Ground-Source Heat Pumps and Underground Thermal Energy Storage—Energy for the future

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We need energy for space heating—but in most cases not where or when energy sources are available. Energy storage, which helps match energy supply and demand, has been practised for centuries, also in Norway. Energy storage systems will increase the potential of utilising renewable energy sources such as geothermal energy, solar heat and waste heat. The most frequently-used storage technology for heat and 'coolth' is Underground Thermal Energy Storage (UTES). The ground has proved to be an ideal medium for storing heat and cold in large quantities and over several seasons or years. UTES systems in the Nordic countries are mostly used in combination with Ground-Source Heat Pumps (GSHP). Several different UTES systems have been developed and tested. Two types of system, Aquifer (ATES) and Borehole (BTES) storage, have had a general commercial breakthrough in the last decades in the Nordic countries. Today, about 15,000 GSHP systems exist in Norway extracting about 1.5 TWh heat from the ground. About 280 of the Norwegian GSHP installations are medium- to large-scale systems (> 50 kW) for commercial/ public buildings and for multi-family dwellings. The two largest closed-loop GSHP systems in Europe, using boreholes as ground heat exchangers, are located in Norway.

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Introduction

We, especially here in chilly Norway, need energy for space heating, but, regrettably, most natural heat sources such as the sun, the air, and rivers are at their coldest when we most need their heat—in winter. Similarly, environmental heat sinks, e.g., the air and shallow surface waters, are at their warmest when we have most need for cooling. The use of rocks, sediments and groundwater in the subsurface as a huge Underground Thermal Energy Storage (UTES) system allows us to store surplus heat (regardless of whether it is solar in origin, radiogenic (geothermal), or simply waste summer heat from buildings) until a time when it is needed. In other words, the ground can be manipulated as a heat store; it can preserve summer heat until winter and winter cold until summer, allowing us to match supply and demand over at least a yearly cycle. The Ground-Source Heat Pump (GSHP) is the tool that we use to 'pump' surplus heat into the ground and to extract heat when we require it for space heating.

More than 80% of the world's current energy resources are stored, in some form, in the subsurface (IEA 2007). Over millions of years of geological time, the geosphere has stored solar energy in the form of chemical potential energy (coal, oil, gas), and is also slowly releasing nuclear potential energy via decay of radionuclides (which manifests itself as a geothermal heat flux of several tens of mW m^{-2}). It is widely believed that the continuation of our modern, industrialised way of life will exhaust available oil and gas resources within a period of two centuries (Hahne and Benner 2000). Coal and oil-shale resources offer some potential to replace these, but with a world energy consumption that has increased 20-fold over the last century (Domanski 2003) and is increasing by 2.1% yearly (IEA 2006), these resources may also be regarded as finite over a similar time scale. Intriguingly, however, the amount of energy stored as carbon-based 'fossil fuel' is negligible compared to the amount of heat that is stored in the Earth.

The Earth's total heat content is estimated to be about 10^{31} J and the current average global terrestrial heat-flux rate is 44 TW (1.4×10^{21} J yr^{-1}, Dickson and Fanelli 2004). Divided by the Earth's surface area of 5×10^{14} m^2, this results in an average geothermal heat flux of 88 mW m^{-2}. This flux of 1.4×10^{21} J yr^{-1} is almost three times the world's primary energy-consumption rate (4.8×10^{20} J yr^{-1} in 2005, Bromley and Mongillo 2008).

It is not solely this geothermal heat flux that provides a potential alternative heat resource for mankind, however. The surficial portion of the crust is also able to absorb and store solar and atmospheric heat, acting effectively as a huge solar collector.

Ground-Source Heat Pumps (GSHP)

One might imagine, given the relatively low geothermal heat flux of 88 mW m^{-2}, that the practical use of geothermal energy is restricted to a few geologically anomalous areas with a very high heat flux (e.g., plate boundaries and volcanic areas). Fortunately, this is not the case. There exists a tool that enables us to extract low-temperature heat (at 'normal' Norwegian temperatures of 6–7°C) from the Earth's subsurface store, to 'concentrate' that heat by compression, and to deliver it as space heating at a higher temperature. This tool is termed the Ground-Source Heat Pump (GSHP). It is based on the fluid compression–expansion cycle, well known from modern refrigerators, first proposed by Oliver Evans in 1805, and constructed by Jacob Perkins and John Hague around 1834 (see references in Banks 2008). It was, however, Lord Kelvin who first proposed using this cycle to artificially heat buildings (Thomson 1852), although his concept was based on using the heat pump to extract heat from outdoor air, rather than the ground.

The idea of using a heat pump to extract heat from the ground was patented by the Swiss Heinrich Zoelly in 1912 (Ball et al. 1983, Spitler 2005, Kelley 2006), and was being used (with rivers and groundwater from wells as a heat source) by the 1930s in America and Switzerland. The 'closed-loop' heat pump, where a carrier fluid or refrigerant is circulated through a loop of pipe in the subsurface to extract heat from rocks and sediments, was first constructed in 1945 by Robert C. Webber in Indianapolis, USA (IGSHPA 2006). He seems to have been inspired by his deep freeze, placing the condenser in his living room and an evaporator in a hole in the ground! It seems that the concept first arrived in Norway when Roger Jansen (Figure 1), Fredrikstad, and Per Stykket, Sørumsand, each installed 10–12 kW horizontal closed-loop systems in 1978 (see below).

Although the USA has over 50% of the current GSHP capacity installed worldwide today, the Scandinavian nations have amongst the highest numbers of GSHP systems per inhabitant. According to a global update given at the World Geothermal Congress in 2005, Sweden and Iceland are among the 'top five' nations for direct use of geothermal energy, while Denmark and Norway have experienced the largest increase in utilisation of ground-source heat during the past five years

Figure 1. Norway's first brochure for a ground-source heat pump from Normann Energiteknikk AS (today Normann Etek AS). It included an interview with Roger Jansen, one of the first people to install a GSHP in Norway. The picture to the right shows Roger Jansen and the heat pump 27 years later. The heat pump still works.

(Lund et al. 2005). The total heat delivered by Norway's GSHP installations is estimated to be 2.1 TWh per year. In Sweden, GSHP systems have become increasingly popular during the past four decades, and are now one of the most common heating systems, satisfying more than 15% (15 TWh) of the nation's total space-heating demand. Several hundred larger UTES systems have been constructed and are currently in operation (Gehlin and Nordell 2006).

Ground-source heat pumps are now one of the fastest growing applications of renewable energy in the world, with annual increases of 10% in about thirty countries over the past ten years (Curtis et al. 2005). According to a Canadian study (Caneta Research 1999), GSHP systems potentially have a larger mitigating effect on greenhouse-gas emissions, and the resulting global-warming impact of buildings, than any other single technology available today.

Ground-source heat pumps in Norway

The first known GSHP systems in Norway were installed in 1978. Per Stykket in Sørumsand installed a heat pump with 500 m of shallowly-buried (0.8 m deep) horizontal pipe as a ground heat exchanger. The pipes were produced and installed by Kjell Nyen, and the heat pump was imported from Sweden. Another GSHP system with horizontal pipes as the ground heat exchanger was installed by Einar Grønnevik for Roger Jansen's house in Fredrikstad in the same year, and is still in operation.

Jens Sagen, a factory owner in Kristiansand, read about ground-source heat in the early 1980s. He contacted a consultant and they travelled together to Sweden to investigate this new 'alternative' energy technology (which had already gained considerable acceptance in Sweden). On their return, they constructed a 50 kW GSHP installation at Jens Sagen AS manufacturing company, based on heat extraction via six 115 m-deep closed-loop boreholes. This was commissioned in 1985. A high groundwater flow through the borehole array is claimed to have been significant in ensuring the system's sustainability (transporting heat by advection with groundwater flow to the collector loops in the boreholes) and maintaining an acceptable temperature in the collector fluid.

Today, there are about 15,000 GSHP installations in Norway (Midttømme 2005). Statistics from NOVAP, the Norwegian heat-pump association, show a clear trend of increasing sales from 1992 to 2006 (Figure 2). Sales of air-sourced heat pumps (which have a lower capital cost, but which are somewhat less efficient than GSHP systems) are even more impressive—indeed, they accounted for around 95% of all heat-pump sales in Norway in the most recent years (Figure 3). The Norwegian state provided subsidies for all types of heat pump in 2003,

Figure 2. The sale of brine/water heat pumps (mainly GSHPs) in Norway in 1992–2006. Data from NOVAP, the Norwegian heat-pump association.

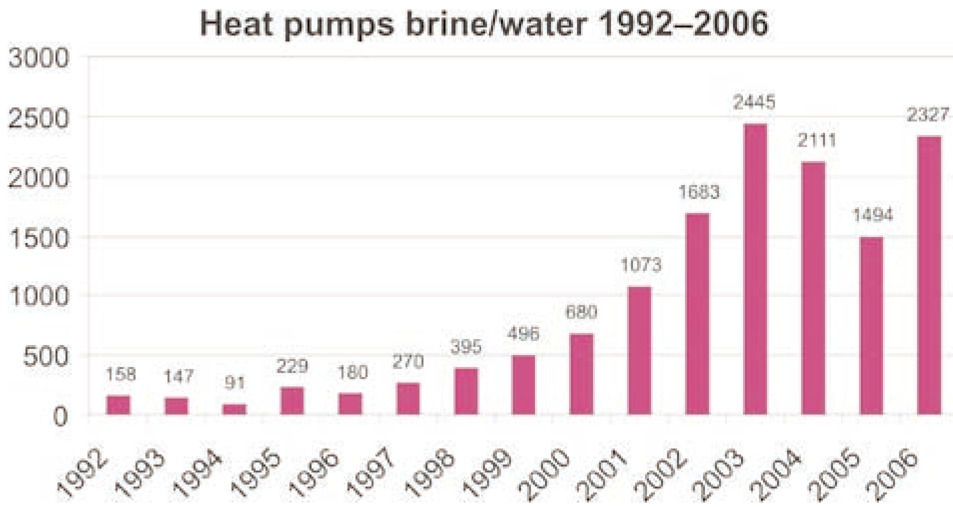
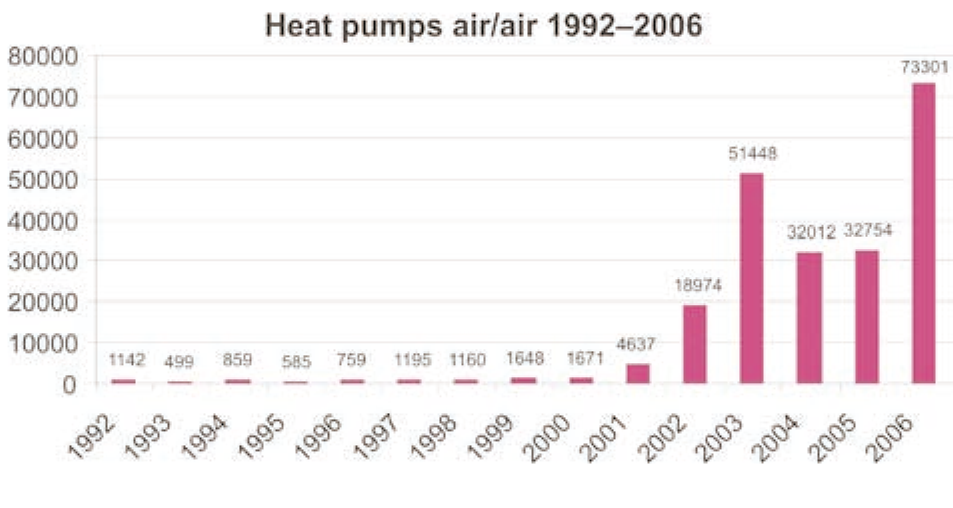


Figure 3. The sale of air/air heat pumps in Norway in 1992–2006. Data from NOVAP.



but only for ground-source heat pumps in 2006–2007, and the availability of these subsidies had a clear impact in terms of increased sales.

About 280 of the Norwegian GSHP installations are medium- to large-scale systems (heating power > 50 kW), for commercial/public buildings and for multi-family dwellings. The two largest closed-loop GSHP systems in Europe, using boreholes as ground heat exchangers, are located in Norway, at Nydalen Næringspark (Business Park) in Oslo and Akershus University Hospital in Lørenskog.

Underground Thermal Energy Storage (UTES) systems

The ground can, of course, be used not only as a heat source, but also as a heat sink for 'waste' heat. Thus, the ground can be used to provide either heating or cooling. Optimally, it can be used to provide a balanced combination of both heating and cooling, with surplus summer heat being stored in the ground for subsequent extraction in winter. Increasingly, larger buildings require some form of active cooling, even in the Nordic climate. In the summer, therefore, a heat pump can be designed to circulate a chilled fluid around a building. This chilled fluid effectively extracts heat from the building, which the heat pump transfers (via a ground heat exchanger) to the ground or to groundwater. In the winter, the direction of the heat pump is reversed, so that heat is extracted from the ground/groundwater and transferred to a warm space-heating fluid. The ground has now effectively become an Underground Thermal Energy Storage (UTES) system.

The concept of environmental thermal storage can be dated back to ancient civilizations. Harvesting of ice and snow from the mountains, and subsequent underground 'cold storage' during the spring and summer, is known from 350 years ago in Persia (Iran). Norway's 'ice-entrepreneurs' (such as Johan Martin Dahll from Kragerø) (Figure 4) have even, during the last half of the 19th and early 20th century, exported Norwegian ice by ship to London to be stored underground in 'ice wells' along the Regent's Canal (Banks 2008). The modern use of UTES applications commenced in China in the 1960s, where groundwater was initially extracted in large quantities to provide industrial cooling. Such excessive extraction resulted in land subsidence, however. To rectify this situation, cold surface water was artificially injected into the aquifers and it was observed that the injected water maintained its cool temperature for a long period, making it an ideal source of industrial cooling (Morofsky 2007).

Several variants of UTES can be envisaged, although the two types that have been developed, tested and commercially operated in Norway are:

- Borehole Thermal Energy Storage (BTES), where no fluid is physically exchanged with the ground, but where the volumetric heat capacity of the rock alone is used to store heat.
- Aquifer Thermal Energy Storage (ATES), where heat transfer and storage is by warm or cold groundwater.

Borehole Thermal Energy Storage (BTES)

Sentermenigheten in Asker installed one of the first BTES schemes in Norway. Much of the installation work was performed by enthusiastic volunteers and, since the year 2000, the resulting BTES array of thirteen 130 m-deep boreholes has provided heating and cooling to the assembly building.

A new BTES system has recently been completed at Falstadsenteret, a 2850 m^2 historical museum in Levanger (Figure 5a). The heating and cooling scheme comprises a 130 kW heat pump (Figure 5b) and nine 180 m-deep closed-loop

Figure 4. Ice production from Nesodden. Ice from Norway was exported to Europe in the 1800s and early 1900s. Photo: courtesy of Nesodden Historielag, Nesoddens Historie, Bind 2.

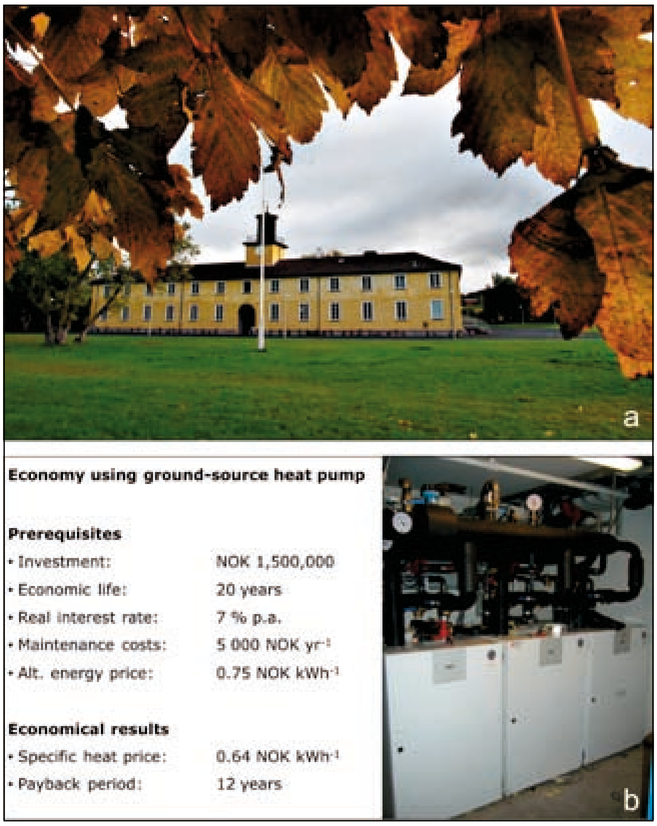


Figure 5. (a) Falstadsenteret, a 2850 m^2 historical museum in Levanger. Photo: Kjell A. Olsen, Adresseavisen. (b) The Falstadsenteret heat pump and economic considerations.

boreholes. The payback time for the extra capital costs of the ground-source system, compared to a conventional heating and cooling system, is estimated to be 12 years.

A BTES system comprising 220 boreholes of 200 m depth, drilled into dioritic rocks, will provide heating and cooling to the new Akershus University hospital. The hospital is under construction and will be fully operational in October 2008 (Stene et al. 2008). The BTES system became operational in May 2007, but a second phase of drilling is planned to provide an extension of the BTES scheme (making a total of up to 350 boreholes). It was originally planned to drill the boreholes close to the hospital, but seismic geophysical surveys and trial borings showed a high density of clay-filled fracture zones. This observation suggested that full-scale drilling would be difficult and expensive. The proposed BTES borehole array was thus relocated to a field about 300 m from the hospital. After drilling, the borehole heads will be completely underground and the farmer will continue to use the field to grow crops.

Aquifer Thermal Energy Storage (ATES)

In 1987, the first known ATES system in Norway was established in Seljord. A 10 m-deep well was drilled for heating and cooling of Seljord lysfabrikk (Dyrud 2008).

The largest UTES system in Norway is at Oslo's Gardermoen international airport. This ATES system has been in operation since the airport opened in 1998 and comprises an 8 MW heat-pump array, coupled to 18 wells of 45 m depth, 9 for extraction of groundwater and 9 for re-injection. The wells are sunk into the Øvre Romerike glaciofluvial sand and gravel aquifer. This system covers the total cooling needs of the airport, of which 25% (2.8 GWh yr^{-1}) is free cooling via direct heat exchange with cold groundwater, and 75% (8.5 GWh yr^{-1}) is active cooling via the use of the heat pumps. The annual heating provision is typically 11 GWh. There have been some problems with clogging of the groundwater loop, and the groundwater wells and heat exchangers require cleaning every few years. Because of a lack of knowledge of ATES systems in Norway, Dutch consultancies were hired to design the ATES system and GSHP installations. The total cost of the system was 17 million NOK and the payback time, compared to traditional heating and cooling systems, is estimated to be less than four years (Eggen and Vangsnes 2005).

Oslo Centre for Interdisciplinary Environmental and Social Research, a component of the Oslo Innovation Centre in Oslo, is a 13,500 m^2 office building with laboratories (Stene et al. 2008). An ATES system, extracting groundwater from the underlying limestone and shale rock, provides both heating and cooling to the building. A closed-loop BTES system was originally intended for the site, but extremely difficult ground conditions were encountered during initial drilling: namely, zones of remarkably high groundwater flow associated with a Permian syenite dyke structure several metres thick. It became clear that it would be both more feasible and cheaper to drill a small number of groundwater wells (using the dyke as an aquifer) than a large number of closed-loop boreholes. Thus, a total of nine wells were drilled. These wells are typically located in extraction–injection pairs, one well drilled to 100 m depth and the second to 100–200 m depth. Using this arrangement, it is possible to access enough groundwater and rock volume to cover the seasonal cooling and heating demands of the building (Stene et al. 2008).

Conclusions

The idea of storing the Earth's natural heat or cold over the passage of several seasons has been practised in many countries for centuries. Norway even successfully exported its natural thermal resource (in the form of winter ice) to England during the late 19th and early 20th century. The concept of the heat pump is not new. It was invented 170 years ago and was first proposed for space heating of buildings some 150 years ago. Efficient GSHP technology has been utilised in Sweden for almost four decades and is now accepted as mainstream. Many other European nations (including both Norway and Great Britain), have been slow in taking up this technology due to a combination of factors, including cheap conventional energy (hydroelectric in Norway, coal and gas in the UK), lack of political will, and lack of awareness of the need to consider the impact of space heating on the national CO_2 budget.

The theoretical framework for describing the flow and storage of heat in the ground is well known—much of it is based on the pioneering work of Horatio Scott Carslaw (Carslaw and Jaeger 1947). It transpires that the fundamental physics describing heat conduction in the ground is directly analogous to that used by hydrogeologists to describe groundwater flow (indeed, modern groundwater-flow theory is directly derived from heat-flow theory, Bredehoeft 2008).

GSHP and UTES can, of course, be seen as 'just another' alternative energy technology. It is probably more correct to regard them as complementary technologies, however. They are a means of utilising Norway's limited resources of hydroelectricity 300% more efficiently than would a conventional panel heater. Alternatively, they can be regarded as a means of avoiding future increased CO_2 emission from fossil fuels. They can also be coupled with other low-CO_2 energy technologies (wind turbines, solar thermal panels) to deliver integrated energy solutions. Unlike wind power and solar cells, however, ground-source heat is not vulnerable to the vagaries of the climate; the ground offers a huge thermal store that can bank heat energy in times of surplus and be drawn upon in times of need. It allows us to match heating and cooling demand with natural resources over a protracted period.

We would never think of producing our drinking water by burning hydrocarbons e.g., methane gas:

$$CH_4 + 2O_2 \rightarrow \mathbf{2H_2O} + \text{heat} + CO_2$$

The hydrogeologist knows that we have abundant natural reserves of groundwater to draw upon. All we need to access them is a hole in the ground (a well) and a pump. In contrast, many nations have generated *heat* by burning fossil carbon:

$$CH_4 + 2O_2 \rightarrow 2H2O + \textbf{heat} + CO_2$$

even though we have abundant reserves of low-temperature ground-source heat in the rocks, sediments and groundwater beneath our feet. All we need to access this heat is a hole in the ground (a borehole or trench) and a heat pump! Why generate heat by burning fossil fuels, when we can use that energy many times more efficiently simply to pump natural ground-source heat into our homes?

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