downtime.

DCs are rarely operating at full server loads, but usually run at an annual average of 10–50% server capacity (Barroso and Hölzle 2007), whereas small DCs averaged at 11% in 2014 and are expected to average at 20% in 2027 and colocation DCs, such as the DC "NTT" in Berlin (NTT Data 2024), the DC "Mahlsdorf" (ScaleUp Technologies xxxx), the "Digital Reality" DCs in Frankfurt (Digital Reality xxxx), Equinix in Dusseldorf (Equinix xxxx) and the "Telemaxx" DCs in Karlsruhe (Telemaxx xxxx) averaged at 20% and 35% (Shehabi et al. 2024). Only hyperscale DCs average at relatively high loads of 45% and 50% respectively (Shehabi et al. 2024). However, even when operating colocation DCs at such low average server capacities, 60–70% of the peak electricity power is required by the servers (excluding cooling equipment) (Barroso and Hölzle 2007). As all electrical energy consumed by servers is converted into heat (Murzakulova et al. 2025), this results in an equivalent cooling load. In comparison, the commonly for DCs used power usage effectiveness (PUE) refers to the factor between total power consumed by a DC to the power of its IT equipment (Brady et al. 2013). Thus, the PUE is a measure of the efficiency of the entire DC (Brady et al. 2013).

Without knowledge about actual server utilisation in each DC, we assume a conservative mean annual server power consumption of 60% of peak power (Brady et al. 2013), directly translating to an annual mean load factor of 60% (or 0.6) for the installed cooling capacity. However, if the ambient temperature is sufficiently low, DCs can make use of free cooling, which typically involves switching off the energy-intensive chiller compressor to directly cool the refrigerant (or the servers) with the outside air (Zhang et al. 2014). Accordingly, we assume that the waste heat produced by free cooling does not contribute to the potential STES system. DCs in the northeast of the US, with similar climatic design conditions as in Germany (ASHRAE 2021), typically have a share of free cooling of 28% (Darrow and Hedman 2009). Thus, we assume 28% free cooling time for the examined German DCs ($F_{free} = 0.28$). Additionally, we include a downtime factor of 0.25% (22 h/a, $F_{down} = 0.0025$), which is the reported mean downtime of Tier II data centres (ADC Telecommunications Inc., 2006).

When thermal energy is seasonally stored by ATES systems, only a part of the injected heat (or cold) can be recovered due to advective and diffusive dissipation of heat in the aquifer (Fleuchaus et al. 2020; Stemmle et al. 2024). The potential heat supply by DC-coupled ATES systems can thus be quantified as:

$$E_{ATES} = E_{th} \times \eta_{ATES} \tag{4}$$

with E_{ATES} being the potential heat supply by ATES systems in kWh/a, and η_{ATES} being the thermal recovery rate of ATES systems. The thermal recovery rate of ATES systems depends mainly on the groundwater flow velocity and is therefore highly site-specific (Stemmle et al. 2024). Most DCs examined in this study are located in areas with groundwater flow velocities < 0.5 m/day (10 DCs), or between 0.5 and 1.5 m/day (6 DCs) (Stemmle et al. 2022). For the remaining three DCs, which are located in 400–800 m distance to the 0.5–1.5 m/day zone, no data is available. As 0.5 m/day was found to correspond on average to a recovery rate of around 60% (Stemmle et al. 2024), this conservative value is adopted for all DC locations.

Delineating potential supply areas

To delineate potential supply areas for waste heat utilisation from DCs using seasonal heat storage by ATES systems, the previously determined potential heat supply E_{ATES} is compared to local heating demand data. Thus, heating demand data for residential and commercial buildings in each city is collected (Table A.2). The data comprises modelled heating demands based on parameters such as climate, building type, age and floorspace (Landesamt für Natur Umwelt und Verbraucherschutz Nordrhein-Westfalen xxxx; Landesanstalt für Umwelt Baden-Württemberg xxxx; Landesbetrieb Geoinformation und Vermessung (LGV) Hamburg. LGV Support. Geschäftsbereich Geobasisinformationen, 2016; LEA LandesEnergieAgentur Hessen GmbH xxxx), as well as heating demands inferred from natural gas consumption and district heating deliveries (Senatsverwaltung für Wirtschaft Energie und Betriebe xxxx). Heating demand data is aggregated on urban block scale for all locations except Dusseldorf, where building-scale heating demand data is utilised.

Feasibility of waste heat utilisation depends on distance of the DHN and thermal capacity (Kumar et al. 2025). Although feasibility varies for each case and location, a study in Stockholm, Sweden found that connecting DCs with a capacity of 11.4 MW to DHNs is feasible within a 5 km radius (Kumar et al. 2025). They also state, that higher capacities enable greater distances. For urban waste heat sources below 2 MW, the feasible distance is found to be 2–3 km (Kumar et al. 2025). For a feasibility study, detailed planning of the network with pipe layout, dimensions and installation cost would be required. In general, piping and installation cost of generation 5 DHC networks (uninsulated pipes) are between 104 €/m (diameter 3.2 mm, rural with unpaved surfaces) and 2900 €/m (diameter 800 mm, urban with paved surfaces) (nPro xxxx). Corresponding costs for insulated pipes as used for previous generations are between 579 €/m and 7230 €/m (nPro xxxx).

For our study, we aim to propose potential supply areas directly adjacent to the DCs to minimise cost. Here, the DC Telemaxx IPC3 has the furthest distance to any potential customers (1.2 km to the closest potential customer) with uninsulated pipes, covering the mostly unpaved distance of 1.2 km from Telemaxx IPC3 to the closest customer would cost 124,800–2,916,000 € depending on the diameter of the pipes (diameter 32–800 mm) (nPro xxxx). Additionally, we consider that the potential supply area should not stretch over a distance of 5 km from the DC, even if the DC capacity in our study exceeds the value of 11.4 MW from Kumar et al. (2025). Covering a straight distance of 5 km with uninsulated pipes can potentially cost 520,000–36,150,000 € (nPro xxxx), although additional costs are expected as the distribution networks are likely not straight. Costs for ATES systems can be minimised by maximising system capacity with around 300 €/kW for a 2 MW system (Herrmann et al. 2026).

DHNs exist near some of the examined DCs. If possible, areas with existing district heating are avoided when delineating possible waste heat supply areas. While existing DHN infrastructure could ease the switch to ATES-coupled waste heat utilisation, and supplying existing networks could imply replacing heat from e.g. gas heating plants, our analysis predominantly aims for areas with little or no existing district heating due to the more imminent need for renewable alternatives for conventional, decentralised heating by gas or oil. If no buildings without district heating are located close to the DC, areas with existing district heating are included in the potential supply areas and labelled accordingly. Data on existing district heating supply areas and networks is summarised in Table A.2. Here, DHNs are indicated on urban block scale or with a buffer around the pipe network for means of data protection.

Results and discussion

ATES suitability of data centre locations

According to the ATES suitability map, 15 out of the 19 examined DCs are located directly over subsurface very well or well suited for ATES systems (Fig. 4). Accordingly, these maps give a first, qualitative indication about the local potential of DC-coupled ATES systems. Two more DCs located in eastern Frankfurt, namely Digital Reality FRA8-16 and FRA15, are situated just along the border between the well suitable and moderately suitable zone, and two more DCs (Vantage and maincubes) are in the less suitable zone (Fig. 4c). This area in eastern Frankfurt was denoted as moderately or less suitable mainly due to missing groundwater flow velocity data and subsequent assumption of relatively high velocities of > 5 m/day (Stemmle et al. 2022). Thus, further analysis, for example, using locally available groundwater data, could show whether the subsurface below these four DCs (Digital reality FRA8-16, FRA15, Vantage and maincubes) is suitable for ATES.

The two DCs in Karlsruhe, Telemaxx IPC3 and IPC4, are located within a very suitable area for ATES, yet also within a water protection zone IIIB (Fig. 4e). While this does not rule out the installation of geothermal systems, it implies the need for additional considerations in the planning, such as the use of an intermediate water circuit (Umweltministerium Baden-Württemberg 2009). Furthermore, according to the spatial

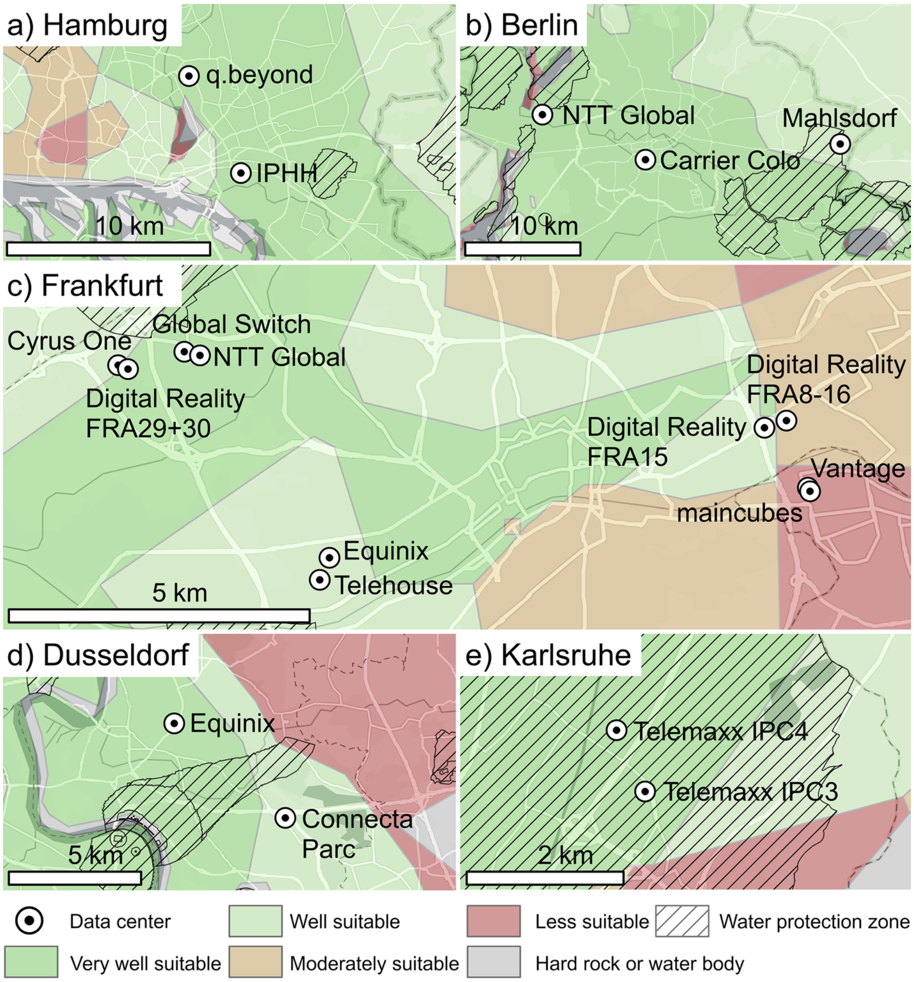

Fig. 4 Locations of the studied data centres within the aquifer thermal energy storage suitability map by Stemmle et al. (2022)

information system for shallow geothermal energy "ISONG", the drilling depth in this area is restricted to 14 m (Landesamt für Geologie Rohstoffe und Bergbau (LGRB) xxxx). The DC "Mahlsdorf" in Berlin is also located in a water protection zone, whereas the DC "NTT Global" is situated at a distance of 400 m from a water protection zone (Fig. 4b), which has implications for delineating potential supply areas. In contrast to Karlsruhe, open geothermal systems are not permitted in water protection zones in Berlin (Senatsverwaltung für Mobilität, Verkehr, Klimaschutz und Umwelt 2024).

Potential heat supply from data centres

All 19 DCs combined have an installed cooling capacity of 461 MW and produce 1740 GWh_{th} of waste heat. If all 19 DCs utilised ATES systems with a thermal recovery rate of 60%, they could supply 1,044 GWh_{th} of heat in total, 819 GWh_{th} of which could be provided in Frankfurt alone (Fig. 5). The three largest DCs (Digital Reality FRA8-16, NTT Global and Digital Reality FRA29 + 30), which are all located in Frankfurt, make up 52% of the total potential heat supply by ATES, highlighting the magnitude of produced

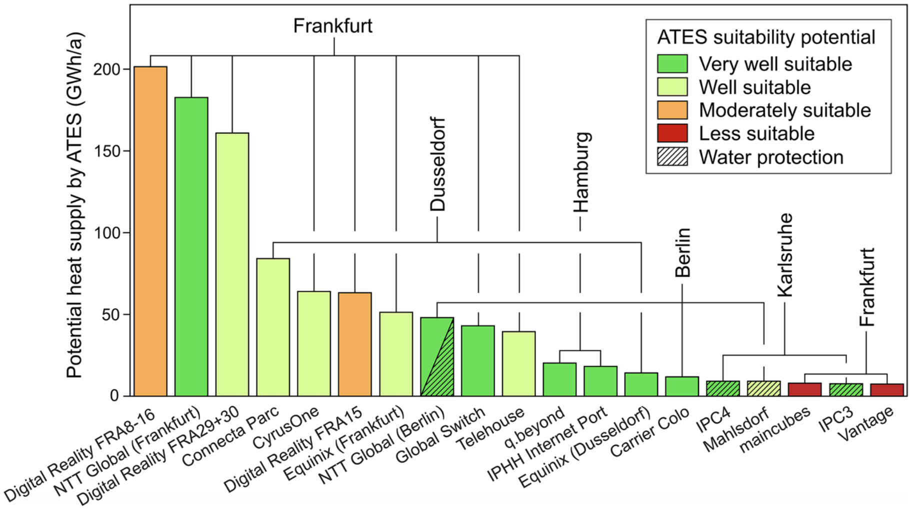

Fig. 5 Potential heat supply by aquifer thermal energy storage (ATES) using data centre waste heat. Colours indicate the ATES suitability of the underground by (Stemmle et al. 2022). Hatching indicates water protection zones; half hatching indicates that the supply area partly overlays a water protection zone

waste heat by large DCs. In general, there are a few large DCs like this in Germany, yet smaller DCs can be found in many cities offering chances for localised waste heat utilisation (Voss 2016).

However, only 13 of the investigated DCs are located both in suitable areas for ATES systems (i.e. in very well or well suitable zones) and entirely outside of restrictive water protection zones in Berlin (Fig. 4). These 13 DC-coupled ATES systems could still utilise a potential heat supply of 743 GWh_{th} (Fig. 5). Of the remaining six DCs, two in Frankfurt with a potential 264 GWh_{th} are located on moderately suitable underground and two systems with 15 GWh_{th} are on less suitable underground. Furthermore, two DCs in Berlin with 21 GWh_{th} are in or close to restrictive water protection zones (Fig. 5). For the DC "Global Switch" in Frankfurt (Figs. 3c and 4c), the known installed cooling capacity of 19 MW is used in this study (Global Switch 2024).

Waste heat supply areas with ATES

This section presents the heat supply areas from the nine DCs in Hamburg, Berlin, Dusseldorf and Karlsruhe, followed by results for the larger region of Frankfurt, which has an exceptionally high density of DCs.

The nine DCs in Hamburg (Districts Wínterhude and Hamm-Süd), Berlin (Districts Haselhorst, Tiergarten and Mahlsdorf), Dusseldorf (Districts Flingern-Süd and Hassels) and Karlsruhe (District Hagsfeld) could supply 100% of the heating demand of overall 5,085 buildings with 223 GWh_{th} of heat per year (Fig. 6). Omitting the two DCs in water protection zones in Berlin, the remaining seven DCs could still supply 3,871 buildings with 166 GWh_{th} of heat. Parts of the possible supply areas in Hamburg and Berlin are currently supplied partially or entirely with district heating, thus offering potential for integrating or upgrading existing district energy systems (Fig. 6a, c and d).

Most potential supply areas are characterised by a mix between residential and commercial buildings (Fig. 7). However, in total, residential floor space prevails in the

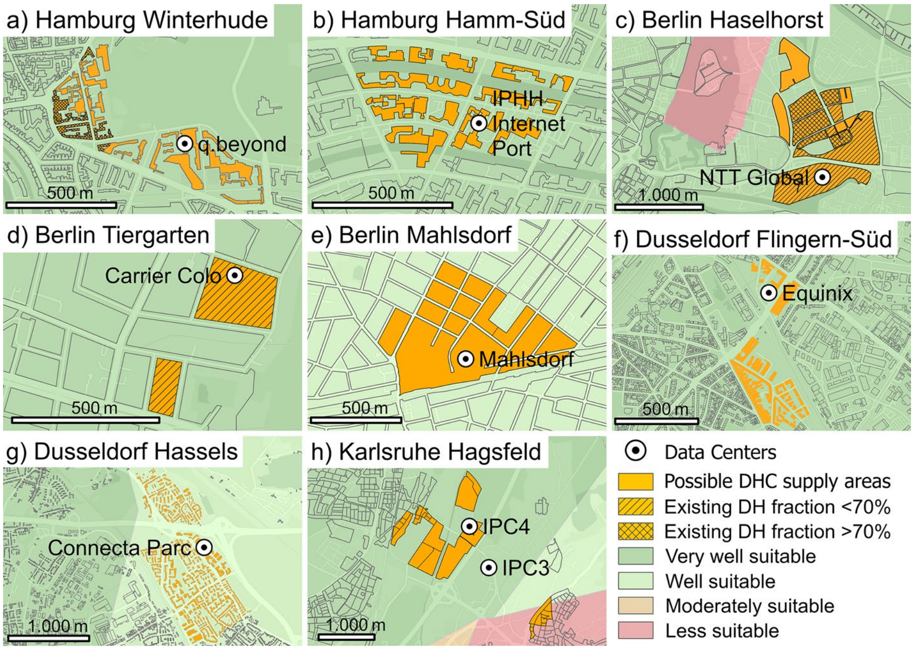

Fig. 6 Potential district heating and cooling (DHC) supply areas, if waste heat from data centres is stored in aquifer thermal energy storage (ATES) systems. Outlines indicate buildings (**a**, **b**, **f**, **g**) or urban blocks (**c**, **d**, **e**, **h**) and background colour indicates the ATES suitability (Stemmle et al. 2022)

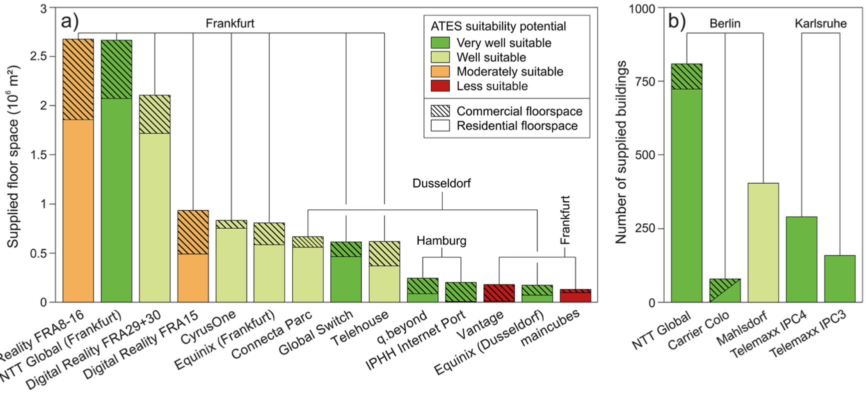

Fig. 7 **a** Share of residential and commercial floorspace of buildings of the potential supply areas utilising data centre waste heat and aquifer thermal energy storage (ATES) systems. **b** Number of supplied residential and commercial buildings ordered by the potential heat supply by ATES. For the supply area of the data centre Carrier Colo, no data on the share of residential and commercial use is available. Colours indicate the ATES suitability of the underground by (Stemmle et al. 2022)

potential supply areas (Fig. 7). Residential buildings are continuous, long-lasting customers for district heat, but individual buildings have relatively low heating demand densities (Schiel et al. 2016). Commercial buildings are often larger, have higher heating demand (densities) (Howard et al. 2012) and can therefore be supplied more cost-efficiently, as the relative cost of thermal storage decreases with storage volume (Herrmann et al. 2026). They might also possess more financial resources to invest in such systems. Thus, a diversified customer base in the potential supply areas can be advantageous.

As floor space data is not available in Berlin and Karlsruhe, these locations are presented separately with the number of supplied buildings (Fig. 7b). Thereby, for the supply area of the DC "Carrier Colo" in Berlin, which contains about 70 properties with large block buildings, we estimate about equal shares of residential and commercial floorspace based on Google Earth and Street View images of the area. The delineated supply area in Karlsruhe comprises residential heating demand from 471 buildings with a potential heat supply of 21 $\mathrm{GWh_{th}}$ (Fig. 7b). However, as mentioned above, restrictions in drilling depth apply to this area due to the presumed presence of aquitard layers (Landesamt für Geologie Rohstoffe und Bergbau (LGRB) xxxx).

Assessments for an urban quarter in 2.5 km distance of IPC4 showed that this regional restriction reduces the potential of open and closed geothermal systems substantially. For closed systems, the potential decreases from 152% heat supply rate without restricted drilling depth to 22% with accounting for shorter borehole heat exchangers (Tissen et al. 2019). In contrast, the impact on the potential with open geothermal systems was significantly smaller, with a reduction from 25 to 16%, respectively (Tissen et al. 2019). Thus, potential utilisation of DC waste heat and seasonal thermal storage by ATES would likely be impacted by that drilling depth restriction, as more wells (and thus a larger surface area) would be required to make up for the shallow drilling depth.

In the region of Frankfurt, all ten DCs combined could supply 819 $\mathrm{GWh_{th}}$ per year through storing waste heat with ATES, corresponding to the heating demand of 21,725 buildings (LEA LandesEnergieAgentur Hessen GmbH xxxx). Thus, 12% (Janßen et al. 2025) to 20% (LEA LandesEnergieAgentur Hessen GmbH xxxx) of Frankfurt's total heating demand could be supplied according to a study on the municipal heat planning of Frankfurt (Janßen et al. 2025) and the "Wärmeatlas Hessen" (LEA LandesEnergieAgentur Hessen GmbH xxxx) (Fig. 8). This comprises a floorspace of $11.6\times10^{6}\ \mathrm{m}^{2}$ with a share of 73% residential and 27% commercial floorspace. The heating demand density of the individual supply areas is 14–63 $\mathrm{GWh/km}^{2}$ (LEA LandesEnergieAgentur Hessen

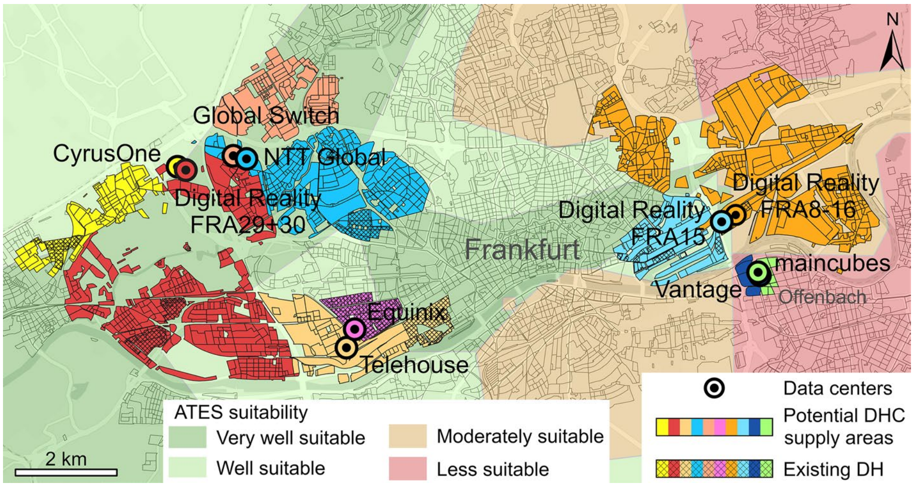

Fig. 8 Potential district heating and cooling (DHC) supply areas, if waste heat from data centres were stored in seasonal aquifer thermal energy storage (ATES) systems in Frankfurt am Main and Offenbach, Germany. Colours indicate the DCs and their respective potential supply area. Outlines indicate urban blocks, and background colour indicates the ATES suitability (Stemmle et al. 2022)

GmbH xxxx), which is moderately dense to dense (Persson et al. 2019), indicating that all areas are feasible for district systems (Sustainable Energy Authority 2022). However, only six of the ten DCs are located in the western region of Frankfurt, which is very well or well suitable for ATES (Fig. 8), summing up to 541 GWh_{th}, 16,342 buildings and 8% (Janßen et al. 2025) to 13% (LEA LandesEnergieAgentur Hessen GmbH xxxx) of the city's heating demand, respectively.

The four DCs in the eastern part of Frankfurt are located along the border between suitable and less suitable ATES areas (Fig. 8). As mentioned previously, this is because of missing hydrogeological data on the scale of the ATES suitability map of Germany, which could be easily overcome by local analysis or expert knowledge. In particular, DCs Digital Reality FRA8-16 and FRA15 would be interesting for further local investigation of the ATES potential, as they have amongst the highest capacities examined in this study (Fig. 5), and their proposed supply areas are partially situated in suitable ATES zones (Fig. 8). For FRA15, a further 63 GWh_{th} of heat supply corresponding to 592 buildings, and for FRA8-16, 201 GWh_{th} of heat supply corresponding to 4,630 additional buildings could be supplied by waste heat.

Frankfurt has a significant industrial waste heat potential of 4.2 TWh, of which 3.3 TWh are located in an industrial park 10 km to the west of the city centre, and the city's process heat is expected to decrease by 22% until 2045 (Janßen et al. 2025). The geothermal potential of decentralised ground source heat pump systems in Frankfurt is estimated at 1,937 GWh, covering 29% (Janßen et al. 2025) to 55% (LEA LandesEnergieAgentur Hessen GmbH xxxx) of the heating demand in Frankfurt. While the economic potential of DC waste heat is deemed significant in the municipal heat planning in Frankfurt, only TES systems with temperatures over 85 °C are currently considered for direct coupling with their district heating systems (Janßen et al. 2025). Thus, low-temperature seasonal TES, such as ATES and BTES systems, are not considered yet (Janßen et al. 2025). However, the economic potential of low-temperature TES systems, such as those proposed in this study, should be investigated.

Limitations and implications

Several limitations and uncertainties are associated with the approach presented above. Firstly, the actually installed cooling capacity can differ from the estimated cooling capacity based on the model and type the installed cooling machines (Barth et al. 2023b). Likewise, many DCs employ backup cooling units in case of cooling system failures, which do not actively contribute to the cooling of the DC all year round and should therefore not contribute to the quantification of waste heat in this study. Accordingly, accurate values gathered directly from DC operators are needed for more detailed potential assessment and system planning.

As shown above, parts of the delineated supply areas overlap with existing district heating systems (Figs. 6 and 8). In these areas, the possibility of replacing conventional, fossil fuel-based heat sources should be further investigated, as such systems (e.g. cogeneration plants) may be decommissioned in the future due to the energy transition. Existing district energy systems are mostly high-temperature systems, such as in Frankfurt and Berlin (Netzdienste Rhein-Main GmbH xxxx; Schubert 2024), while DC waste heat temperatures usually are lower and need boosting with heat pumps (Janßen et al. 2025).

ATES and also other geothermal systems in Germany are subject to temperature restrictions. If not specified otherwise, typical allowed injection temperatures range between 5 and 20 °C, whereas in Berlin, water can only be injected with a ± 3 K difference compared to the local groundwater temperature (Hähnlein et al. 2013). Thus, increasing the temperature from storage temperature [< 20 °C (Hähnlein et al. 2013)] to usable levels for space heating and domestic hot water [25–60 °C (Staffell et al. 2012)] is required, e.g., by heat pumps (Gudmundsson et al. 2022). Also, the aforementioned drilling depth restriction of 14 m in Karlsruhe (Landesamt für Geologie Rohstoffe und Bergbau (LGRB) xxxx) might limit the amount of heat, which can actually be stored here. Boosting the temperature with heat pumps consumes electricity, resulting in an increase in total heat output according to the COP of the heat pump. Considering, e.g., COPs of 5–10 (Reiners et al. 2021), boosting waste heat results in an increase in heating energy output by 10–25%. This effect, however, counteracts potential thermal losses of DHNs. Both the heating energy increase from heat pumps, as well as potential network losses are not considered in our study.

The qualitatively assessed ATES suitability of the subsurface below DCs (Stemmle et al. 2022) could be quantified based on detailed local information, and for example, a combination of data-driven and physical modelling approaches. Hereby, accurate information on the groundwater flow velocity is one of the most critical and uncertain factors, as it significantly impacts the recovery rate of ATES systems (Stemmle et al. 2024). A thermal recovery of 60% is assumed in accordance to the mean groundwater flow velocity of these areas (Stemmle et al. 2022, 2024). However, variations can alter the recovery rate from about 40% to > 80% in the examined areas (Stemmle et al. 2024), affecting the quantified potential heat supply by ATES negatively or positively. For the DC Digital Reality FRA8-16, for example, where no information on groundwater flow velocity is available, a recovery rate of 40% and 80% would account for a potential heat supply by ATES of 134.3 GWh_{th} and 268.6 GWh_{th}. Additionally, hydrogeological parameters can impact the efficiency of ATES systems due to their impact on heat transport, such as total and effective porosities (total and actually usable pore space), longitudinal dispersivity and groundwater recharge (Tas et al. 2025). Another important factor which determines long-term efficiency of ATES systems is the iron and manganese content of the groundwater, as high concentrations can lead to clogging and thus decrease efficiency over time (Lu et al. 2019).

Additionally, the space requirements in terms of surface area of ATES systems can be estimated by modelling power densities of the systems (Stemmle et al. 2024). Available surface and subsurface space for well placement can be quantified, for example, via analytical simulation of the thermal plume (Tissen et al. 2019). Ideally, groundwater flow and heat transport should be modelled numerically based on site-specific hydrogeology (Stemmle et al. 2024), also for the optimisation of well layout and thus increase thermal recovery.

Also, energy consumption of the DCs themselves can be reduced through seasonal thermal energy storage with cold ATES wells (Drenkelfort et al. 2015). For example the DCs can benefit from excess cold from nearby heat production in winter, or even utilise free cooling, reducing the cost of cold production for the DCs (Voss 2016). Additionally, also the end users could utilise cold from such a cold storage to supply residential space cooling demands, which, however, are usually far below the heating demands in Germany (Persson and Werner 2015; Werner 2016). One of the biggest challenges for the realisation of DC waste heat utilisation in DHNs is the participation of the DCs (Janßen et al. 2025). Wide-spread barriers for ATES systems include, e.g., lack of awareness, know-how, complex permitting procedures and high investment costs alongside general geological and feasibility criteria (Jackson et al. 2024; Stemmle et al. 2025).

Finally, additional low-temperature waste heat sources besides DCs, such as hospitals (Noethen et al. 2025; Schüppler et al. 2019), universities (Schüppler et al. 2022), supermarkets and industry (Revesz et al. 2020) should be considered for inclusion in district energy systems. These waste heat sources can increase the geothermal potential in other areas, utilising similar waste heat-coupled ATES systems. Nearby buildings could benefit from the waste heat while functioning as a heat sink for the heat producers.

Conclusion

In this study, we investigate the potential of DCs to serve as a waste heat source for nearby buildings and districts using seasonal thermal energy storage such as aquifer thermal energy storage (ATES) systems. Hence, 19 DCs in Germany are examined regarding the hydrogeological suitability of their location for ATES systems, the amount of produced waste heat and the resulting potential heat supply by DC-coupled ATES systems are quantified, and potential supply areas are identified and delineated.

The 19 examined DCs produce 1740 $\mathrm{GWh_{th}}$ of waste heat and are in close vicinity to residential and commercial areas with existing heating demand. However, only 13 of the 19 examined DCs are located in areas with very well or well-suited subsurface conditions for ATES systems and outside of regulated water protection zones. Assuming a moderate thermal recovery rate of 60% for the ATES systems, the 13 DCs could provide a total of 707 $\mathrm{GWh_{th}}$, covering the heating demand of about 20,000 nearby buildings in Berlin, Dusseldorf, Frankfurt, Hamburg and Karlsruhe. In Frankfurt, particularly, six of the ten DCs are located on very well or well suitable underground for ATES systems and could supply up to 13% of Frankfurt's heating demand. Accounting also for the four DCs on the edge of the moderately suitable or less suitable zone in eastern Frankfurt, even up to 20% of Frankfurt's heating demand could be supplied with waste heat.

The majority of the proposed supply areas is not currently supplied with district heating, but with conventional and decentralised heating systems, which increases the potential of renewable and efficient alternatives to reduce CO_2 emissions and also costs. Our study shows that storing waste heat from DCs in ATES systems offers significant possibilities for densely built-up urban areas, such as Frankfurt, where other shallow geothermal systems without waste heat utilisation might struggle to meet the heating demands of buildings due to high heat demand densities and limited available space for system installation. Thus, DC-coupled ATES systems should be carefully considered in municipal heat planning, such as in Frankfurt, where currently only high-temperature thermal storage is investigated. Likewise, other low-temperature waste heat sources, such as hospitals, universities, supermarkets and industry, can provide further opportunities for coupling with ATES systems to increase the geothermal potential and cost savings in a similar manner.

Abbreviations

ASHP	Air-source heat pump
ATES	Aquifer thermal energy storage
CDD	Cooling degree day
COP	Coefficient of performance
DC	Data centre
DHC	District heating and cooling
DHN	District heating network
GSHP	Ground-source heat pump
HDD	Heating degree day
PUE	Power usage effectiveness
TES	Thermal energy storage

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40517-026-00383-8.

Supplementary material 1.

Acknowledgements
Financial support for Florian Barth was provided by the German Federal Ministry for Economic Affairs and Energy (BMWE) through the project GOES (FZK: 03EE4040). The financial support for Kathrin Menberg via the Margarete von Wrangell-program of the Ministry for Science, Research and Arts (MWK) Baden-Württemberg is gratefully acknowledged. Additionally, thanks go to Maya Nakajima for the efforts in mapping the data centres and the initial quantification of the installed cooling capacities. Thanks also go to the consortium of project GOES for the scientific discussions and feedback. Finally, we thank the four reviewers for their constructive feedback.

Author contributions

F.B.: Conceptualisation, Methodology, Formal Analysis, Investigation, Visualisation, Writing—Original Draft. G.S.: Methodology, Formal Analysis, Investigation, Visualisation, Writing- Review & Editing. P.B.: Conceptualisation, Writing- Review & Editing, Supervision. K.M.: Conceptualisation, Methodology, Writing- Review & Editing, Supervision, Funding Acquisition. All authors read and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL.

Data availability

The ATES suitability map (Stemmle et al. 2022) can be accessed via: https://www.google.com/maps/d/viewer?mid=1Dc8rP96oR6jicjfHFdktAQeym3hnvbs&ll=52.298599890908186%2C10.594144349191138&z=9. Further information on the deep learning detection algorithm can be found in Barth et al. (2025).

Declarations

Competing interests

Financial support for Florian Barth was provided by the German Federal Ministry for Economic Affairs and Energy (BMWE) through the project GOES (FZK: 03EE4040). Financial support for Kathrin Menberg was provided via the Margarete von Wrangell-program of the Ministry for Science, Research and Arts (MWK) Baden-Württemberg.

Received: 19 November 2025 Accepted: 31 March 2026

References

ADC Telecommunications Inc. TIA-942, Data Center Standards Overview, ADC, Inc. 2006.
Alkrush AA, Salem MS, Abdelrehim O, Hegazi AA. Data centers cooling: a critical review of techniques, challenges, and energy saving solutions. Int J Refrig. 2024;160:246–62. https://doi.org/10.1016/j.ijrefrig.2024.02.007.
Alley A. Facebook plugs its Danish data center into Odense district heating system. 2020. https://www.datacenterdynamics.com/en/news/facebook-begins-installing-district-heating-system-odense-data-center-denmark/. Accessed 23 Oct 2025.
ASHRAE. Ashrae climatic design conditions. 2021. https://ashrae-meteo.info/v2.0/index.php. Accessed 29 Jan 2024.
Bakema G, Snijders AL, Nordell B. Underground thermal energy storage. State of the art 1994. ISBN: 90-802769-1-x. 1995. https://www.researchgate.net/profile/Guido-Bakema-2/publication/322520179_Underground_Thermal_Energy_Storage_state_of_the_art_1994/links/5a5df201458515c03edfa908/Underground-Thermal-Energy-Storage-state-of-the-art-1994.pdf. Accessed 26 June 2025.
Barroso LA, Hölzle U. The case for energy-proportional computing. 2007. https://people.eecs.berkeley.edu/~culler/cs262b/papers/energyProp.pdf. Accessed 25 Oct 2024.

Barth F, Schüppler S, Menberg K, Blum P. Estimating cooling capacities from aerial images using convolutional neural networks. Appl Energy. 2023a. https://doi.org/10.1016/j.apenergy.2023.121561.

Barth F, Schüppler S, Menberg K, Blum P. Quantifying the cooling demand of urban areas using aerial images. Build Simul Conf Proc. 2023;18:869–76. https://doi.org/10.26868/25222708.2023.1259.

Barth F, Menberg K, Sulzer M, Blum P. Quantifying the cooling demand of Manhattan using aerial images. Energy Build. 2025. https://doi.org/10.1016/j.enbuild.2025.116526.

Baxter G, Srisaeng P, Wild G. An assessment of airport sustainability, part 2-energy management at Copenhagen Airport. Resources Basel. 2018. https://doi.org/10.3390/resources7020032.

Biba E. The city where the internet warms people's homes. 2017. https://www.bbc.com/future/article/20171013-where-data-centres-store-info---and-heat-homes. Accessed 13 Nov 2025.

Bloemendal M, Olsthoorn T. ATES systems in aquifers with high ambient groundwater flow velocity. Geothermics. 2018;75:81–92. https://doi.org/10.1016/j.geothermics.2018.04.005.

Bracco S, Caligaris O, Trucco A. Mathematical models of air-cooled condensers for thermoelectric units. WIT Trans Ecol Environ. 2009;121:399–410. https://doi.org/10.2495/ESU090351.

Brady GA, Kapur N, Summers JL, Thompson HM. A case study and critical assessment in calculating power usage effectiveness for a data centre. Energy Convers Manag. 2013;76:155–61. https://doi.org/10.1016/j.enconman.2013.07.035.

Bryne Wallace Shields LLP. WasteHeat and the Future of District Heating Systems in Ireland. 2025. https://www.byrnewallaceshields.com/news-and-recent-work/publications/waste-heat-and-the-future-of-district-heating-systems-in-ireland.html. Accessed 24 Oct 2025.

Bundesamt für Justiz. Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden (Gebäudeenergiegesetz - GEG). 2020. https://www.gesetze-im-internet.de/geg/BJNR172810020.html#BJNR172810020BJNG000500000. Accessed 29 Oct 2024.

Bundesamt für Justiz. Gesetz für die Wärmeplanung und zur Dekarbonisierung der Wärmenetze (Wärmeplanungsgesetz-WPG). 2023a.

Bundesamt für Justiz. Gesetz zur Steigerung der Energieeffizienz in Deutschland (Energieeffizienzgesetz-EnEfG). 2023b. https://www.gesetze-im-internet.de/enefg/BJNR1350B0023.html. Accessed 29 Oct 2024.

Bundesverband Geothermie. ATES. 2022, August 25. https://www.geothermie.de/aktuelles/nachrichten/news-anzeigen/ates?tx_news_pi1%5BactbackPid%5D=137&cHash=45cea28bc5612327cf7aba755f33c620. Accessed 17 Jan 2025.

Chi YQ, Summers J, Hopton P, Daekin K, Real A, Kapur N, Thompson H. Case Study of a Data Centre Using Enclosed, Immersed, Direct Liquid-cooled Servers. 30th SEMI-THERM Symposium. 2014. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6892234. Accessed 20 Jan 2026

CollocationIX. DE-CIX Frankfurt-Internet Exchange-Wiki. 2025. https://www.colocationix.de/wiki/internet-exchanges/de-cix-frankfurt-internet-exchange-wiki/. Accessed 27 Mar 2025.

Darrow K, Hedman B. Opportunities for Combined Heat and Power in Data Centers. 2009. https://www.energy.gov/sites/prod/files/2013/11/f4/chp_data_centers.pdf. Accessed 25 Oct 2024.

Digital Reality. Globales Colocation-Portfolio. 2025. https://go2.digitalrealty.com/rs/087-YZJ-646/images/BR_Digital_Realty_1905_Global_Colocation_Portfolio.pdf. Accessed 2 Feb 2026.

Drenkelfort G, Kieseler S, Pasemann A, Behrendt F. Aquifer thermal energy storages as a cooling option for German data centers. Energy Effic. 2015;8(2):385–402. https://doi.org/10.1007/s12053-014-9295-1.

Ebrahimi K, Jones GF, Fleischer AS. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sustain Energy Rev. 2014;31:622–38. https://doi.org/10.1016/j.rser.2013.12.007.

Equinix. DU1. Dusseldorf IBX-Rechenzentrum. n.d. https://www.equinix.com/de/de/data-centers/europe-colocation/germany-colocation/frankfurt-data-centers/fr5. Accessed 03 Feb 2026.

Fleuchaus P, Godschalk B, Stober I, Blum P. Worldwide application of aquifer thermal energy storage – a review. Renew Sustain Energy Rev. 2018;94:861–76. https://doi.org/10.1016/j.rser.2018.06.057.

Fleuchaus P, Schüppler S, Godschalk B, Bakema G, Blum P. Performance analysis of aquifer thermal energy storage (ATES). Renew Energy. 2020;146:1536–48. https://doi.org/10.1016/j.renene.2019.07.030.

Fleuchaus P, Schüppler S, Stemmle R, Menberg K, Blum P. Aquifer thermal energy storage (ATES) in Germany. Grundwasser. 2021;26(2):123–34. https://doi.org/10.1007/s00767-021-00478-y.

Gao L, Zhao J, An Q, Wang J, Liu X. A review on system performance studies of aquifer thermal energy storage. Energy Procedia. 2017;142:3537–45. https://doi.org/10.1016/j.egypro.2017.12.242.

Global Switch. Frankfurt Rechenzentrum Campus. 2024. https://www.globalswitch.de/locations/frankfurt-data-centres/. Accessed 04 Jun 2024.

Google. Google Earth Pro. 2023.

Gudmundsson O, Schmidt RR, Dyrelund A, Thorsen JE. Economic comparison of 4GDH and 5GDH systems – using a case study. Energy. 2022. https://doi.org/10.1016/j.energy.2021.121613.

Hähnlein S, Bayer P, Ferguson G, Blum P. Sustainability and policy for the thermal use of shallow geothermal energy. Energy Policy. 2013;59:914–25. https://doi.org/10.1016/j.enpol.2013.04.040.

Hanley S. waste heat from data centers can bolster district heat systems. 2022. https://cleantechnica.com/2022/12/29/waste-heat-from-data-centers-can-bolster-district-heat-systems/. Accessed 23 Oct 2025.

Herrmann M, Fleuchaus P, Godschalk B, Verbiest M, Niemi Sørensen S, Blum P. Capital costs of aquifer thermal energy storage (ATES): a review. Renew Sustain Energy Rev. 2026. https://doi.org/10.1016/j.rser.2025.116202.

Hoekstra N, Pellegrini M, Bloemendal M, Spaak G, Andreu Gallego A, Rodriguez Comins J, et al. Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage. Sci Total Environ. 2020. https://doi.org/10.1016/j.scitotenv.2019.136142.

Howard B, Parshall L, Thompson J, Hammer S, Dickinson J, Modi V. Spatial distribution of urban building energy consumption by end use. Energy Build. 2012;45:141–51. https://doi.org/10.1016/j.enbuild.2011.10.061.

International Energy Agency. Renewables 2019. Analysis and forecast to 2024. 2019. www.iea.org/renewables2019. Accessed 28 Oct 2024.

International Energy Agency. Data centres and data transmission networks. 2023. https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks#tracking.

Jackson MD, Regnier G, Staffell I. Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: current status and future prospects. Appl Energy. 2024. https://doi.org/10.1016/j.apenergy.2024.124096.

Jagdale A, Aljbour J. Data center heat reuse technology innovation. Quick Insight. 2024. https://restservice.epri.com/publicdownload/000000003002031316/0/Product&ved=2ahUKEwjlrZqElZqSAxU7g_0HHfTYOY0Q1fkOegQIBxAi&opi=89978449&cd&psig=AOvVaw3_7-KSK-YTHSlr21AtbYzw&ust=1769000096626000. Accessed 20 Jan 2026.

Janßen K, Vorspel L, Koch F, Noga M, Tries C. Kommunale Wärmeplanung Frankfurt am Main. Ergebnisse Potentialanalyse. 2025. https://klimaschutz-frankfurt.de/wp-content/uploads/2025/09/Praesentation_2025_09_29_KWP-FFM_Potenzialanalyse_Ergebnisse.pdf. Accessed 21 Oct 2025.

Kong R, Zhang H, Tang M, Zou H, Tian C, Ding T. Enhancing data center cooling efficiency and ability: a comprehensive review of direct liquid cooling technologies. Energy. 2024;308:246–62. https://doi.org/10.1016/j.energy.2024.132846.

Kumar S, Kök A, Dalgren J, Thakur J, Martin V, Gardumi F. Strategic integration of urban excess heat sources in a district heating system: a spatio-temporal optimisation methodology. Appl Energy. 2025. https://doi.org/10.1016/j.apenergy.2025.126236.

Landesamt für Geologie Rohstoffe und Bergbau (LGRB). Informationssystem für oberflächennahe Geothermie Baden-Württemberg (ISONG). n.d. https://isong.lgrb-bw.de/. Accessed 08 Jan 2025.

Landesamt für Natur Umwelt und Verbraucherschutz Nordrhein-Westfalen. Duesseldorf_Fernwaerme_Energieatlas NRW. n.d.-a.

Landesamt für Natur Umwelt und Verbraucherschutz Nordrhein-Westfalen. WBM-NRW_05111000_Duesseldorf. n.d.-b. https://www.opengeodata.nrw.de/produkte/umwelt_klima/klima/kwp/KWP-NRW_05111000_Duesseldorf_EPSG25832_Shape.zip. Accessed 11 July 2024.

Landesanstalt für Umwelt Baden-Württemberg. Absoluter Wärmebedarf. n.d.-a. https://www.energieatlas-bw.de/waerme/waermebedarf_wohnen/absoluter-warmebedarf-detail. Accessed 11 July 2024

Landesanstalt für Umwelt Baden-Württemberg. Wärmenetz Gebietsübersicht. n.d.-b. https://www.energieatlas-bw.de/waermenetze/waermenetze-gebietsuebersicht. Accessed 10 July 2024.

Landesbetrieb Geoinformation und Vermessung (LGV) Hamburg. LGV Support. Geschäftsbereich Geobasisinformationen. Wärmenetzeignungsgebiete Hamburg. n.d. https://geoportal-hamburg.de/. Accessed 16 Oct 2024.

Landesbetrieb Geoinformation und Vermessung (LGV) Hamburg. LGV Support. Geschäftsbereich Geobasisinformationen. Wärmekataster Wärmebedarf Hamburg. Abs. Nutzwärmebedarf, Gebäude unsaniert. 2016. https://geoportal-hamburg.de/. Accessed 17 Oct 2024.

LEA LandesEnergieAgentur Hessen GmbH. Wärmeatlas Hessen. Wärmebedarfsdichte Baublöcke. n.d. https://www.waermeatlas-hessen.de/#z=12.8714&c=8.693%2C50.1159&r=0&l=top_plus_open%2Cbaubloecke3. Accessed 11 July 2024.

Li Z, Kandlikar SG. Current status and future trends in data-center cooling technologies. Heat Transfer Eng. 2015;36(6):523–38. https://doi.org/10.1080/01457632.2014.939032.

Lu H, Tian P, He L. Evaluating the global potential of aquifer thermal energy storage and determining the potential worldwide hotspots driven by socio-economic, geo-hydrologic and climatic conditions. Renew Sustain Energy Rev. 2019;112:788–96. https://doi.org/10.1016/j.rser.2019.06.013.

Lu T, Lü X, Välisuo P, Zhang Q, Clements-Croome D. Innovative approaches for deep decarbonization of data centers and building space heating networks: modeling and comparison of novel waste heat recovery systems for liquid cooling systems. Appl Energy. 2024. https://doi.org/10.1016/j.apenergy.2023.122473.

Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th generation district heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy. 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

Lund H, Østergaard PA, Nielsen TB, Werner S, Thorsen JE, Gudmundsson O, et al. Perspectives on fourth and fifth generation district heating. Energy. 2021. https://doi.org/10.1016/j.energy.2021.120520.

Lygnerud K, Nielsen S, Persson U, Wynn H, Wheatcroft E, Antolin-Gutierrez J, Leonte D, Rosebrock O, Ochsner K, Kein C, Perez-granados P, Romanchenko D, Langer S, Ljung M. Handbook for increased recovery of urban escess heat. 2022. https://dbdh.org/wp-content/uploads/2023/08/ReUseHeat-Handbook-For-Increased-Recovery-of-Urban-Excess-Heat.pdf. Accessed 22 Oct 2025.

Midtomme K, Kocbach J, Manstad RK, Henne I. AQUIFER THERMAL ENERGY STORAGE (ATES). Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój Nr 2/2017. 2017.

Miocic JM, Krecher M. Estimation of shallow geothermal potential to meet building heating demand on a regional scale. Renew Energy. 2022;185:629–40. https://doi.org/10.1016/j.renene.2021.12.095.

Murzakulova Z, Öztürk D, Noster R, Groß C, Sorge L, Chebotarova S, Kieweg S, Schulze M, Stüer J, Hintemann R, Hinterholzer S, Beucker S, Radgen P, Ott B, Brugger H, Fritz M, Mandel T, Hohenstein-Bartholl C, Fritz J, Debray P. Stand und Entwicklung des Rechenzentrumsstandorts Deutschland. Gutachten im Auftrag des Bundesministeriums für Wirtschaft und Klimaschutz. 2025.

Naik BK, Muthukumar P. Empirical correlation based models for estimation of air cooled and water cooled condenser's performance. Energy Procedia. 2017;109:293–305. https://doi.org/10.1016/j.egypro.2017.03.070.

Netzdienste Rhein-Main GmbH. Netzdokumentation (N1-ND). n.d. https://energiemanagement.stadt-frankfurt.de/Investive-Massnahmen/Leitlinien-wirtschaftliches-Bauen/Waermeversorgungsnetze-Frankfurt.pdf. Accessed 12 July 2024.

Noethen M, Stemmle R, Siebert N, Herrmann M, Menberg K, Blum P, et al. Identifying aquifer thermal energy storage (ATES) key locations for hospitals in Lower Saxony, Germany. Geothermics. 2025. https://doi.org/10.1016/j.geothermics.2025.103334.

nPro. Technologies: Cost and Price Overview. District heating network. n.d. https://www.npro.energy/main/en/help/technology-costs. Accessed 06 Feb 2026.

NTT Data. Berlin 1 Data Center. 2024.

Persson U, Werner S. Quantifying the Heating and Cooling Demand in Europe Work Package 2 Background Report 4 The STRATEGO project (Multi-level actions for enhanced Heating. 2015.

Persson U, Wiechers E, Möller B, Werner S. Heat Roadmap Europe: heat distribution costs. Energy. 2019;176:604–22. https://doi.org/10.1016/j.energy.2019.03.189.

Reiners T, Gross M, Altieri L, Wagner HJ, Bertsch V. Heat pump efficiency in fifth generation ultra-low temperature district heating networks using a wastewater heat source. Energy. 2021. https://doi.org/10.1016/j.energy.2021.121318.

Revesz A, Jones P, Dunham C, Davies G, Marques C, Matabuena R, et al. Developing novel 5th generation district energy networks. Energy. 2020. https://doi.org/10.1016/j.energy.2020.117389.

ScaleUp Technologies. Colocation. n.d. https://www.scaleuptech.com/rechenzentrum-spandau/. Accessed 03 Feb 2026.

Schiel K, Baume O, Caruso G, Leopold U. GIS-based modelling of shallow geothermal energy potential for CO2 emission mitigation in urban areas. Renew Energy. 2016;86:1023–36. https://doi.org/10.1016/j.renene.2015.09.017.

Schubert M. Meilensteine für Berlins Klimaziele: Grundsteinlegung für "Reuters Sustainable Heat and Power". (Press release). 2024. https://group.vattenfall.com/de/newsroom/pressemitteilungen/2024/meilenstein-fur-berlins-klimaziele-grundsteinlegung-fur-reuter-sustainable-h. Accessed 24 Jan 2025.

Schüppler S, Fleuchaus P, Blum P. Techno-economic and environmental analysis of an aquifer thermal energy storage (ATES) in Germany. Geotherm Energy. 2019. https://doi.org/10.1186/s40517-019-0127-6.

Schüppler S, Fleuchaus P, Duchesne A, Blum P. Cooling supply costs of a university campus. Energy. 2022. https://doi.org/10.1016/j.energy.2022.123554.

Senatsverwaltung für Mobilität, Verkehr, Klimaschutz und Umwelt. Erdwärmenutzung in Berlin. 2024. https://www.berlin.de/sen/uvk/_assets/umwelt/wasser-und-geologie/publikationen-und-merkblaetter/merkblatt_geothermie.pdf?ts=1763638888. Accessed 31 Jan 2026.

Senatsverwaltung für Wirtschaft Energie und Betriebe. Energieverbrauch - Fernwärme (Umweltatlas). n.d.-a. https://fbinter.stadt-berlin.de/fb/index.jsp. Accessed 10 July 2024.

Senatsverwaltung für Wirtschaft Energie und Betriebe. Energieverbrauch-Gas (Umweltatlas). n.d.-b. https://fbinter.stadt-berlin.de/fb/index.jsp. Accessed 11 July 2024.

Shehabi A, Newkirk A, Smith SJ, Hubbard A, Lei N, Siddik MAB, Holecek B, Koomey J, Masanet E, Sartor D. 2024 United States data center energy usage report. 2024. https://doi.org/10.71468/P1WC7Q.

Shinde Y. Data Center Cooling Market Soar to USD 60.4 billion by 2033. 2024. https://scoop.market.us/Data-Center-Cooling-Market-News/. Accessed 20 Jan 2026.

Staffell I, Brett D, Brandon N, Hawkes A. A review of domestic heat pumps. Energy Environ Sci. 2012;5(11):9291–306. https://doi.org/10.1039/c2ee22653g.

Stahlhut M, Sekulla M, Großöhme P, Auweter A, Urbaneck T. Data centers with direct liquid-cooled servers: experimental analysis and modeling. Energy Sci Eng. 2025;13(7):3605–19. https://doi.org/10.1002/ese3.70116.

Stemmle R, Blum P, Schüppler S, Fleuchaus P, Limoges M, Bayer P, et al. Environmental impacts of aquifer thermal energy storage (ATES). Renew Sustain Energy Rev. 2021. https://doi.org/10.1016/j.rser.2021.111560.

Stemmle R, Hammer V, Blum P, Menberg K. Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany. Geotherm Energy. 2022. https://doi.org/10.1186/s40517-022-00234-2.

Stemmle R, Lee H, Blum P, Menberg K. City-scale heating and cooling with aquifer thermal energy storage (ATES). Geotherm Energy. 2024. https://doi.org/10.1186/s40517-023-00279-x.

Stemmle R, Hanna R, Menberg K, Østergaard PA, Jackson M, Staffell I, et al. Policies for aquifer thermal energy storage: international comparison, barriers and recommendations. Clean Technol Environ Policy. 2025;27(3):1455–78. https://doi.org/10.1007/s10098-024-02892-1.

Sustainable Energy Authority. District Heating and Cooling. Spatial Analysis of Infrastructure Costs and Potential in Ireland. 2022.

Tas L, Hartog N, Bloemendal M, Simpson D, Robert T, Thibaut R, et al. Efficiency and heat transport processes of low-temperature aquifer thermal energy storage systems: new insights from global sensitivity analyses. Geotherm Energy. 2025. https://doi.org/10.1186/s40517-024-00326-1.

Telemaxx. IP CENTRE 3 (IPC 3). n.d. https://www.telemaxx.de/en/data-centre/data-centre/telemaxx-data-centres/ipc-3. Accessed 02 Feb 2026.

Tissen C, Menberg K, Bayer P, Blum P. Meeting the demand: geothermal heat supply rates for an urban quarter in Germany. Geotherm Energy. 2019. https://doi.org/10.1186/s40517-019-0125-8.

Tissen C, Menberg K, Benz SA, Bayer P, Steiner C, Götzl G, et al. Identifying key locations for shallow geothermal use in Vienna. Renew Energy. 2021;167:1–19. https://doi.org/10.1016/j.renene.2020.11.024.

Toffanin R, Caputo P, Belliardi M, Curti V. Low and ultra-low temperature district heating equipped by heat pumps—an analysis of the best operative conditions for a Swiss case study. Energies. 2022. https://doi.org/10.3390/en15093344.

Umweltministerium Baden-Württemberg. Leitfaden zur Nutzung von Erdwärme mit Grundwasserwärmepumpen für Ein-und Zweifamilienhäuser oder Anlagen mit Energieentzug bis zirka 45.000 kWh pro Jahr. 2009. https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/2_Presse_und_Service/Publikationen/Energie/1_Leitfaden_Erdwaerme_Grundwasserwaermepumpen.pdf. Accessed 08 Jan 2025.

U.S. Department of Energy - Office of Energy Efficiency and Renewable Energy - Geothermal Technologies Office. Geothermal Heat Pump Case Study: Epic Systems Corporation. 2024. www.energy.gov/eere/geothermal/geothermal-heat-pump-case-studies. Accessed 17 Jan 2025.

Vanhoudt D, Desmedt J, Van Bael J, Robeyn N, Hoes H. An aquifer thermal storage system in a Belgian hospital: long-term experimental evaluation of energy and cost savings. Energy Build. 2011;43(12):3657–65. https://doi.org/10.1016/j.enbuild.2011.09.040.

Voss M. Junges Startup - unternehmen aus Dresden erzielt Rekord. 2016, March 4. https://michael-voss.eu/junges-startup-unternehmen-aus-dresden-erzielt-rekord/. Accessed 31 Jan 2025.

Wahlroos M, Pärssinen M, Manner J, Syri S. Utilizing data center waste heat in district heating – impacts on energy efficiency and prospects for low-temperature district heating networks. Energy. 2017;140:1228–38. https://doi.org/10.1016/j.energy.2017.08.078.

Walch A, Li X, Chambers J, Mohajeri N, Yilmaz S, Patel M, et al. Shallow geothermal energy potential for heating and cooling of buildings with regeneration under climate change scenarios. Energy. 2022. https://doi.org/10.1016/j.energy.2021.123086.

Werner S. European space cooling demands. Energy. 2016;110:148–56. https://doi.org/10.1016/j.energy.2015.11.028.

Yuan X, Liang Y, Hu X, Xu Y, Chen Y, Kosonen R. Waste heat recoveries in data centers: A review. Renew Sustain Energy Rev. 2023. https://doi.org/10.1016/j.rser.2023.113777.

Zhang H, Shao S, Xu H, Zou H, Tian C. Free cooling of data centers: a review. Renew Sustain Energy Rev. 2014;35:171–82. https://doi.org/10.1016/j.rser.2014.04.017.

Zhang Q, Meng Z, Hong X, Zhan Y, Liu J, Dong J, et al. A survey on data center cooling systems: Technology, power consumption modeling and control strategy optimization. J Syst Archit. 2021. https://doi.org/10.1016/j.sysarc.2021.102253.

Publisher's Note