Geothermal Energy Use, Country Update for Sweden

Signhild Gehlin[1], Olof Andersson[2]
[1] Swedish Center of Geoenergy, P.O. Box 1127, SE-22104 Lund, Sweden
[2] Geostrata HB, Kärrsångarvägen 14, SE-24735, S Sandby, Sweden
signhild.gehlin@geoenergicentrum.se

Keywords: Sweden, Country Update, Shallow geothermal energy, BTES, ATES, deep geothermal, ground source heat pumps

ABSTRACT

This paper presents the status of geothermal energy use and market in Sweden by the end of 2018. The geothermal energy in Sweden consists of shallow geothermal energy systems, mostly ground source heat pump systems (GSHP) for space heating and domestic hot water heating for single-family buildings. While the market for small GSHP systems has decreased over the last decade, due to market saturation, the market for larger shallow geothermal energy systems for residential as well as non-residential buildings is expanding. By the end of 2018, GSHP systems provided some 23 TWh of heating in Sweden of which approximately 17 TWh is renewable heat from the ground. The total installed GSHP heating capacity was 6.5 GW. These figures include the contribution of 250 GWh of geothermal heat produced by the Lund geothermal system plant connected to the district heating. In addition to the heat from the ground, approximately 1 TWh is provided as ground source direct-cooling from the UTES applications in Sweden.

1. INTRODUCTION

Sweden has a long history of geothermal energy utilization, reaching over a half-century. The development of geothermal energy utilization was triggered by the oil crises in the 1970's and 1980's, when nationwide efforts were made to achieve an oil-independent energy system. Following these national efforts, heat pump technology was promoted, and was further favoured by the national power production strategy based on nuclear power and hydropower. During the 1990's the heat pump technology in general and ground source heat pump (GSHP) technology in particular, developed rapidly in Sweden, resulting in a world-leading role in the GSHP research and industry.

Most of the geothermal development in Sweden relates to shallow geothermal systems, but there have also been some activities related to deep geothermal resources. So far these activities have only resulted in one geothermal district heating plant with moderate depth in the south of Sweden. This plant was established in the 1985, and is still in operation (Aldenius 2017). However, the plant does not meet the criteria for the EGC definition of deep geothermal district heating system, as its extraction temperature is <25°C.

In the 2015 world geothermal survey (Lund and Boyd 2015), Sweden is rated as top three world leading country in geothermal energy utilisation, in terms of installed units, installed capacity, as well as extracted thermal energy.

1.1 Geology, hydrogeology and climate in Sweden

The Swedish geology is characterized by the massive Baltic shield and its diverse crystalline eruptive and metamorphic rocks. In the southern parts of the country, sedimentary rock formations of significant thickness are found, spot-wise containing porous sandstones at considerable depth and with very good hydraulic properties (Figure 1).

The geothermal gradient reaches approximately 30ºC/km in the south but seldom more than 15 ºC/km within the Baltic shield regions (NE 1980:7).

The crystalline rock consists mainly of granites and gneisses. It is normally solid for drilling, and has a generally low groundwater yield. The rock type is favourable for drilling holes down to 200-300 m or more without technical problems.

Groundwater in the form of aquifers is mainly found in eskers. These are glaciofluvial deposits from the melting of the inland ice that covered Scandinavia some 10-20 000 years ago. The eskers with highly permeable gravel and sand deposits are located along the river valleys where also the population is dense. Apart from their use for drinking water supply, these eskers are also highly interesting for groundwater-based shallow geothermal systems for heat or cold extraction, as well as for thermal energy storage.

A limited number of large aquifers are also found in the sedimentary rock, mainly located in the southernmost part of Sweden. In particular it is the younger sandstones and limestones that are of interest for groundwater-based shallow geothermal systems.

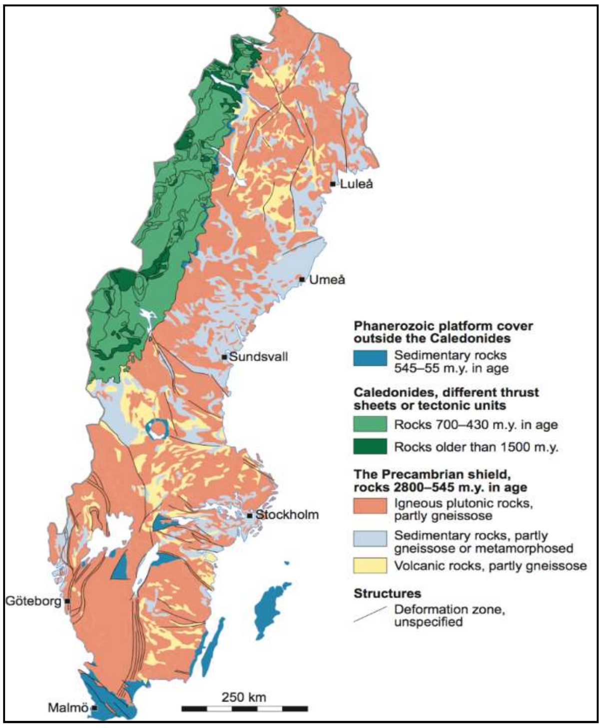

Figure 1: The bedrock geology of Sweden (© *Swedish Geological Survey)*

Sweden is a country with a climate that varies over the surface from north to south. According to the Köppen-Geiger climate classification system (Köppen 1884), the southern half of Sweden has a temperate continental climate, while the northern half has a cool continental climate. The variation in average high summer temperatures is small, with 21ºC in the south and 20ºC in the north. Variation in winter temperatures is more pronounced, with average winter season temperatures varying from -3ºC in the south to -14ºC in the north (climatedata.eu 2019). The seasonal swing between summer and winter is favourable for underground seasonal storage systems. Ground temperatures at a depth of 10 m vary between +9ºC in the south and +2ºC in the north. The ground temperature features the annual mean temperature in the air at the location, but is slightly higher in the north due to the insulating effect from snow cover in the winters.

2. DEEP GEOTHERMAL

In the Swedish crystalline bedrock, which has a moderate geothermal gradient, very large borehole depths are required to reach sufficiently high geothermal temperatures. In Skåne in the south of Sweden, where the geothermal gradient in the sedimentary rock is approximately 30ºC/km, temperatures above 100°C may be reached at a depth of 3-3.5 km. The first deep temperature logging in the southwest of Skåne was carried out in 1955 in a 2270 m deep borehole at Ljunghusen 1 (LTH 1977). The measured temperature gradient at the location was close to 35°C/km. Further investigation of the potential for geothermal energy in Skåne was reported in the late 1970's by a research group at Lund University (Bjelm et al. 1977, Bjelm et al. 1979), and for Sweden as a whole by Eriksson et al. (1979).

Apart from in Skåne, the potential for deep geothermal heat extraction in sedimentary bedrock may also be found on the island of Gotland and in the Siljan area in the middle parts of Sweden (Erlström et al. 2016).

Due to the low geothermal gradient in the Swedish bedrock in general, there is no deep geothermal power production in Sweden.

2.1 The Lund geothermal plant

The Lund geothermal plant is the largest geothermal heat pump installation in Sweden. The first unit started operating in 1984, and the second in 1985. It was first reported by Bjelm and Schärnell (1983).

The geothermal resource at the well site Värpinge consists of a set of very porous sandstones at 400-800 m depth. The formation belongs to the Campanian of Upper Cretaceous located at the border zone of the Danish-Polish embayment, known as the Tornquist tectonic deformation zone. The sandstone aquifer is highly permeable with a transmissivity of about 3 x 10^{-3} m^2/s. The four production wells initially produced 450 l/s (1 620 m^3/h) at a production temperature of 22ºC. This temperature is lower than 25°C, which sets the EGC criteria for a deep geothermal district heating system. The Lund geothermal plant is therefore included in Table E (GSHP applications).

The gravel pack in the injection wells tends to clog and has therefore been subject to air-lift treatment several times each year. A hydro-jetting method was introduced for cleaning the wells in 2011, and resulted in significantly improved specific capacity (Andersson and Bjelm 2013).

The geothermal fluid is used as the heat source for two heat pumps. These heat pumps have a combined capacity of 48 MW. After >30 years run-time, the geothermal plant was re-evaluated by Aldenius (2017). At its peak in 1993, the plant produced 350 GWh of heat, providing 40% of the energy in the Lund district heating network. Today the heat production is 250 GWh/year, which is 25% of the total district heating in Lund.

2.2 Deep geothermal exploration

Between 1984 and 1995 geological, hydrogeological and hydro-mechanical tests were carried out at the Fjällbacka test site in the Gothenburg area in western Sweden. The tests were part of the HDR project, Hot Dry Rock (Wallroth et al. 1999). Two wells of each 500 m depth were drilled into a horizontal reservoir. An open-loop circulation test was performed between the wells and gave a flow recovery of about 50%.

In 2002-2005, deep exploration wells were drilled a fault zone in the eastern part of Lund, aiming to find hot geothermal water. The first well was drilled to 3700 m depth, of which the lower half was drilled in in the crystalline basement. This was partly a drilling technology project (Bjelm 2006; Bjelm and Rosberg 2006). The second well was drilled into a sandstone formation at approximately 1.6 km. The wells were never put into production due to insufficient water production from the second well.

Two geothermal exploration boreholes were drilled in Malmö some 20 kilometres west of Lund in 2002-2003. The wells were drilled to a depth of 2 km where Triassic sandstones occur. Only one of the wells provided sufficient production capacity, and the wells were therefore abandoned (Malmö Stad 2007).

The Royal Institute of Technology in Stockholm started exploration for deep geothermal energy related to impact craters around 2005. Two core-drilled wells of 1000 m depth were drilled at Birka, nearby Stockholm, but were abandoned when they were found to be too dry (Henkel et al. 2005).

A number of not-so-deep (500-600 m) exploration wells were drilled in the Siljan impact crater area in 2010-2013, exploring a shallow geothermal sandstone aquifer. The formation may also contain natural gas resources, dissolved in the geothermal water (www.igrene.se 2016).

In 2009, the National Science Foundation released around 4 million USD to Lund University for purchase and implementation of a wire-line core drill rig capable of drilling to a depth of 2500 m in NQ size (borehole size 76 mm and core size 47.6 mm). Lund University is responsible for serving all national research institutions with deep drilling capability and expertise (Andersson and Bjelm 2013). There are several scientific subtasks in the so-called COSC-1 project. One of them is to investigate the heat flow properties of the bedrock.

The interest in deep geothermal energy in Sweden has increased in the last few years. This is to some part related to the development in Finland with the EGS pilot project in Espoo, where drilling started in 2015 (Kallio 2016).

3. SHALLOW GEOTHERMAL

The typical shallow geothermal energy systems in Sweden is a ground source heat pump (GSHP) system used for pure heat extraction for space heating and domestic hot water (DHW) production for a single-family house. Over time, an increasing number of commercial and institutional buildings with need for both heating and cooling demand, also use borehole thermal energy storage (BTES) or aquifer thermal energy storage (ATES) systems for space heating and cooling, sometimes in combination with other energy sources, such as solar energy and district heating.

Over the last decade, the reported sales figures for GSHPs up to 10 kW nominal capacity have decreased, and since 2016 sales have levelled out at 13 000 sold units per year (Figure 2). It is likely that these numbers will increase again over the coming years, not because of increasing numbers of new system installations, but because many GSHPs that were installed in the late 1990s now reach their technical life span and need to be replaced.

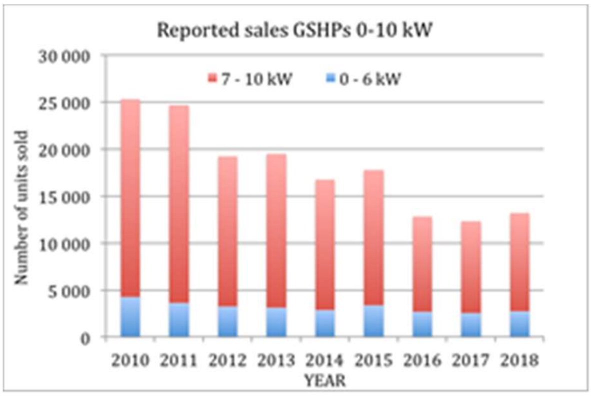

Figure 2: Reported sales of GSHPs up to 10 kW capacity in Sweden (SKVP 2019).

Sales figures for larger GSHPs for multi-family buildings and commercial buildings have been steadily growing during the last years, and the number of sold ground source heat pump units with capacity >10 kW has doubled since 2013 (Figure 3). Larger heat pump units (>100 kW) are not always reported to the Heat Pump Association. Hence, many of the larger systems are missing in the statistics.

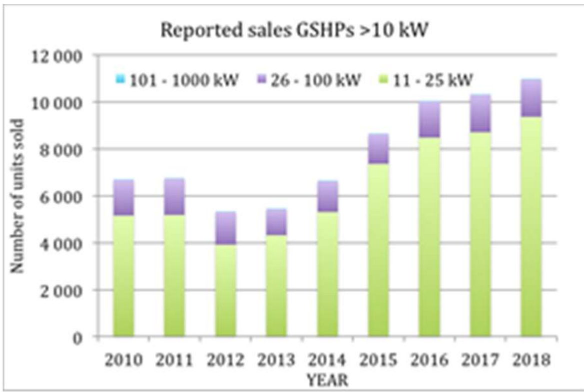

Figure 3: Reported sales of GSHPs >10 kW for large buildings in Sweden (SKVP 2019).

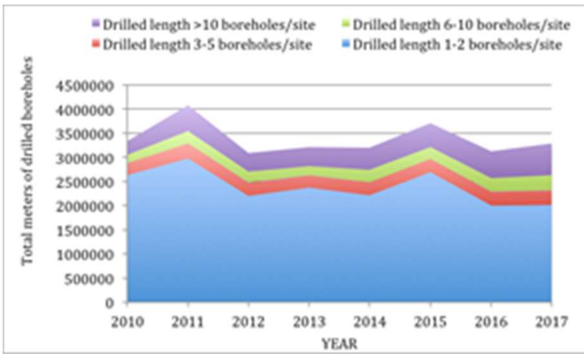

Figure 4: Reported annual number of drilled borehole meters for different system sizes. (SGU Well database 2019).

Looking at the amount of drilled borehole meters (Figure 4), it can be seen that although there is a slight decrease in drilled borehole meters for systems using 1-2 boreholes, this is compensated for by the increased number of larger systems (>10 boreholes).

A vast majority of the Swedish shallow geothermal energy systems are vertical boreholes in hard rock. The trend with increasing borehole depth for GSHPs and BTES systems, previously observed by Gehlin and Andersson (2013) continues (Figures 5). The preliminary overall average borehole depth in Sweden in 2018 was 190 m, as compared to 162 m in 2010, an increase in depth with 17%. The trend with increasing borehole depth started in the late 1990's when drill rig compressor capacity increased. Following the heat pump development with increasing COP, and decreasing use of auxiliary heating for small units, the overall average borehole depth for GSHP systems has almost doubled in 20 years.

The preliminary average borehole depth for the system size of one or two boreholes, i.e. single-family buildings, was 176 m in 2018, which is an increase with 22 m (14%) since 2010. For system size >10 boreholes, the average borehole depth has increased from 187 m in 2010 to 245 m in 2018, an increase with 58 m (30%).

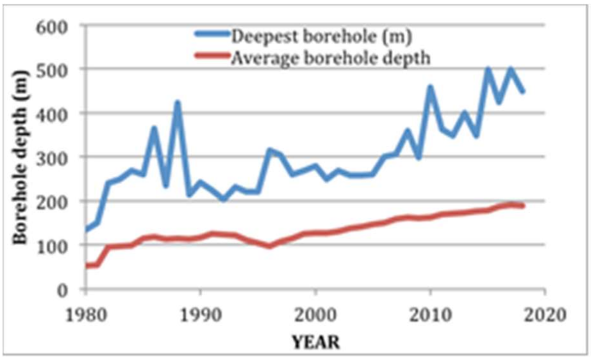

Figure 5: Average borehole depth and deepest borehole. (SGU Well database 2019).

Sales figures from the Swedish Heat Pump Association show that some 580 000 ground source heat pumps were installed in Sweden by the end of 2018. Of these GSHP systems, roughly 450 000 are vertical closed loop borehole systems. An estimate of 140 000 systems are horizontal loops in soil and lake sediments and 10 000 are estimated to be open loop systems using groundwater or surface water as the heat source. Since 2016 around 22 000 ground source heat pump units in sizes ranging from 3 kW to 25 kW have been installed per annum. The number of new installed larger GSHP units of >25 kW nominal capacity has increased from 1550 in 2016 to 1750 in 2018.

By the end of 2018 the calculated heating energy provided by GSHP systems in Sweden reached 23 TWh, with a total installed nominal capacity of 6.5 GW. The calculations are based on the assumption of an average heat pump running time of 3500 hours/year. In addition to this, ATES and BTES systems provide approximately 1 TWh direct cooling from the ground. The latter estimation is derived from an assumption that approximately 1000 systems run with 1000 full load hours of cooling on average. Commercial and institutional buildings often need cooling throughout the year and may reach 2 000 full-load hours. Within the residential sector the need for comfort cooling is approximately 500 full-load hours annually. A small number of ATES and BTES systems are used for cooling only, and may reach 4 000 full-load hours per year.

4. HEAT AND COLD EXTRACTION SYSTEMS

The typical Swedish shallow geothermal energy system is a groundwater filled vertical closed loop GSHP system, drilled in crystalline rock, used for heat extraction only. The heat pump is typically electrically driven and is used for both space heating and domestic hot water (DHW) heating. GSHP systems for larger residential buildings are sometimes actively recharged with waste heat from exhaust air or solar.

Horizontal ground loops, placed in the soil require larger surface areas. These are most commonly found on the countryside where enough space for the loops can be found more easily than in urban areas. In Sweden these systems are used only for heat extraction. Horizontal loops are sometimes placed at the bottom of lakes, streams or dams.

Vertical boreholes in rock and groundwater wells are also sometimes used for direct-cooling only. Examples of such users are found in the telecom and industrial sectors.

5. UNDERGROUND THERMAL ENERGY STORAGE

Most of the Swedish larger underground thermal energy systems (UTES) applications combine heating and cooling. The two commercial systems are Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES). Cavern Thermal Energy Systems (CTES), where heat or cold is stored in rock caverns exist in Sweden, but in very small numbers.

5.1 Aquifer thermal energy storage (ATES)

ATES systems use groundwater for carrying the thermal energy into and out of an aquifer. The wells are normally designed with a double function – both as production and injection wells. Energy is stored in the groundwater and in the grains (or rock mass) that form the aquifer. Between 10-15% of the Swedish land area contains aquifers suitable for ATES, and approximately 25% of the population lives in these areas (Andersson and Sellberg 1992). The use of groundwater is strictly regulated, making the real potential for ATES systems considerably smaller.

An estimate of some 180 ATES plants with a capacity of 100 kW or more are installed in Sweden, as of 2018. This estimate is based on the number of boreholes that are classified as “energy wells” in the SGU well data base, and are not deep enough to belong to the closed system category. The larger systems (>1 MW) are fairly well known from engineering reports, articles etc.

Systems larger than 100 kW nominal capacity are estimated to represent a total of some 170 MW. These are mainly located to aquifers in eskers, sandstones and limestones (Table 1). In addition to these ATES plants, there is an estimate of approximately 300 installed groundwater-source heat pumps with an average capacity of 50 kW. Some of these may still be ATES applications, but the majority is probably used only for heat extraction within the residential sector.

Table 1: Estimated number and size distribution of ATES plants with a capacity > 100 kW

Capacity size (MW)	Number of units	Total capacity (MW)
0,1-0,49	110	30
0,5-0,99	40	30
1,0-5,0	25	70
>5,0	5	40
Sum	**180**	**170**

Typical ATES system storage temperature levels are 12-16ºC on the warm side and 4-8ºC on the cold side (Andersson 2007).

One of the largest ATES systems in Sweden is the Stockholm Arlanda Airport ATES plant. An esker is used for seasonal storage of heat and cold. The cold is used for air conditioning of the airport buildings, while the heat is used for pre-heating of ventilation air and for snow melting at some airport gates. Cold is stored at 2-3ºC and heat at 20-25ºC. The system has been designed for a capacity of 10 MW and uses no heat pumps (Andersson 2009). The system delivers 22 GWh of heat and cold annually (Arvidsson 2016).

The very largest ATES plant in Sweden was designed in 1998 for short-term storage of cold. It is connected to the district cooling system for Stockholm City, and was designed for a cooling capacity of 25 MW for peak shaving during hot summer days. Due to well problems it is working at approximately 15 MW capacity. The working temperature is +3/+14ºC and when fully charged it holds around 1 000 MWh of cold (Andersson 2007).

5.2 Borehole thermal energy storage (BTES)

BTES systems in Sweden typically consist of several closely spaced boreholes with a depth of 150-300 m. The boreholes are typically groundwater-filled and fitted with single or double U-pipe borehole heat exchangers (BHE). The storage temperature typically ranges between +2ºC in the winter and +8ºC in the summer.

Sweden was one of the early adopters of BTES systems in the 1970’s and 1980’s, and built several pilot plants (Gehlin 2016). After a rather slow period during the 1990’s, the market for BTES systems is now growing in Sweden. The currently reported number of GSHP and BTES systems with more than 1 000 borehole meters is 3895, and there are 1701 registered systems with 10 boreholes or more (SGU Well database 2019). For the time being an estimate of 700 systems with more than 10 boreholes are true BTES applications used for both heating and cooling, while the rest are applied for heating only in the residential sector.

Table 2: Number of new BTES systems of various sizes reported in SGU Database *(SGU Well database 2019)*

Year	Units 1-2 holes	Units 3-5 holes	Units 6-10 holes	Units 11-19 holes	Units ≥20 holes
2000	5669	134	27	8	4
2001	7860	150	26	6	2
2002	12814	223	41	10	6
2003	14660	294	52	25	4
2004	18034	374	78	21	7
2005	18702	565	139	39	9
2006	20621	596	152	43	23
2007	14124	552	171	50	34
2008	10780	488	146	61	33
2009	13265	389	114	47	16
2010	15025	399	130	38	25
2011	16646	486	176	67	44
2012	12136	420	157	61	34
2013	13012	389	130	45	35
2014	11968	408	169	52	32
2015	14336	414	167	68	37
2016	10366	398	179	71	46
2017	10202	448	196	80	52
2018*	7355	221	104	39	22

**Data for 2018 incomplete due to delay in reporting.*

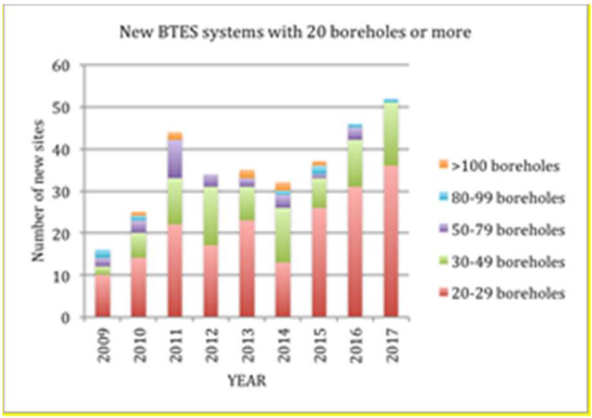

Figure 6: New large plants dominated by BTES 2009-2018 registered in the SGU Well Database (SGU Well database 2019).

The growth rate for large GSHP and BTES systems is currently 11% per annum. Since 2014 there is an increasing annual number of registered new systems with 20 boreholes. In 2017 over 50 new such systems were added to the database, and it is the system size of 20-50 boreholes that accounts for the most part of this increase (Table 2 and Figure 6).

The largest BTES system in Sweden is currently the BTES system at the Volvo Powertrain plant in Köping. This system comprises a total of 215 boreholes with average borehole depth of 270 m, giving a total borehole length of 58 200 m (Svensk Geoenergi 2017). The system was constructed in 2015-2016.

Two high temperature BTES systems are currently in operation in Sweden; Anneberg residential plant and the Xylem Emmaboda HT- BTES plants.

In Anneberg the plant is used for seasonal solar heat storage for residential heating of 50 houses. It uses no heat pumps and had a measured solar fraction of 40% after 12 years in operation (Heier 2013).

The Emmaboda Xylem HT-BTES plant is used for seasonal storage of industrial waste heat, and also for process cooling (Andersson & Rydell 2012, Nordell et al. 2016). This plant has recently been provided with a heat pump system for extraction of stored heat. The installation of heat pumps was necessary for the efficient function of the storage. The system is now one of 17 Swedish case studies in the TERMO program, IEA HPT Annex 52.

The first HT-BTES plant in Sweden, the Lulevärme project (Nordell 1994), is no longer operating. It stored industrial waste heat from a steel industry and was used for space heating of a university building in wintertime. It was an experimental plant that was operational during 1981-1989.

One large BTES plant is used for cooling only (the Karlskrona cogeneration plant). It consists of 108 boreholes, 200 m deep, in which cold from the outdoor air is stored to be used for cooling a generator during the summer season. The cooling capacity is 800 kW (Rozenberg 2010).

A handful of Swedish office buildings use the Skanska “Deep Green Cooling” concept, which is a ground-coupled system without heat pumps. It provides direct cooling in the summer and direct pre-heating of in-coming air in the winter. Additional heating demand is covered by district heating (Skanska 2014).

Another example of concept for ground-coupled pre-heating of ventilation air without the use of heat pumps is used in the residential sector by the Swedish cooperative housing association HSB (Kempe and Jonsson 2015).

6. FUTURE AND TRENDS

The stagnation of the market for small residential building GSHPs observed in the previous country update (Gehlin and Andersson 2016) has continued, and the market growth for larger GSHPs and UTES is now growing rapidly. The trend with larger system size and deeper boreholes also continues.

A road de-icing pilot project is carried out at Chalmers University in cooperation with the Swedish Transport Administration (Johnson 2017) and indicates a rising interest in geothermal energy use for infrastructural applications.

In the last few years the possibilities for three pilot projects on large-scale high-temperature BTES for district heating have been investigated at Linköping, Helsingborg and Gothenburg. In Gothenburg the system are under construction, while the projects at Linköping and Helsingborg are still at the investigation stage.

Since 2016 two strategic documents on geothermal energy (Räftegård and Gehlin 2017) and heat pumping technology and thermal energy storage (Ölén 2016) were compiled for the Swedish Energy Agency. These documents have contributed to the newly launched research program TERMO (Swedish Energy Agency 2017) on heating and cooling technologies. The research program encourages development of geothermal and thermal storage applications combined with district heating and small to medium scale thermal networks. Several research and development projects related to geothermal energy have started in 2018 with funding from the TERMO program. These include studies of new high-temperature ground heat exchangers, and high-temperature underground thermal energy storage applications. A four-year long-term GSHP system performance monitoring project comprising 17 Swedish case studies is also partly funded by the TERMO program, as part of IEA HPT Annex 52.

7. CONCLUSIONS

In the latest geothermal energy utilization world overview from World Geothermal Congress, Sweden was rated number three world leading country in shallow geothermal energy utilisation (Lund et al 2015). The geological conditions in Sweden are not favourable for deep geothermal power and heat production, but there is a budding new interest in deep geothermal energy for district heating following the recent pilot project in Finland.

The market for shallow geothermal systems and in particular GSHP systems with vertical boreholes in hard rock is growing steadily, in particular with regard to larger system size.

BTES applications tend to be designed with increasing size, deeper boreholes and higher capacities. Several newly started R&D projects open up for new applications and system combinations that may even further boost the general geothermal energy market, particularly regarding high-temperature storage and borehole storage as part of thermal networks.

ATES applications are suffering from comprehensive permit processes that lower the growth rate. Still a number of large-scale systems are now passed the permit process and are under construction. At KTH research is ongoing regarding the chemical and thermal behaviour of the Rosenborg ATES plant in Stockholm. The project is linked to the IEA HPT Annex 52 project, together with a few other ATES applications.

REFERENCES

Aldenius, E.: Lunds Geotermisystem, en utvärdering av 30 års drift. Master's Thesis in geology. Lund University. (2017).

Andersson, O. Sellberg, B.: Swedish ATES Applications. Experiences after Ten Years of Development. *Proceedings of SAE International Engineering Conference*, San Diego, Aug. 3-7, 1992.

Andersson, O.: Aquifer Thermal Energy Storage (ATES). In Thermal energy storage for sustainable Energy Consumption, Chapter 6. *Springer*, 2007.

Andersson, O. The ATES Project at Stockholm Arlanda Airport-Technical Design and Environmental Assessment. *Proceedings of Effstock, the 11th International Conference on Underground Thermal Energy Storage, June 2009*, Stockholm, Sweden, (2009).

Andersson, O., and Bjelm, L.: Geothermal Energy Use, Country Update for Sweden. *Proceedings, European Geothermal Congress 2013*, Pisa, Italy, (2013).

Andersson, O., Ekestubbe, J., Ekdahl, A.: UTES (Underground Thermal Energy Storage – Applications and Market Development in Sweden, *Journal of Energy and Power Engineering 7* (2013), 669-678.

Andersson, O., and Gehlin, S.: State-of-the-Art: Sweden. Quality Management in Design, Construction and Operation of Borehole Systems *IEA ECES Annex 27.* (2018). Available from http://media.geoenergicentrum.se/2018/06/Andersson_Gehlin_2018_State-of-the-Art-report-Sweden-for-IEA-ECES-Annex-27.pdf

Andersson, O., Rydell, L. The HT-BTES plant at Xylem in Emmaboda, Sweden – Experiences from design, construction and initial operation. *Proceedings of Innostock, the 12th International Conference on Underground Thermal Energy Storage*, May 16-18 2012, Lleida, Spain, (2012).

Arvidsson, K: Arlanda Energi AB. *Verbal information* from Kent Arvidsson, Nov. (2016).

Bjelm, L., Hartlén, Rösshoff, Bennet, Bruch, Persson, Wadstein. *Geotermisk utvinning i Skåne. Slutrapport Etapp 1. Förutsättningarna för utvinning i sydvästra Skåne*. Nämnden för energiproduktionsforskning. Lund University. Project number 4560 040. (1977). In Swedish.

Bjelm, L., Hartlén, Rösshoff, Bennet, Bruch, Persson. *Geotermisk utvinning i Skåne. Slutrapport Etapp 2 och 3. Förutsättningarna för utvinning I sydvästra Skåne.* Nämnden för energiproduktionsforskning. Lund University. LUTVDG/(TVGL-3003)/1-95/(1979). In Swedish.

Bjelm, L. and Schärnell, L.: Large heat pump plants for district heating utilizing geothermal energy. Lund Institute of Technology, Dept. of Engineering Geology and Stal Laval Turbin AB, Finspång. *International symposium on Geothermal Energy*. Portland, USA. (1983).

Climatedata.eu: Retrieved February 11, 2019, from https://www.climatedata.eu

Eriksson, K.G., Ahlbom, K., Landström, O., Larson, S.Å., Lind, G., Malmqvist, D.: Investigation for Geothermal Energy in Sweden. Pageoph, Vol. 117 (1978/79). *Birkhäuser Verlag*, Basel, (1979)

Erlström, M., Mellqvist, C., Schwarz, G., Gustafssib, M., Dahlqvist, P.:Geoenergi. Geologisk information för geoenergianläggbingar – en översikt. Swedish Geological Survey, SGU, Report 2016:16. (2016). In Swedish.

Gehlin. S.: Chapter 11. Borehole Thermal Energy Storage. In S.J. Rees <u>Advances in ground-source heat pump systems</u>. London: Woodhead Publishing. (2016).

Gehlin, S., and Andersson, O.: Geothermal Energy Use, Country Update for Sweden. *Proceedings from European Geothermal Congress 2016*, Strasbourg, France, 19-24 September 2016. (2016).

Igrene.se: http://www.igrene.se/geotermi.html, March 2016. (2016).

Johnsson, J.: Winter Road Maintenance using Renewable Thermal Energy. Licentiate thesis, division of building technology, Chalmers university of technology, Sweden. (2017).

Kallio, J.: Geothermal Energy use, Country Update for Finland. *Proceedings of the European Geothermal Congress 2016*, Strasbourg, France, September 19-24 (2016). 5 p.

Kempe, P., Jonsson, R.: Nybyggt flerbostadshus med förvärmning med borrhålsvatten - HSB-FTX geoenergi utan värmepump. BeBo-utvärdering. (2015).

Köppen, W.: Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet (The thermal zones of the earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world). – Meteorol. Z. **1**, 215–226. (1884). (Translated and edited by Volken E. and S. Brönniman. – Meteorol. Z. **20** (2011), 351–360).

Lund, J.W., and Boyd, T.L.: Direct Utilization of Geothermal Energy 2015 Worldwide Review. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia (2015), 31 p.

NE: Geotermisk energi. Resultat, utvecklingsläge och förutsättningar. Nämnden för energiproduktionsforskning, NE, Rapport 1980:7 (1980) In Swedish.

Nordell, B.: Borehole Heat Store Design Optimization. PhD-thesis, 1994:137D. Division of Water

Resources Engineering. Luleå University of Technology, Sweden. (1994).

Nordell, B., Scorpo, A.L., Andersson, O., Rydell, L., Carlsson, B.: Long-term Long Term Evaluation of Operation and Design of the Emmaboda BTES. Operation and Experiences 2010-2015. Research Report Luleå university of technology. (2016).

Malmö Stad; Faktablad om Malmös lokala investeringsprogram LIP 2002-2005 (In Swedish). (2007).

Rozenberg, H.: Borrhålslager i Karlskrona – miljövänlig frikyla för miljövänligare fjärrvärme (Borehole storage – environmentally friendly free-cooling for more environmentally friendly district heating). *Borrsvängen*, #4 (2010), 32-35. (In Swedish).

Räftegård, O., S.Gehlin. (2016). Energin under mark ska upp till ytan – Strategisk innovationsagenda för Geoenergi (Energy below the ground shall surface – Strategic innovation Agenda for Geoenergy). Swedish Energy Agency project number: 41906-1. SP Report 2016:93. 24 p.

SGU Well database: The Swedish Geological Survey Well Database, Data retrieved February 1, 2019. (2019).

SKVP: Annual sales figures received from the Swedish Heat Pump Association, received in January 2019. (2019).

SKANSKA: Entré Lindhagen, Sweden. Case Study 122. Skanska AB. April 2014. (2014).

Svensk Geoenergi, No. 2/2017, page 25. www.geoenergicentrum.se. (2017).

Swedish Energy Agency: Utlysning: TERMO – värme och kyla för framtidens energisystem. (Call: TERMO – heat and cold for the future energy system). Swedish Energy Agency. DNR 2017-009832. (2017).

Wallroth, T., Eliasson, T. and Sundquist, U.: Hot dry rock research experiments at Fjällbacka, Sweden. *Geothermics* 28, 617-625. (1999).

Ölén, V.: Strategi för resurseffektiv värme & kyla. Nuläge, 2030 & 2050. (Strategy for efficient heat and cold. Current situation, 2030 & 2050). EffysExpand. (2016). Available for download at http://effsysexpand.se/wp-content/uploads/2016/10/Strategi-för-värme-kyla-final.pdf

Acknowledgements

The support from the authors' employers and the Swedish Energy Agency as part of TERMO research programs Grant 46972-1 and Grant 138501 is gratefully acknowledged.

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

There is no geothermal power production in Sweden.

Table B: Existing geothermal power plants, individual sites

There is no geothermal power production in Sweden.

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

There is no present or planned deep geothermal DH plant in Sweden that meets the criteria of >25°.

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

There is no existing deep existing geothermal DH plant, nor individual ones, in Sweden that meets the criteria of >25°C

Table D2: Existing geothermal large systems for heating and cooling uses other than DH, individual sites

There is no existing large geothermal systems for heating and cooling in Sweden that meets the criteria >500 MW.

Table E: Shallow geothermal energy, ground source heat pumps (GSHP). (Direct cooling from BTES and ATES is not included in this table)

	Geothermal Heat Pumps (GSHP), total			New (additional) GSHP in 2018		
	Number	Capacity (MW_{th})	Production* (GWh_{th}/yr)	Number	Capacity (MW_{th})	Share in new constr. (%)
In operation end of 2018	580 000	6 520	22 950	13 990	252	n.a
Projected total by 2020	605 000	6 750	25 000			

* Including electricity for heat pumps, based on 3500 hrs/year

Table F: Investment and Employment in geothermal energy

	in 2018		Expected in 2020	
	Expenditures (million €)	Personnel (number)	Expenditures (million €)	Personnel (number)
Geothermal electric power	0	0	0	0
Geothermal direct uses	0	0	0	0
Shallow geothermal	3000	10 000	3000	10 000
total	3000	10 000	3000	10 000

Table G: Incentives, Information, Education

	Geothermal electricity	Deep Geothermal for heating and cooling	Shallow geothermal
Financial Incentives – R&D	none	none	Research projects on monitoring, high-temperature storage and GSHPs and UTES in thermal grids, partly financed by the Swedish Energy Agency through the TERMO research program.
Financial Incentives – Investment	none	none	New GSHP installations for private residential buildings are partly deductible from tax, as is the case for a number of other types of renovation work.
Financial Incentives – Operation/Production	none	none	None
Information activities – promotion for the public	none	none	The platform Swedish Center of Geoenergy arranges courses, conferences/workshops, seminars, information activities, and issues the journal Svensk Geoenergi (Swedish Geoenergy). The association IGSHPA-Sweden arranges a bi-annual conference on GSHPs.
Information activities – geological information	none	none	Through the Database administered by the Swedish Geological Survey (SGU).
Education/Training – Academic	none	none	- Short courses and lectures at universities
Education/Training – Vocational	none	none	- Annual courses in basic geoenergi and EED training by Swedish Center of Geoenergy - 2 weeks education of new drillers, once every year

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	O	Other (please explain)