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 2015. Geothermal energy in Sweden is dominated by low temperature, shallow geothermal energy systems. The vast majority of installed geothermal energy systems are ground source heat pumps (GSHP) for space heating and domestic hot water heating for single-family buildings. About a fifth of the Swedish buildings use GSHP, making Sweden a leading country within this technology. The market for larger shallow geothermal energy systems for residential as well as non-residential buildings has been expanding over the last years. Shallow geothermal energy systems provide some 23 TWh of heating and cooling in Sweden (including free-cooling and electricity for heat pumps), of which approximately 17.5 TWh is renewable heat from the ground and approximately 1.1 TWh is free-cooling from the ground (assumed COP free-cooling 40). The total installed capacity (heating and cooling) is 6.8 GW.

Most part of Sweden lacks the geological conditions for deep geothermal exploitation. However, there is one plant in Lund from the mid-1980's that is still in operation, providing some 140 GWh of geothermal heat to the Lund district heating system.

1. INTRODUCTION

The extensive use of ground source heat pumps (GSHP) nationwide has made Sweden the third leading country in geothermal energy utilisation in the world, in terms of installed units, installed capacity, and extracted thermal energy (Lund and Boyd 2015).

Geothermal energy utilisation started in Sweden in the 1970's and 1980's, triggered by the oil crises, and the following nationwide efforts to achieve an oil-independent energy system. Heat pump technology was promoted, favoured by the national power production strategy based on nuclear and hydropower. Ground source heat pump technology developed rapidly during the 1990's, and is still a strong area of research and development in Sweden.

While shallow geothermal energy exploitation is continuously thriving in Sweden, deep geothermal energy exploitation remains minimal. Only one deep geothermal plant, taken into operation in the 1980's, is currently in operation.

1.1 Geology and hydrogeology in Sweden

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. The geothermal gradient reaches 28-30^{o}C/km in the south and seldom more that 15-16^{o}C/km within the Baltic shield regions. The bedrock is commonly covered by glacial deposits.

The crystalline rocks consist mainly of granites and gneisses. These are normally stable to for drilling, and have generally low yield of groundwater. These rocks are favourable for drilling holes down to 200-300 m without technical problems.

Ground temperatures at a depth of 10 m vary between +9^{o}C in the south and +2^{o}C 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.

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 to the river valleys where also the population is dense. Besides the usage for drinking water supply, these eskers are also of high interest for shallow geothermal systems, based on heat or cold extraction from the groundwater, but also for storage of thermal energy.

A few large aquifers are also found in the sedimentary rocks, mainly in the southernmost Sweden. Especially younger sandstones and limestones are of interest for groundwater based shallow geothermal systems.

1.2 Climatic conditions

The climate in Sweden varies much from north to south, especially winter conditions. Average high temperatures in summer are 21°C in the south and 20°C in the north, while average low temperatures in winter are -3°C in the south and -14°C in the north (climatedata.eu 2014).

According to the Köppen-Geiger climate classification system the southern half of Sweden has a temperate continental climate, while the northern half has a cool continental climate. From a shallow geothermal point of view this means that the seasonal swing between summer and winter is large enough to make underground seasonal storage systems feasible.

The annual precipitation is around 1 200 mm in the western mountain with a large portion in the form of snow. The west coast, exposed to the Northern Sea, has a precipitation of approximately 900 mm (mainly rain), while the east coast is considerably dryer with approximately 600 mm. This also goes for southernmost Sweden (SMHI 2016).

The solar radiation is approximately 1 MWh/m^2 over a year and the sun hours vary between 1500-1800 hours annually. The highest values are recorded in the eastern part of the country.

2. DEEP GEOTHERMAL

Most part of Sweden lacks geological conditions suitable for deep geothermal exploitation. There is today only one deep geothermal plant in operation in Sweden; the Lund geothermal heat pump plant that was taken into operation in the mid 1980's. There is no deep geothermal power production in Sweden.

2.1 The Lund deep geothermal plant

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

The geothermal resources consist of a set of very porous sandstones belonging to Campanian of Upper Cretaceous sitting in the border zone between the Danish-Polish embayment and the Tornquist tectonic deformation zone crossing the province of Scania. 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 22°C. The gravel pack in the injection wells tends to settle and has therefore been subject to air-lift treatment several times each year. A few years ago a new hydro-jetting method was introduced for cleaning the wells, and the specific capacity has been significantly improved (Andersson and Bjelm 2013).

The geothermal fluid is used as a source of heat to two heat pumps, with a combined capacity of 48 MW. Up to the year 2014 the plant was producing some 250-370 GWh of geothermal heat annually. However, from 2014 the production has been lowered to 140 GWh since a new cogeneration plant was taken into production giving less baseload space for geothermal heat in the district heating system of Lund (Kraftringen 2014).

2.2 Deep geothermal exploration

In 2002-2005, deep exploration wells were drilled in south Sweden, of which one of the wells was drilled to a depth of 3 700 m. The lower half of the borehole was drilled in crystalline basement, partly as a drilling technology project (Bjelm 2006; Bjelm and Rosberg 2006). The wells were never put into production due to limited 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 kilometres where Triassic sandstones occur. Only one of the wells provided sufficient production capacity, and they were therefore abandoned (Malmö Stad 2007).

The Royal Institute of Technology in Stockholm started exploration for 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 found too dry (Henkel et al. 2005).

A number of shallow (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 purchasing and implementing a top-of-the-line core-drilling package 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 institution 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 heat flow properties of the bedrock.

3. SHALLOW GEOTHERMAL

The majority of shallow geothermal energy systems in the country are pure heat extraction systems (GSHP). However, for commercial and institutional buildings the cooling demand is commonly considerable on an annual basis due to internal heat loads.

There are today around two million single-family houses in Sweden of which approximately 20% are heated with a GSHP (Swedish Energy Agency 2015). The number of such small systems has grown rapidly for several years, however during the last few years the number of new installed small systems has levelled out (Figure 1).

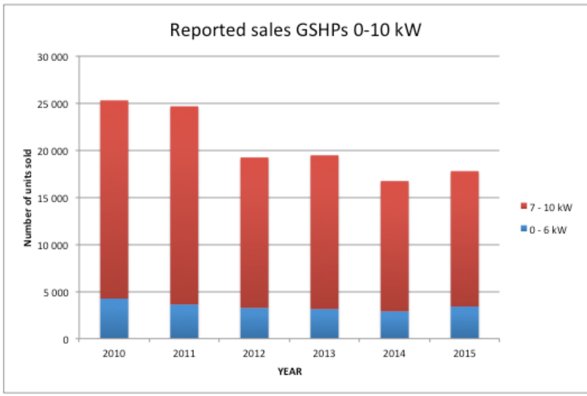

Figure 1: Reported sales of GSHPs up to 10 kW capacity in Sweden.

The number of larger GSHP systems for residential and commercial buildings as well as the market for larger underground thermal energy storage (UTES) for large facilities is now steadily growing. (Figure2). Note that heat pump capacities above 60 kW are normally covered by more than one heat pump unit. Single larger heat pumps, used in UTES systems, are not reported to the Heat Pump Association and therefore not included in the statistics.

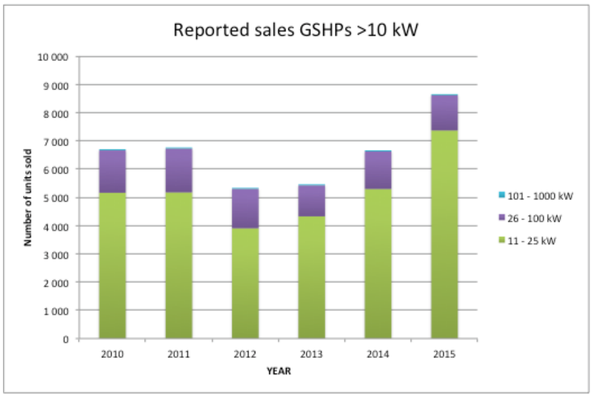

Figure 2: Reported sales of GSHPs >10 kW for large buildings in Sweden.

Geothermal energy is considered an environmentally friendly technology by the general public and tends to increase the commercial value of a building. Geothermal energy has played a major part in replacing fossil fuel heating in the Swedish building stock, especially for small residential buildings. As the market for larger geothermal energy systems increases, it helps to regulate the pricing of alternative energy sources such as biofuel and district heating. This has led to strong reactions from the district heating sector, which has a dominant market share in space heating and domestic hot water heating in Swedish buildings.

The vast majority of the Swedish shallow geothermal energy systems are vertical boreholes in hard rock. Boreholes for GSHPs and BTES systems tend to be drilled to an increasing depth (Figures 3 and 7), and with an increasing system capacity and efficiency.

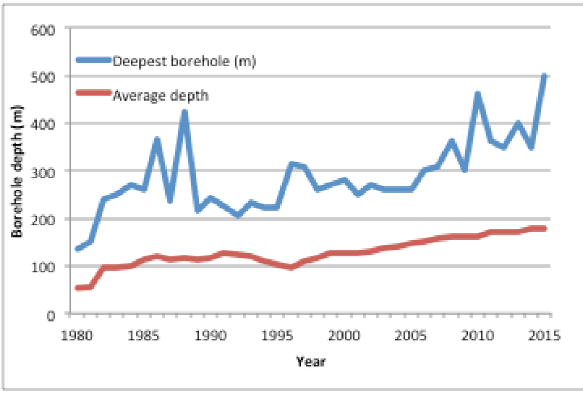

Figure 3: Average borehole depth and deepest borehole. Swedish Geological Survey Well Database (2016).

3.1 Heat 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.

Some systems for space heating of larger residential buildings, are actively recharged with waste heat from exhaust air or solar. In such cases they are classified as cooling loops or BTES systems, see further section 4.2.

A minor portion of all shallow geothermal energy systems in Sweden are horizontal ground loops, placed in the soil. Horizontal loops require larger surface areas, where plastic tubing is buried at about 1 m depth below the ground surface. In Sweden these systems are only used for heat extraction, and will freeze the moisture in the ground around the ground loops, thus taking advantage of the phase change energy. Horizontal ground loops work best in finely grained soil with high porosity and moisture content. They are most common on the countryside where enough space for the loops can be found more easily than in urban areas.

Horizontal loops are also sometimes placed at the bottom of lakes or dams. These tubes must be firmly anchored to the lake bottom by weights to prevent the tubes from floating, especially when ice forms around the tubes. In running water (rivers and creeks) special and denser tube collectors are used.

Sales figures from the Swedish Heat Pump Association tell that currently some 540 000 ground source heat pumps are installed in Sweden. Of these between 100 000-130 000 are estimated to be horizontal loops in soil and lake sediments. Only about 10 000 are estimated to be open loop systems using groundwater or (rarely) surface water as a heat source, and the remaining 400 000 are vertical loops in boreholes. The last five years around 25 000 ground source heat pump units in sizes ranging from 3 kW to 25 kW, and around 1500 units >25 kW have been installed per annum. .

Shallow geothermal energy extraction is also used as heat source for large heat pumps in district heating networks around Sweden. Figures from the Swedish District Heating Association show that in 2012 these plants provided some 0.65 TWh to the Swedish district-heating network (Trad 2014). However, the use of ground- and surface water heat pumps in the Swedish district-heating network has decreased in recent years, and no updated figures are available.

3.2 Cold extraction systems

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

In the industrial sector groundwater, which has a constant temperature all year around, is sometimes used for cooling. However, these applications are rare and true statistics on the number and size of plants are not available.

The main sector is telecom where "rock cooling" of AXE stations was the first application, beginning in the 1990's. However, this grid is gradually replaced by digital systems, which has become a succeeding market for "rock cooling".

Reliable statistics from this sector is missing. However, it has been estimated that there are over 150 "rock cooling" systems in operation, with 5-30 boreholes and 35-220 kW free-cooling capacity. These systems are mainly for process cooling and it is estimated that this sector use approximately 120 GWh of free cooling annually.

4. UNDERGROUND THERMAL ENERGY STORAGE (UTES)

While shallow geothermal energy extraction systems are passively recharged by heat transport in the ground from the ground surface and with a minor contribution from the geothermal heat flux, underground thermal energy systems (UTES) actively store heat and cold in the underground, commonly as seasonal storage. This means that heat is stored from the summer season to be utilised during the winter season. Likewise, cold is stored during winter to be recovered and used as free cooling during the summer season.

Most of the Swedish larger UTES applications combine heating and cooling. The two commercial systems are Aquifer Thermal Energy Storage (ATES) (Figure 4), and Borehole Thermal Energy Storage (BTES) (Figure 5). Cavern Thermal Energy Systems (CTES), where heat or cold is stored in rock caverns also exist, but in small numbers.

Figure 4: Aquifer Thermal Energy Storage (ATES). Illustration: Geotec.

Figure 5: Borehole Thermal Energy Storage (BTES). Illustration: Geotec.

4.1 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 contain aquifers suitable for ATES, and approximately 25% of the population lives in these areas (Andersson and Sellberg 1992), however using groundwater is strictly regulated making the real potential considerably smaller.

Still, some 160 ATES plants with a capacity of 100 kW or more are currently estimated to be installed in Sweden, see Figure 6. These systems represent some 300 MW capacity and are mainly located to aquifers in eskers, sandstones and limestones.

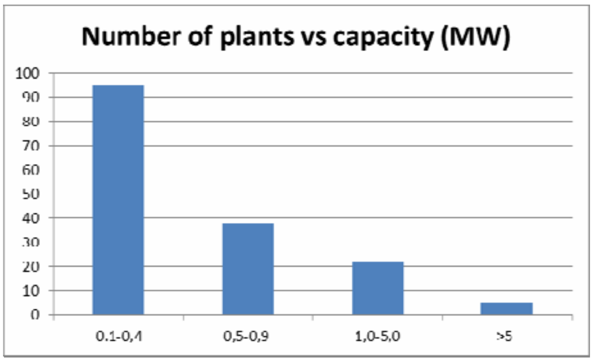

Figure 6: Estimated number and size distribution of Swedish ATES plants.

The estimation is mainly based on official permit documents that can be found in reference lists from consultants, drillers and installers and in scientific articles. The smaller systems can also be traced in the SGU well database. From these sources the growth rate of larger ATES (> 0,5 kW) seems to be rather stable over the years with approximately 5 new plants per year. By experiences, it takes around 2 years to develop one single plant; about one year for site investigations and one year for the permit procedure.

Typical storage temperatures are 12-16^{o}C on the warm side and 4-8^{o}C on the cold side (Andersson 2007). They have high SPF, often in the order of 5-7. They are fast responding and highly efficient, and have generally low pay-back times, often less than 3 years (Andersson et al 2013). On the other hand, the ATES systems are sensitive to potential chemical problems such as corrosion and clogging, mainly by iron precipitation. The cost for well maintenance must therefore be taken into consideration.

One of the largest ATES systems in Sweden is the Stockholm Arlanda Airport ATES plant. Here an esker is used for seasonal storage of heat and cold. The cold is used for air conditioning of the airport surrounding buildings, while the heat is used for pre-heating of ventilation and for snow melting of gates at the airport. Cold is stored at 2-3^{o}C and heat at 20-25^{o}C. It has been designed for a capacity of 10 MW and uses no heat pumps (Andersson 2009). This system has now been in operation for 5 years and has produced 20 GWh of heat and cold annually. The upcoming years some measures will be taken to increase the turnover of the system further (Arvidsson 2016).

Stockholm also hosts the largest ATES plant in Sweden. It was designed for short-term storage of cold and linked to the district cooling system for Stockholm city. It was taken into operation in 1998 and is run with a capacity of approximately 15 MW for peak shaving during hot summer days. The working temperature is +3/+14^{o}C and when fully charged it contains around 1 000 MWh of cold.

Recently ATES has become subject for a new research and development project (Effsys Expand). The project will be run over three years and ends in 2018. The purpose of this project is to quantify the performance and environmental impact of large-scale ATES systems, as well as give recommendations for operation and how to estimate the environmental footprint of future systems (KTH 2016).

4.2 BTES

BTES systems consist of several closely spaced boreholes, normally 150-250 m deep, serving as heat exchangers to the underground. In Sweden the boreholes are typically groundwater-filled and fitted with a closed loop of single or double plastic U-pipe. The heat transfer between the heat carrier and the underground is mainly conductive and the temperature change in the rock reaches only a few meters around each borehole. The temperature in the ground storage typically ranges between +2^{o}C in the winter and +8^{o}C in the summer.

Figure 7 shows how the numbers of drilled boreholes for BTES systems and vertical GSHP systems have changed over the last 15 years. The figures for 2015, and to some degree also 2014, are incomplete due to delay in reporting to the well database. The average depth of drilled boreholes has increased significantly over the years. This is partly due to development in drilling equipment, but also a result of increased COP in newer heat pumps (which means they are using more energy from the ground and consequently requiring deeper boreholes).

Year	Drilled boreholes	Average depth (m)	Drilled meters (m)
2000	7351	127.8	932126
2001	9642	127.1	1216926
2002	15759	130.1	2007659
2003	18551	137.9	2513099
2004	22820	141.1	3164312
2005	25112	146.5	3619777
2006	27805	151.0	4148283
2007	21203	158.4	3326101
2008	17136	162.1	2759932
2009	18224	160.3	2905875
2010	20674	161.9	3337983
2011	23231	170.2	4132804
2012	17749	171.5	3185764
2013	13536	172.6	3211709
2014	18015	177.2	3192206
2015*	14391	176.6	2541348

Figure 7: Reported boreholes from SGU Database *(*Data for 2015 is incomplete due to delay in reporting.)*

Sweden was one of the earliest countries to test and develop BTES systems in the 1970's and 1980's, and a number of pilot plants were built (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 systems with more than 1 000 borehole meters is 2887, and there are 1287 systems reported with 10 boreholes or more (SGU 2016). A large portion of these are applied for heating and cooling of commercial and institutional buildings. However, some of these systems are used for space heating only (commonly larger residential buildings) and there is no information available on the distribution of each type of application. For the time being an estimate of 650 systems with more than 10 boreholes are true BTES application, while the rest are applied for heating only in the residential sector.

The rate of growth for large GSHP and BTES systems is currently 10-12% per annum. During the last decade, around 30 systems with 20 boreholes or more have been registered per annum (see Figures 8 and 9).

Year	Units 1-2 bh	Units 3-5 bh	Units 6-10 bh	Units 11-19 bh	Units ≥20 bh
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	63	32
2013	13012	389	130	45	35
2014	11968	408	169	52	32
2015*	10209	278	115	35	26

Figure 8: Number of new BTES systems of various size reported in SGU Database. ***(*Data for 2015 is inclomplete due to delay in reporting.)***

The system capacities are typically ranging between 50-500 kW with a SPF of 4.5-5.5. The size of the systems tends to increase and include an increasing number of boreholes and deeper boreholes (Andersson et al. 2013).

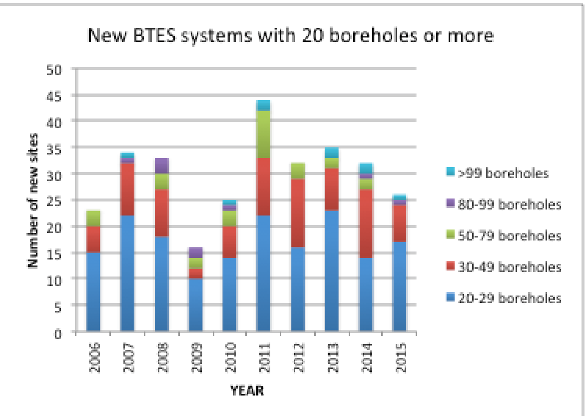

Figure 9: New large plants dominated by BTES 2006-2015 registered in the SGU Well Database (SGU 2016). (Note that the registered number of BTES plants for 2015 is not complete).

The largest BTES system in Sweden is currently the BTES system at Karlstad University Campus, with 204 boreholes to a depth of 240-250 m, giving a total borehole length of 28 240 m (Svensk Geoenergi 2014). The system was taken into operation in 2015.

By the end of 2015 there were more than 50 BTES systems in Sweden with a total borehole length of 10 000 m or more according to SGU statistics (2016). However, an ongoing mapping of large systems shows that this number is underestimated. A more realistic figure would be in the order of 80-90 plants.

There are currently two high temperature BTES systems in operation in Sweden. The Anneberg high-temperature BTES is used for seasonal solar heat storage for residential heating without heat pumps and had a measured solar fraction of 40% after 12 years in operation (Heier 2013). The Emmaboda Xylem high temperature BTES plant is used for seasonal storage of industrial waste heat (Andersson & Rydell 2012, Nordell et al. 2016). The first high temperature BTES plant in Sweden, The Lulevärme project (Nordell 1994) is no longer in operation. It stored industrial waste heat from a steel industry to be used for space heating of a university building in wintertime. It was in operation during 1981-1989.

Only 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 chilling a generator during the summer season. The cooling capacity is 800 kW (Rozenberg 2010).

The Swedish construction company Skanska has recently patented a special BTES concept called “Deep Green Cooling.” It provides office cooling in the summer and pre-heating of in-coming air in the winter without the use of heat pumps, and operates at temperatures close to undisturbed ground temperature. Free-cooling with outdoor air is used in combination with the BTES system, and additional winter heating demand is provided from the district heating network. Skanska’s headquarter office building, Entré Lindhagen, in Stockholm (Skanska 2014) equipped with this BTES concept, and uses supplementary heating from the Stockholm district-heating network.

The Swedish cooperative association for housing in Sweden, HSB, has recently developed a BTES concept with pre-heating of ventilation air using boreholes and no heat pumps. The idea is to limit the need for heating capacity by eliminating the need for de-frosting of the air-conditioning. This is done by pre-heating of incoming air for ventilation by the low-temperature heat source in the ground (Kempe and Jonsson 2015).

Energy piles, used for heat or cold extraction through the building foundation, have so far not been used in Sweden. However in recent year there is an increasing interest for this possibility and we are likely to see examples of energy piles in parts of Sweden within a few years.

4.3 Future trends

While the market for GSHPs for small residential buildings is becoming saturated, the market for larger GSHPs and UTES is growing. The systems tend to be made larger and with deeper boreholes. The number of systems with 6 boreholes or more increases with 10-15% per annum. There is also a budding new interest in geothermal energy solutions for new markets such as infrastructural applications. There is a new research pilot project carried out at Chalmers University in cooperation with the Swedish Transport Administration, developing UTES for keeping roads, bridges and biking paths free from ice. There is some interest in developing geothermal solutions for de-icing of railway switches, platforms and airport gates.

Another recent trend is a renewed interest for UTES applications in district-heating networks. Areas of interest include UTES for buffering and peak shaving, large CTES for high-temperature storage, cold networks with distributed heat pumps, and so-called energy clusters where several buildings with different heating and cooling loads are connected to a common UTES system.

Research related to geothermal energy is currently being carried out at several academic institutions, and the Swedish Energy Agency has recently expanded its research program on heat pumps to include energy storage,

Since the foundation of the Swedish Center for Geoenergy in 2013, the platform for communication and promotion of geothermal energy has been significantly enhanced. The center is currently involved in working out a strategic innovation agenda for geothermal energy in Sweden. A similar initiative is also going on for heat pumps and energy storage.

5. CONCLUSIONS

Sweden is a world leading country in shallow geothermal energy utilisation (Lund et al 2015), and geothermal energy has a general goodwill among the public as an environmentally friendly and economically feasible technology. The market is dominated by shallow geothermal systems, and in particular GSHP systems with vertical boreholes in hard rock. The potential for deep geothermal energy exploitation is Sweden is limited and only on plant is in operation.

The market for small GSHP systems has stabilised during the last years, but there is a steady market growth for larger systems for residential buildings as well as for larger ATES and BTES systems in the commercial and institutional sector. Systems for BTES tend to be designed with increasing size, deeper boreholes and higher capacities, and new applications are investigated.

REFERENCES

Andersson, O. Sellberg, B.: Swedish ATES Applications. Experiences after Ten Years of Development. 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), p 669-678.

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.: Verbal communication, March 2016. (2016).

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).

Bjelm, L.: Under Balanced Drilling and Possible Well Bore Damage in Low Temperature Geothermal Environments. Proceedings, Thirty-First Conf. On Geothermal Reservoir Engineering. Stanford University, Stanford, California, (2006).

Bjelm, L. and Rosberg, J-E.: Recent Geothermal Exploration for Deep Seated Sources in Sweden. Engineering Geology, Lund University, Sweden. *Geothermal Resources Council Transactions*, Vol. 30, San Diego. (2006)

Climatedata.eu: www.climatedata.eu. (2014).

Gehlin.S. Chapter 11: Borehole Thermal Energy Storage. In S.J. Rees, Advances in ground-source heat pump systems. London: Woodhead Publishing. (2016). *In press.*

Heier, J. Energy Efficiency through Thermal Energy Storage: Possibilities for the Swedish Building

Stock. Licentiate Thesis, The Royal Institute of Technology, Stockholm, Sweden. (2013).

Henkel, H., Bäckström, A., Bergman, B., Stephansson, O. and Lindström, M.: Geothermal Energy from Impact Craters? The Björkö Study, *Proceedings*, World Geothermal Congress 2005, Turkey, 5pp. (2005)

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

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

KTH; https://www.kth.se/en/itm/inst/energiteknik/forskning/ett/projekt/energibrunnar/ates/beskrivning-1.627294 . March 2016. (2016).

Kraftringen: Hållbarhetsredovisning. (2014).

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.

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).

SGU: The Swedish Geological Survey Well Database, February 2016. (2016).

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

SMHI: www.smhi.se/kunskapsbanken/meteorologi. March 2016. (2016).

Svensk Geoenergi, No. 1/2014, page 12. www.geoenergicentrum.se. (2014).

Swedish Energy Agency: Energistatistik för småhus, flerbostadshus och lokaler 2014. Summary of energy statistics for dwellings and non-residential premises for 2014. ES 2015:07. (2015). (In Swedish).

Trad, S. The Swedish District Heating Association. Personal communication (2014).

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

There is no existing or planned geothermal power production in Sweden.

Table B: Existing geothermal power plants, individual sites

There is no geothermal power production in Sweden.

Explanation to tables C, D1 and D2: 'Geothermal district heating or district cooling' (Geothermal DH plants) is defined as the use of one or more production fields as sources of heat to supply thermal energy through a network to multiple buildings or sites, for the use of space or process heating or cooling, including associated domestic hot water supply. If greenhouses, spas or any other category is among the consumers supplied from such network, it should be counted as district heating and not within the category of the individual consumer. In case heat pumps are applied in any part of such a network, the also should be reported as district heating and not as geothermal heat pumps. An exception is for distribution networks from shallow geothermal sources supplying low-temperature water to heat pumps in individual buildings; systems of this kind should be reported in table E. For table D2, please give information on large systems only (>500 MW_{th}); installations with geothermal source temperatures <25 °C and depth <400 m should be reported in table E.

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

	Geothermal DH plants		Geothermal heat in agriculture and industry		Geothermal heat for individual 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 2015	48	140	0	0	0	0	0	0
Under constru-ction end 2015	0	0	0	0	0	0	0	0
Total projected by 2018	48	140	0	0	0	0	0	0
Total expected by 2020	48	140	0	0	0	0	0	0

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})	2015 produc-tion (GWh_{th}/y)	Geoth. share in total prod. (%)
Lund	Kraftringen	1984	-	-	48	n.a	140	15%
total					48	n.a	140	15%

Table D2: Existing geothermal direct use other than DH, individual sites

There is currently no geothermal direct use of this kind in Sweden.

Explanation to tables E1 and E2: 'Shallow geothermal' installations are considered as not exceeding a depth of 400 m and (natural) geothermal source temperatures of 25 °C. Installations with geothermal source temperatures >25 °C and depth >400 m should be reported in table D1 or D2, respectively. Distribution networks from shallow geothermal sources supplying low-temperature water to heat pumps in individual buildings are not considered geothermal DH *sensu strictu*, and should be reported in table E also.

Table E1: Shallow geothermal energy, ground source heat pumps (GSHP)

	Geothermal Heat Pumps (GSHP), total			New (additional) GSHP in 2015		
	Number	Capacity (MW_{th})	Production* (GWh_{th}/yr)	Number	Capacity (MW_{th})	Share in new constr. (%)
In operation end of 2015	540 000	5 800	20 100	22 000	287	n.a
Projected total by 2018	600 000	6 500	22 750			

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

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 2015	160	H:300 C:320	H:1050 C:600	650	H:195 C: 220	H:680 C:340
New (additional) in 2016	10	H:18 C:18	H:20 C:20	35	H:14 C:10	H:50 C:30
Projected total by 2018	190	H:350 C:370	H:1100 C:660	750	H:240 C:280	H:830 C:430

*Excluding electricity

Table F: Investment and Employment in geothermal energy

	in 2015		Expected in 2018	
	Expenditures ** (million €)	Personnel *** (number)	Expenditures ** (million €)	Personnel *** (number)
Geothermal electric power	none	none	none	none
Geothermal direct uses	none	none	none	none
Shallow geothermal	3000	10 000	3000	10 000
total	3000	10 000	3000	10 000

** 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 el. power	Geothermal direct uses	Shallow geothermal
Financial Incentives – R&D	None	None	Occasional demonstration projects partly financed by the Swedish Energy Agency.
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 (Svenskt Geoenergicentrum) arranges courses, conferences/workshops, seminars, information activities, and issues the journal Svensk Geoenergi (Swedish Geoenergy).
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 a 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)