Geothermal Energy Use, Country Update report for Denmark

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ABSTRACT

The deep Danish onshore subsurface contains huge geothermal resources, but only a very limited fraction of these resources are utilized. At the Thisted plant deep situated warm formation water is pumped to the surface from a production well and, after heat is transferred to the district heating system, the cooled water is returned to the reservoir through injection well(s). To stimulate the exploitation of the geothermal resource and thus the transformation to a more sustainable energy mix in Denmark the research project GEOTHERM (under the Innovation Fund Denmark) has thoroughly evaluated seismic reflection surveys and well data acquired during former hydrocarbon and geothermal exploration activities. The results of the last years research and geological assessments presented in a public available WebGIS portal have reduced the exploration risks significantly and has stimulated the interest from the industry leading to newly awarded exploration licenses. This development in combination with the existing high implementation of district heating in Denmark is promising for a much larger utilization of geothermal heat in Denmark.

The Danish sedimentary basins are classic low enthalpy basins characterized by long-term subsidence and infilling by sediments. The widely distributed fluviatile Lower Triassic Bunter Sandstone and the mainly marginal marine Upper Triassic–Lower Jurassic Gassum formations constitute the most important geothermal reservoirs. The latter is utilized in Thisted geothermal plants and are under development in Aarhus. Furthermore, formations with more local distribution also have geothermal potentials. In many areas, where existing detailed geological subsurface data are limited, predrilling reservoir prognosis are associated with large uncertainties, especially regarding the reservoir permeability. The temperature gradient of typical 25–30°C/km in the Danish subsurface implies that at depths shallower than 800 m the temperature is generally too low for conventional district heating implementation, whereas at depths greater than 3000 m, diagenetic alterations related to high pressure-temperature conditions reduce the porosity and permeability of the reservoir sandstones. Pronounced temperature anomalies are absent and variations in the temperature gradients are mainly due to differences in the thermal conductivity of the geological strata.

Shallow geothermal energy (down to ca. 250 m) with the use of ground source heat pumps (GSHP) has been utilized in Denmark since the late 1970's following the oil crisis. Annual sales of GSHPs surged between 2021 and 2023, peaking at nearly 5000 units, more than twice the previous annual sales, primarily due to the sharp rise in natural gas prices following the Russian invasion of Ukraine. However, in 2024, sales declined to a level slightly below that of 2014–2020. Most of the shallow geothermal energy systems in Denmark use horizontal heat exchangers (HHE). A few hundred use borehole heat exchangers (BHE), and >55 use open aquifer wells (aquifer thermal energy storage, ATES). In addition, Denmark has fourteen collective 5th generation district heating and cooling (5GDHC) grids (termonet), up from nine in 2021. These systems utilize shared BHEs, HHEs, helix probes, and ATES, providing an efficient heating and cooling solution for urban areas without district heating and for newly built homes with low heating demand and summer cooling needs. Two large termonet projects are under

development, with a total of 850 connected buildings in addition to a multitude of smaller projects. If realized, these projects will more than triple the number of buildings connected to a termonet.

1. INTRODUCTION

Over the last years there has been an increasing interest in geothermal energy among district heating companies and municipalities. Geothermal plants receive no subsidies, but high taxes on fossil fuels and the focus on reduction of CO_2 emissions makes it attractive to substitute the combustion of fossil fuels on CHP plants with wind turbine power, biomass and geothermal heat.

Several publicly financed research projects during the last decade have identified the presence of huge deep geothermal resources in the deep Danish subsurface below ca. 800 m and have stimulated the interest for utilizing the resource as a component of a green sustainable energy mix. The GEOTHERM project (supported by the Innovation Fund Denmark) addressed geological, technical and commercial obstacles for utilization of the geothermal resources including the entire geothermal life cycle as well as the whole geothermal brine circuit from reservoir to the plant on the surface and back to the reservoir. The main goal of the GEOTHERM project was to provide data and guidelines to ensure stable operation and realization of commercially profitable geothermal projects by describing the governing key elements for utilizing geothermal energy and for optimal integration into the existing district heating infrastructure (e.g. Vosgerau et al. 2022; Weibel et al. 2020). The GEOTHERM project also developed a business case model for large-scale utilization of geothermal energy.

Denmark has moderate temperature gradients, but widespread geothermal aquifers and district heating networks in most of the Danish towns supplying heat to up to 65 % of Danish houses. Aquifers have been identified around many of these towns with sufficient heat to cover 20–50 % of their heat demand for hundreds of years. A previous study has assessed the reserves in a license for Greater Copenhagen Area to 60’000 PJ or 1/3 of the heat demand for about 5000 years (Mahler et al. 2010).

In Denmark shallow geothermal energy is commonly described as Ground Source Heating and Cooling and covers energy extraction from shallow geological formations using ground source heat pumps (GSHP) in combination with horizontal heat exchangers (HHE) as well as borehole heat exchangers (BHE), foundation pile heat exchangers and open aquifer wells (aquifer thermal energy storage, ATES).

Shallow geothermal energy has been utilized in Denmark since the late 1970's following the oil crisis. Most systems are installed with HHEs and some with BHEs and ATES wells. ATES systems are used mostly for cooling of e.g. hospitals and larger office buildings but to some extent also for heating.

The use of shallow geothermal resources (down to ca. 250 m) is still limited, but GSHP systems is beginning to play a significant role in Denmark in the transition towards a sustainable heat supply, especially in areas without district heating. In recent years, the termonet concept for collective GSHP-based sustainable heating and cooling outside the district heating network (1/3 of consumers) has emerged, and it has been shown to be economically feasible when compared to alternative solutions. Moreover, the termonet facilitates passive cooling/seasonal heat storage and balancing of the power grid by storing electrically heated water when electricity prices are favorable, giving it significant added value compared to traditional alternatives.

1.1 Licenses, legislation and administration – Deep geothermal energy

Exploration for and production of deep geothermal energy requires a license pursuant to the provisions of the Danish Subsoil Act. It is the Danish Energy Agency, which administrates and supervise the licenses. The updated map of geothermal licenses and applications in Denmark reveals several existing and new applications for license areas (Fig. 1). This illustrates that the industry is taking interest in geothermal exploration and sees it as a promising business case into which it is willing to invest and share the exploration risks. Especially one major private investor and operator (Innargi A/S) together with district heating companies has shown interest and has a license in the Aarhus area and has applied in the larger Copenhagen area (‘Virum’ in Fig. 1).

1.2 Legislation and administration – Shallow geothermal energy

Ground Source Heating and Cooling is regulated pursuant to the Danish Environmental Protection Act and the Danish Water Act and permissions are issued by the Municipalities, who must include groundwater interests in their considerations.

Protection of groundwater is normally not a limitation for HHEs, but for BHEs, the regulation provides the municipalities with a possibility to increase the required safety distance to water wells and to stipulate special conditions in the permit regarding e.g. the construction of the installation, to protect a water catchment against contamination. Some municipalities reject applications for BHEs if there is uncertainty regarding a possible content of anti-corrosives in the brine. Others are generally very reluctant to issue permits for BHEs because of general considerations regarding the groundwater protection and drinking water quality. Brine temperatures to the heat pump are restricted to > -4°C.

For ATES, the regulation specifies investigations and documentation regarding the geology and hydrogeology of the aquifer as well as the hydraulic and hydrothermal properties and the chemical and microbiological conditions.

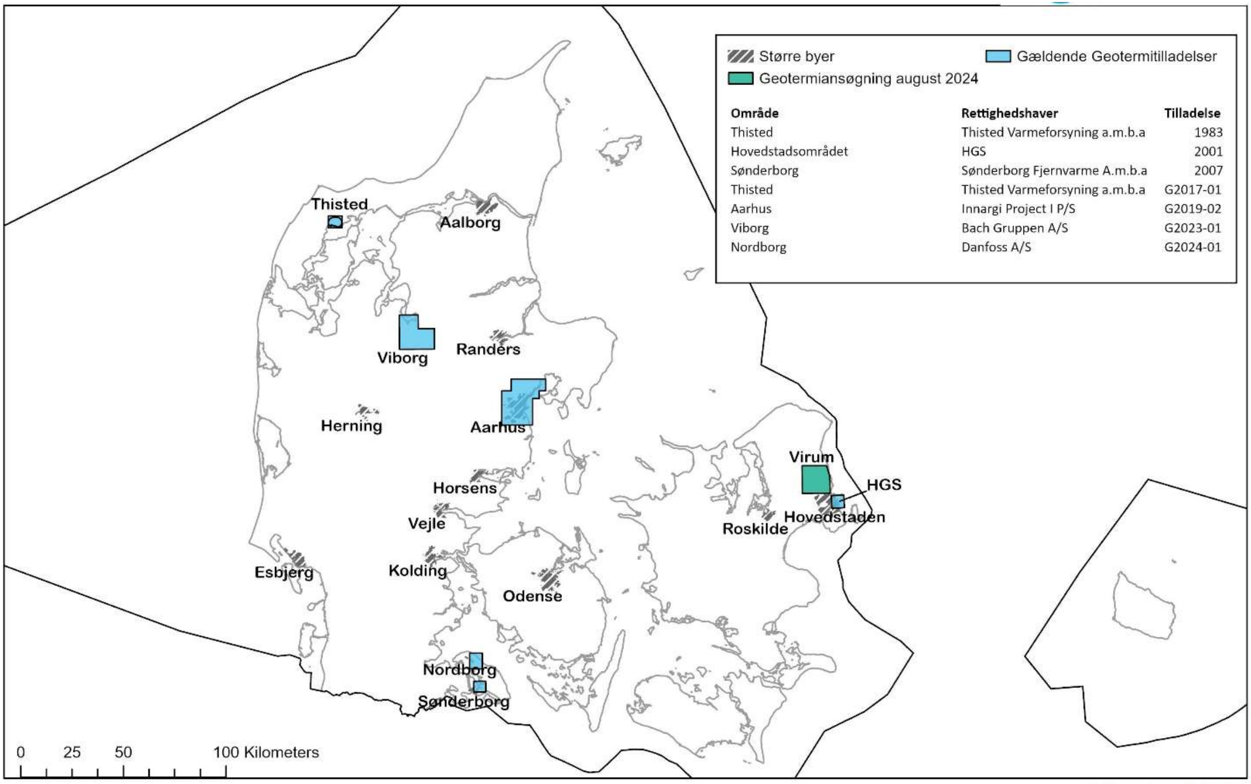


Figure 1: Geothermal licenses and applications in Denmark, Marts 2025 (in Danish from www.ens.dk). Solid light blue areas are existing licenses already granted while the area in green is a pending application.

The average monthly temperature of the water infiltrated into the ground or reinjected into the aquifer is restricted to 2°C–20°C (the maximum allowed peak of the latter is 25°C). Finally, ATES systems are not allowed to raise the fluid temperature for existing drinking water or ATES cooling systems by more than 0.5°C.

Unlike traditional district heating with insulated pipes, termonet projects are not regulated under The Danish Heat Supply Act and is therefore not eligible for municipal loan guarantees and financing.

2. GEOLOGICAL BACKGROUND

Information about the deep geological setting in Denmark originates largely from hydrocarbon exploration activities with seismic profiles and wells covering most of the country, however with an uneven distribution (Vosgerau et al. 2016). The interpretation of these data provides information on the regional structural setting and spatial distribution of sedimentary units.

The Danish onshore subsurface is divided into five major structural units (largely from north to south): the Skagerrak-Kattegat Platform (SKP), the Sorgenfrei-Tornquist Zone (STZ), the Danish Basin (DB), the Ringkøbing-Fyn High (RFH) and the North German Basin (NGB). The geothermal resources relate mainly to the to two deep sedimentary basins: the Danish Basin (DB) and the North German Basin (NGB) (Fig. 2).

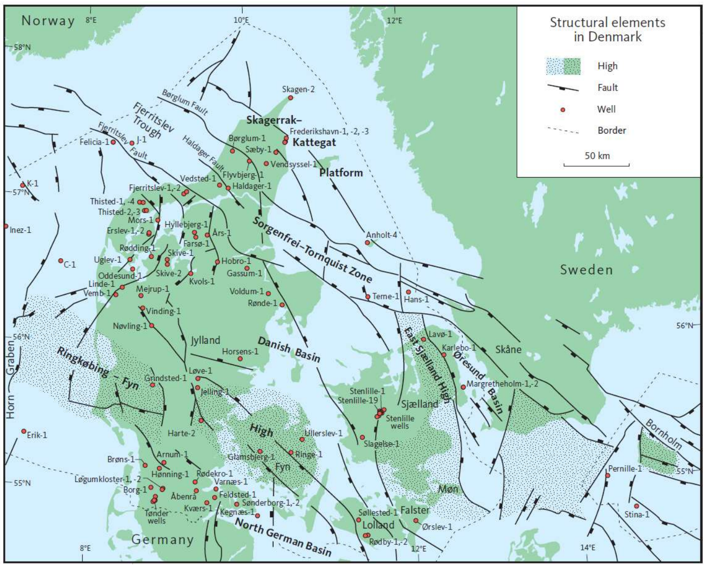


Figure 2: Well locations and principal structural elements in southern Scandinavia. Updated based on Nielsen (2003).

The sedimentary basins contain Palaeozoic, Mesozoic and Cenozoic sedimentary sequences of up to 5–10 km in total thickness. In contrast, sedimentary thicknesses of 1–2 km, and less, are found in areas with shallow basement highs (the RFH and SKP). The Ringkøbing-Fyn High consists of shallow basement blocks, where the thin Mesozoic sedimentary cover mainly comprises erosional remnants of Triassic sediments and Upper Cretaceous Chalk with a low geothermal potential. Both sedimentary basins host very large geothermal resources and several potential reservoirs and are classic low-enthalpy sedimentary basins formed by crustal thinning followed by long-term thermal subsidence and infilling by a variety of sediments (e.g. Michelsen & Nielsen 1991; Michelsen et al. 2003). These structural differences exert a decisive influence on the geothermal prospectively of the Danish subsurface, as they essentially determine the distribution, thicknesses, facies types and burial depths of the potential reservoirs (e.g. Erlström et al. 2018; Weibel et al. 2020).

Five important geothermal reservoirs have been identified based on their stratigraphical and spatial extent where the best described includes the Lower to Upper Triassic Bunter Sandstone and Skagerrak reservoirs, the Upper Triassic–Lower Jurassic Gassum reservoir (Nielsen et al. 2004; Mathiesen et al. 2010; Weibel et al. 2020). The other important reservoirs, e.g. the Middle Jurassic Haldager Sand reservoir and the Upper Jurassic–Lower Cretaceous Frederikshavn reservoir and the Upper Cretaceous Arnager Greensand may locally also contain potential aquifers. Each reservoir generally comprises several sandstone layers with reservoir properties. So far, the focus has been on the combined Bunter Sandstone-Skagerrak reservoir and the Gassum reservoir, with current geothermal production (Røgen et al. 2015; Mathiesen et al. 2020).

The geographical coverage and quality of the data vary considerably. The mostly 2D seismic data combined with information from deep wells have been used in a major mapping campaign for mapping of depth, thickness and lateral extent of lithostratigraphic units, and with special emphasis on units known to contain geothermal reservoir sandstones, as well as for identification and mapping of major faults and salt domes (Vosgerau et al. 2016). Regional maps were interpreted in two-way travel time (TWT) and were converted to depth ensuring that the difference between measured depths in wells and those extracted from the depth-converted maps are as small as possible. The deepest mapped seismic reflector is the Top Pre-Zechstein horizon. The maps are accessible from the WebGIS portal, as is a number of seismic cross-sections and an interactive 3D tool that exemplify the structural distribution of the onshore subsurface units. The lack of coverage and high-quality data hampers the interpretation and mapping of the deepest horizons and consequently, mapping uncertainties are generally larger for the deepest horizons than for the shallower horizons and the associated reservoir units.

The derived subsurface 3D structural (and geological) model with main lithological units includes information on potential geothermal reservoirs with burial depth and spatial distribution. Well data contain information about the reservoir quality (e.g. distribution of sandstone layers, facies type, heterogeneity, porosity, and permeability) as well as information on temperature and geochemistry of the formation water, where such data were measured (e.g. Olivarius et al. 2015; Kristensen et al. 2016; Weibel et al. 2017; Fuchs et al. 2020).

The shallow geology is dominated by soft sediments and characterized by a variable depth to the groundwater table. The sediments consist of glacial sand and clay deposits of variable thickness. In the western part of Denmark, they are found on top of Miocene fluvio-deltaic sands and marine silts and muds, whereas in the eastern and northeastern part, the glacial deposits overlay relatively soft limestone from the Danien and Cretaceous.

The energy extraction from shallow installations depends on the thermal properties of the sediments surrounding the heat collectors, (e.g. Vangkilde-Pedersen et al. 2012). Relatively few investigations of thermal properties of Danish sediments have been carried out (Balling et al. 1981; Porsvig 1986; Møller et al. 2019), and thermal conductivity values for different rock and sediment types published by e.g. VDI (2010) show large variations for sediments relevant in a shallow geological context. However, a recent investigation has narrowed down this span for a number of relevant shallow sediments (Ditlefsen et al. 2014).

3. DEEP GEOTHERMAL RESOURCES AND POTENTIAL

The geothermal resources in the deep Danish onshore underground are enormous (corresponding to around 3 times the heat from the Danish North Sea oil) and may potentially constitute the district heating to 1/3–1/2 of the Danish households for hundreds of years. At present, only a very limed fraction of the resources is utilized (the Thisted plant in northern Jutland, Fig. 3).

Several initiatives have been undertaken in order to stimulate the exploitation of the geothermal resource and thus contribute to the transformation to a more sustainable energy mix in Denmark. A number of public financed research projects has thus been carried out over the last decades, focusing on the implementation of deep geothermal energy for district heating and thereby replacing fossil fuel, especially coal and oil. These research projects have considerably increased our knowledge of the Danish subsurface and confirmed the presence of its huge geothermal resource and indicated where the geological conditions are most suitable for the extraction of deep geothermal energy.

In Denmark, successful geothermal exploitation in the deep subsurface requires the presence of thick and laterally coherent sandstone reservoirs with high porosity and permeability, which can ensure effective and long-term extraction and re-injection of formation water. A thick and coherent reservoir that is not hydraulically compartmentalized by faults, lateral lithological changes (e.g. grain size) or diagenetic features implies that a large volume of warm water may be accessible, and that production and injection wells can be placed at appropriate distances from each other while remaining hydraulically connected.

The temperature gradient of typical 25–30°C/km in the Danish subsurface implies that at depths shallower than 800 m the temperature is generally not sufficiently high to be economically profitable for a district heating plant, whereas at depths greater than 3000 m, diagenetic alterations related to high pressure–temperature conditions reduce the porosity and permeability of the reservoir sandstones. Thus, most interest is currently devoted to reservoirs with burial depth within the range of 800–3000 m and with a cumulative thickness of good quality reservoir sand of more than ca. 15 m (Vosgerau et al. 2016).

An outcome of the major mapping campaign resulted in 2015 in a user-friendly WebGIS portal providing an overview of the amount and quality of existing geodata, the geological composition of the subsurface, and interpreted thematic products such as depth and thickness maps of potential geothermal reservoirs in the deep Danish subsurface:

http://DybGeotermi.GEUS.dk

(Vosgerau et al. 2016). An important thematic map outlines where in Denmark the geothermal potential appears most promising based on current knowledge and may thereby ensure that future explorations are directed towards these areas, thereby also reducing the risk of making unsuccessful wells in areas where the geothermal potential is low (Fig. 3).

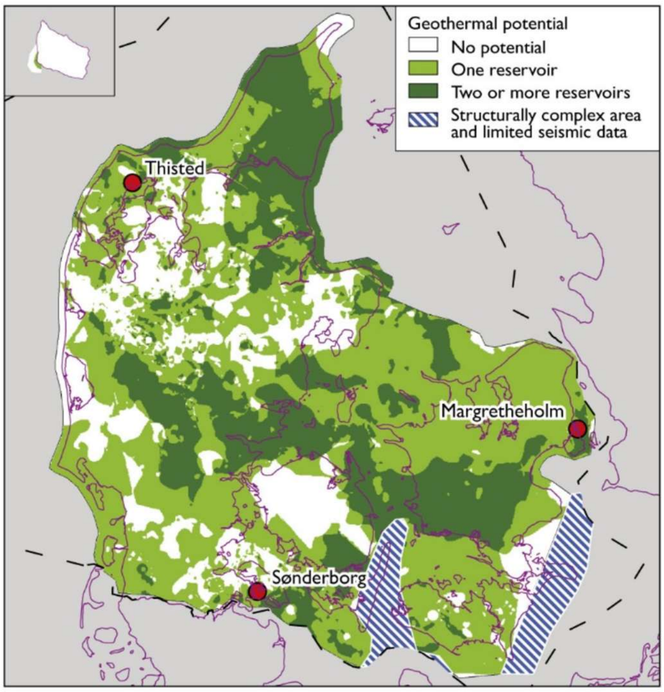


Figure 3: Distribution of lithostratigraphic units with reservoir properties suitable for geothermal exploration in the geothermal depth zone (800–3000 m). Notice the location of the three existing geothermal plants of which only the Thisted plant is in operation. From the Deep Geothermal WebGIS Portal (2015) (after Vosgerau et al. 2016).

The WebGIS portal has reduced the exploration risks significantly and has stimulated the interest from the industry. It provides a robust and consistent frame for more comprehensive estimates of the regional geothermal potential. Estimates in specific local geothermal license areas must however be based on more detailed analysis of the local dataset defining local geological models that may serve as the geoscientific background for technical and economic assessment.

4. DEEP GEOTHERMAL UTILIZATION

Exploration activities are ongoing in the Aarhus license, while activities in the greater Copenhagen area are at the planning stage. The existing three geothermal plants were all projected to use absorption heat pumps and produce heat for district heating. Absorption heat pumps can be driven at low cost if other heat producers such as biomass boilers can supply 160°C driving heat at district heating cost levels.

Furthermore, all the geothermal plants use the doublet concept; warm formation water is pumped to the surface from a production well using no stimulation of the geothermal reservoir. After heat is transferred to the district heating system, the cooled water is returned to the reservoir through injection well(s). In Thisted, the production well produces ca. 43°C warm water from the Gassum Formation at a depth of 1250 m where the water has a salinity of 15%. The plant produces up to 7 MW from 200 m^3/h geothermal water and transfer 10 MW heat to the district heating net by heat exchange and with the aid of absorption heat pumps driven by heat primarily from a biomass boiler. In Sønderborg, the production well produced 48°C warm water from the Gassum Formation at a depth of 1200 m where the water has a salinity of 15%. The plant was designed to produce up to 12 MW from 350 m^3/h geothermal water with the use of absorption pumps driven by biomass. The Margretheholm plant was projected to exploit a geothermal reservoir in the Lower Triassic Bunter Sandstone Formation at 2600 m depth where 19% saline geothermal water is available at ca. 74°C. The plant was designed to extract 14 MW heat from 235 m^3/h geothermal water and transfer 27 MW heat to the district heating net by heat exchange and through 3 absorption heat pumps driven by 14 MW steam primarily from wood pellet-based CHP plant. Comprehensive descriptions of the technical part of the three geothermal plants are given in previous Country updates, e.g. Mahler, at al. 2010; Mahler et al. 2013; Røgen et al. 2015; Mathiesen et al. 2020; Mathiesen et al. 2022).

4.1 Current status, future development and installations

Assessment of the geothermal resources in Denmark indicates a great potential in large parts of the country. Several private investors and district heating companies are planning to exploit this potential for establishing geothermal production and are considering new exploration licenses (Fig. 1).

The huge amounts of geothermal energy resources that are present in the Danish subsurface may play an important role in future sustainable energy supply and has resulted in the need for e.g. accurate thermal information and thermal models. A recent published 3D numerical crustal temperature and heat-flow model for onshore Denmark including a comprehensive analysis of well-log data provides well-constrained input for a fully parameterized and calibrated numerical subsurface temperature model (Fuchs et al. 2020). The study shows that pronounced temperature anomalies are absent and variations in the temperature gradients are mainly due to local salt diapirs and differences in the thermal conductivity of the geological strata.

In Aarhus, Innargi are currently in the exploration phase and have planned seven plants in Aarhus, covering up to 20% of the city's district heating demand, and taking the full responsibility for exploration, establishment and operational risks the following 30 years. The first three exploration wells have been drilled, and a pilot plant is under construction involving two of these wells. The geothermal plants are expected to be completed within the next years and to operate at least 30 years.

The plants on Margretheholm and in Sønderborg have experienced problems with reinjection causing the plants to be out of operation. The Sønderborg geothermal plant is now under decommissioning. In contrast, the Thisted plant has been running smooth since it came into operation in 1984 and without experiencing any breakthrough to the production well of the cooled, re-injected water from the injection well situated ca. 1500 m from the production well. An extra injection well was added to the plant in 2018 as the existing injection well over the years gradually demanded increasing injection power. The new injection well reduces the electricity consumption and extends the lifetime of the plant and is expected to increase the proportion of geothermal heat of the total district heating supply in Thisted from 15 to 25 %.

Several research projects, including the GEOTHERM project are investigating the possibilities of integrating heat storage with exploitation of the geothermal resource. One scenario may thus be to transfer surplus heat to the water in the production well in the summertime and then extract it when needed during the winter (Major et al. 2018). Thus, geothermal plants can be used for long term heat storage with low temperature losses.

Deep Danish aquifers have not been found suitable for power production using the doublet concept, as sufficiently permeable sandstone layers are too cold due to the moderate temperature gradient of typical 25–30°C/km subsurface.

During the last years new technologies and new concepts are emerging. GreenTherma's concept focuses on harnessing deep geothermal energy using a single, horizontal wellbore in a closed-loop system (Maver et al. 2023).

GEUS is part of the newly awarded GO-Forward project aims to improve pre-drilling predictions of geothermal reservoir properties to reduce mining risk. Instead of using geostatistical methods, it simulates geological processes for pre-drill assessment, calibrated to geological or geophysical data. The project extends forward modeling methods from hydrocarbon exploration, such as stratigraphic, diagenesis, and fracture network modeling, for geothermal settings in Europe. These methods are tested in areas with abundant subsurface information to optimize and de-risk exploration, then applied in areas with limited data to increase pre-drill Probability of Success (POS). GO-Forward also advances ML-based methods for calibration, uncertainty quantification, and techno-economic performance assessment. Additionally, it promotes public awareness and engagement in geothermal developments to increase societal readiness. GEUS will contribute to the project with data, knowledge, and geological models to simulate the deposition and composition of the Gassum Formation on both local and regional scales.

5. SHALLOW GEOTHERMAL ENERGY

Shallow Geothermal Energy encompasses GSHP systems with HHEs as well as BHEs (vertical or inclined) and ATES wells. Moreover, the term includes ambient temperature district heating and cooling grids that utilize shallow geothermal energy as a primary energy source (termonet/5GDHC – 5th generation district heating and cooling). In areas where traditional district heating is not possible (typically rural regions), termonet/5GDHC has a large potential for efficient conversion from oil and gas to heat pumps.

Despite a large potential, the application of shallow geothermal energy in Denmark is relatively limited compared to e.g. Sweden or Germany. Between 2014 and 2024 the number of GSHPs installed annually varied between 1800 and 4800 with a significant increase in sales in the period from 2021–2023, mainly caused by the war between Russia and Ukraine and the high costs of natural gas that followed (Figure 4).

In the period 2014–2024, 9–20 kW heat pumps for larger single-family houses and medium size buildings tend to dominate sales. The smaller 0–6 kW heat pumps, typical for terraced houses, comes in second up until 2021, at which point they are overtaken by the larger 6–9 kW HPs. Large heat pumps >20 kW make up only a limited fraction of the total sales. In 2024, sales returned to the level observed in the years 2014–2020, perhaps even slightly below.

Most of the existing GSHP systems use HHEs. A few hundred use BHEs and >55 (Fleuchhaus et al. 2028) use ATES wells. During the last four years the installed length of BHEs has increased quite substantially from around 6000 m per year five-ten years ago to ca. 15'000 in 2021–2022 and 28'000 m in 2023. In 2024, the total installed length decreased to

19’000 m. approximately, following partially the general trend of decreasing GSHP sales (see Figure 5).

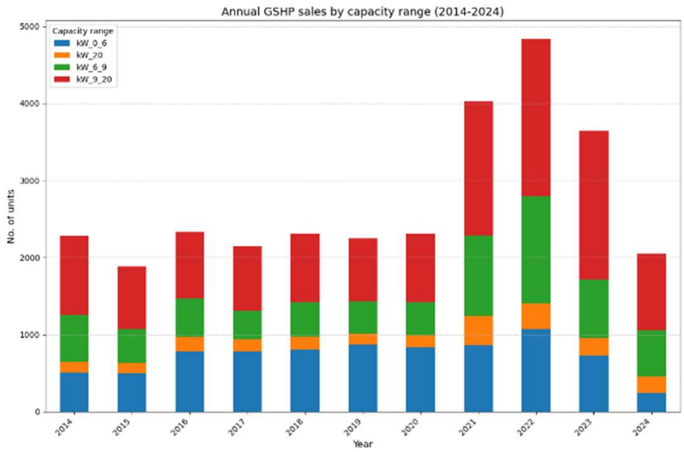


Figure 4: Number of GSHP installed annually and grouped by nominal power for the period 2014-2024. Source: ens.dk

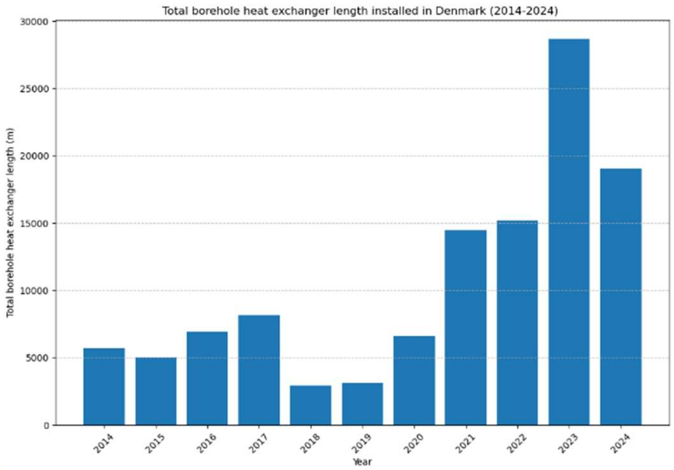


Figure 5: The total installed BHE length in Denmark in the period 2014–2024. BHEs that have not been put into operation are excluded from the plot. Source: geus.dk.

Some single-family house ATES systems were installed in the eighties, but later installations were primarily for industrial cooling and now large systems are applied with alternating operation (heating in winter and cooling in the summertime). In the period 2014-2024 40-50 new ATES wells has been drilled.

A new 5th generation district heating and cooling concept for collective shallow geothermal district heating and cooling of residential areas has emerged in Denmark in the past years. The concept is referred to as “termonet” where ground heat exchangers (GHE) are connected to a horizontal network of uninsulated geothermal distribution pipes from which individual consumers extract or reject heat with decentralized heat pumps (Figure 6).

During the hot season, excess heat from buildings with cooling demands can be rejected to the ground and stored for winter by direct or active cooling. In addition to improving the COP of the heat pump, seasonal heat storage significantly improves the thermal comfort during the hot season in buildings that otherwise suffer from overheating. There are currently 14 known termonet in operation in Denmark (Figure 7).

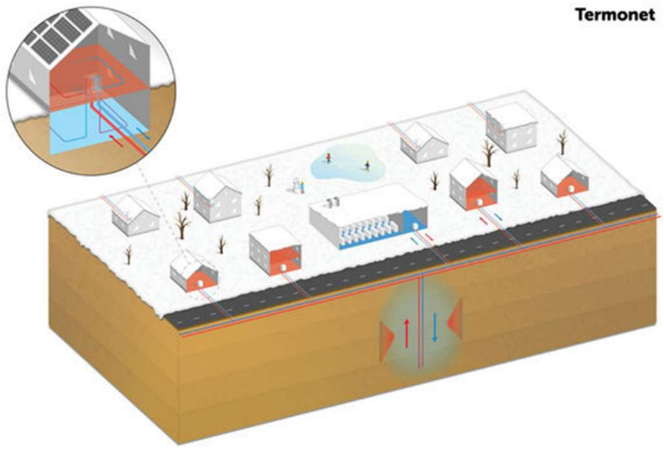


Figure 6: A termonet shown here with BHEs and the horizontal uninsulated distribution network that supplies houses with heating by means of distributed heat pumps and passive cooling/seasonal heat storage. Source: www.termonet.dk

The Danish termonet systems serve between 2 and 71 buildings, with nominal heating capacities ranging from 23 kW to 550 kW. These projects are evenly distributed between new-built and existing buildings. The most common type of GHE used is BHEs, implemented in nine of the projects. In Mageløse, thermal energy is extracted from an existing remediation well, showcasing an innovative integration of the water and energy sectors.

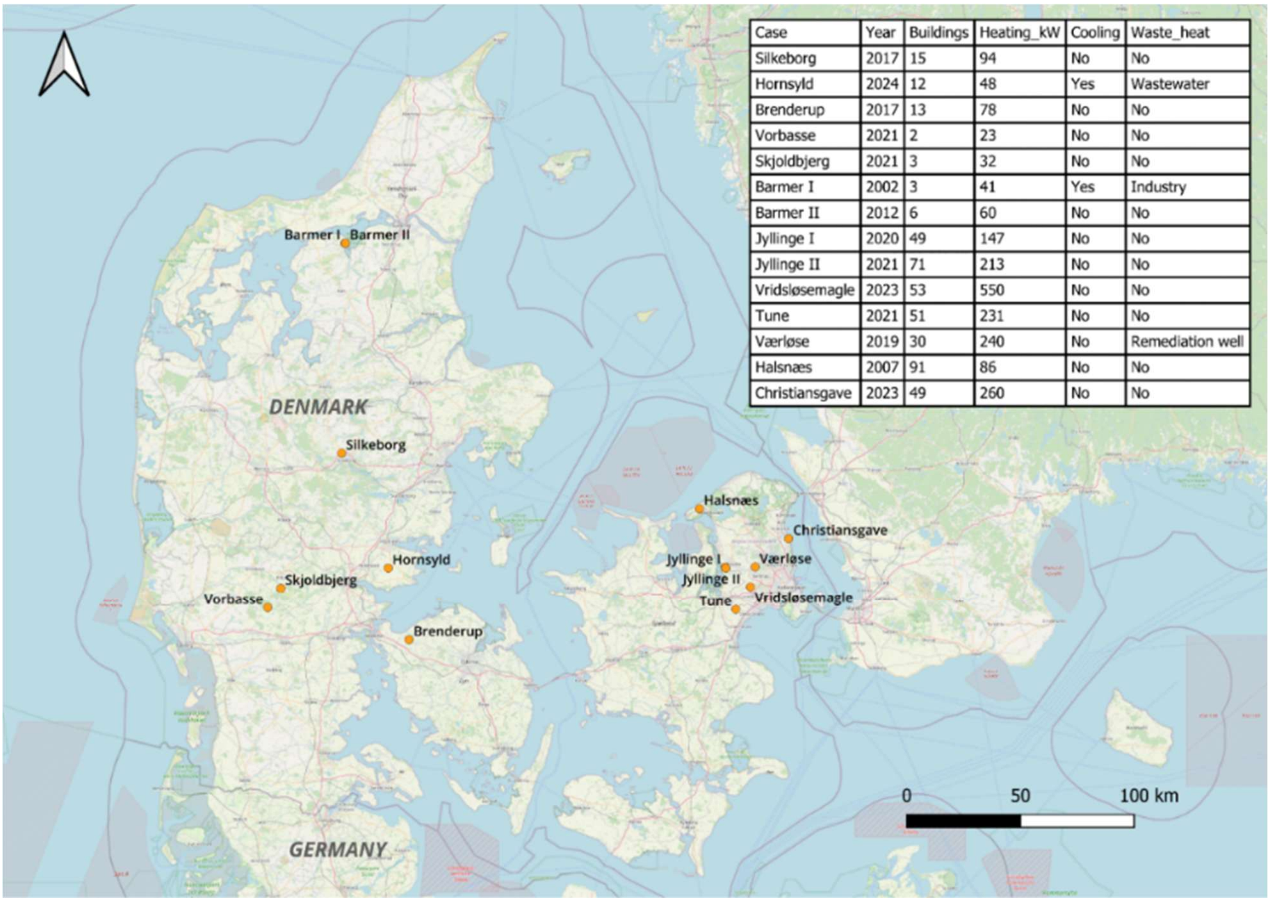
Two termonet systems, along with their heat pumps, are publicly owned by district heating (DH) companies. The remaining projects follow one of two financing models:

(1) direct consumer financing through mortgages or bank loans, or

(2) funding by a private DH company, which charges a connection fee but does not own the heat pumps.

5.1 Underground thermal energy storage

Large scale seasonal storage of heat by means of Underground Thermal Energy Storage (UTES) is also beginning to play a significant role in Denmark. A pilot borehole thermal energy storage (BTES) established by the local district heating company in Brædstrup with 48 boreholes, 45 m deep, in combination with a thermal solar installation, demonstrated that the storage efficiency during operation were according to expectations. However, the pilot is no longer in operation as other solutions were more efficient from an economic point of view. Another 4 district heating companies have established pit thermal energy storage (PTES) also combined with solar energy.



Case	Year	Buildings	Heating_kW	Cooling	Waste_heat
Silkeborg	2017	15	94	No	No
Hornsyld	2024	12	48	Yes	Wastewater
Brenderup	2017	13	78	No	No
Vorbasse	2021	2	23	No	No
Skjoldbjerg	2021	3	32	No	No
Barmer I	2002	3	41	Yes	Industry
Barmer II	2012	6	60	No	No
Jyllinge I	2020	49	147	No	No
Jyllinge II	2021	71	213	No	No
Vridsløsemagle	2023	53	550	No	No
Tune	2021	51	231	No	No
Værløse	2019	30	240	No	Remediation well
Halsnæs	2007	91	86	No	No
Christiansgave	2023	49	260	No	No

Figure 7: Termonet in Denmark shown with the number of connected consumers, heating capacity and building types.

In the European HEATSTORE project funded by EUDP and EU GEOTHERMICA-ERA NET (Koornneef et al. 2019), the Danish activities comprised description of lessons learned from existing UTES systems, internationally (Kallesøe et al. 2020; Kallesøe & Vangkilde-Pedersen 2019), and development of general specification and design for UTES systems (Nielsen & Vangkilde-Pedersen 2019) as well as establishing a web-based GIS platform demonstrating the technical future potential for underground thermal energy storage in the partner countries (Guglielmetti et al. 2021). Pilot UTES projects were developed in the Netherlands (high temperature aquifer thermal energy storage, HT-ATES), Switzerland (HT-ATES), France (BTES) and Germany (mine thermal energy storage, MTES), while in Denmark the geological conditions have been characterized in selected areas with a potential for UTES. A stakeholder-survey has indicated a specific interest in UTES among district heating companies, and Danish BTES and PTES systems have been used as case studies and for modelling of storage efficiency.

5.2 New initiatives

The COOLGEOHEAT II project (CG II), funded by Interreg ÖKS, aims to accelerate the adoption of termonet by improving design methodologies, business models, and regulatory frameworks. The project seeks to reduce both costs and emissions of termonet compared to traditional heating and cooling solutions. The collaboration continues the work in the original CG project.

A core focus of the project is the development of design guidelines to optimize the efficiency of heat pumps in termonet systems while ensuring user comfort. Additionally, the project is working on a demand prediction tool that can estimate heating and cooling needs in buildings, allowing for more precise and cost-effective network design. To support the financial and regulatory viability of termonet, CG II is analyzing existing projects in Denmark and Sweden to refine business models and policy recommendations that address economic and legislative barriers. The project also explores enhancements to existing termonet networks by integrating alternative energy sources such as wastewater, solar heat, and process heat, thereby increasing system flexibility and sustainability and minimizing the investment cost.

Between them, the two projects have produced tangible results. The CG I & II project partner Sustain has carried out more than 60 termonet screenings in Denmark as a direct result of the project. Moreover, the company has entered into agreement with a local energy community on developing the first stage of a large termonet to supply 650 buildings with heating, at an estimated initial cost of 120 mio. DKR, using the commercial financing model developed in the CG II project.

REFERENCES

Balling, N., Kristiansen, J.I., Breiner, N., Poulsen, K.D., Rasmussen, R. and Saxov, S.: Geothermal measurements and subsurface temperature, modelling in Denmark. GeoSkrifter 16, 176 pp. Aarhus University, Denmark, (1981).

Ditlefsen, C., Sørensen, I., Slott, M. and Hansen, M.: Estimating thermal conductivity from lithological descriptions. Web-based tool for planning of ground-source heating and cooling. Geological Survey of Denmark and Greenland Bulletin 31, 2014, 55–58, (2014).

Erlström, M., Boldreel, L.O., Lindström, S., Kristensen, L., Mathiesen, A., Kamla, E. and Nielsen, L.H.: Stratigraphy and geothermal assessment of Mesozoic sandstone reservoirs in the Øresund Basin – exemplified by well data and seismic profiles. Bulletin of the Geological Society of Denmark, Vol. 66, pp. 123–149, (2018).

Fleuchaus, P., Godschalk, B., Stober, I and Blum, P.: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, pp. 861–876, (2018).

Fuchs, S., Balling, N. and Mathiesen, A.: Deep basin temperature and heat-flow field in Denmark – New insights from borehole analysis and 3D geothermal modelling. Geothermics, 83, pp 1–18, (2020).

Guglielmetti, L., Daniilidis, A., Valley, B., Maragna, C., Maurel, C., Dinkelman, D., Koornneef, J., Oerlemans, P., Drijver, B., Kallesøe, A.J., Mortensen, M.H., Ditlefsen, C., Vangkilde-Pedersen, T. and Klein, S.: Screening of the national potential for UTES. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 87 pp, (2021).

Kallesøe, A.J. and Vangkilde-Pedersen, T. (eds): Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 130 pp + appendices, (2019).

Kallesøe, A.J., Vangkilde-Pedersen, T., Nielsen, J.E., Bakema, G., Egermann, P., Maragna, C., Hahn, F., Guglielmetti, L., Koornneef, J.: HEATSTORE – Underground Thermal Energy Storage (UTES) – State of the Art, Example Cases and Lessons Learned. Proceedings World Geothermal Congress 2020+1, Online and On-Site, Reykjavik, Iceland, March–October, 2021. 9 pp, (2020).

Koornneef, J., Guglielmetti, L., Hahn, F., Egermann, P., Vangkilde-Pedersen, T., Aradóttir, E.S., Allaerts, K., Viveiros, F. & Saaltink, M.: HEATSTORE: high temperature underground thermal energy storage. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019. 8 pp, (2019).

Kristensen, L., Hjuler, M.L., Frykman, P., Olivarius, M., Weibel, R., Nielsen, L.H. and Mathiesen, A.: Pre-drilling assessments of average porosity and permeability in the geothermal reservoirs of the Danish area. Geotherm Energy, 4(6), 2–27, (2016).

Mahler, A. and Magtengaard, J.: Country update report for Denmark, in Proceedings World Geothermal Congress 2010, Bali, Indonesia, 9 pp, (2010).

Mahler, A., Røgen, B., Ditlefsen, C., Nielsen, L.H. and Vangkilde-Pedersen, T.: Geothermal Energy Use, Country Update for Denmark. European Geothermal Congress 2013, (2013).

Major, M., Poulsen, S.E. and Balling, N.: A numerical investigation of combined heat storage and extraction in deep geothermal reservoirs. Geothermal Energy, 6(1), 1, (2018).

Mathiesen, A., Nielsen, L.H. and Bidstrup, T.: Identification of the potential geothermal reservoirs in Denmark. Geological Survey of Denmark and Greenland Bulletin 20, 19–22, (2010).

Mathiesen, A., Nielsen, L.H., Vosgerau, H., Poulsen, S.E., Bjørn, H., Røgen, B., Ditlefsen, C. and Vangkilde-Pedersen, T.: Country update report for Denmark, in Proceedings World Geothermal Congress 2020+, Reykjavik, Iceland, 9 pp + tables, (2020).

Mathiesen, A., Vosgerau, H., Olivarius M., Nielsen, L.H., Poulsen, S.E., Andersen T.R., Tordrup, K.W., Røgen, B., Ditlefsen, C. and Vangkilde-Pedersen, T.: Country update report for Denmark, in Proceedings World Geothermal Congress 2022, Berlin, Germany, 9 pp + tables, (2022).

Maver, K.G., Vestavik, O.V., Rasmussen, J.P. and Larsen, C-E.: First Break, Vol 41, Issue 9, Reservoir Engineering & Geoscience, (2023).

Michelsen, O., Nielsen, L.H., Johannessen, P., Andsbjerg, J. and Surlyk, F.: Jurassic lithostratigraphy and stratigraphic development onshore and offshore Denmark. In: Ineson, J. R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1, 147–216, (2003).

Michelsen, O. and Nielsen, L.H.: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark. Hans-1, Sæby-1, and Terne-1 wells. Danm. geol. Unders., Ser. A 29, 39 pp, (1991).

Møller, I., Balling, B and Ditlefsen, C.: Shallow subsurface thermal structure onshore Denmark: temperature, thermal conductivity and heat flow. Bulletin of the Geological Society of Denmark 67, pp-29–52, (2019).

Nielsen, J.E. and Vangkilde-Pedersen, T. (eds.): Underground Thermal Energy Storage (UTES) – general specifications and design. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 58 pp, (2019).

Nielsen, L.H., Mathiesen, A. and Bidstrup, T.: Geothermal energy in Denmark. Review of Survey activities 2003. Geological Survey of Denmark and Greenland bulletin 4 p.17–20, (2004).

Nielsen, L.H.: Late Triassic–Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1, 459–526, (2003).

Olivarius, M., Weibel, R., Hjuler, M.L., Kristensen, L., Mathiesen, A., Nielsen, L.H. and Kjøller, C.: Diagenetic effects on porosity-permeability relationships in red beds of the Lower Triassic Bunter Sandstone Formation in the North German Basin. Sedimentary Geology 321, 139–153, (2015).

Picard, D.; Helsen, L. A New Hybrid Model For Borefield Heat Exchangers Performance Evaluation. In Proceedings of the 2014 Ashrae Annual Conference, Seattle, WA, USA, 28 June–2 July 2014; pp. 857–866, (2014).

Porsvig, M.: Varmeovergangsforhold omkring jordslanger. Energiministeriets varmepumpe-forskningsprogram 33, 56 pp, (1986).

Røgen, B., Ditlefsen; C., Vangkilde-Pedersen, T., Nielsen, L.H. and Mahler, A.: Geothermal Energy Use. Country Update for Denmark. World Geothermal Congress 2015, (2015).

Vangkilde-Pedersen, T., Ditlefsen, C. and Højberg, A.L.: Shallow geothermal energy in Denmark. Geological Survey of Denmark and Greenland Bulletin 26, 37–40, (2012).

VDI (Verein Deutscher Ingenieure): Thermische Nutzung des Untergrundes: Grundlagen, Genehmigungen, Umweltaspekte. Richtlinie 4640, Blatt 1, 33 pp. Dusseldorf: Verein Deutscher Ingenieure. 2010, (2010).

Vosgerau, H., Balling, N., Mathiesen, A., Mathiesen, T., Nielsen, L.H., Oliveira, A. and Weibel, R: Reducing obstacles for large scale utilization of geothermal energy for district heating – the GEOTHERM project. European Geothermal Congress, Berlin, Germany, (2022).

Vosgerau, H., Mathiesen, A., Andersen, M.S., Boldreel, L.O., Hjuler, M.L., Kamla, E., Kristensen, L., Pedersen, C.B., Pjetursson, B. and Nielsen, L.H.: A WebGIS portal for exploration of deep geothermal energy based on geological and geophysical data. Geological Survey of Denmark and Greenland Bulletin, 35, 23–26, (2016).

Weibel, R., Olivarius, M., Kristensen; L., Friis, H., Hjuler, M. L., Kjøller, C., Mathiesen, A. and Nielsen, L. H.: Predicting permeability of low enthalpy geothermal reservoirs: examples from the Upper Triassic−Lower Jurassic Gassum Formation, Norwegian-Danish Basin. Geothermics 65, 135-157, (2017).

Weibel, R., Olivarius, M., Vosgerau, H., Mathiesen, A., Kristensen L., Nielsen, C.M. and Nielsen, L.H.: Overview of potential geothermal reservoirs in Denmark. Netherlands Journal of Geosciences, 99, e3, 14 pp., (2020).

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Tables A-G

Table A: Present and planned geothermal power plants, total numbers

	Geothermal Power Plants		Total Electric Power in the country		Share of geothermal in total electric power generation	
	Capacity (MW_e)	Production (GWh_e/yr)	Capacity (MW_e)	Production (GWh_e/yr)	Capacity (%)	Production (%)
In operation end of 2024	None-					
Under construction end of 2024						
Total projected by 2028						
Total expected by 2032						
In case information on geothermal licenses is available in your country, please specify here the number of licenses in force in 2024 (indicate exploration/exploitation if applicable):					Under development:	
					Under investigation:	

* Please refer to the guideline at the end of this template for classification as *under development* or *under investigation*

Table B: Existing geothermal power plants, individual sites

There are no geothermal power plants in Denmark at present.

Table C: Present and planned deep geothermal district heating (DH) plants and other uses for heating and cooling, total numbers

	Geothermal DH plants		Geothermal heat in agriculture and industry		Geothermal heat for buildings		Geothermal heat in balneology and other *	
	Capacity (MW_{th})	Production (GWh_{th}/yr)	Capacity (MW_{th})	Production (GWh_{th}/yr)	Capacity (MW_{th})	Production (GWh_{th}/yr)	Capacity (MW_{th})	Production (GWh_{th}/yr)
In operation end of 2024	7	20						
Under construc-tion end 2024	18	50						
Total projected by 2028	120	600						
Total expected by 2032	140	700						

* Note: spas and pools are difficult to estimate and are often over-estimated. For calculations of energy use in the pools, be sure to use the inflow and outflow temperature and not the spring or well temperature (unless it is the same as the inflow temperature) for calculating the energy parameters, as some pool need to have the geothermal water cooled before using it in the pools.

Table D1: Existing geothermal district heating (DH) plants, individual sites

Locality	Plant Name	Year commis-sioned	CHP *	Cooling **	Geoth. capacity installed (MW_{th})	Total capacity installed (MW_{th})	2024 produc-tion (GWh_{th}/y)	Geoth. share in total prod. (%)
Thisted	Thisted	1984	N	N	7	7	19	12
Copenhagen	Margretheholm	2005	N	N	13,7	-	0	-
Sønderborg	Sønderborg	2013	N	N	12,5	-	0	-
total					**7**	**7**	**19**	**-**

* If the geothermal heat used in the DH plant is also used for power production (either in parallel or as a first step with DH using the residual heat in the brine/water), please mark with Y (for yes) or N (for no) in this column.

** If cold for space cooling in buildings or process cooling is provided from geothermal heat (e.g. by absorption chillers), please mark with Y (for yes) or N (for no) in this column. In case the plant applies re-injection, please indicate with (RI) in this column after Y or N.

Table E1: Shallow geothermal energy, geothermal pumps (GSHP)

	Geothermal Heat Pumps (GSHP), total			New (additional) GSHP in the year 2024 *		
	Number	Capacity (MW_{th})	Production (GWh_{th}/yr)	Number	Capacity (MW_{th})	Share in new constr. (%)
In operation end of 2024	40’000-45’000	410-465	720-815	4031	45	Not known
Of which net-works *	173	1.8	3			
Projected total by 2028	**264**	**2.7**	**4.8**			

* Distribution networks from shallow geothermal sources supplying low-temperature water to heat pumps in individual buildings (“cold” DH, Geothermal DH 5.0 etc.)

Table E2: Shallow geothermal energy, Underground Thermal Energy Storage (UTES)

	Aquifer Thermal Energy Storage (ATES)			Borehole Thermal Energy Storage (BTES)		
	Number	Capacity (MW_{th}) Heat / Cold	Production (GWh_{th}/yr) Heat / Cold	Number	Capacity (MW_{th}) Heat / Cold	Production (GWh_{th}/yr) Heat / Cold
In operation end of 2024 *	ca. 45	H: 41’000 C: 27’000	H: NA C: NA	0	H: C:	H: C:
New (additional) in the year 2024	0	H: 0 C: 0	H: 0 C: 0	0	H: C:	H: C:
Projected total by 2028	**ca. 47**	**H: 43’000** **C: 28’000**	**H: NA** **C: NA**	**0**	**H:** **C:**	**H:** **C:**

Table F: Investment and Employment in geothermal energy

	in 2024		Expected in 2028	
	Expenditures * (million €)	Personnel ** (number)	Expenditures * (million €)	Personnel ** (number)
Geothermal electric power	0	0	0	0
Geothermal direct uses	0	15	?	30
Shallow geothermal	80	670	100	840
total	**80**	**685**	**?**	**870**

* Expenditures in installation, operation and maintenance, decommissioning

** Personnel, only direct jobs: Direct jobs – associated with core activities of the geothermal industry – include “jobs created in the manufacturing, delivery, construction, installation, project management and operation and maintenance of the different components of the technology, or power plant, under consideration”. For instance, in the geothermal sector, employment created to manufacture or operate turbines is measured as direct jobs.

Table G: Incentives, Information, Education

	Geothermal electricity	Deep Geothermal for heating and cooling	Shallow geothermal
Financial Incentives – R&D			-None-
Financial Incentives – Investment			DIS
Financial Incentives – Operation/Production			O Reduction of tax on GSHP electricity use above 4 MWh/yr
Information activities – promotion for the public			www.termonet.dk
Information activities – geological information			None-
Education/Training – Academic			None-
Education/Training – Vocational			None-

Key for financial incentives:

DIS	Direct investment support	FIT	Feed-in tariff	-A	Add to FIT or FIP on case the amount is determined by auctioning
LIL	Low-interest loans	FIP	Feed-in premium		
RC	Risk coverage	REQ	Renewable Energy Quota		
TC	Tax credits	O	Other (please explain)		