Preliminary evaluation of the Estonian geoenergy potential and overview of available technologies, expert opinion for using those technologies in the Estonian geological conditions, suggestions for possible further actions and examples of case studies.

Pekka A. Nurmi, PhD, Prof.

Penurco Oy

geoenergyeurope.com

Tallinn 5 May 2021

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Executive summary

The deep decarbonisation of electricity, transport, industry, and buildings is an environmental imperative for Europe. The Estonian government has decided to develop an action plan to achieve climate neutrality by 2050 and make it as a national objective. This will include continued support for energy-efficient buildings, and the use of renewable energy in households. In addition to wind, bio, and solar energy, geoenergy (or geothermal energy) offers a potential sustainable energy source for heating, cooling, and energy storage. Heat pumps are needed to retrieve energy from the rather low temperature geoenergy sources prevailing in northern Europe. There has been fast development in various geoenergy applications and techniques, e.g., in the Nordic countries and wider in the EU, but large-scale systems have not yet been built in Estonia.

Geoenergy systems may require rather high investments but can produce low-cost energy 24/7 all year-round sustainably over decades. About two thirds of the total energy comes “free” from the ground or water, and the rest from electricity needed for the heat pumps. Provided that electricity used for heat pumps is produced in a sustainable way, the overall carbon footprint will be exceedingly small. Central heating energy prices have shown increasing trends in many countries over the last several years, which has improved the competitiveness of geoenergy. Geoenergy is local energy, which cannot be transported more than a few kilometres, and therefore the plants should be built adjacent to the users. Geology has considerable impact on local geoenergy potential in a kilometre scale.

Geoenergy refers to energy that is stored in bedrock, soil, groundwater, or surface water, and can be used for energy recovery. Shallow heat in the subsurface derives from the Sun, whereas heat in deeper bedrock has been formed within the Earth and steadily increases with depth.

Geology of the Estonian crystalline basement particularly in the northern part of the country is similar as the exposed Precambrian bedrock in southern Finland. Information on the Estonian Precambrian is rather sporadic and based only on widely spaced drill holes and regional geophysical studies. Therefore, distribution on different rock types, and their thermogeological and structural features are not known in detail. The major geological difference is the younger sedimentary rock sequence overlying the Precambrian bedrock in Estonia. It has a thickness of about 100 m in the north gradually thickening towards south where it exceeds 700 m at the deepest. Therefore, geoenergy applications dependent on wells in the heat producing basement rocks would be most cost effectively applicable in northern Estonia.

Geoenergy potential in northern Estonia can be considered reasonably good for practical geoenergy applications. Thermogeological properties are better or at least as good as in southern Finland, where numerous economically feasible plants operate. So called ”blanketing effect” of the 150 to 200 m thick insulating sedimentary rock sequence has caused accumulation of temperature in the upper crystalline basement and lower sedimentary aquifers at least in northern Estonia, which increases the feasibility of geoenergy applications. On the other hand, geoenergy wells need to be drilled deeper through the sedimentary rocks increasing the drilling costs.

Anomalously high temperatures occur in a large area in NE Estonia, but its true extend is not known because of sparse data. This area exhibits the best geoenergy potential known so far in Estonia. Temperatures tend to be 4 to 6°C higher than in other parts of northern Estonia at respective depths.

Rapakivi granites are enriched in radioactive heat producing elements and generally have distinctly higher heat flow values than gneissic bedrock and thus increased geoenergy potential. Rapakivi granites occur, e.g., in west Tallinn and Maardu, but their exact location and composition would need more detailed evaluation.

Geoenergy potential of central and southern Estonia appears to be poorer than in the northern part of the country, although it cannot be defined in detail. Much thicker sedimentary rock formations would increase drilling costs. Bedrock temperatures tend to be somewhat lower than in the north. Groundwater energy might be an option for southern Estonia, but this would need additional studies of water conductivity and temperature of the deep aquifers.

Based on the geological and thermogeological studies, and experience on geoenergy plants and projects in neighbouring countries, particularly in southern Finland, geoenergy is considered a relevant additional energy source for heating, cooling, and seasonal energy storage in Estonia. It would give more flexibility for the smart optimization of the energy networks and decrease burning of fossil and biofuels and diversify the heating and cooling energy systems towards zero emissions. However, geoenergy would need detailed geoscientific and feasibility studies case by case, and rather big initial investments are needed to build the plants. These should be located adjacent to buildings which will use geoenergy or existing district heating/cooling networks.

Five types of geoenergy applications are considered potentially applicable in Estonian conditions. Bore hole energy wells or well fields (400 to 2000 m deep) could be used for local heating, cooling, and energy storage, as well as groundwater pumped from deep sedimentary rock aquifers. Water within old mine workings in the oil shale mining area is a potential source for local geoenergy applications. Seawater is an endless source for large scale energy production and the Tallinn bay has deep water depths near the shore, which would ensure sufficiently warm water all year round. Underground energy storage is an option to balancing large energy systems but would need building of underground caves. All applications require site specific geoscientific, technical, scoping and feasibility studies to ensure sustainable investments.

Thermogeological properties of the bedrock can show considerable variation even in small areas. Therefore, pilot energy wells should be bored in the locations of potential future geoenergy users to make real-world demonstrations and to show the proof of concept of various geoenergy systems. Close connections to real estate developers, energy companies, architects and regulators would be needed to market geoenergy and to find interested parties for pilot testing and possible future development. Geoenergy plants are usually integral parts of hybrid energy systems. Legal, permitting, and environmental issues should be studied, and possible problems solved to promote large-scale geoenergy building in Estonia.

Tallinn would be an important target for follow-up studies and geoenergy pilots as the populated and fast-developing area. There would evidently be markets for a new low-emission energy concept applying geoenergy in heating and cooling systems. Geoenergy could also be connected to existing buildings to lower energy costs and increase sustainability. Seawater is an option to build a new large-scale and sustainable heating application for the city.

The Narva region and northeaster Estonia in general has increased natural potential for geoenergy using bore hole or groundwater geoenergy applications, because of higher heat flow than in the rest of Estonia. Water within old mine workings could be used as an energy source in the oil shale mining region. Geoenergy could be a new solution to speed up the energy shift.

Initiation of a government supported project or larger program is suggested to demonstrate the feasibility of versatile geoenergy applications in Estonian conditions, as an integral part of the energy transformation. The project should make real-world testing and build pilot demonstration sites. This would be the way to promote geoenergy for developers and energy companies and speed up wide commissioning of large-scale geoenergy applications in Estonia. Permitting, legal and environmental issues, possibilities for public support and ways to promote public-private partnerships, as well as, geoenergy PR and promotion should be integral tasks of the program.

Suggested geoenergy applications for Estonia, sites for pilot projects and potential yield of energy plants.

Geoenergy application	Energy recovery principle	Type of energy	Potential scale of plants	Suggested locations	Geological/technical notes	Prio rity
Shallow (< 500 m) well field	Heat pumps using collectors in wells (closed system)	Heating/cooling /storage	30-50 kW per 300-400 m well	Tallinn, Narva, Maardu	Rapakivi granite, Narva thermal anomaly	1
Middle-deep (0.5 – 2 km) wells	Heat pumps using collectors in wells (closed system)	Heating/cooling /storage	0.2 – 0.7 MW per 2 km well	Tallinn, Narva	Rapakivi granite, Narva thermal anomaly	1
Groundwater geoenergy	Heat pumps using groundwater aquifers (open system)	Heating/cooling /storage	1 to 10 MW	Narva region	Deep (Vendian) sedimentary rock aquifers	1
Mine-water geoenergy	Heat pumps using water in old mine workings	Heating/cooling /storage	5 to 30 MW	Jõhvi, Kohtla-Järve, Kiviõli	Water filled old oil shale mine workings	1
Seawater energy	Heat pumps using deep seawater	Heating/cooling	100 to 200 MW	Tallinn, Viimsi, Maardu	Deep sea (>50 - 60 m) required	2
Cave energy storage	Heat pumps using water stored in manmade caves	Storage of distance heating/wind energy	Potentially large	Tallinn area	Large underground caves need to be built	2

1. Introduction

The European Union has pursued a proactive climate policy and has integrated a significant number of renewable technologies – such as solar and wind – into the established energy system. These efforts have proved successful and continuing along this pathway, increasing renewables, and improving energy efficiency would not require substantial policy shifts. But the EU now needs a much deeper energy transformation to 1) decarbonise in line with the Paris agreement; 2) seize the economic and industrial opportunities offered by this global transformation; and 3) develop an EU approach to energy competitiveness and security (Tagliapietra et al. 2019). The deep decarbonisation of electricity, transport, industry, and buildings is an environmental imperative for Europe, and a unique economic opportunity.

Estonia has been among the European Union countries that are least dependent on energy imports, which has been based on the extensive use of oil shale and increasingly also renewable fuels. The government has now decided to develop an action plan to achieve climate neutrality by 2050 and make it as a national objective. This will include continued support for energy-efficient buildings, and the use of renewable energy in households. Transition to renewable energy in manufacturing as well as in consumption will be speeded up. Further investing into fossil fuels will be finished. This means that production of oil shale power will be stopped by 2035 at the latest, and the use of oil shale in the entire energy sector by 2040 at the latest. Simultaneously the transition to renewable energy in manufacturing as well as in consumption needs to be speeded up.

In addition to wind, bio, and solar energy, geoenergy (or geothermal energy) offers a potential sustainable energy source (Fig. 1). Traditionally, geoenergy has been used in geological areas exposing high geothermal gradient, which means areas exhibiting high underground temperature near the Earth surface. However, there has been in the past few decades a rapid growth also in the utilization of low-temperature (also called low-enthalpy) geoenergy in geological regions where the underground temperature is relatively low, such as in Estonia and northern Europe. These applications are depended on the use of heat pumps and these have been vastly applied for single house heating.

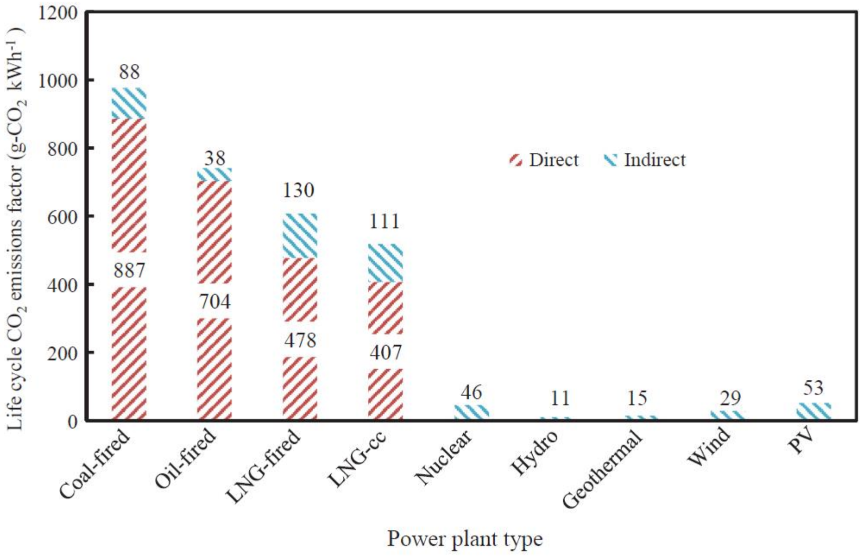


Fig. 1. Emissions of different power plant types in Japan over the course of their life cycle. Source: Hondo 2005.

Recent development in the neighbouring countries, e.g., in Finland and Sweden, has shown that geoenergy has good potential in building renewable and economically feasible heating, cooling and energy storage applications also in a bigger scale. These applications have become popular for large complexes (logistic centres, hospitals, hotels, apartment blocks etc.), and adjusting and balancing hybrid energy systems. The applications are mostly based on the use of shallow energy wells fields (<500 m), but semi-deep (500-2000 m), and deep (>3000 m) geoenergy sources in hot dry rocks or groundwater aquifers have gained increasing attention. Development of drilling and heat-pump technologies and the rise of energy price have made the progress economically viable. Furthermore, seawater is a potential source of energy, and underground caves can be used to store energy to optimize the use of existing power plants.

The seasonal performance factor (SPF) of a heat pump is usually about 3 (from 2.5 to 4), which means that approximately 2/3 of the energy comes from the Earth, free of charge. The rest is electricity required to run the pumps. Geoenergy is a renewable, sustainable, and environmentally friendly energy form, which provides continuous production of energy (24/7, 365 days of the year) unlike wind and solar energy which are strongly dependent on weather conditions and seasonal variations.

2. Scope and methods of the study

This study, ordered by the Ministry of Economic Affairs and Communications of Estonia, has five major tasks:

- Give a preliminary assessment of geothermal energy potential in Estonian energy sector.
- Overview of current technologies that are applicable in Estonian geological conditions.
- Present case studies from neighbouring countries, such as in Finland.
- Suggest possible future actions.
- Suggest possible pilots.

The study was made between January and May in 2021. It is mainly based on scientific publications, reports, and Web sites of various organisations and companies, and data made available, particularly, by the Geological Survey of Estonia. For the case studies, also mass media articles, company presentations, and promotion material have been used where deemed relevant. All sources are referred to. In addition to written sources numerous people in academia, research institutes and in the business sector have been interviewed.

This report is a preliminary overview on the topic and all the recommendations should be verified in more detail before any further actions.

3. General overview of geoenergy

The term geoenergy (instead of geothermal energy) is commonly used in the Nordic countries and is also used here. It refers to any heat derived from the ground, from depths of a few metres to multiple kilometres beneath the Earth’s surface. Geoenergy is energy that is stored in soil, bedrock, groundwater, sediment layers, or lake, river, or sea water, and can be used for energy recovery.

Most of shallow geoenergy in the subsurface down to the depth of a couple hundred metres is largely derived from solar radiation that is absorbed by the ground or surface waters. The heat of the Earth increases steadily with depth, a phenomenon described as the geothermal gradient. This heat is partly the primordial heat from the time when the Earth was formed over 4 billion years ago, and partly heat generated from within the Earth's crust from the decay of radioactive elements, which occur small amounts in rocks. This upward heat flow in the Earth crust varies a lot across the globe but commonly heat increases towards the depth by about 20 °C/km in continental areas (Figs. 2 and 3).

Geothermal heat flow is the amount of heat flowing outward from the interior of the Earth as measured at different points near the surface. Heat flow is commonly referred as heat flow density, which is a flow of energy per unit of area, and its units are watts per square metre (W/m^2). Radiogenic heat production of rocks, caused by radioactive decay, is expressed as watts per cubic meter (W/m^3). Depending on the rock type, uranium contributes 30-70%, thorium 20-50% and potassium 5-20% of radiogenic heat production. Heat-flow density is not constant over large areas but shows considerable variation even in a kilometre scale. Regional variations are due to thickness, composition and structure of the crust and deeper parts of the Earth, whereas local variations are notably related to radiogenic heat production properties and structure of rocks and groundwater conditions in the upper part of the crust. Therefore, detailed thermogeological studies are needed to define geoenergy potential of any area for possible geoenergy application.

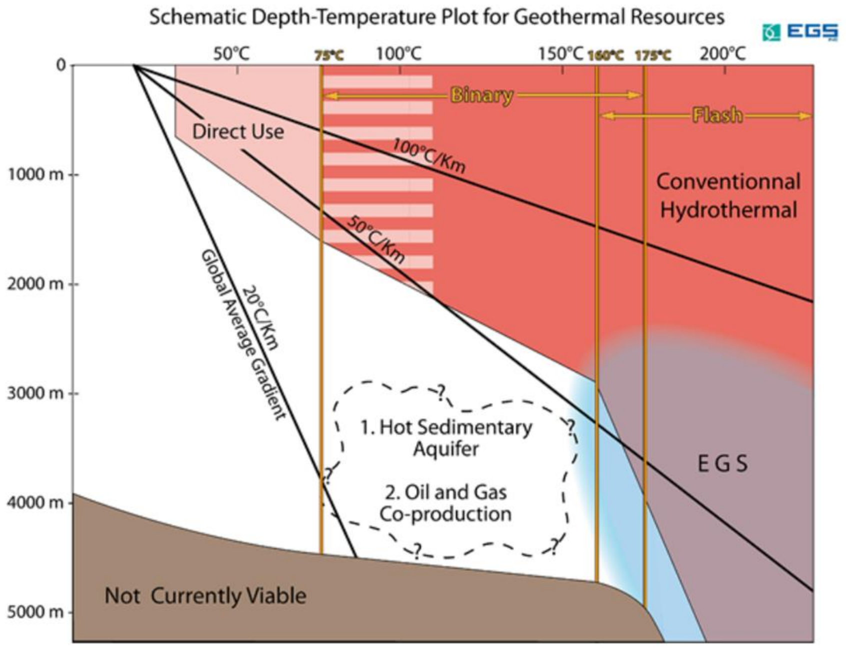


Fig. 2. The average temperature gradient for planet Earth is 20 °C per kilometre. In many areas around the world the gradient is higher, and the temperature increases at a faster rate with depth below the ground. With a temperature gradient of between 50 and 100 °C geothermal resources are more readily accessible. Above 20 °C geothermal waters can be used for direct uses like greenhouses, aquaculture and district heating applying heat pumps. Above 75 °C the water is hot enough to be used for electricity generation using binary cycle technology. Above 160 °C flash steam generation can be used to produce clean, renewable electricity. Source: Geothermal Resources Council (https://archive.geothermal.org/what.html).

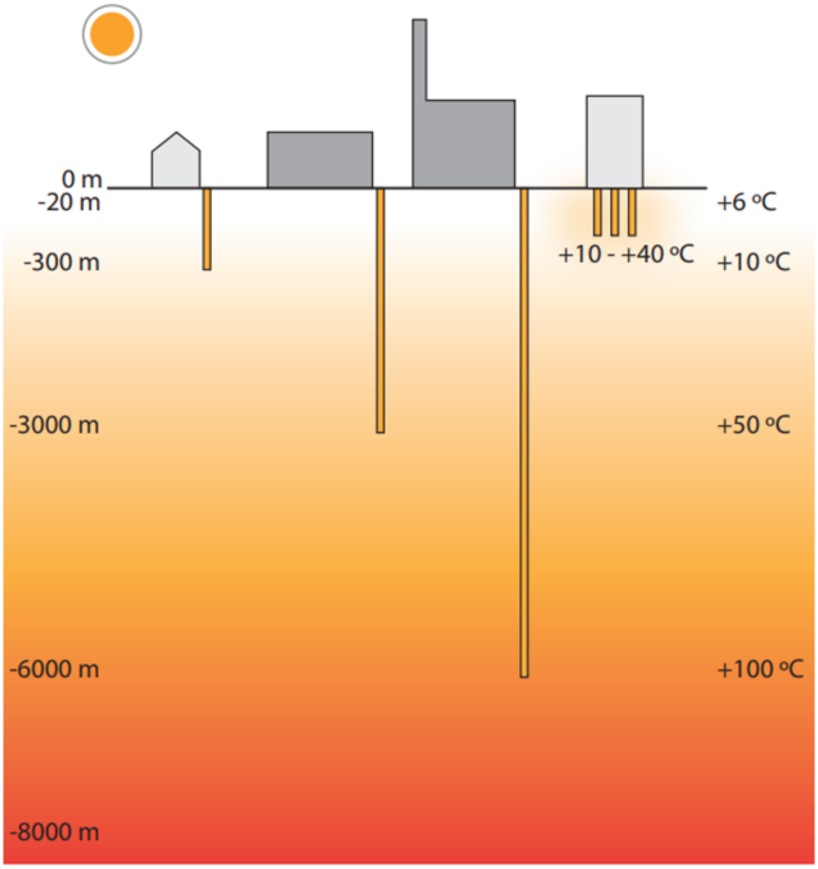


Figure 3. A schematic diagram on typical temperatures in different depths of the bedrock in Estonia and Finland. Locally, bedrock temperatures vary in different areas depending on local thermogeological conditions. Source: RT 2020.

In the past, the term geoenergy (usually defined as geothermal energy in this context) was used to describe high temperature resources extracted from deep, subterranean reservoirs. The definition has since been broadened to encompass *low temperature (low-entalphy) geothermal resources*, as well. Low-temperature geoenergy refers to energy resources derived from the earth's subsurface, i.e., at temperatures below 150°C. *High temperature (high-entalphy) geothermal* resources exhibit temperatures above 150°C and are typically only found in active volcanic regions. They comprise convective systems characterised by surface geothermal features such as hot springs and geysers, or just known thermal anomalies in the Earth's crust. The thermal energy extracted from the high-enthalpy systems allows direct production of electricity.

The low-enthalpy systems are inefficient in this conversion, and that is why they are mainly used for heating, cooling, and energy storage applications. Electricity is needed for running heat pumps. Usually, low temperature geoenergy is applied as a part of larger hybrid energy systems.

Exploitation of low-grade heat resource requires use of *ground-source heat pump (GSHP) systems*. These extract heat from the ground or water and utilise heat pumps to extract the low-grade heat and upgrade it to more useful temperatures (>40°C) required for the heating of buildings (Fig. 4). The cold carrier fluid or groundwater is then returned to the subsurface to be heated again. The system is reversable and can be used for heating in the winter and cooling in the summer. Cooling allows downloading of heat in the ground, which makes the system more sustainable.

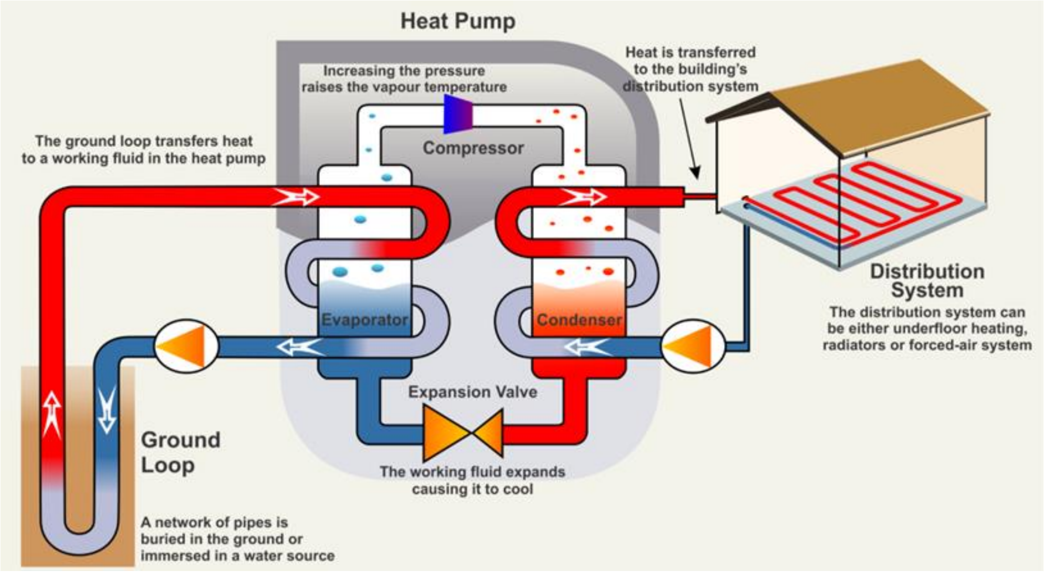


Fig. 4. Basic operating principle of a ground sourced heat pump (GSHP). Source: BC Geothermal (https://www.bcgeo.ca/contact/how-geothermal-works/geothermal-heat-pumps/).

Geoenergy applications are generally defined in the Nordic countries as shallow (<500 m), middle deep (500 m to 3000 m) and deep (>3000 m) systems. These can be open or closed systems. Closed systems use water or another carrier liquid, which is circulating within pipes in the ground or bedrock, for heat transfer. Open systems apply generally groundwater, water in old mine workings or surface waters. Heat pumps are needed to recover heat from low-temperature sources. Over 70 °C water could be directly used for heating, but these conditions could only be found at several kilometres' depth in Estonia and nearby areas.

In non-porous rocks, such as crystalline rocks in the basement underlying the sedimentary rocks in Estonia, a carrier fluid must be applied in closed loop systems containing one drill hole as, e.g., in single house systems or an array of multiple bore holes in larger systems. In addition to temperature, heat conductivity and fracturing of surrounding rocks, and groundwater flow are important factors to determine feasibility of the geothermal system in crystalline rocks, because they have a direct impact on the heat transfer from the surrounding rock mass. Shallow geoenergy uses horizontal ground-heat piping or vertical energy wells. The wells may have U shape or coaxial piping. In the latter, cold water is pumped along the outer tube and pumped up within an insulated inner pipe. One energy well is typically enough to heat a single house, but bigger complexes can be heated using deeper wells or an energy well field.

Energy can also be stored underground using bore holes. The application is called *borehole thermal energy storage (BTES)* system consisting of arrays of tubes installed in the subsurface or deeper energy wells. The operating principle is shown in Fig. 5.

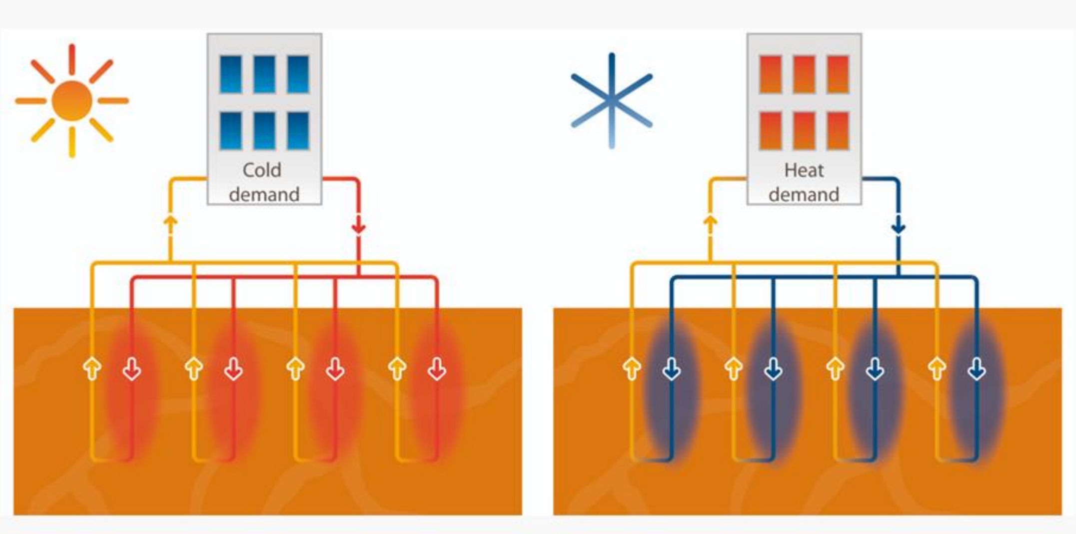


Fig. 5. Basic principle of the bore hole thermal energy storage systems (BTES). Source: IF Technology https://www.iftechnology.com/borehole-thermal-energy-storage.

Enhanced (or engineered) geothermal systems (EGS) have been applied to extract geoenergy from several kilometres depth in crystalline, non-porous rocks, which are called *hot dry rocks*. The EGS concept is to extract heat by creating a fracture system at several kilometres depth below the surface to which water can be added through injection wells and recovered using production wells. Creating an EGS requires improving the natural permeability of rocks by a method called *hydraulic stimulation*. Rocks are permeable due to minute fractures and pore spaces between mineral grains. Injected water is heated by contact with the rock and returned to the surface through production wells. EGS are manmade reservoirs created to improve the economics of deep resources in hot dry rocks without adequate water and/or permeability.

Groundwater geoenergy can be recovered from porous sedimentary rocks, such as sandstones, which have good water conductivity to allow water circulation in aquifers. Groundwater is pumped from an aquifer to heat pumps and returned after heat recovery back to the geological formation using another well. Aquifers can be located at shallow levels or at up to a few kilometres' depth. This is also called an *aquifer thermal energy storage (ATES) system* (Fig. 6). ATES is applied to provide heating and cooling to buildings and storage of energy. In a simple setting, geoenergy is exploited via a so-called 'doublet system' consisting of two boreholes drilled on suitable distance. One is for abstracting the hot water and the other is for re-injecting the cooled water back into the aquifer. In addition to groundwater, geoenergy systems may directly apply surface waters or waters in old underground mine workings.

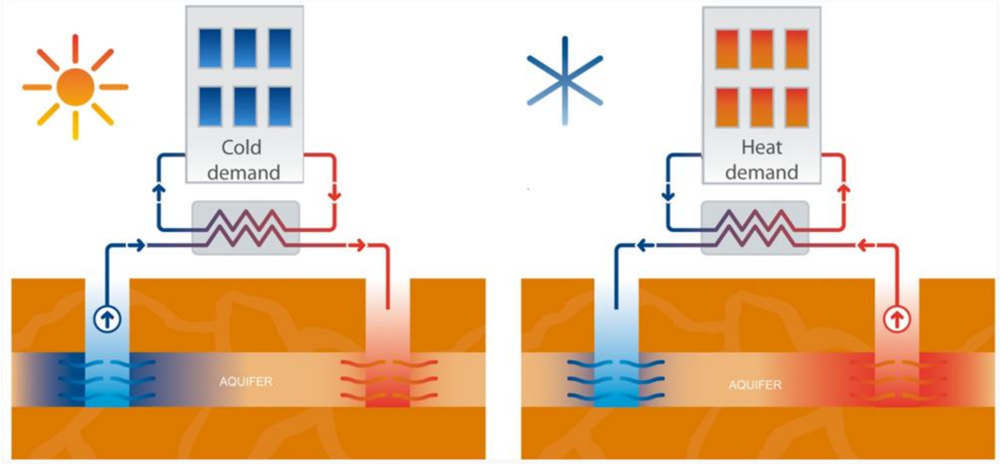


Fig. 6. Principle of aquifer thermal energy storage systems (ATES). Source: IF Technology https://www.iftechnology.com/aquifer-thermal-energy-storage.

ATES commonly operate in a seasonal mode. The groundwater that is extracted in summer, is used for cooling by transferring heat from the building to the groundwater. Subsequently, the heated groundwater is injected back into the aquifer, which creates a storage of heated groundwater. In wintertime, the flow direction is reversed such that the heated groundwater is extracted and can be used for heating (often in combination with a heat pump). Therefore, operating an ATES system uses the subsurface as a temporal storage to buffer seasonal variations in heating and cooling demand. When replacing traditional fossil fuel dependent heating and cooling systems, ATES can serve as a cost-effective technology to reduce the primary energy consumption of a building and the associated CO_2 emissions (Kallesøe et al. 2019).

For example, in Sweden 20% of small houses apply geoenergy, which is the highest percentage in Europe (Gehlin 2019). There are over 500,000 geoenergy wells in total (Fig. 7). Shallow geothermal energy systems provide some 23 TWh of heating and cooling in Sweden (including free cooling and electricity for heat pumps). Approximately 17.5 TWh of the geoenergy is renewable heat from the ground and approximately 1.1 TWh is free cooling from the ground. Geoenergy degreases CO_2 emissions by 4.8 million tonnes per annum in Sweden.

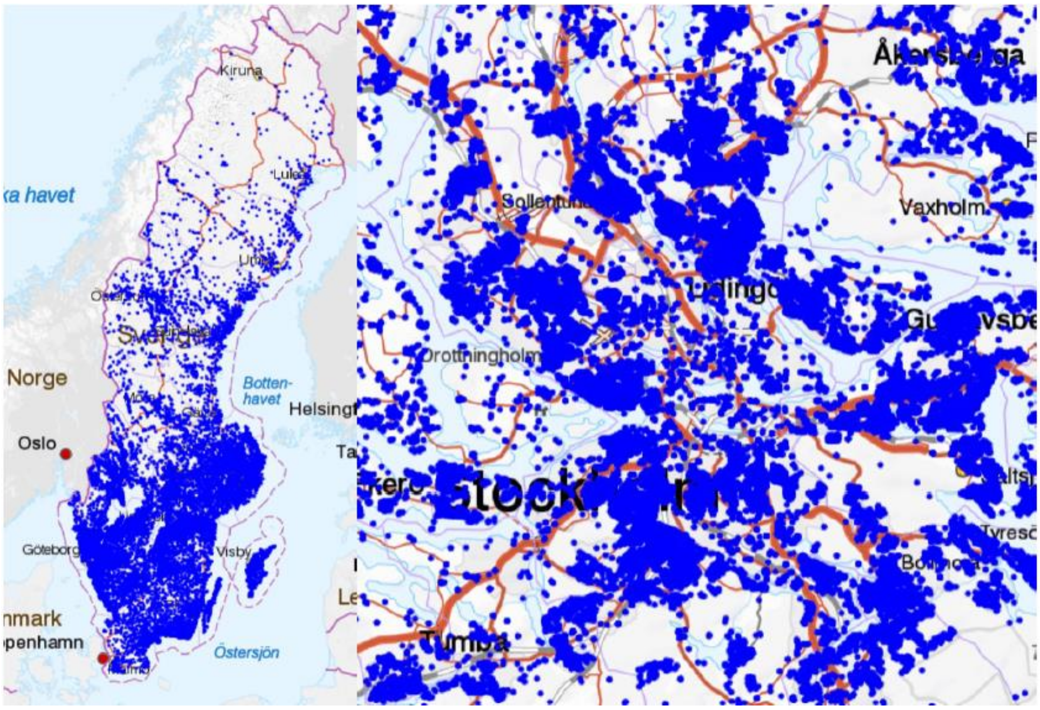


Fig. 7. Location of 500,000 geoenergy wells in Sweden. Source: Rototec, unpublished company presentation 2021.

3.1. What are the advantages and disadvantages of geoenergy?

Geoenergy is a sustainable and renewable energy source that is yet largely unutilized, although there is a rapid growth on the use of geoenergy, and new applications and technological improvements are currently being developed. In geological areas, such as in Estonia, geoenergy has the potential to meet heating, cooling and seasonal energy storage demands for the future as an environmentally friendly solution.

Low temperature geoenergy systems produce local energy. They do not need large space and can be fitted also in densely build areas. Carefully planned systems are sustainable and, regardless of high initial investments, geoenergy plants can be economically profitable and prevent CO_2 emissions. Usually, larger geoenergy systems are part of a hybrid energy solutions including several sources for electricity, heating, and cooling energy, and they utilize seasonal energy storage concept.

Geoenergy has many advantages but also some challenges that need to be overcome to fully exploit this natural resource. First, geoenergy is environmentally friendly compared to conventional fuel sources, and the carbon footprint of a geoenergy is low. About 60 to 75% of geoenergy is “free” energy yield from the ground or water 24 hours a day all year-round. Provided that electricity used for heat pumps is produced in a sustainable way, the overall carbon footprint will be exceedingly small.

Geoenergy provides a reliable and local source of energy as compared to other renewable resources. This is because the resource is available 24 hours a day 7 days a week all year round, unlike wind or solar energy, which are strongly dependent on daily and seasonal climate conditions. This makes geoenergy systems also easy to calculate and predict the power output from a geoenergy plant with a high degree of accuracy.

Geoenergy is also sustainable, depending on the style of the plant and local conditions, at least for over 30 to 50 years. This requires careful feasibility studies which include detailed geological, geophysical, and thermogeological surveys, and engineering to define the right type and scale of geoenergy. The studies are largely site specific and should be done individually in each area where geoenergy is planned to be built.   During operation, geoenergy needs to be properly monitored and managed to maintain its sustainability.

Despite the many advantages of geoenergy, there are also certain disadvantages. The largest single disadvantage of geoenergy is that it is location specific. Geothermal plants need to be built in places where the energy potential is economically and technically viable for exploitation, and where the user’s facilities are located. Energy transfer is economically feasible only for a maximum distance of a few kilometres. On the other hand, geoenergy plants do not require large areas and can easily be fitted in densely built environments in cities. Plants are mostly located inside or adjacent to buildings using geoenergy or close to a distance heating network.

Even, most of the larger geoenergy applications can produce of energy in the range of one to tens of megawatts and can therefore work only as an additional energy source in large hybrid energy systems, or as a solution for smaller energy needs. Plants may require large investments, and the payback time may exceed 10 years. However, where the upfront costs are high, the outlay can be recouped as part of a long-term investment and produce two thirds of free and clean energy over several decades. Central heating energy prices have shown steadily increasing trends in many countries over the last several years, which has improved the competitiveness of geoenergy.

4. Assessment of geoenergy potential in Estonia

4.1. General geological setting

Estonia is located within the large East European Craton, which is exposed in the Fennoscandian Shield in Finland and neighbouring countries. In Estonia, the Precambrian crystalline basement is covered by younger sedimentary rocks deposited from Ediacaran to Palaeozoic times (Fig. 8). These comprise a variety of sedimentary rocks ranging in composition from sandstones, dolomites, limestones, silts to clays. Thickness of the sedimentary sequence varies from about 100 m on the northern coast to over 700 m in the southern part of the country.

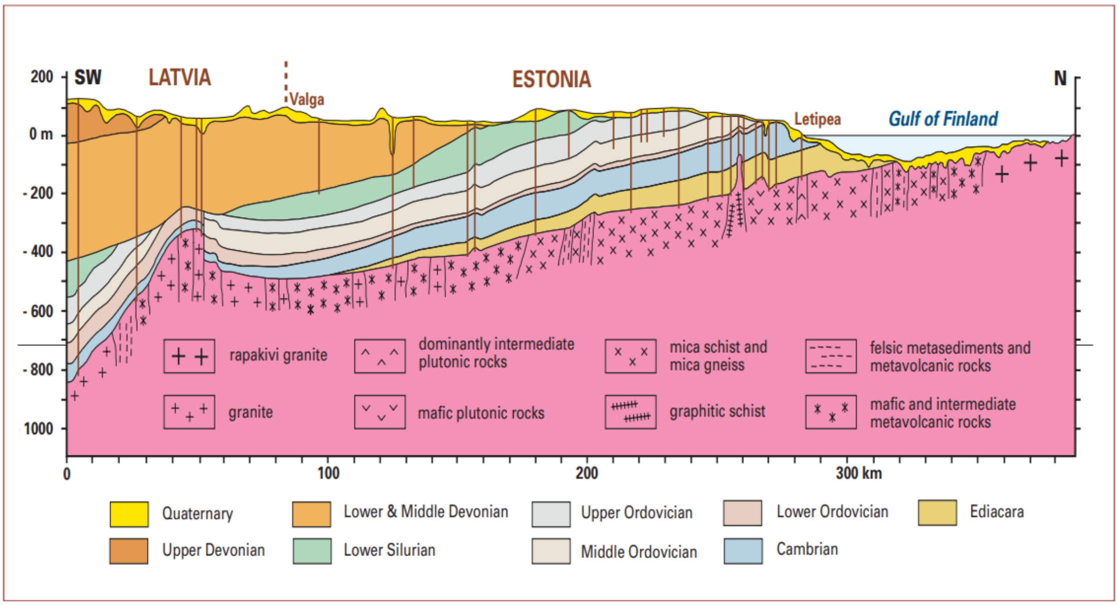


Fig. 8. A cross section of Estonian bedrock showing Precambrian crystalline basement gently dipping towards south under much younger sedimentary sequence varying in thickness from 120 m in the northern cost up to over 700 m in the south. Source: Eklund et al. 2007.

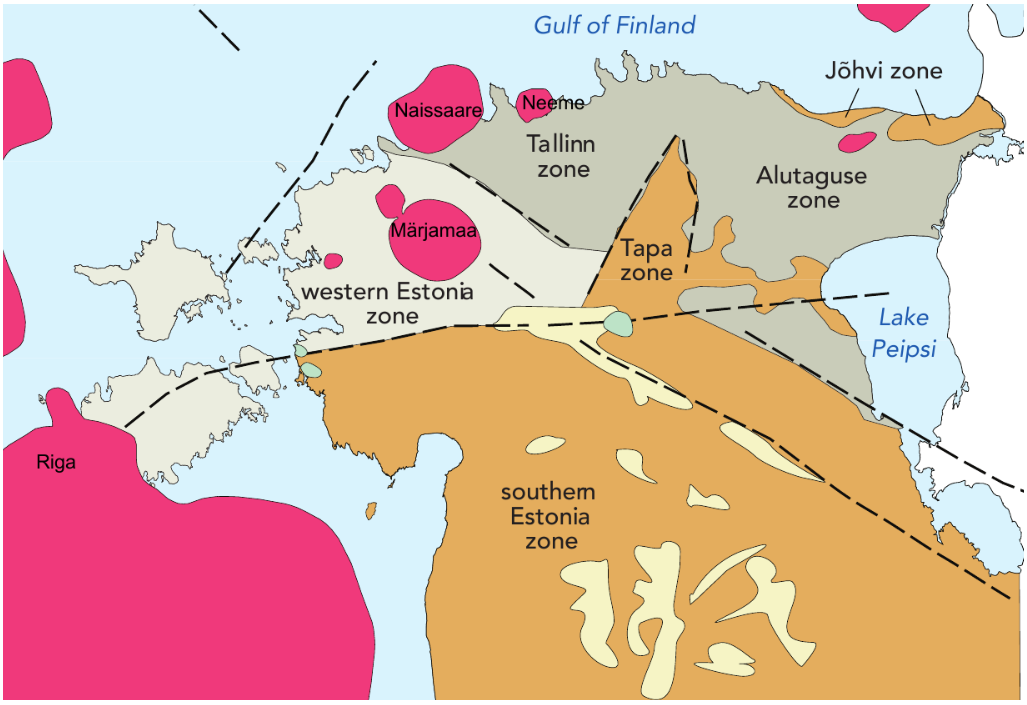


Fig. 9. A simplified geological map of the Precambrian crystalline basement showing the location of various metamorphic gneissic terrains and rapakivi granite areas (in red). Eklund et al. 2007.

Geology of the Precambrian basement is not known in detail. Samples have only been obtained from about 500 drillholes across Estonia, which give sporadic and spot-like information of the basement. Regional geophysical surveys give additional information on the geology of the basement. The crust in Estonia is relatively thick varying between 41 km to 51 km (Puura and Vaher 1997). Most of the crystalline basement comprises the 1.8 – 1.9-billion-year-old gneissic complexes of different composition and metamorphic grade (Fig. 9). In northern Estonia, the bedrock can be regarded as an extension of the well-exposed and studied geological units of southern Finland.

The gneissic rocks are intersected by several generations of intrusive rocks, of which the most important ones are the rapakivi granites (in Estonia Naissaare, Neeme, Märjamaa, Ereda and Riga plutons). Rapakivi granites in the northern coast of Estonia can be correlated with those in southern Finland (Rämö et al. 1996). In general, rapakivi granites are interesting regarding geoenergy, because they are typically enriched in radioactive elements thorium, uranium and potassium, and thus have elevated heat producing properties compared to the prevailing gneisses.

4.2. Thermogeology of Estonia

Geothermal heat flow in cratonic Areas, such as in Estonia, consists of two components: (1) heat produced within deep in the Earth's mantle and core, and (2) heat produced within the Earth's crust. The contribution from the Earth's interior arises from the cooling of the Earth and formation of a solid core, and from radiogenic heat production (e.g., Pollack et al. 1993). The crustal component consists of a radiogenic heat production where heat is produced by the natural radioactive decay of uranium, thorium, and potassium. The heat flow from the Earth's interior has a smooth spatial variation, whereas the spatial variation in radioactively decaying nuclides in the crust generates a heat flow with large spatial variations in a kilometre scale.

4.2.1. Regional heat-flow in northern Europe

Cratons constitute the oldest part of continental crust and usually exhibit low heat flow density values. The exposed Fennoscandian Shield and the East European Craton exhibit generally relatively low heat flow density values and is surrounded by normal to high values in western, central and southeaster Europe (Näslund et al. 2005). The lowest heat flow values are found in the central Fennoscandian Shield in central Finland and NW Russia (Fig. 10).

Artemieva and Mooney (2001) made a compilation of 300 observed heat flow density values for the Fennoscandian Shield, which is sufficient to show a generalized heat flow pattern but not regional or local variations. Their compilation demonstrates increasing heat flow density values from the northeast (35–50 mW m^{-2}) to the south and southwest (60–70 mW m^{-2}).

Näslund et al. (2005) made more exact calculations in Sweden and Finland (Fig. 10). The regional heat flow density pattern does not generally correlate with gravity variations, magnetic anomalies, or crustal thickness. However, within the Fennoscandian Shield, as well as, in other areas with similar geological setting, there is close correlation between heat flow density and regional geological units at the surface of the crust. Locally, heat flow may show considerable differences (e.g., Veikkolainen and Kukkonen 2019). Areas of higher heat flow are predominated by potassic granitic rocks, and areas of lower heat flow values from areas predominated by mafic rocks, granitic gneisses, and schist belts, which is caused by different heat production properties of the rock types.

The measured heat flow in Finland in the uppermost 1 km of bedrock range from extremely low values of <15 mWm^{-2} to 69 mWm^{-2}, while temperatures varying between 14 to 22°C at 1 km depth (Kukkonen 2000). Geothermal gradient (rate of temperature increase with depth) is about 17 °C/km in the 2 km deep OTN-1 test well in Otaniemi, Espoo, and corresponding heat flow is about 52 mWm^{-2}

(Kukkonen et al. 2021). This implies that 100°C temperature level should be reached at about 6 km depth, as later shown in the St1's deep energy project in Espoo.

The natural heat flow density is yet suffering from so called *paleoclimatic effect* caused by last ice age when cold climate cooled the upper crust during several tens of thousands of years. This cooling effect can yet be recorded to the depth of 500 m and weakly to 1000 m depth (Kukkonen and Jõeleht 2003). It is proposed an average correction of +15 mWm^{-2} at 500 m depth, and +5 mWm^{-2} at 1000 m, respectively, to remove the paleoclimatic impact.

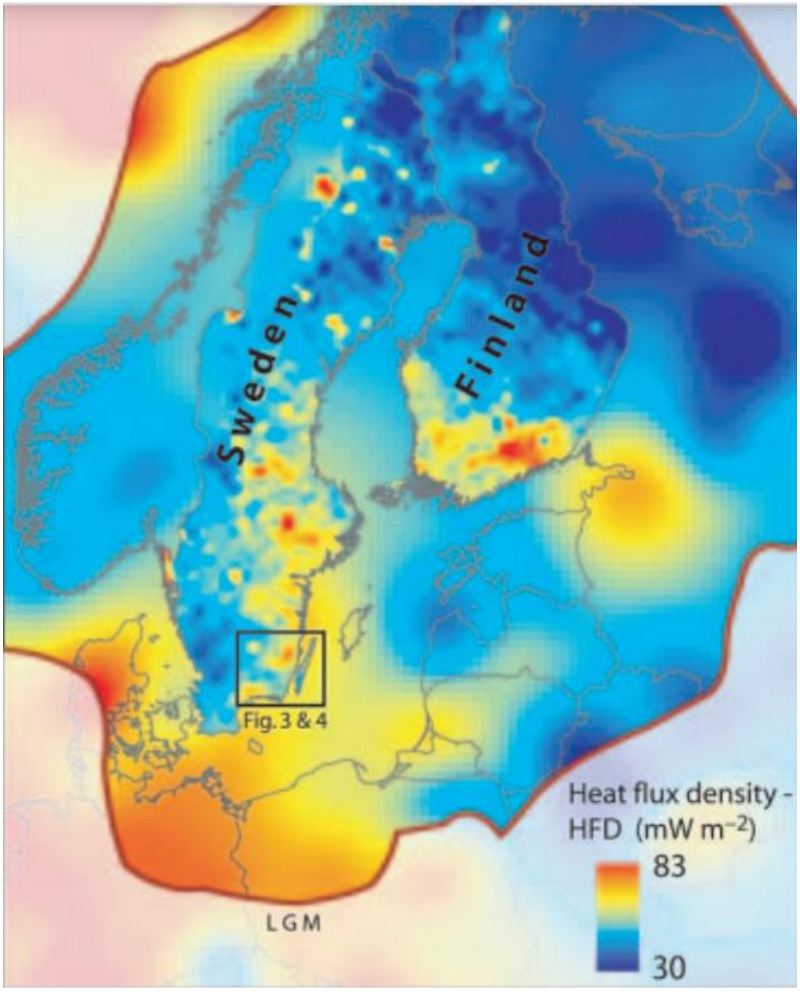


Fig. 10. Heat flow density distribution in the Fennoscandian Shield and surrounding areas. High-resolution data have been calculated for Sweden and Finland, while only much coarser data for surrounding regions are available. The geothermal heat flow ranges between 30 and 83 mWm^{-2}, with an average value of 49 mWm^{-2}. Source: Näslund et al. 2005.

The Atlas of Geothermal Resources in Europe includes a regional map on estimated bedrock temperatures at 1000 m depth (Hurter and Haenel 2002). Figure 11. is a clip of that map and shows temperatures in Estonia and surrounding areas. In most of Estonia, as well as in southern Finland, temperature at 1000 m depth is steadily around 20°C. The extensive geothermal anomaly south from St. Petersburg showing over 30 °C temperatures at 1000 m depth continues, according to this map, to the Estonian Russian border and may indicate elevated bedrock temperatures also in the easternmost Estonia.

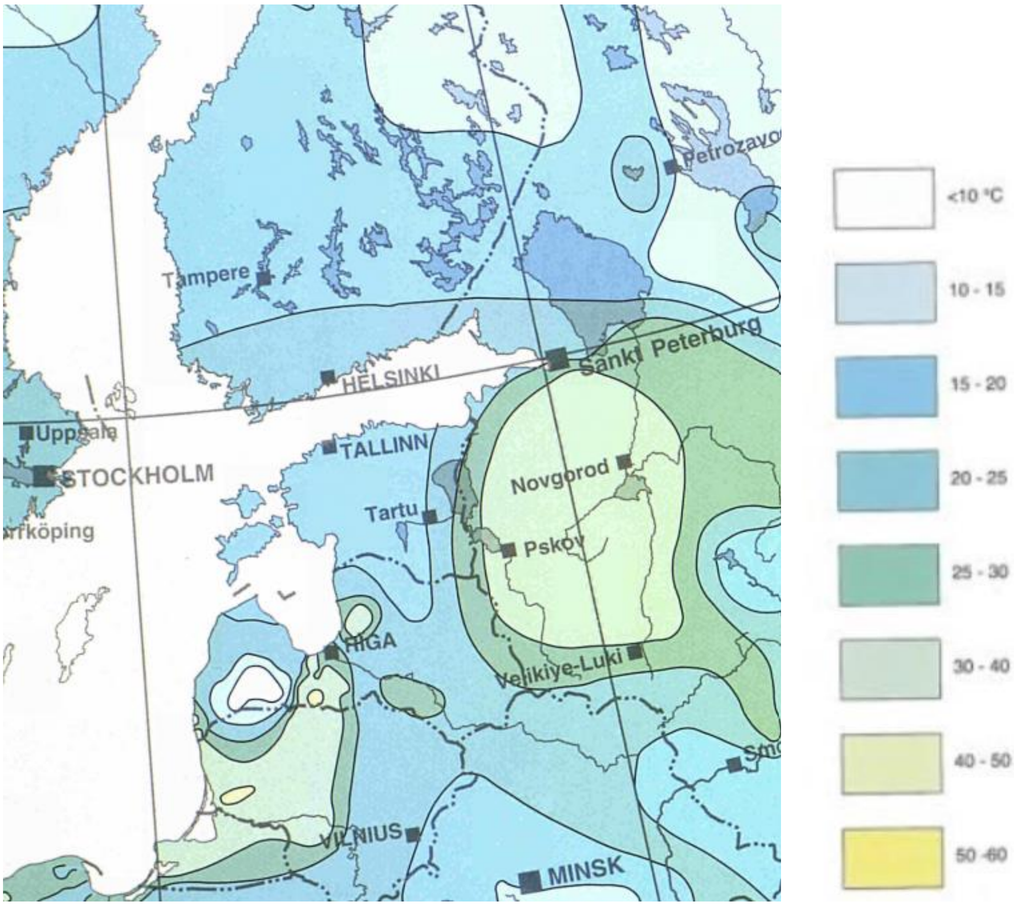


Fig. 11. A clip of a European geothermal map showing approximate estimated bedrock temperatures at 1000 m depth in Estonia and surrounding areas (Hurter and Haenel 2002).

Veikkolainen and Kukkonen (2019) have studied in detail the heat production of rocks in Finland based on 6465 samples representing all major rock types across Finland (GTK 2021). They estimate that the average heat flow density in Finland is 42 ± 4 mWm^{-2} with considerable regional variation. It is further suggested that most of the surface heat flow (22–40 mWm^{-2}) originates from the crustal rocks, in the way that uranium represents 37%, thorium 47% and potassium 16% of the total heat production, respectively.

4.2.2. Geoenergy potential and heat flow in southern Finland

Southern Finland can be geologically correlated to northern Estonia. The Precambrian basement is well exposed in southern Finland and has been studied in detail also from thermogeological point of view. Therefore, the studies in southern Finland provide a good analogue to evaluate thermogeology of northern Estonia, as well.

The Geological Survey of Finland (GTK) has made detailed modelling of geoenergy potential both nation-wide and for different regions using the comprehensive geoscientific data sets available in Finland. The work has involved a combination of sophisticated techniques. Figure 12. shows geoenergy potential for the Uusimaa county. It is defined in this study as megawatts energy received annually from a 300 m deep well (diameter 140 mm) for 50 years before the well theoretically starts to freeze and loses its sustainability (Uudenmaan liitto 2020). Similar nationwide study demonstrates comprehensive difference between southern and northern Finland (small map in Fig. 12). Steady consumption profile was assumed in the calculations neglecting seasonal variation, which means that in practise the geoenergy yield is better.

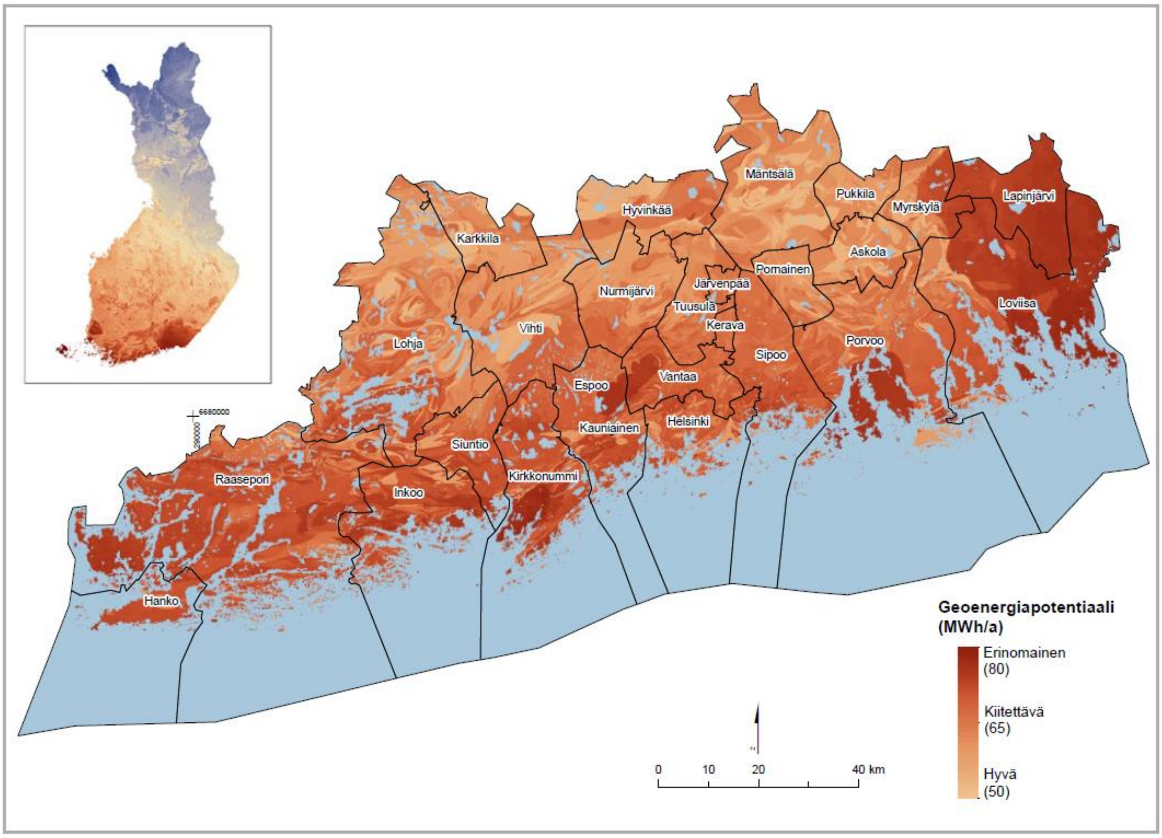


Fig. 12. Geoenergy potential in the Uusimaa county, defined by the Geological Survey of Finland (GTK), exhibit considerable local variations between good (hyvä) and excellent (erinomainen) geoenergy potential (50–80 MWh/a). Small map shows geoenergy potential in Finland with much larger variation between southern and northern Finland (20–80 MWh/a). See text for details. Geoenergy potential © GTK. Source: Uudenmaan liitto 2020.

The potential was also defined for middle-deep geoenergy (Fig. 13). This map shows how many megawatts energy could be received annually from 2000 m deep wells for 50 years before the well theoretically starts to freeze and loses its sustainability (Uudenmaan liitto 2020).

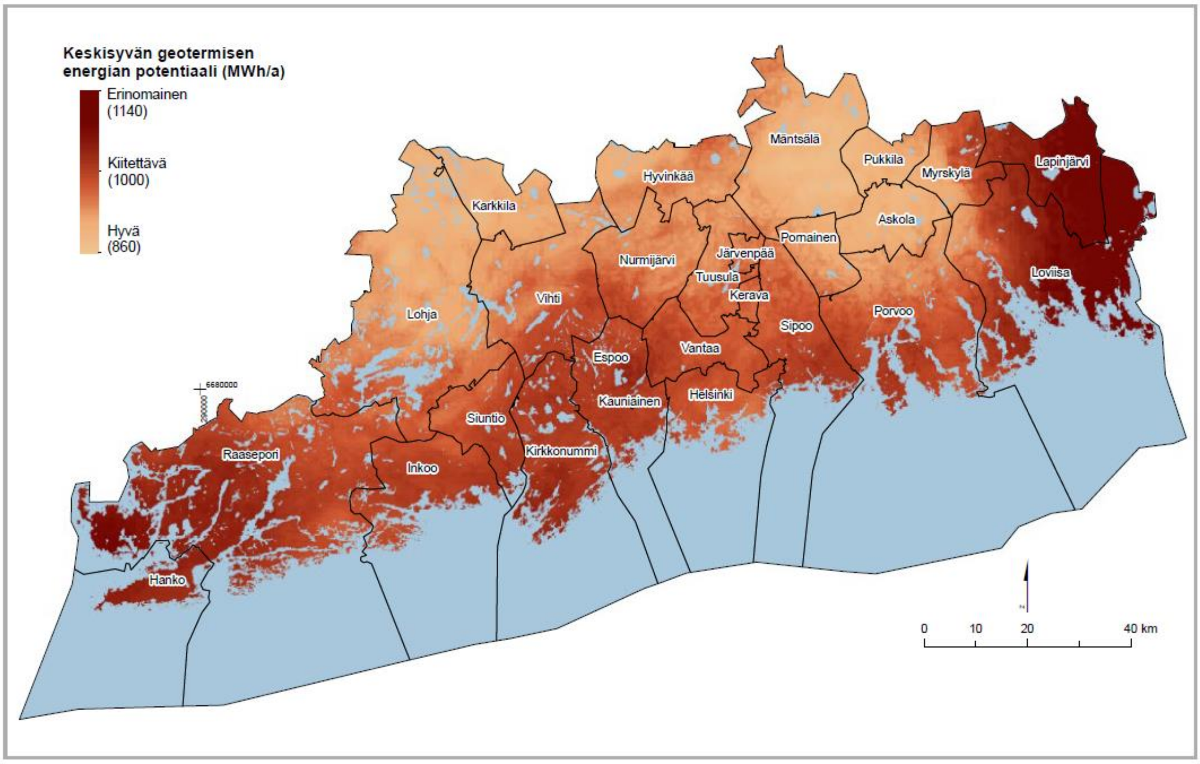


Fig. 13. Potential for middle-deep geoenergy in the Uusimaa county, defined by the Geological Survey of Finland (GTK), exhibiting considerable local variations between good (hyvä) and excellent (erinomainen) geoenergy potential (860–1140 MWh/a). See text for details. Geoenergy potential © GTK. Source: Uudenmaan liitto 2020.

Geoenergy potential has been defined in detail for the Helsinki city area using available geological datasets, ground and bedrock temperature information, thermal conductivity and heat capacity of rocks, and geothermal heat flow density information (Kallio et al. 2019). This map shows estimated theoretical geoenergy potential defined as MWh per year per hectare for the uppermost 1 kilometre of the bedrock (Fig. 14). The study shows that there is considerable local variation of the geoenergy potential from 1740 to 1380 MWh/a per hectare in a hundred metres to kilometre scale. This is largely due to variation of rock types and demonstrates the importance of understanding thermogeological properties of the study area in detail before selection of sites for geoenergy plants.

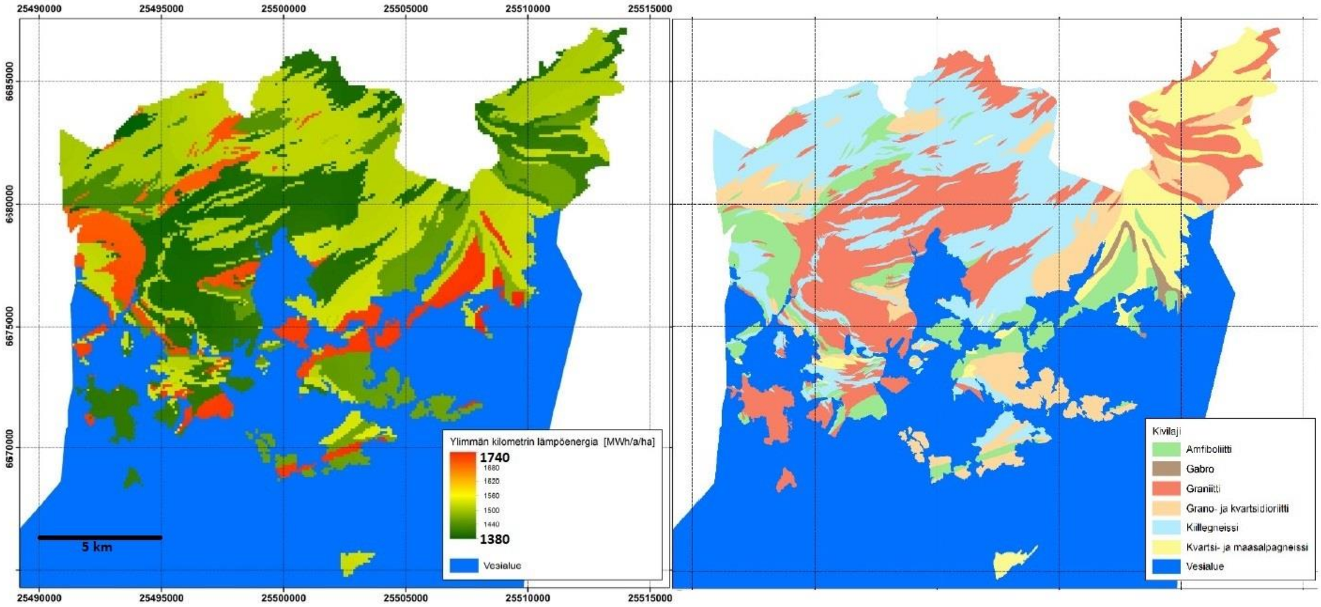


Fig. 14. Calculated theoretical geoenergy potential for Helsinki (on the left), defined as MWh per year per hectare for the uppermost 1 kilometre (modelled by the Geological Survey of Finland), and a simplified geological map of Helsinki (on the right). See text for details. Source: Kallio et al. 2019.

4.2.3. High heat producing rapakivi granites

The highest heat flow values in Finland occur along the southern coast of Finland (Fig. 12). This can directly be correlated with the geology of the area, and is due to the large rapakivi granite plutons and potassic granites in southern Finland. These rocks have distinctly increased heat production properties, because of elevated uranium, thorium, and potassium concentrations. Figure 15. shows distribution of rock types according to their heat-production properties in Finland. Toni Veikkolainen (personal communication 2021) estimates that heat flow density values in rapakivi granite areas are generally about 60 mWm^{-2}, which is considerably higher than the average value of 42 ± 4 mWm^{-2}. This suggests that rapakivi granite areas have particularly good potential for geoenergy applications. Furthermore, rapakivi granites are generally easy to drill and they typically have well-developed cubic jointing, which improve groundwater movement and increases heat conductivity.

Rapakivi granites occur on both sides of the Gulf of Finland, but the volume of potassic granites may be smaller in Estonia, although this cannot be estimated in detail due to the sedimentary rock cover in Estonia. Rämö et al. (1996) has shown that the Estonian rapakivi granites can be directly correlated with those in SE Finland on the basis of the same geologic age (1.65 to 1.62 Ga in SE Finland and 1.63 Ga in Estonia), and neodymium and strontium isotopic composition.

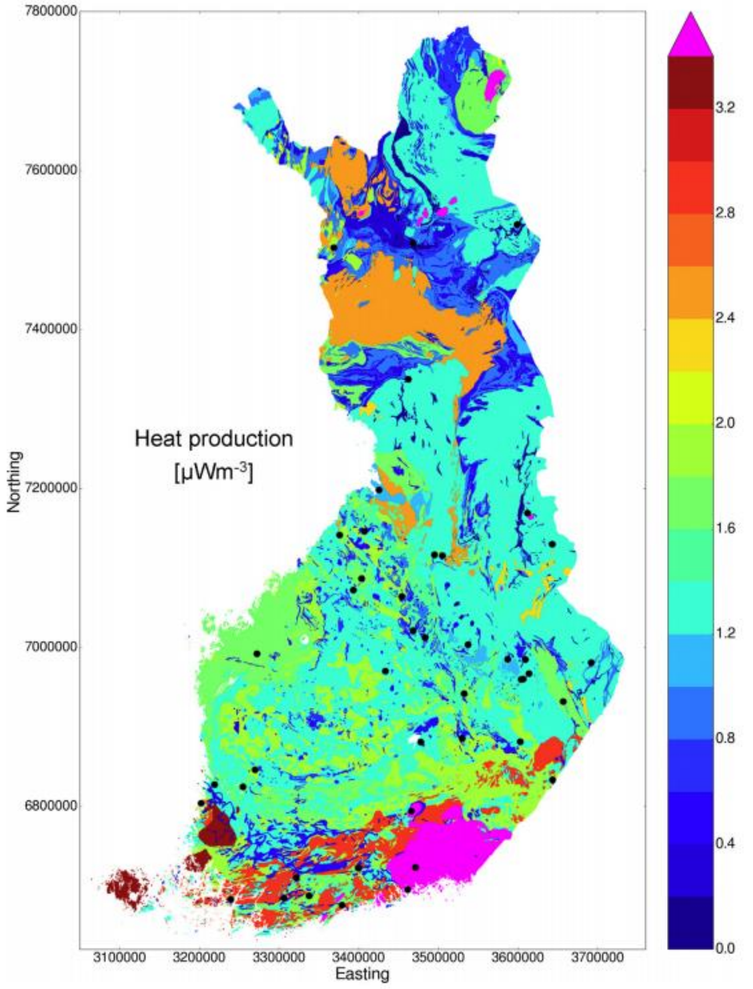


Fig 15. Heat-production of geological units in Finland. Southern Finland shows elevated heat flow densities cause by rapakivi granites and other potassium-rich granites. The Wiborg rapakivi pluton shown in purple, and Vehmaa, Laitila and Åland plutons in brown exhibit the highest heat production values 3.38 ± 1.1 μWm^{-3} and 3.26 ± 1.04 μWm^{-3}, respectively. Potassic granites (in red) show an average of 2.45 ± 1.87 μWm^{-3}. Average heat-production value of all analysed 6565 rock samples across Finland is 1.11 ± 1.19 μWm^{-3}. Source: Veikkolainen and Kukkonen (2019).

Table 1. shows the concentration of radiogenic heat producing elements of rapakivi granites in Finland and Estonia. Only sporadic unpublished data is available from Estonia, but it is sufficient to demonstrate roughly similar range of concentrations than in Finland. Rapakivi plutons typically comprise of multiple intrusive phases which may exhibit distinctly different heat producing properties. Therefore, detail studies are needed to define the local heat production of rapakivi granites and their geoenergy potential in Estonia.

Table 1. Average concentration and range of radiogenic heat producing elements of selected rapakivi plutons in southern Finland, and range of the concentration in the Neeme and Naissaare plutons in Estonia. Finnish data from Geological Survey of Finland, rock geochemical data base (GTK 2021). Estonian data provided by Alvar Soesoo 2021.

Rapakivi pluton	Number of samples	Uranium (ppm)	Thorium (ppm)	Potassium (K_2O in %)
Wiborg	82	6.0 (2.3-15.7)	23.9 (11.9-79.8)	5.40 (4.40-6.44)
Small plutons in SE (Ahvenisto, Obnäs, Bodom, Onäs, Suomenniemi)	12	3.70 (2.15–5.87)	28.0 (12.0–51.9)	5.58 (4.89–5.98)
Åland rapakivi suite	47	4.98 (2.0–11.2)	23.6 (13.5–49.9)	5.22 (3.92–5.74)
Naissaare and Neeme	Not known	3–11	4–59	4.2–7.7

4.2.4. Review of heat flow studies in Estonia

Heat flow density in Estonia and geothermal properties of Estonian rocks have been studied, e.g., by Jõeleht and Kukkonen (1996), Jõeleht (1998), Jõeleht and Kukkonen (2002) and Jõeleht (2002). Soesoo (personal communication 2021) has compiled a general overview of geoenergy potential in Estonia, which is largely based on the studies and data by Eesti Geoloogiakeskus and the publications above. The studies are based on limited data mostly obtained from shallow (<350 m) drill holes intersecting a few tens of metres of the basement rocks at the most. Therefore, the data are sensitive to surficial disturbances caused by paleoclimatic factors and groundwater flow. However, the data are sufficient to give reliable overall understanding of Estonian thermogeology.

The heat flow density, corrected for palaeoclimatic effects, ranges according to Jõeleht (2002) between 28 - 68 mWm^{-2} with a mean value of 42 mWm^{-2} (Fig. 16). The average value is the same as the mean value in Finland calculated by Veikkolainen and Kukkonen (2019). In northern Estonia, the slightly higher temperatures in the upper part of the basement are attributed to the thermal blanketing effect caused by the about 100 m thick Lower Cambrian clays, which have a low thermal conductivity (Jõeleht 2002).

A similar temperature anomaly has been observed under the thick Muhos sedimentary formation in northern Finland (Kukkonen 2002). Sedimentary rocks form also there a heat-insulating layer, so that temperatures are 5 - 10 °C higher in the lower part of the sedimentary rocks and in the upper basement rocks in comparison to the surrounding area. According to (Jõeleht 2002), aquifers in Cambrian and Vendian sandstones are interesting for geothermal energy applications.

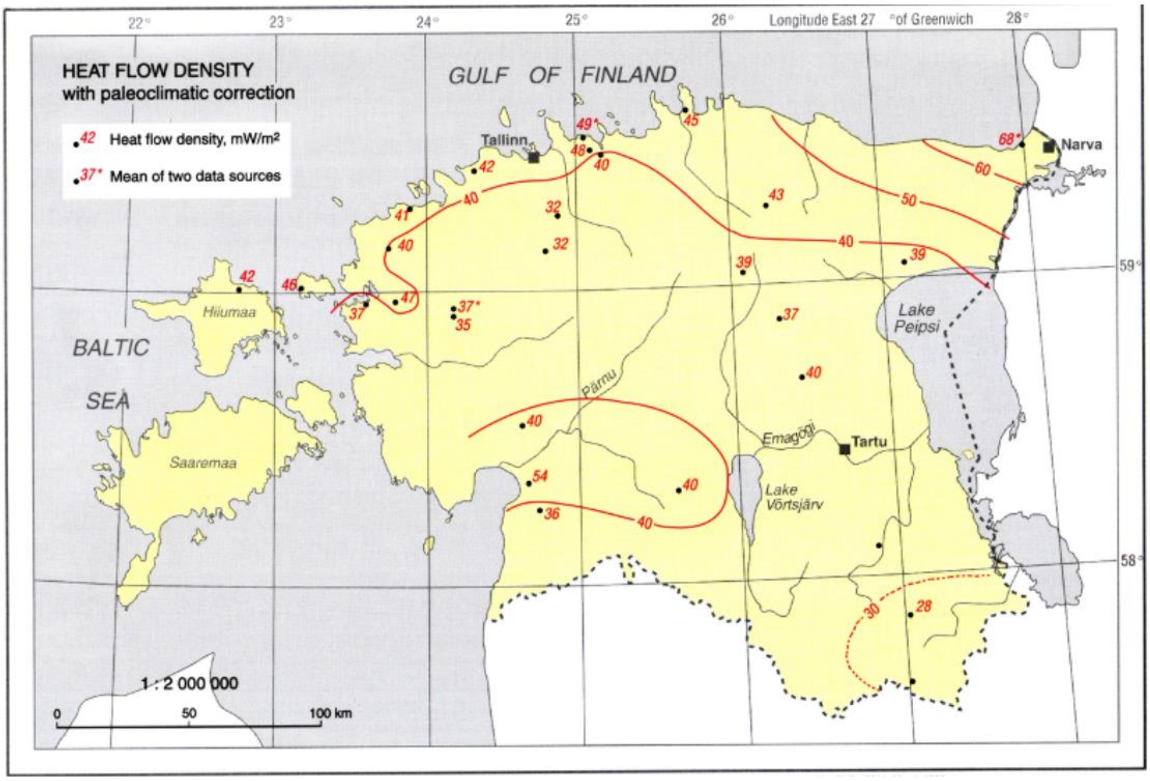


Fig. 16. Paleoclimatically corrected heat flow density observations in Estonia (Jõeleht 2002).

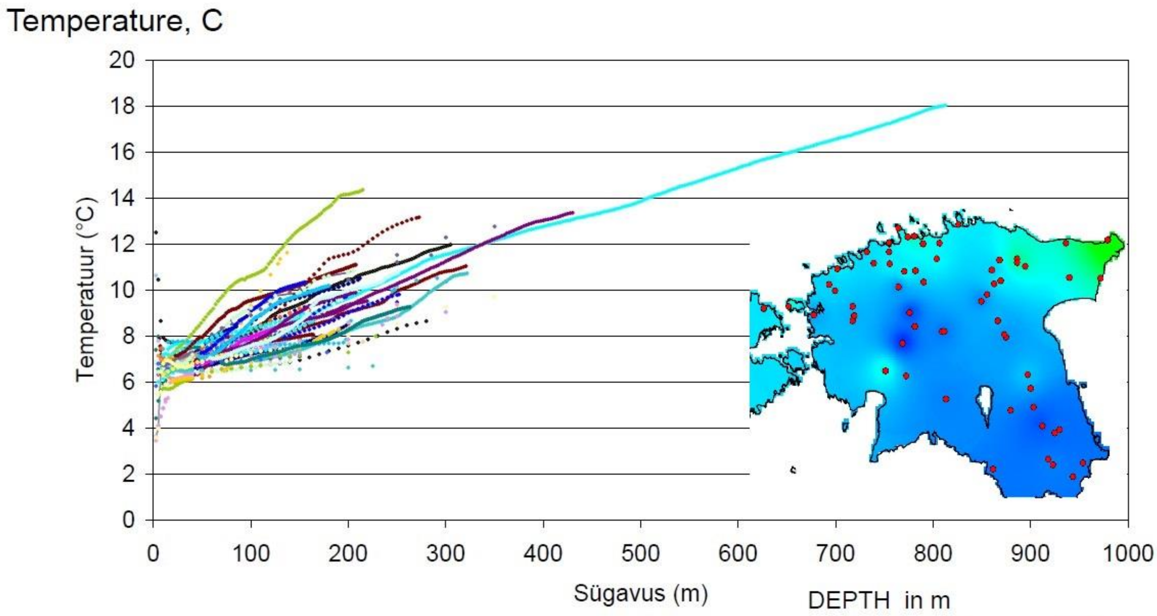
The highest heat flow density value (68 mWm$^{-2)}$ was calculated for the Meriküla drill hole in NE Estonia, which obviously demonstrates that the extensive thermal anomaly on the Russian side of the border continues to northeaster Estonia, as well (see: Fig. 11). Another anomalously high heat flow density value (48 mWm^{-2}) was recorded in the Saviranna hole located in Neeme. It has been interpreted to be caused by an anomalously high heat production of the Neeme rapakivi granite compared to generally predominating gneissic rocks in the surroundings (Jõeleht 1994). As discussed earlier, the rapakivi granites are generally high heat producing rocks, although their geochemistry has not been studied in detail in Estonia.

The Estonian Precambrian basement consists predominantly of metamorphic rocks of amphibolite facies in the north and of granulite facies in the southern part of the country. In general, the mean radiogenic heat production rate decreases with the increasing metamorphic grade from 3.23 µWm^{-3} (amphibolite facies rocks) to 1.26 µWm^{-3} (granulite facies rocks) (Jõeleht 2002).

Soesoo (2012) has compiled existing down-hole temperature measurements in Estonia (Fig. 17). Most of the data comes from shallow (200 to 300 m) drill holes and only the Kärdla hole intersects several hundreds of metres the Precambrian basement. Temperatures at 300 m depth mostly vary between 9 and 13 °C except for Meriküla where the temperature is slightly higher.

Figure 18. shows the estimated temperatures in Estonian bedrock at 500 m depth. They vary between 11 and 16 °C with the highest values (14 to 16 °C) in the northern and northeaster part of the country (Soesoo 2012). Temperatures in southern Finland at 500 m depth are generally quite similar varying between 12 °C and 14 °C (Kukkonen 2000).

The existing data give a generalized thermogeological understanding of Estonia but are yet too sparse to allow more detailed analysis of geoenergy potential in specific areas of interest. Therefore, follow-up studies are needed for possible geoenergy application.



DATA: Jõeleht, Soesoo, EGK

Fig. 17. Temperature-depth diagram based on logging of drill holes in Estonia. Location of the measured holes is shown in the small map with tentative temperature variation as a shading colour. The deepest hole (blue) is in Kärdla, Hiiumaa, and the green hole in Meriküla, Ida-Virumaa. Soesoo personal communication 2021, data from Jõeleht, Soesoo and Eesti Geoloogia Keskus.

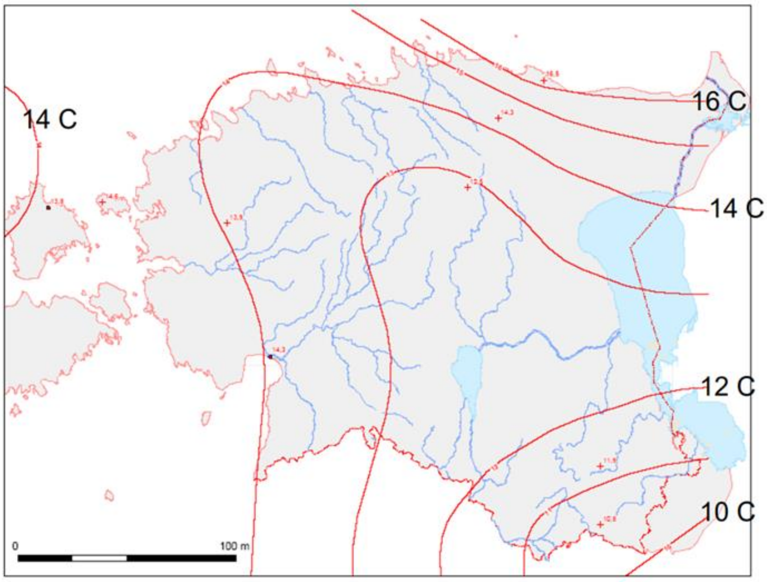
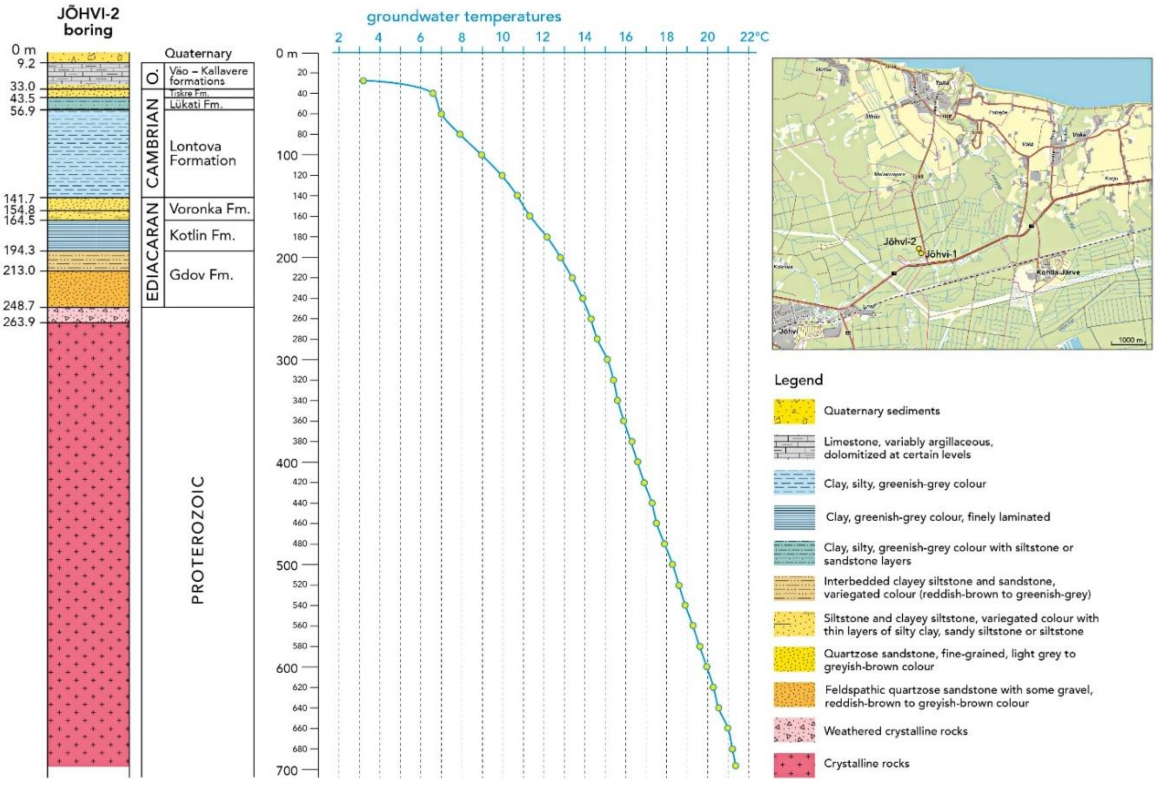


Fig. 18. Estimated temperatures at 500 m depth (Soesoo personal communication 2021, data from EGT and Jõeleht).

4.2.5. Temperature measurements in deep drill holes in northern Estonia

New temperature measurements have recently been made in two deep drill holes located in Paldiski and in Jõhvi. The Jõhvi hole was drilled to study an iron formation and a strong magnetic anomaly, whereas the Paldiski hole was drilled to give engineering geological information on the Precambrian basement for possible underground construction of an energy storage system.

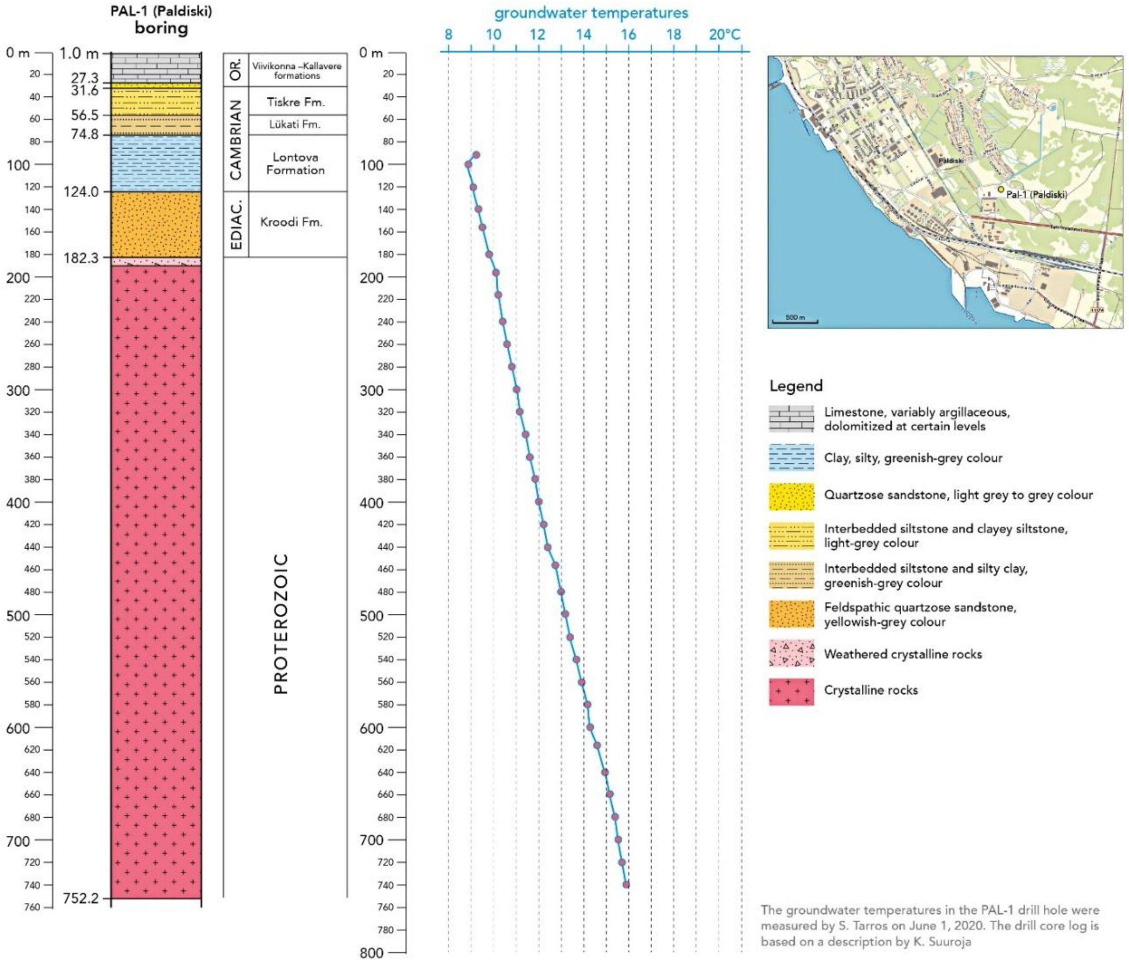
Temperature in the Jõhvi drill hole (J-2) was measured a couple of times. The values of the last measurement done on 25 Nov. 2020 are used here, because they most reliably show the natural thermal conditions in the bedrock. Water used for drilling can cause disturbances in temperature readings for several months. The hole intersects typical sedimentary rock sequence in northern Estonia down to the depth of 249 m (Fig. 19). The Precambrian rocks contain predominantly of various mica and garnet bearing gneisses with layers of quartz-magnetite rock. Bottom temperature at 696 m is 21.4 °C. Temperature gradient is growing fast in the sedimentary sequence (averaging 0.029 °C/m) but stabilizing to 0.014 °C/m in the Precambrian. This is evidently due to the "blanketing effect" of the sedimentary rocks accumulating heat in the deep sedimentary rock hosted aquifers.



The water temperatures in the Jõhvi-2 drill hole were measured by S. Tarros on November 25th, 2020. The measured depths of the inclined (65°) Jõhvi-2 drill hole were recalculated to the vertical depths. The Ediacaran–Ordovician sequence of the Jõhvi-2 drill hole was drilled without the core retrieval. Therefore the Jõhvi-2 log is based on rock description from the Jõhvi-1 drill core which was drilled 80 m apart from the Jõhvi-2 drill hole. The Jõhvi-1 drill core description was provided by K. Suuroja.

Fig. 19. Temperature measurement on the Jõhvi drill hole on May 14, 2020 Source: Data and drafting of the figure, Estonian Geological Survey 2021.

Geology and temperature of the Paldiski hole are shown in Fig. 20. Sedimentary rocks continue down to 182 m depth, from where the Precambrian, presumably gneissic bedrock starts. Bottom temperature at 760 m is 16.0 °C. The temperature logging was done soon after the drilling, and the results may yet show a slight disturbance caused by the drilling water. Temperature gradient is quite steady (0.011 °C/m) from surface to bottom.



The groundwater temperatures in the PAL-1 drill hole were measured by S. Tarros on June 1, 2020. The drill core log is based on a description by K. Suuroja

Fig. 20. Temperature measurement on the Paldiski drill hole on June 1, 2020 Source: Data and drafting of the figure, Estonian Geological Survey 2021.

New data fit well with the earlier interpretation on thermogeological variation in northern Estonia. The Paldiski and Kärdla logs are quite similar and correlate well also with the log from the 1.3 km deep geoenergy well at Koskelo in Espoo (Fig. 21), whereas the Jõhvi log shows consistently about 5 °C higher temperatures at respective depths. The much shorter Meriküla hole penetrating only the sedimentary rock sequence is also shown in Fig. 21. because it is the only historic measurement available from northeaster Estonia. The Meriküla hole exhibits similar temperature trend as the Jõhvi hole, but yet 2.8 °C higher temperature at 200 m depth. Jõhvi is located 25 km west from Meriküla well site and 40 km west from the Russian border in Narva. This further indicates the existence of regionally higher temperatures in the bedrock and therefore better geoenergy potential of northeaster Estonia, compared to other parts of the country.

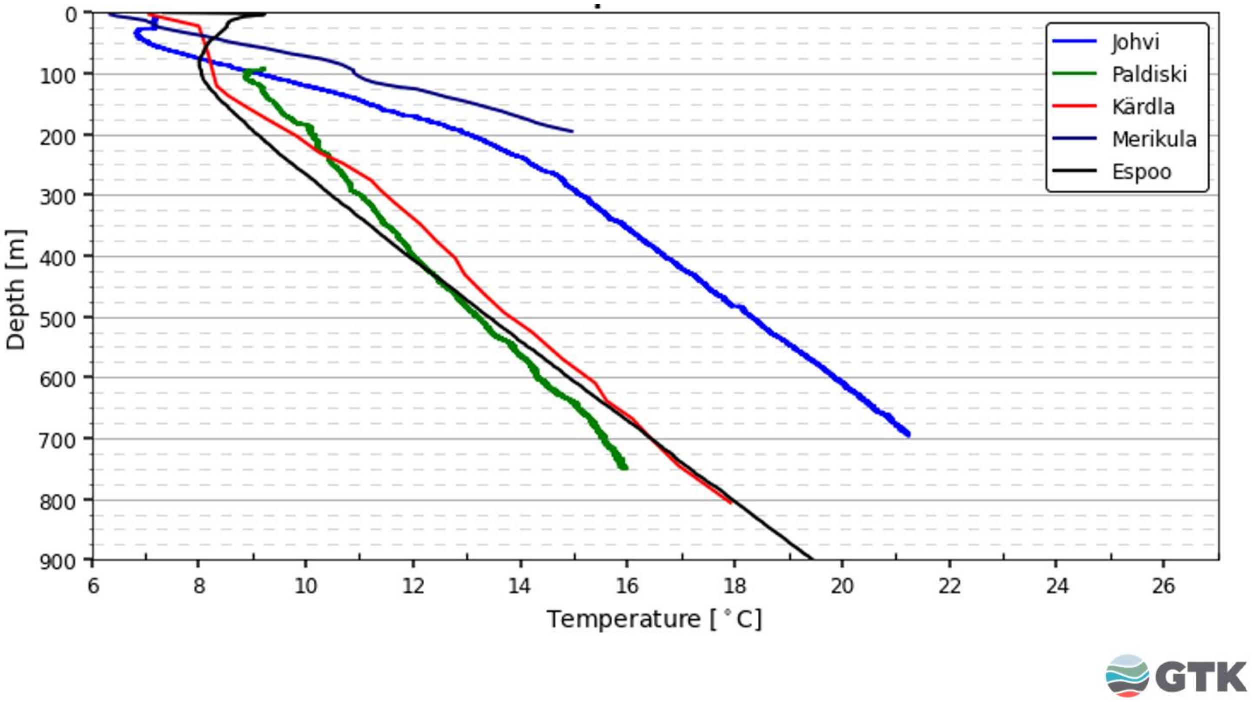


Fig. 21. Temperature – depth logs of deep drill holes in northern Estonia. The black graph refers to 1300 m deep energy well in Koskelo, Espoo. Estonian data by the Estonian Geological Survey, and Koskelo data and drafting of the figure by the Geological Survey of Finland.

Table 2. and Fig. 22. show extrapolated temperatures to 3 km depth at the sites of deep drilling. Temperatures at Jõhvi are estimated to be about 6 °C higher at 1 km depth, 9 °C higher at 2 km depth, and 12 °C higher at 3 km depth than temperatures at Paldiski, respectively. Meriküla modelling includes bigger uncertainties because of the shallow hole but is expected to give quite similar deep temperatures as estimated for Jõhvi. One hundred degrees temperature should be reached at about 5.8 km depth at Jõhvi, whereas in Paldiski the respective depth is estimated to be 7.3 km. As a comparison, 100 °C temperature was recorded in the St1's deep drill hole in Espoo at 6 km depth.

Table 2. Estimated temperatures at 1 km, 2 km and 3km depths at the sites of deep drill holes in northern Estonia. Modelling by the Geological Survey of Finland.

Drilling site	T (°C) at 1 km	T (°C) at 2 km	T (°C) at 3 km
Kärdla	20	35	50
Paldiski	19	32	44
Jõhvi	25	41	57
Meriküla	26	42	58

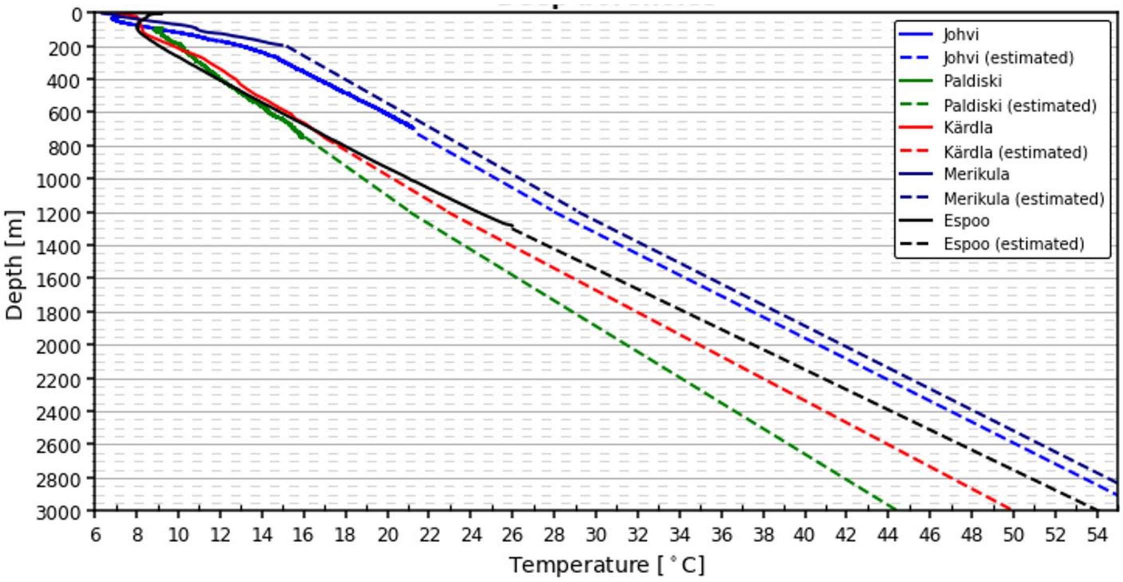


Fig. 22. Measured temperatures (solid lines) in deep drill holes of northern Estonia and Espoo, and estimated temperatures (broken lines) at the sites down to 3 km depth. The estimates apply a Paleoclimatic correction. Modelling by the Geological Survey of Finland. Data by the Geological Surveys of Estonia and Finland.

4.3. General evaluation of Estonian geoenergy potential

Geoenergy potential in northern Estonia can be considered reasonably good for practical geoenergy applications. Thermogeological properties are better or at least as good as in southern Finland, where numerous economically feasible plants already operate. So called ”blanketing effect” of the 150 to 200 m thick insulating sedimentary rock sequence has caused accumulation of temperature in the upper crystalline basement and lower sedimentary aquifers at least in northern Estonia. On the other hand, geoenergy application would need deeper wells drilled through the sedimentary rocks, which increases the drilling costs in Estonia.

Anomalously high temperatures occur in a large area in NE Estonia, but its true extend is not known because of sparse drilling. Elevated underground temperatures have been recorded in Jõhvi, 40 km west from Narva. This area exhibits the best geoenergy potential known so far in Estonia. Temperatures tend to be 4 to 6°C higher than in other parts of northern Estonia at respective depths.

Rapakivi granites are enriched in radioactive heat producing elements and thus have distinctly better geoenergy potential than gneissic bedrock. Rapakivi granites, e.g., in west Tallinn and Maardu are geologically remarkably similar than those in southern Finland and may show enhanced potential for geoenergy applications. Current information does not allow more detailed evaluation.

Geoenergy potential of central and southern Estonia appears to be poorer than in the northern part of the country, although it cannot be defined in detail. Much thicker sedimentary rock formations would increase drilling costs and bedrock temperatures are somewhat lower than in the north at respective depths. The best option for geoenergy application is related to groundwater energy using deep aquifers. A potential target could be Kuressaare town which is in an area of a large heat producing rapakivi granite.

5. Case studies of geoenergy applications in neighbouring countries

5.1. Geoenergy plants and projects in the Helsinki region

The cities of the Helsinki region have ambiguous plans to cut carbon emissions. Helsinki aims to be carbon neutral by 2035 (Helsinki 2018), and Vantaa already in 2030 (Berger 2019). The use of coal will be phased out earlier and by 2029 at the latest. This a big challenge particularly for Helsinki, because currently more than half of Helsinki's distance heating energy comes from coal.

To find intelligent ways to solve the problem and achieve carbon-neutrality, Helsinki launched the Helsinki Energy Challenge in 2020. It was a global one-million-euro challenge competition to answer the question: "How can we decarbonise the heating of Helsinki, using as little biomass as possible" (Helsinki Energy Challenge 2021)? As many as 252 teams from 35 countries, from all around the world, submitted their ideas for the Helsinki Energy Challenge. Ten finalist teams, with more than 100 people from over 40 organizations, from 12 countries, proceeded to the co-creation phase, and further developed their game changing concepts and ideas (Helsinki Energy Challenge 2021). The win was divided between four proposals (Fig. 23).

Award winner: HIVE

Award winner: Beyond Fossils

Award winner: Smart Salt City

Award winner: The Hot Heart

Fig. 23. The four award winners in the Helsinki Energy Challenge. Source: Helsinki Energy Challenge 2021.

There is no simple solution to substitute coal, but intelligent hybrid energy systems should be developed. Almost without an exception the finalists of the Energy Challenge suggest different kind of heat pumps and seasonal heat storage as part of the solution in their proposals.

In addition to various shallow, middle deep and deep geoenergy solutions, the utilization of seawater heat and underground heat storage are currently operating, under construction or at the feasibility study stage in the Helsinki region. The new heat production model combines the best aspects of district heating, and energy from geothermal and other renewable heat sources, and optimizes their use.

5.1.1. Large-scale well fields

SOK logistics centre in Sipoo

A large scale geoenergy system was built in Sipoo for SOK's logistic centre in 2012 (Fig. 24). It consist of 150 wells which are each 300 m deep and have been partially drilled under the building. Heat pumps supply heating energy with a power of more than 2 MW. SOK's geoenergy system is the first of this size systems in Finland and one of the biggest in Europe using a well field system. The design of the geoenergy system began in 2008 with site-specific surveys by the Geological Survey of Finland, after which the well field was modelled to suit the energy demand. The system is a geo-bio energy hybrid, where wood pellets produce energy for the high heat network and geoenergy for the low heat network. Geoenergy is also used to cool the building. Energy well fields are charged in the summer also with solar energy collected by the asphalt of the yard area.

Geoenergy system of a logistics centre produces about 4000-5000 MWh annually heating energy, which covers about 55% of the building's heat consumption. Clean geoenergy accounts for about 3,000 to 3,600 MWh of the total considering the share of electricity used by heat pumps. The annual reduction in CO_2 emissions is about 470 to 550 t (Kakko 2020).

Unique measurement data exist on the well field since its introduction. Behaviour of the geoenergy well field has been continuously monitored and modelled by the Geological Survey of Finland using a DTS (Distributed Temperature System) method to ensure sustainable energy production for decades from the well field (Korhonen et al. 2018). Results demonstrate that the temperature effect of a large energy well field is quite small and local, when the field is correctly designed and the energy input from the field is on an appropriate level. The temperature disturbance created by the geoenergy well field has not advanced far even though the field is large, and the amount of thermal energy extracted from the system has been larger than the amount of injected thermal energy.

Within the first 5 years of operation the temperature decrease appears to be about 2 °C. The system was initially designed for a 25-year lifetime. Because the steepest decrease in temperatures is expected during the first years of operation the results indicate that with these load levels the heat reservoir will not be depleted. However, further balancing the energy loads would improve the performance of the system.

Positive experience from the first geoenergy system led to the implementation of a similar system for the adjacent SOK's grocery logistics centre built a few years later, and currently there are 300 geoenergy wells in total.

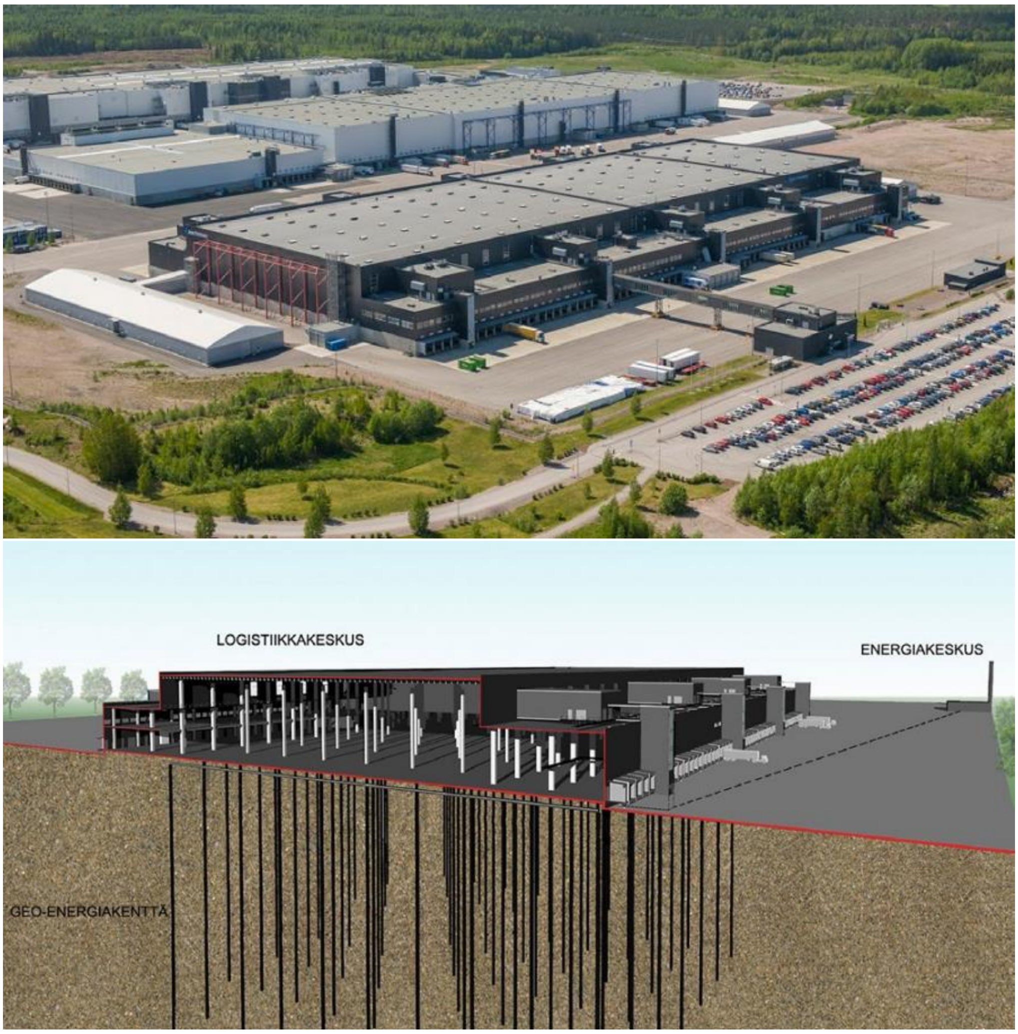


Fig. 24. SOK's logistic centre in Sipoo. In front of the photograph is the older complex, and below a diagram showing its geoenergy well field (1st phase). Similar geoenergy system was built later for the new white complex on back of the photo. Source: Uudenmaan liitto 2020, photo and figure by Parviainen Arkkitehdit Oy.

Facts of SOK logistic centre geoenergy (1st phase)

- Floor space 68,000 m^2, volume 1,100,000 m^3
- 150 wells, each 300 m deep
- Geoenergy 2 MW (heating / cooling)
- 8 heat pumps each 250 kW
- Geoenergy production about 4 000 to 5 000 MWh per annum contributing about 55% of total energy demand
- Clean energy 3 000 to 3 600 MWh per year
- CO_2 reduction 470 to 550 t CO_2 per year
- Turned out to be economically viable
- Monitoring shows that geoenergy is sustainable for over 25 years

Source: Korhonen et al. 2018, Kakko 2020, Leppäharju 2020, Uudenmaan liitto 2020

Helsinki University Tower Hospital, Meilahti

The energy solution for the Tower Hospital of the Helsinki University Hospital complex in Meilahti (35,620 m^2) was decided to be built as partially carbon neutral (Fig. 25). Geoenergy was planned to be an integral part of the hybrid energy system in 2012. Before the actual design work, thermogeological properties of bedrock were studied by the Geological Survey of Finland (GTK). Three test holes were drilled, and thermal response test (TRT measurement) were made to model the geoenergy well field.

Fig. 25. The Tower Hospital of the Helsinki University Hospital complex in Meilahti, Helsinki. Source: https://sarc.fi/en/reference/meilahden-potilastorni-2.

Geoenergy is based on 49 wells which are 250 m deep and located in the underground parking lot of the building. The system was designed so that it would produce part of the heating energy needed by the hospital, and cooling of the premises. Another part of heating energy is from district heating and a small fraction from solar heating. The designed capacity for geoenergy, based on two 692 kW heat pumps, is 1700 MWh/a for heating and 730 MWh/a for cooling.

The geoenergy system was implemented in 2014 after general renovation of the building. However, the system did not originally work well in all load situations and there were also some technical problems. Normal operation was achieved in 2018.

Geoenergy has been produced 3000 MWh/a, of which one third comes from electricity used by the heat pumps. Annual savings are estimated to be € 50,000 per year (in 2018), and reduction of CO_2 emissions 320 t/a. Total investment for geoenergy was almost € 1 million (Sinervä 2014).

Facts of Meilahti Tower Hospital

- 49 wells, each 250 m deep, located in the underground parking lot below the building.
- Geoenergy: name-plate capacity 1700 MWh/a for heating and 730 MWh/a for cooling
- 2 heat pumps each 692 kW
- Geoenergy production 3000 MWh per annum (2018)
- CO_2 reduction 320 t/a
- Total investment slightly under € 1 million

Source: Uudenmaan liitto 2020

New campus block of Aalto University in Otaniemi, Espoo

The Aalto University implemented a geoenergy district heating hybrid system for the complex of the College of Arts and Design and the School of Economics (Fig. 26). The complex also includes a small shopping centre and entrance to Otaniemi metro station. It was opened in 2018. The geoenergy system consists of 74 energy wells, which are each 320 meters deep. Heat pump capacity is 9 times 88 kW. Most energy wells are located under the campus building to make the wellfield fit on the site.

Prior to the implementation of the energy well field, the Geological Survey of Finland performed a geoenergy potential survey covering a larger area in Otaniemi, as well as site-specific geoenergy surveys in the new campus building area. Otaniemi is located on a granite-migmatite bedrock area and is well suited for geoenergy production. Site-specific measurements provided detailed information on modelling and sizing the energy wellfield. The geoenergy system was designed to produce 80% of the heating energy demand and 95% of the cooling energy needed. Geoenergy is utilized in the site also for snow melting of the yard areas applying horizontal piping placed under the paving.

Fig. 26. Aalto University's new campus block in Otaniemi, Espoo heats and cools with geoenergy. In the building there is also a small shopping centre and entrance to the metro station. The energy well field was mainly implemented under the building next to the metro tunnel. Photo © Aalto University / Mikko Raskinen.

In practice, the energy needs of buildings vary annually depending, e.g., on weather conditions and the use of the building. The energy well field is continuously monitored with a DTS (Distributed Temperature System) method to ensure sustainable energy production for decades. The DTS and building automated control system data are used in combination to enhance optimal function of the entire energy system.

Source: Uudenmaan liitto 2020

Social and health care centre, Järvenpää

The complex was built in 2016. The floor area of the building is 13,600 m^2 (Fig. 27). The geoenergy system is based on careful planning and comprise 50 wells, which are 310 m deep. Heat pump capacity (heating/cooling) is 800 kW. Initial investment was € 1.09 million. This is considerably more than investment needed for distance heating (estimated € 0.490 million), but the payback time is calculated to be only 7.1 years because of high annual savings. Return of investment is 14.1% which does not include the obvious rise of the energy price in the coming years. Geoenergy based heating and cooling costs are on an average € 83,000 per year. This is considerably less than estimated costs of an alternative solution including district heating and additional cooling equipment (€ 171,000).

Fig. 27. Social and health care centre in Järvenpää. Photo. Rototec Oy.

Facts of the Järvenpää social and health care

- Floor space 13,600 m^2, built in 2016
- 50 wells, each 310 m deep
- Geoenergy 800 kW (heating / cooling)
- Initial investment € 1.09 million
- Payback time 7.1 years
- Annual energy costs 48% of traditional distance heating and cooling

Source: Rototec 2021, Nikkinen 2019

Price comparison between traditional central heating and geoenergy using well fields, Espoo case

Rototec Oy has compared the price of energy between traditional distance heating and well field based geoenergy in Espoo city (Fig. 28). The calculation is based on the average spot price of distance heat in Espoo by Fortum and Rototec’s estimate of the price of geoenergy (Rototec Oy, unpublished company presentation 2021). The gap between the energy types shows considerable increase in the last twenty years and this trend is expected to continue. Rototec further estimates that investment costs of geoenergy varies depending on the size and type of the case between € 30-70 per m^2 and the return of investment is 6-15%.

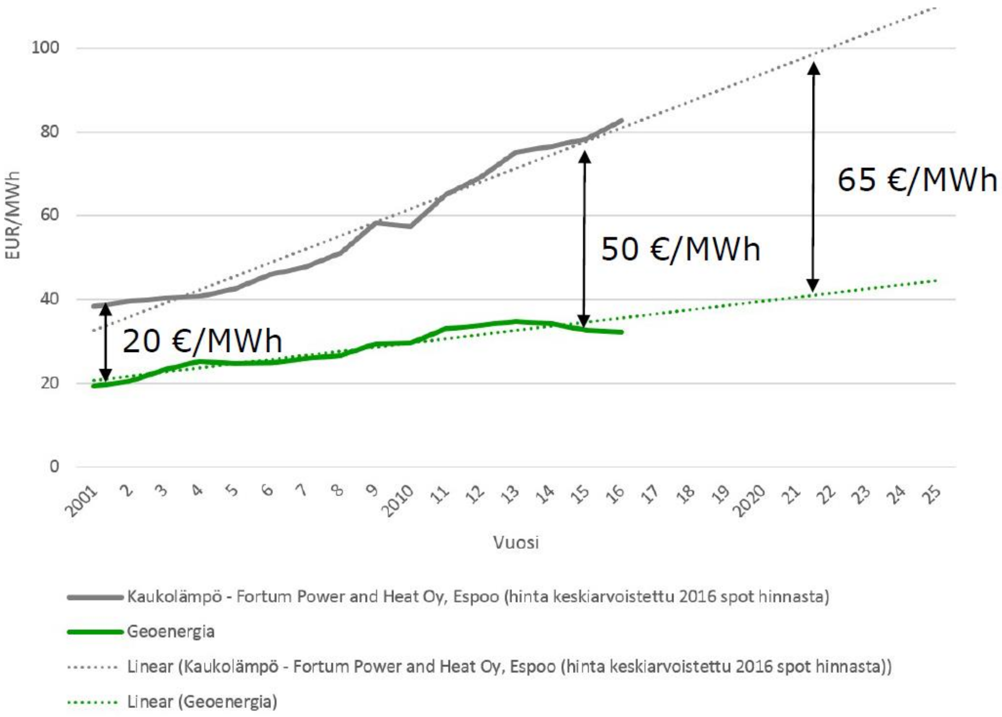


Fig. 28. A comparison of energy price between traditional distance heat in Espoo and geoenergy. Source: Rototec Oy, unpublished company presentation 2021.

5.1.2. Middle-deep geoenergy well projects

The basic principle of these 1 to 2 km geoenergy wells is like that of shallow geoenergy. Cold water is pumped underground where it gets heated before raising back to the surface. The system is based on a coaxial pipe structure, which have a maximum diameter of about 30 cm (Fig. 29). Water heated by the bedrock is pumped up along the central pipe with an inside diameter of about 10 cm. This inner tube has an insulating vacuum so that the upcoming warm water cools as little as possible on the way to the ground. However, energy lost naturally rises with increasing depth of the well, as well as drilling costs and the cost of the collector piping. Therefore, the system needs to be optimised regarding number and depth of wells. It is estimated that one watt consumed electricity for pumping will produce 3 to 4 watts of heat.

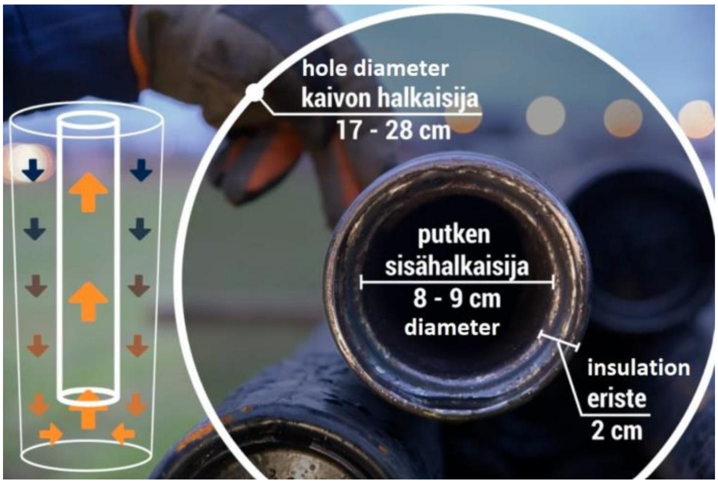


Fig. 29. Principle of a middle-deep geoenergy well. Source: Quantitative Heat 2021.

Koskelo, Espoo

The first middle-deep geoenergy well in Finland was drilled in the Koskelo area in Espoo. This pilot project is operated by Quantitative Heat Oy for a 16,000 m^2 logistic centre owned by NREP Oy. The original plan was to drill a 2 km deep well but due to an unexpected fracture zone and tight budget drilling was stopped at 1.3 km depth. The plant started production in 2020 and can contribute 60 to 80% of the energy needed. Half of financing of the project was received from BusinessFinland.

The 1.3 km deep Koskelo well can produce 250 to 300 kW constant energy, 500 kW of peak energy and over 1000 MWh per annum. This would be enough for heating four medium size (2,500 m^2) apartment buildings.

Source: Juuti 2020a, Quantitative Heat 2021.

Ruskeasuo, Helsinki

Helen Oy is designing its first geoenergy plant in Ruskeasuo. This will be made a pilot site to test and develop drilling technology and other technical solutions. The production volume of the first phase pilot plant is designed to be about 1.8 GWh of heat per year, the depth of the test geoenergy well is planned to be 2 to 3 km. The goal is to have the new plant in production in 2021.

The Ministry of Employment and the Economy has granted Helen investment support of € 5.9 million. for piloting geothermal energy. The investment aid will enable the promotion of the first medium-sized geothermal plant towards a construction decision in the coming months, as well as research into geothermal technical solutions for future projects. A medium-deep well is being used as a test site for new technology. At the same time, a unique 3D seismic reflection study and the use of artificial intelligence in the analysis of research results are developed to study geoenergy potential in urban conditions (Fig. 30). The experiences and research results of the Ruskeasuo pilot plant will be utilized in Helen's future geothermal projects. Based on the research results and the experience gained from the first geothermal plant, drilling of additional geoenergy wells is planned.

Fig. 30. Reflection seismic studies in Keskuspuisto, Helsinki. (Photo GTK).

The Ruskeasuo geoenergy well will be somewhat wider and deeper than that in Koskelo, and therefore, it will also yield more heat. It is expected to generate heat for the needs of almost seven apartment buildings. It would be important that Helen's district cooling network runs through the area. Helen plans to use the heat pumps of her geothermal plants also for district cooling in summer.

The current view is that Helen will increase the amount of geoenergy by drilling more wells in connection to one plant. It is cheaper to build one bigger geoenergy plant that utilizes several wells than to build separate plants. Another good reason for such a well field is the cost of detailed bedrock studies. For example, expensive three-dimensional studies cannot be afforded for just one middle-deep well. It is estimated that medium deep geoenergy wells can be drilled at about 100 m distance between the holes without a disturbing cooling effect.

Source: Helen 2020, Juuti 2020b.

Varisto, Vantaa

Vantaan Energia Oy is building a geothermal plant in Varisto based on a 2 km deep well (Figs. 31). The heat will be directed to the Vantaa’s district heating network and sold to customers interested in geoenergy. The plant will be built by Quantitative Heat Oy and will be commissioned in 2021. The € 400,000 support from the Ministry of Employment and the Economy covers almost a third of the EUR 1.4 million price of the facility.

The well is also suitable for energy storage, making it possible to compensate for seasonal fluctuations in energy. An animation of the system can be seen at: https://yle.fi/uutiset/3-11539531. The plant is expected to produce about 1,400 MWh of heat, which corresponds to a volume of about 40 traditional 300 m deep geoenergy wells. The solution offers customers the benefits of geoenergy without their own investment as a carefree service and at a stable price. Geoenergy is an addition to other renewable heat products in Vantaa and is considered as an innovative way to produce renewable heat.

The downside of middle deep geoenergy is that it is still a more expensive source of district heating than Vantaa's current plants. However, Vantaa Energy has a many reserve heating plants for the peak winter frosts, which are unused for most of the year. Secondly, the Vantaa waste burning plant generates heat from rubbish all year round, so in the summer there would be more heat available than is needed. Furthermore, if waste heat from, for example, data centres and building cooling could be stored, the amount of extra summer heat will continue to grow. If this extra heat can be stored underground for later use, then it would improve the economics of the plant.

Fig. 31. Drill bit of the drilling machine for middle-deep geoenergy wells. Photo. Vantaan Energia.

Source: Juuti 2020c.

5.1.3. St1's enhanced deep geoenergy project in Espoo

St1 Oy started to build an ambiguous geoenergy project in Otaniemi, Espoo in 2014 (Saarno 2018, Kukkonen et al. 2021). The project is based on the enhanced geoenergy concept (EGS), in which two (or several) deep holes are drilled down to several kilometres in crystalline rocks (Fig. 32). Water conductivity is enhanced between the holes using high pressure water pumping (stimulation). Geoenergy is recovered by a doubled well system. Heat is fed through a heat exchanger directly to the district heating network.

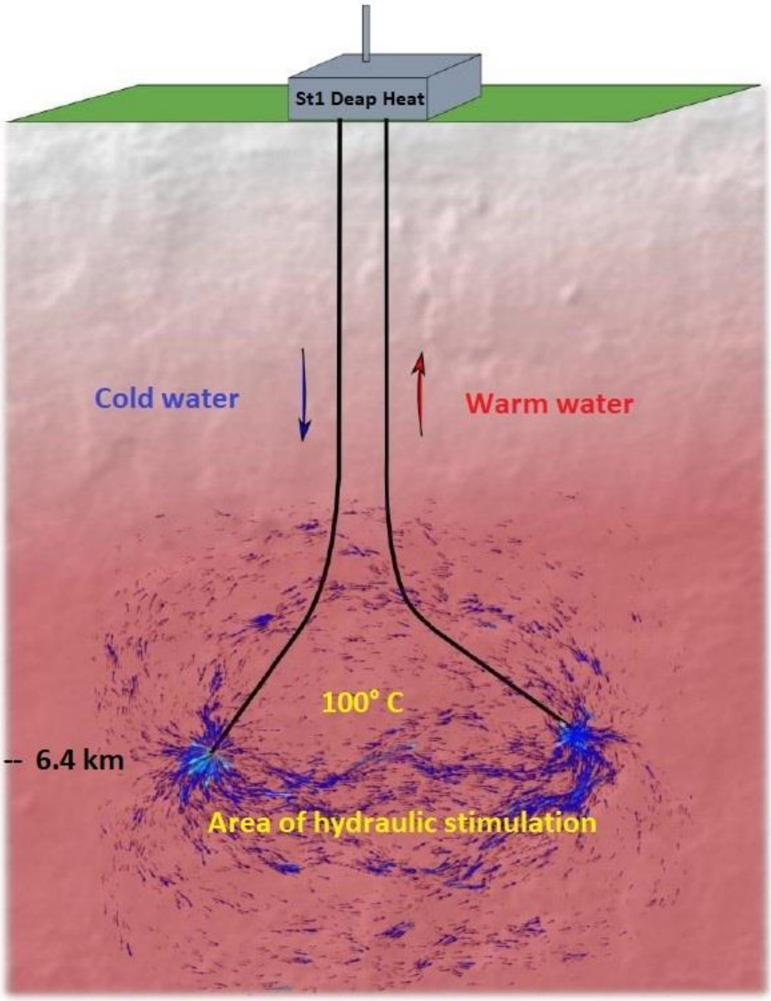


Fig. 32. Schematic diagram showing the enhanced geoenergy (EGS) concept of the St1 project, in Otaniemi, Espoo. Modified from Uski and Piipponen 2019.

The St1 project with its two deep wells extending to 6.2 km and 6.4 km depth is the world's deepest industrial geoenergy project. The project is a pilot aiming at exploring the technical and economic feasibility of deep geoenergy in the crystalline rock conditions of Finland for production of thermal power directly to a district heating network. Due to the demands of the district heating, the goal is to produce hot fluid at about 100°C and re-inject it to the formation at 50°C. The completed plant was originally planned to generate up to 40 MW of energy, which is aimed to sell to Fortum Oyj.

Fig. 33. Drilling to six kilometres depth in Otaniemi, Espoo. Source: St1, Tero Saarno.

The drilling of the deep wells was challenging, and several different drilling technologies were needed (Fig. 33). Air hammer technology was first used to reach a depth of 4.5 km. After that, the drilling was continued with water hammer technology, as well as traditional rotary drilling technology.

Another challenging point in the project is to create enhanced water flow between the drilled holes. The stimulation phase, which forced the flow of water into the cracks inside the rock, was completed in July 2018. The flow of water in the rock was monitored using geophones installed in boreholes in the surrounding area. Stimulation caused micro earthquakes in the surrounding areas.

After stimulation, analyses of water flow in the bedrock were performed. The aim of this was to specify in which direction the deep part of the second hole should be drilled to allow water flow between the holes. During the project, drilling technology has been continuously developed to become more cost-effective. One of the main problems in the project appears to be the low conductivity of water in the stimulated rock (Kukkonen et al. 2021), which does not allow large volumes of water to flow between the wells.

The project has met many difficulties, delays, and budget expansions. Currently (Q2/2021), St1 is building the plant on the ground and doing further water flow tests. The pilot project's main goal is to develop and test technically and economically viable solutions for all work phases of a deep EGS geoenergy business concept so that the concept can be commercialized after the pilot. The results of the St1 project remain to be reported.

International experiences from other countries demonstrate that many the EGS projects have failed or can produce only much less energy than originally expected (Table 3). Building of EGS geoenergy plants require high investments and seem to be risky according to experiences so far. Main problems include deep drilling to depths of over 5 km and effective stimulations of rocks to enhance sufficient water conductivity. Can the water conductivity be increased considerably to get large volumes of water circulating between the wells? Will the fractures remain open deep in the bedrock at huge pressure? How much energy will be gained, how sustainable it is, and particularly, what is the price of energy?

Table 3. Examples of enhanced geothermal systems (EGS) based power plants and projects (Uski and Piipponen 2019).

Plant/location	Depth (m)	Distance between holes (m)	Temper-ature (°C)	Energy production	Plant status	Geological setting
Soultz-sous-Forets, France	5000	650	200	30 MW heat 3 MWe electricity	Operating	Rhein graben, granite under 1.4 km sedimentary unit
Basel, Switzerland	5000		190		Closed	Rhein graben
Landau, Germany	3000	1500	160	3 MW heat 3.8 MWe electricity	Operating	Rhein graben
Cooper Basin, Australia	4300	700	260	1 MW heat	Closed	Granite under 3.6 km sedimentary unit
Pohang, Korea	4300	600	140		Closed	
Otaniemi St1, Finland	6400		100		Demonstration plant	Migmatitic granite gneisses

Facts of St1 Deep Heat project

- Two wells drilled at 6.2 and 6.4 km depth
- Stimulations of bedrock at about 6 km depth to enhance water circulation between the wells
- Water conductivity appears to remain low
- Bottom temperature 100 °C
- Initial energy production goal 40 MW
- Building and testing continues Q2/2021

Source: Saarno 2018, Uski and Piipponen 2019, Juuti 2019, Kukkonen et al. 2021.

5.1.4. Seasonal heat storage using underground caves

The need of heating energy is strongly variable depending on the season and outside temperature. Figure 34. shows the variation of heating energy in Helsinki in 2019. During cold days in January maximum need was about 2000 MW but the peak energy need can be much higher during exceptionally cold days. Average consumption in the winter was from 1000 MW to 1500 MW. In the summer months the need was around 250 MW. This means that reserve plants to contribute energy for the peak consumption need to be built, although these are only used for a limited time of the year. On the other hand, not necessary all the energy produced from different sources, such as cooling of buildings, data centres and waste burning, can be used during the summertime and should be stored.

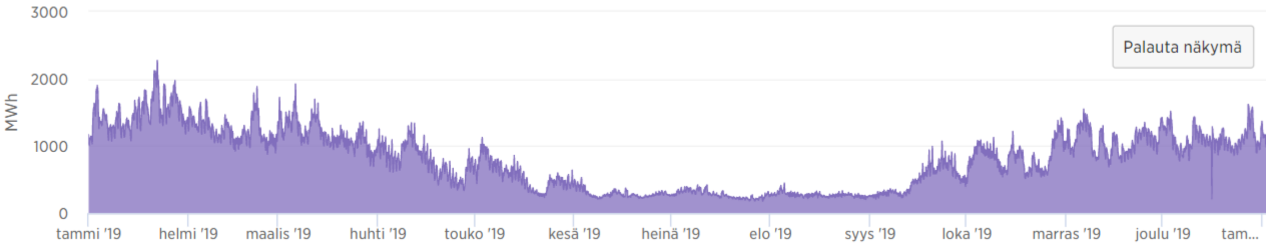


Fig. 34. Consumption of distant heat in Helsinki in 2019. Source: Helen 2021 (https://www.helen.fi/helen-oy/vastuullisuus/ajankohtaista/avoindata).

Helen Oy's projects, Helsinki

Helen Oy has used so called heat batteries in its power plants in Vuosaari and Salmisaari (Fig. 35). In Salmisaari there are two connected tanks with total volume of 20,000 m^3, which can store about 1000 MWh. In Vuosaari the volume is 25,000 m^3, and storage capacity about 1250 MWh. Both can store water at the temperature of about 90 °C.

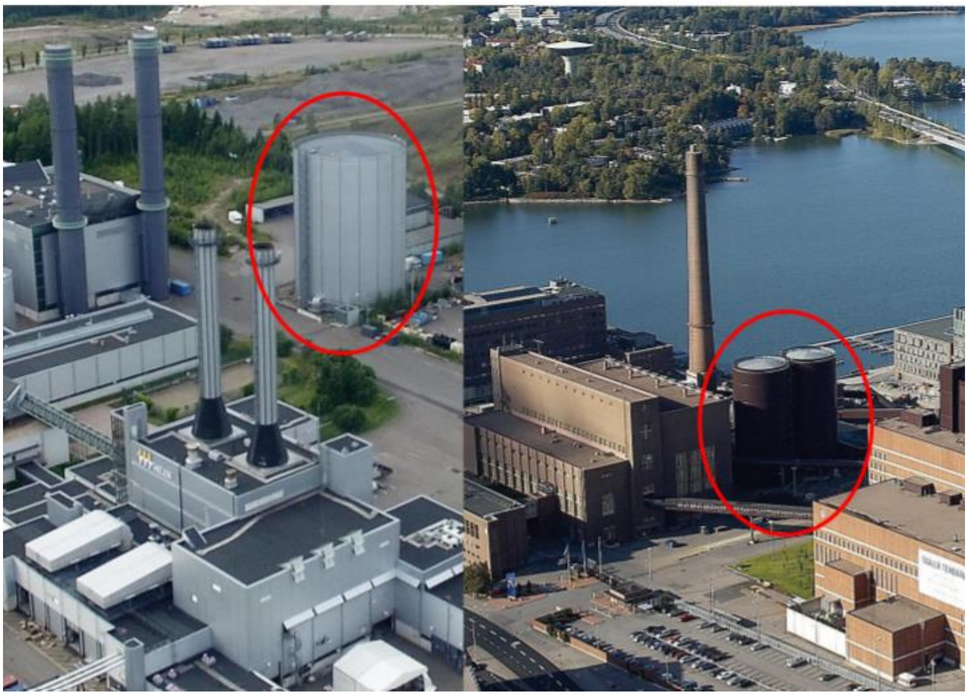


Fig. 35. Heat-storage tanks in the Vuosaari and Salmisaari power plants. Photo: Helen Oy.

The use of underground caves for energy storage have turned out be a feasible solution to balance the energy system in a larger scale by storing excess energy in water and use it during times of peak energy needs. These can be seasonal or daily variations. This kind of a smart balancing system will also decrease the need of investing in reserve energy plants and the use of these plants, which are mostly run by fossil fuels.

Helen Oy is currently constructing two underground heat storage sites. Finland's largest heat storage facility will be located in the old oil storage caves of the Mustikkamaa island (Fig. 36). Two of the three oil caves are converted into a heat battery, and the third cave is left as a water catchment area.

The connected heat storage caves are located under the pumping station. The bottom of the cave is 80 meters below sea level. Five heat exchangers have a total capacity of 120 MW. The heat storage cave can be loaded with heat in four days and unloaded also in four days.

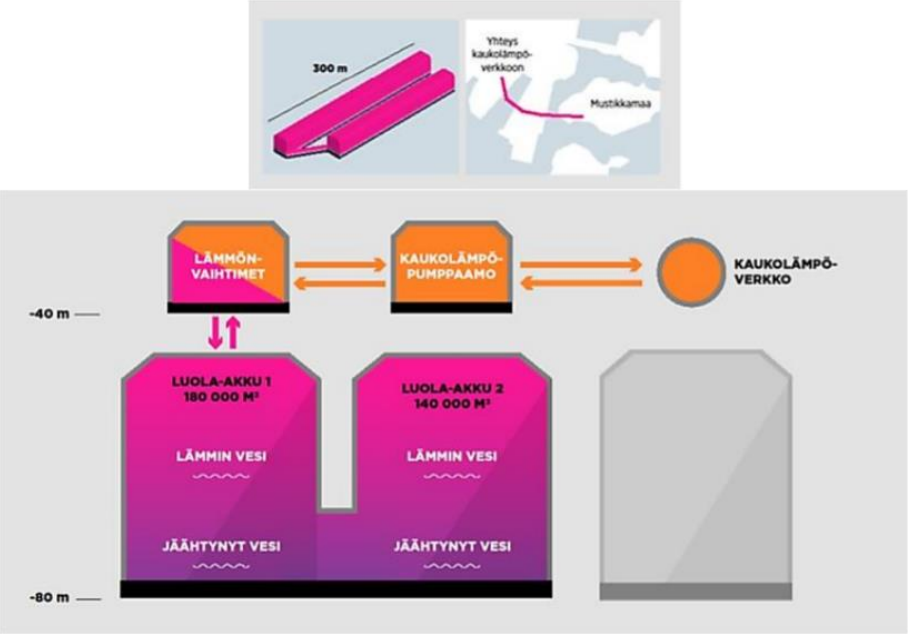


Fig. 36. Schematic diagram of the underground cave heat-storage plant at the Mustikkamaa island in Helsinki. Source: Helen Oy.

Heat storage brings flexibility to the energy system, as it compensates for varying heat consumption through charging and discharging. Thanks to the Mustikkamaa cave heat storage, not all heat needs to be used and produced at the same time. For example, it can be used to avoid the start-up of separate oil or gas-fired heating plants during the cold winter days. Heat storage reduces the use of fossil fuels and increases the use of renewable fuels and cogeneration electricity.

Facts of the Mustikkamaa heat storage cave

- Hot water is used to store energy
- Effective water volume of the caves 320,000 m^3
- Energy storage capacity 11.6 GWh
- The storage has a loading / unloading capacity of 120 MW
- Can be loaded or unloaded in four days
- Will reduce Helen's CO_2 emissions by 21,000 t
- Heat storage plant does not affect other uses of the island
- Investment is approximately € 15 million
- New technology investment support granted by the Ministry of Employment and the Economy covers € 2.1 million
- Plant completed for production in 2021

Another project is planned for the Kruunuvuorenranta area, where a new area is built by 2030. Kruunuvuorenranta will be home to 13,000 residents and 800 jobs. Two old oil caves in the area are planned to be used for heat storage applying seawater (Fig. 37). In the summer, warm seawater is stored in the caves and utilized by heat pumps as a heat source in the winter. Heat pumps can also be used to produce distance cooling. During the summer season, excess heat from buildings is also stored. The capacity of the heat storage is sufficient for approximately one third of the Kruunuvuorenranta district's heating energy demand.

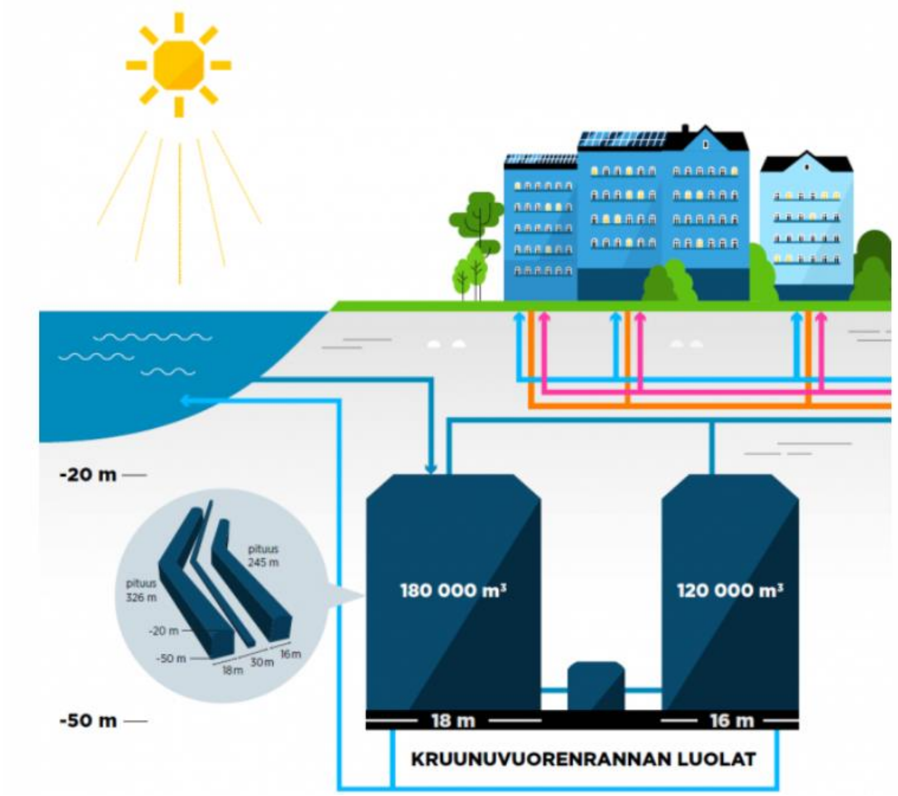


Fig. 37. Seasonal heating concept using underground caves in Kruunuvuorenranta. Source: Helen 2018. See video: https://yle.fi/uutiset/3-10036485.

Facts of the Kruunuvuorenranta seasonal heat storage cave

- Two caves with a combined volume of 300,000 m^3
- Storage capacity about 4,500 MWh
- Charging in summer with seawater at temperature about 18 °C
- Recharging in winter
- Capacity about 1.5 MW

-

Source: Galkin-Aalto 2018, Helen 2018, Ylioja and Marttinen 2018, Tiittanen 2019

Vantaa Energy’s VECTES project

Vantaa Energy has decided to stop using fossil fuels by 2026. Investments for renewable energy will be about € 200 million in the coming years. Innovative energy storage solutions will play a key role in the carbon-free energy systems of the future. The VECTES (Vantaa Energy Cavern Thermal Energy Storage) is a seasonal energy storage project, which enables harnessing the warmth of summer for the cold winter days (Fig. 38). The facility will be the world’s largest cavern thermal energy storage with 1,000,000 m^3 in size. It will have a storage capacity of 90 GWh of energy – the annual heat consumption of a medium-sized town.

VECTES answers to the challenge posed by the increasing share of variable renewable energy sources. Seasonal fluctuation of energy demand and generation is significant, and the supply of renewable energy cannot meet peak demand. Seasonal storage makes it possible for excess heat to be stored in the summertime and used to cut the demand peaks during high-demand days in the winter. The seasonal storage will be charged with energy in the summer that is either renewable or would otherwise be wasted, such as waste heat from air conditioners, solar and geoenergy.

This state-of-the-art project is a major milestone in the path to fossil free energy production in Vantaa. Stored energy replaces natural gas usage in winter and reduces district heat’s CO_2 emissions by 26,000 t per year. The facility will contribute to multiple policy objectives of the European Green Deal: increasing resource-efficiency by exploiting waste heat sources, accelerating the integration of renewable energy generation, and enabling the full integration of different energy systems.

The feasibility of the facility is based on the unique and innovative storage of hot water at exceptionally high temperature of 140°C, a solution which enables much larger storing capacity while being cost-efficient. The application is competitive and scalable also to other regions, thus contributing to the decarbonization of energy systems across Europe. Planned completion of the project is in 2026.

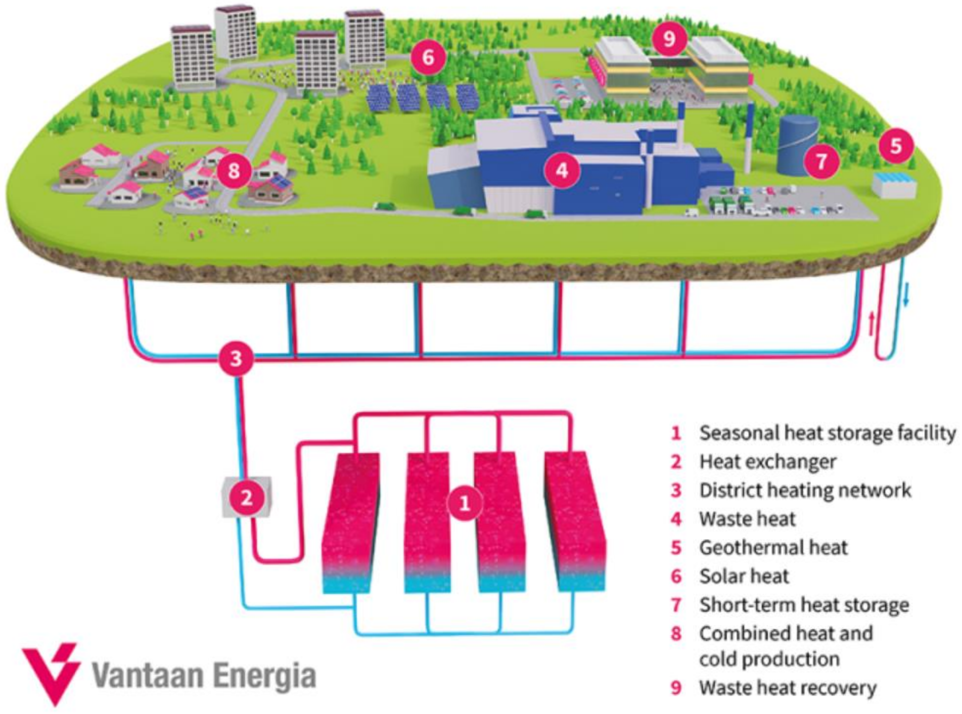


Fig. 38. Operating principle of Vantaa Energy Cavern Thermal Energy Storage system. Source: Vantaan energia 2021.

Facts of Vantaa Energy's heat storage cave

- Four caves with combined volume of 1,000,000 m^3
- Storage capacity 90 GWh
- Water temperature 140 °C
- Reduces district heat CO_2 emissions by 26,000 t per year
- Investment € 200 million
- Planned completion in 2026

Source: Vantaan energia 2021

5.2. Groundwater energy plants in Lithuania and Sweden

5.2.1. Klaipeda groundwater energy plant, Lithuania

The Klaipėda demonstration plant is a geoenergy heating plant using groundwater energy. It was constructed during the late 1990s and early 2000s (Fig. 39). It was the first geoenergy heating plant in the Baltic Sea region. Its purpose was to reduce carbon dioxide, sulphur dioxide, nitrogen oxide, and particle emissions in the area, as well as to reduce Lithuania's dependence on foreign energy sources. The plant supplied district heating to the city. Construction was financed by a loan from the World Bank (US$ 5.9 million) and a grant from the Global Environment Facility (US$ 6.9 million). The Danish state company Dansk Olie og Naturgas (now DONG Energy) provided technical support, and

Enterprise Geoterma EG served as the implementing agency. The total cost of the plant was US$ 19.5 million.

Between 1992 and 1994, the Government of Denmark financed a study of the geoenergy potential in Lithuania and Latvia. The project was called Baltic Geothermal Energy Project. Regional aquifers within the Devonian and Cambrian strata were analysed along with the energy needs and geothermal potential of 12 urban areas. Based on this project's findings and other investigations, Klaipėda was chosen as a pilot location. According to preliminary estimates, the plant would satisfy about 10% of the city's heat demand.

Fig. 39. Klaipeda geoenergy demonstration plant. Photo: https://en.wikipedia.org/wiki/Klaip%C4%97da_Geothermal_Demonstration_Plant

The plant used 38 °C water from a well drilled into a Devonian aquifer about 1,100 m depth. The heat was extracted from groundwater using a heat pump and water was circulated in a closed loop. It contributed energy to the existing district heating system.

During its construction, difficulties arose when gypsum clogged the well's filters, but these problems were overcome, and in 2004 the plant capacity was 35 MWt, of which geothermal constituted 13.6 MWt. Heat production has varied between 103,000 MWh and 215,000 MWh. Annual production rose from 100 MWth in 2001 to its maximum of 230 MWth. After 2010, the production decreased gradually before the plant was shut down in 2017, due to unfavourable economic environment and problems with injection of used water back to the aquifer. Reconstruction of the geoenergy plant is seen as the only way to solve the injection problems and restart the plant operation.

Facts of the Klaipeda groundwater energy plant

- Constructed during the late 1990s and early 2000s
- Closed in 2017
- Total cost of the plant was US$19.5 million, financed partially by World Bank and Global Environment Facility
- Used 38 °C groundwater from a Devonian aquifer at about 1,100 m depth
- Heat production 103,000 to 215,000 MWh
- Problems with injection of used used water back to the aquifer

Sources: Saulius et al. 2019, Wikipedia 2021

5.2.2. Lund groundwater energy plant, Sweden

Lund is the second largest geoenergy heat pump installation in Sweden after Värtaverket seawater plant in Stockholm (Fig. 40). The first stage of a full-scale geothermal project started in 1984. Two production wells and two injection wells were drilled to a depth of 600-700 m and a heat pump plant was built and taken into operation. Evaluation of the project during 1985 showed that the installations fulfilled the requirements and exceeded expectations. Later in the same year the next stage was initiated. This included another two production wells and three injection wells. Simultaneously a second heat pump was installed commissioned in 1986.

The geoenergy resources consist of a set of very porous sandstones belonging to the Upper Cretaceous. The sandstone aquifer is highly permeable with a transmissivity of about 3×10^{-3} m^2/s. The four production wells initially produced 450 l/s (1620 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.

Groundwater is used as a source of heat to three heat pumps, with a combined capacity of 27.9 MW. Up to 2014, the plant was producing some 250-370 GWh of 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 geoenergy heat in the district heating system of Lund. In total, the plant has produced 7.7 TWh of heat since its operation started in the 1980's.

Fig. 40. Inside view of Inside view of Lund's energy centre, and the buffer tank built for flexibility of district heating. Photos: Friotherm AG and Lunds Energi AB.

Facts of the Lund groundwater plant

- Built in 1984
- Three heat pumps, each with 9.3 MW capacity
- Heating capacity 27.9 MW
- Co-efficient of performance (COP) 2.8
- Four production wells initially produce 450 l/s (1620 m^3/h) at a production temperature of 22 °C
- Aquifer is a highly permeable sandstone at 600 to 700 m depth

Sources: Bjelm and Lindeberg 1995, Gehlin et al. 2020, Friotherm 2021.

5.3. Seawater energy in Stockholm and Helsinki

5.3.1. Värtavärket, Stockholm

Värtaverket, located in centre of Stockholm, is one of Europe's largest plants for production of district heating, district cooling and electricity. It is one of the top modern and unique cogeneration plant in the world, which produces renewable energy to approximately 190,000 apartments and electricity to be able to run 150,000 electric cars.

Ropsten seawater using heat-pump plant is an integral part of Värtaverket (Fig. 41). It is a heating plant consisting of several heat pumps centred in the harbour. Large amounts of sea water are used as the heat source. Warm surface water is taken during summer, but in winter, the water inlet is at 15 m depth where the temperature is at constant +3°C. In the Stockholm area, the seawater temperature does not drop lower at this relatively shallow level, because of the constant flow of fresh water from the rivers. This fresh water, when mixed with salt water, raises warm water from the depths of the Baltic Sea to surface near the shores of Stockholm.

Fig. 41. Ropsten is the largest sea water heat pump facility worldwide, Värtaverket cogeneration power plant in Stockholm. Photo: Friotherm AG.

Facts of the Ropsten seawater plant

- First commissioned around 1987
- The largest sea water heat pump facility worldwide
- 6 heat pumps with a total capacity of 180 MW
- In winter sea water is ingested from 15 m depth at +2.5°C and and returned at 0.5°C
- In the summer surface water is used
- Can produce 80 °C forward temperature
- Direct cooling from sea water
- Profitable business

Sources: Nowacki 2014, IEA Technology 2018, Friotherm 2021.

5.3.2. Projects in Helsinki

A new heat pump is currently built in connection with the Vuosaari power plants, which uses the power plant's own cooling water circulation and seawater heat as heat sources. This is a heat pump that is unique in this size class and utilizes seawater heat in Finland. The heat pump will be built as part of the Vuosaari cogeneration power plant development and will be located next to the existing power plant building. The heat sources of the heat pump are the waste heat from the power plant's internal cooling water circuit during the winter months and the seawater heat during other seasons, which can be utilized on an average about half a year. It is estimated that the heat pump can utilize an average of 20% of seawater heat and 80% of cooling water waste heat.

Facts of the Vuosaari heat pump

- The district heating capacity about 13 MW and district cooling capacity 9.5 MW
- Utilize an average of 20% of seawater heat and 80% of cooling water waste heat
- Ready for production in 2022
- The value of the investment € 15 million
- Reduces CO2 emissions by about 30,000 t per year

Helen is also considering building a large-scale heat pump using only seawater. The key issue in seawater heat pumps is that water warm enough should be available all year round. This means that water should be transferred to the heat pumps further away from places with sufficient water depth. Because of the shallow cost of Helsinki water should be taken about 20 km away.

Minimum seawater temperature is a matter of the optimization. The warmer the water, the less water is needed to produce heat. The lower the amount of water, the smaller the equipment needed and the lower the investment per same heat output. The warmer the water, the better the efficiency and the less electricity is needed to produce heat.

Helen estimates that a reasonable minimum seawater temperature is about 3 °C. Seawater temperatures vary somewhat from year to year depending on the weather (Fig. 42). The minimum sea water depth to produce constantly over 3 °C water is 65 m at the test site.

Because the plant should produce 90 °C warm water for distance heating, huge amount of seawater would be needed. It is estimated that about 40% of the energy would be from electricity needed to run the pumps and 60% from seawater. Therefore, the efficiency coefficient (COP) is only about 2.5, which is much lower than in ground-sourced geoenergy showing typically efficiency of 3 to 4.

Seawater heat pumps are one possible solution for energy production in Helsinki depending on future technological development and favourable market development, such as the electricity tax. Feasibility study of the seawater plant should be ready at the end of 2021.

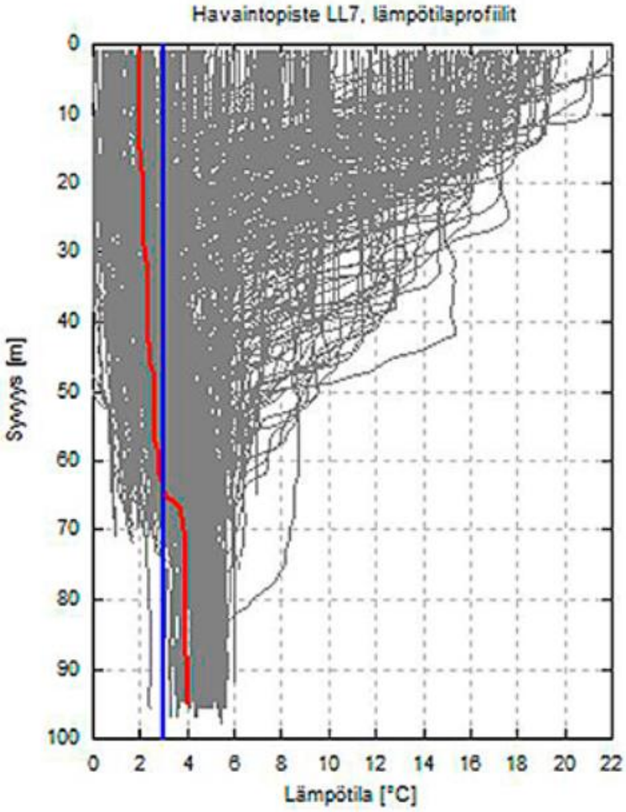


Fig. 42. Seawater temperature profiles in the Gulf of Finland. Typical temperature profile shown in red. Survey by Finnish Meteoroligal Institute. Source: Rauhamäki 2019.

Source: Rauhamäki 2019, Uusitalo 2019, Juuti 2020d. See video: https://yle.triplet.io/articles/helsinki-etsii-hyisesta-merivedesta-korvaajaa-kivihiilen-lammolle.

6. Current technologies potentially applicable in Estonian geological conditions

Geology of the Estonian crystalline basement particularly in the northern part of the country is similar as the exposed Precambrian bedrock in southern Finland. However, information on the Estonian Precambrian is rather sporadic and based only on widely spaced drill holes and regional geophysical studies. Therefore, distribution on different rock types, and their thermogeological and structural features are not known in detail. The major geological difference is the younger sedimentary rock sequence overlying the Precambrian bedrock in Estonia. It has a thickness of about 100 m in the north gradually thickening towards south where it exceeds 700 m at the deepest. Therefore, geoenergy applications dependent on wells in the heat producing basement rocks would be most cost effectively applicable in northern Estonia. However, groundwater energy might be an option for southern Estonia, but this would need additional studies of water conductivity and temperature of the deep aquifers.

The regional thermogeological properties in northern Estonia and southern Finland are roughly similar demonstrated typically about the same heat flow density values and underground bedrock temperatures. Along with the northern and particularly northeaster coast of Estonia, underground temperatures at 500 m to 1000 m depth tend to be 2 to 6 °C higher in Estonia than in southern Finland. This may be due to the “blanketing effect” of the 150 m to 250 m thick sedimentary rock sequence, which has low thermal conductivity, particularly in the thick clay units.

Detailed studies, e.g., in Finland have demonstrated that thermogeological properties can exhibit considerable local variation that is, particularly, related to different heat producing properties of various rock types. Furthermore, groundwater flow and can locally affect geothermal properties, and shear zones may cause difficulties for drilling of deep wells at individual sites. Therefore, detailed, site-specific geoscientific studies are needed to plan geoenergy utilisation.

Based on the geological and thermogeological studies, and experience on geoenergy plants and projects in neighbouring countries, particularly in southern Finland, geoenergy is considered a relevant additional energy source for heating, cooling, and seasonal energy storage also in Estonia. It would give more flexibility for the smart optimization of the energy networks and decrease burning of fossil and biofuels and diversify the heating and cooling energy systems towards zero emissions. However, geoenergy would need rather big investments and its economic viability needs to be studied case by case. Geoenergy is always a local solution, which needs to be built adjacent to existing district heating/cooling networks or buildings which will use it.

Based on thermogeological setting in Estonia, and experiences of geoenergy plants and development projects in neighbouring countries, several types of geoenergy applications are considered potentially viable in Estonia (Table 4).

Table 4. Suggested geoenergy applications and sites for pilot projects in Estonia. Priorities: 1 = Technology tested and economically viable in favourable conditions; 2 = Technology tested; economics needs to be verified.

Geoenergy application	Type of energy	Potential energy scale of plants	Suggested locations	Geological and technical notes	Priority
Shallow (<500 m) geoenergy well field	Heating/cooling/seasonal storage	Depends on no. and depth of wells, 30-50 kW per 300-400 m well[3]	Tallinn (Kopli – Haabersti), Maardu, Narva	Rapakivi granite, Narva thermal anomaly[1]	1
Middle-deep (0.5 – 2 km) geoenergy well/well field	Heating/cooling/seasonal storage	Variable 0.2 – 0.7 MW per 2 km well[3]	Tallinn (Kopli – Haabersti), Narva	Rapakivi granite, Narva thermal anomaly[1]	1
Groundwater geoenergy	Heating/cooling/seasonal storage	1 to 10 MW	Narva Jõesuu, Narva	Vendian aquifers[2]	1
Mine-water geoenergy	Heating/cooling/seasonal storage	Potentially medium to large 5 to 30 MW	Jõhvi, Kohtla-Järve, Kiviõli	Water in old oil shale mines	1
Seawater energy	Heating/cooling	Potentially large 100 to 200 MW	Tallinn, Viimsi, Maardu	Deep sea (50 - 60 m) required	2
Underground cave energy storage	Storage of daily to seasonal/heating/cooling and excess wind power	Potentially large	Tallinn area	Underground caves needed	2

[1] Rapakivi granite areas and Narva region have elevated underground temperatures.

[2] Vendian aquifers exhibit elevated water temperatures, high thickness and moderate to high water conductivity.

[3] Rough estimates by the Geological Survey of Finland (Teppo Arola personal communication 2021)

7. Suggestions for future actions and pilot projects

Larger scale geoenergy plants do not currently exist in Estonia, although there has been fast development in geoenergy applications and techniques in neighbouring Nordic countries and wider in Europe. It is suggested to a take a pragmatic and business-oriented approach for follow-up geoenergy studies and piloting in Estonia.

A government supported project, or a larger programme would be a pragmatic way to speed up the development. The possible follow-up Project should further investigate and define geoenergy potential of the selected target areas in detail, define economic viability of different applications and build the first pilot plants. This would need geological, geochemical, and geophysical studies, and boring of test energy wells. These should be used to defining site-specific energy potential in detail by giving real life figures for energy yield. The wells should be planned to be demonstration sites for the business sector to prove that the concept works.

Geoenergy plants are typically part of a hybrid energy system and should be built adjacent to the users' facilities. Therefore, close connections to real estate developers, energy companies, architects and regulators would be needed to market geoenergy and find interested parties for piloting and development. Thermogeological properties of the bedrock is very much site specific. Therefore, the test wells should be bored in locations of potential future geoenergy users to get best potential information from practical point of view and to demonstrate the proof of concept of geoenergy systems.

7.1. Location and types for pilot projects

Figure 43. shows the suggested areas for follow-up studies and pilot plants. These are selected based on expected potential for geoenergy development combined with expected needs of the society. The follow-up project should define the geoenergy potential in more detail and make scoping studies on possible applications in cooperation with the possible future users.

Fig. 43. Suggestions for follow-up study areas. 1. = Tallinn, 2 = Narva region, 3 = Mining area, and 4 = Maardu (optional).

7.1.1. Tallinn area

Tallinn would naturally be the most important target for follow-up studies and geoenergy pilots as a populated and fast-developing area. Numerous projects are under construction or planned to offer a great choice of potential partners. There would obviously be markets for a low-emission and cost-effective energy concept applying geoenergy as an integral part of heating and cooling energy systems. Geoenergy could also be connected to existing buildings to increase sustainability and possibly lower energy costs. Large-scale geoenergy systems would need seawater heating or energy storage cave-based applications.

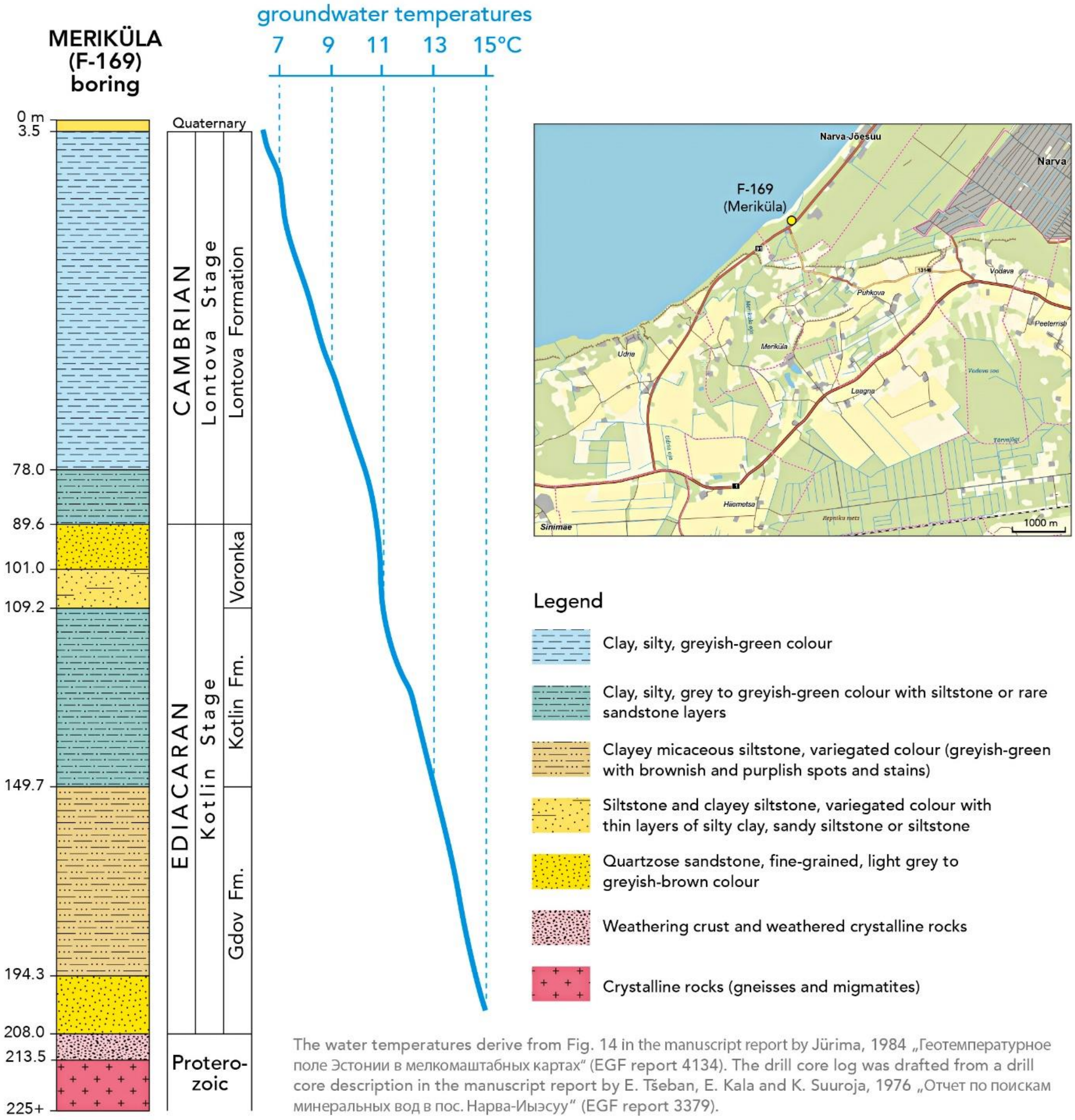
From thermogeological point of view, Kopli, Haabersti and Kakumäe areas in the northwest Tallinn would evidently be remarkably interesting, because the underlying Precambrian bedrock is expected to be part of the extensive Naissaare rapakivi granite, but relatively good geoenergy potential can be expected also in other parts of the city. However, Precambrian geology is not known in detail. Test wells are needed to define the thermogeological potential in detail. These should preferably be planned in cooperation with real estate owners and developers interested in geoenergy applications as possible part of their future energy system.

7.1.2. Narva region

Northeaster Estonia has the best natural potential for geoenergy development. This is due to a few degrees' higher underground temperatures of the bedrock than in other parts of the country at representative depths. Thermal energy seems to be concentrated in the lower part of the sedimentary rock sequence and in the upper part of the basement. This is probably due to the blanketing effect of the sedimentary rocks, which have low thermal conductivity. The Vendian aquifer in the bottom part of the sedimentary rocks is a natural temperature reservoir, as well. Suggested geoenergy applications are shallow to mid-deep energy wells or well fields and groundwater energy.

Figure 44. shows a geological section and temperature log on bore hole in the Meriküla area. The Gdov aquifer, lying directly on the Precambrian basement, is in this well 58 m thick and consists of mixed-grained sandstone and siltstone. The clay of the Kotlin Formation serves as an upper confining unit. Conductivity of water-bearing rocks is typically 3 to 9 m/d, averaging 5 to 6 m/d (Marandi et al., 2019). The thick Gdov aquifer has moderate to good water conductivity and anomalously high water temperature. Therefore, it is a potential target to be used as a groundwater energy source. Water quality of the aquifer do not allow its use as drinking water. Preliminary modelling by the Geological Survey of Finland demonstrates that the aquifer could be a significant source of energy, obviously with low investments compared to deeper wells (Table 5). Groundwater energy could potentially be used, e.g., for heating, cooling and energy storage of the Narva Jõensuu town and, for example, make the spas and hotels carbon neutral.

Also, the geoenergy wells and well fields bored in the Precambrian bedrock could be productive in the Narva region. However, there may be significant local variation in the energy productivity depending on the geology. Optimal depth, number and location of energy wells would need detailed studies and modelling. A rough estimate by the Geological Survey of Finland demonstrates that a single 300 m to 400 m deep well could yield continuously about 30-50 kW thermal energy depending on local thermogeological conditions and the collector geometry (coaxial vs. u-tube) and grouting solutions (Teppo Arola personal communication 2021).



The water temperatures derive from Fig. 14 in the manuscript report by Jürima, 1984 „Геотемпературное поле Эстонии в мелкомаштабных картах“ (EGF report 4134). The drill core log was drafted from a drill core description in the manuscript report by E. Tšeban, E. Kala and K. Suuroja, 1976 „Отчет по поискам минеральных вод в пос. Нарва-Иыэсуу“ (EGF report 3379).

Fig. 44. Geology and temperature log of F-169 bore hole in Meriküla. Data and drafting by the Geological Survey of Estonia.

Table 5. Preliminary estimates of the energy potential of the Vendian Gdov aquifer in Meriküla with various pumping rates (modelling by the Geological Survey of Finland; Teppo Arola, personal communication 2021). Parameters: water inlet temp. = 13 °C, outlet temp. = 3 °C and coefficient of performance (COP) = 4.

Pumping rate (m^3/d)	Continuous heating power (MW)	Continuous cooling power (MW)
1000	0.65	0.33
2000	1.3	0.66
5000	3.2	1.6
10000	6.5	3.3

7.1.3. Oil-shale mining area

Extensive underground oil shale mine workings are in northeaster Estonia. The yet operating mines have been decided to be closed by 2035. The towns of Jõhvi, Kohtla-Järve and Kiviõli within the mining area could apply water in old mine workings for energy purposes.

Karu et al. (2013) have estimated that huge amount of water occurs within the mine workings. Water quantity varies in the seven studied old mines between 4 and 66 million m^3. They suggested that energy production could be started with a 10 MW heat pump from one of the mines near the Ahtme power plant. Potentially, mine water could be also used for cooling and seasonal energy storage in connection with the power plants in the mining area.

A small-scale operation (0.5 MW) was installed in the Kiikla village in 2011 (Maasoojus 2021).

7.1.4. Seawater energy, Tallinn/Wiimsi/Maardu

Helen Oy has made preliminary evaluation on the application of seawater energy on a large-scale energy production in Helsinki. A feasibility study of the project is expected to be finished by the end of 2021. The project is good benchmark for Tallinn. Helen estimates that a reasonable minimum seawater temperature is about 3 °C. Seawater temperatures vary somewhat from year to year depending on the weather. The minimum sea water depth to produce constantly over 3 °C water is 65 m in the cost of Helsinki.

In the Helsinki case this means that a 20 km long pipe should be built to reach larger deep-water areas (Fig. 45). The situation is much better on both sides of the Viimsi peninsula, where >60 m deep water can be found about 5 km or less away from the shore of Paljassaare or Viimsi peninsula. Helen estimates that the efficiency coefficient in the Helsinki case is only about 2.5, which is much lower than in ground-sourced geoenergy showing typically efficiency of 3 to 4. This is due to the high need of pumping energy. However, in the Tallinn context, much less pumping energy would be needed, and seawater would practically offer an endless energy source.

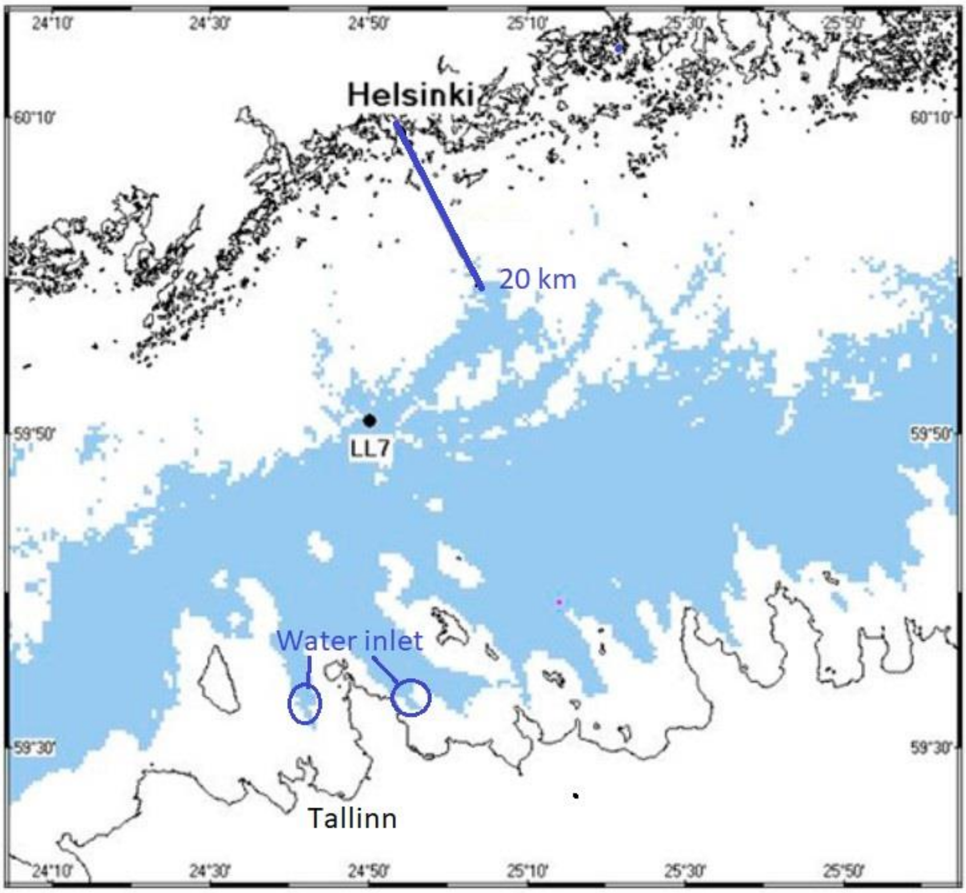


Fig. 45. Over 60 m deep sea (in blue) in the Gulf of Finland. Possible water inlet areas in Tallinn are shown. Modified from Rauhamäki 2019.

Seawater temperature has been monitored between 2017 and 2020 all year round close to the Keri island, about 20 km northwest from the Viimsi peninsula, by Tallin Technical University (Fig. 46). There are some breaks in the data caused by energy availability of the measuring system in the wintertime, but the data demonstrate quite reliably that in the Keri area over +3 °C water can be found all year round at about 55 m depth, and water temperature at 60 m depth has typically been over 4 °C. This may indicate that about 1 °C warmer seawater may be found on the Estonian coast compared to Helsinki coast, at respective depths. Temperatures at depth should, however, be monitored in the Tallinn bay and east from Viimsi for possible further scoping of the seawater energy option. Seawater offers potentially a very large-scale system, in the range of 100 to 300 MW, for energy production, but its feasibility needs to be verified.

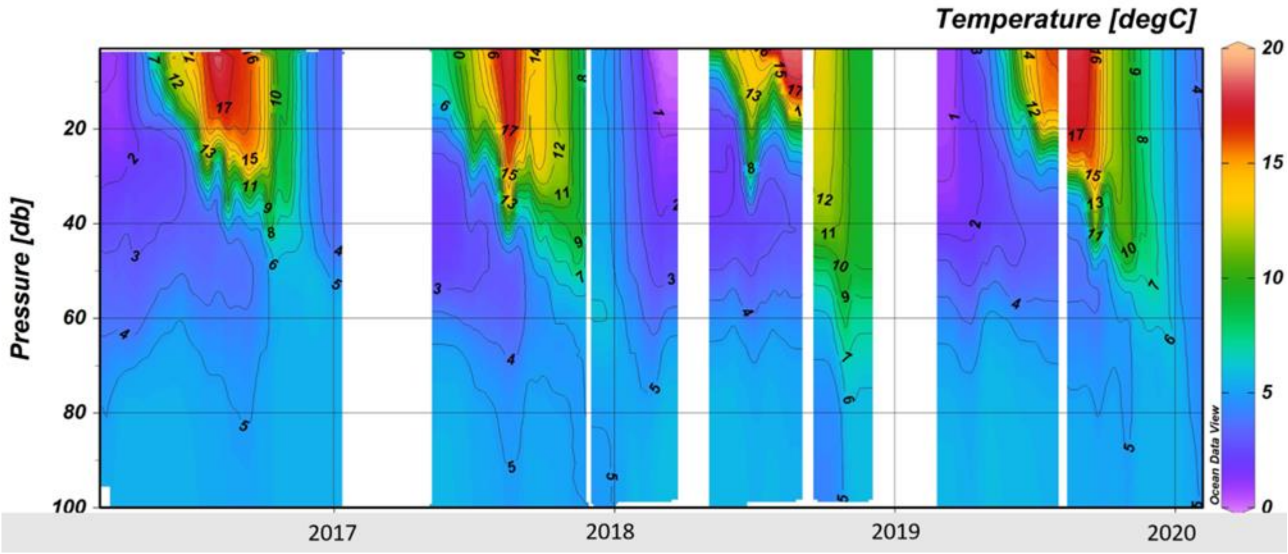


Fig. 46. Annual seawater temperature variation during 2016-2020 at bottom-mounted profiling station close to the Keri island, Gulf of Finland. Source: unpublished data by Urmas Lips (Taltech), personal communication 2021.

7.1.5. Maardu area

The Neeme rapakivi granite is the predominant rock type in the Maardu area and offers enhanced potential for geoenergy production likewise the northwest Tallinn area. Maardu can be considered as an optional area.

7.1.6. Cave energy storage, Tallinn

Seasonal energy storage is gaining an increasing role in adjusting and seasonal balancing of the energy networks. Examples of activities in Helsinki and Vantaa are described earlier in this report. Helsinki has largely used existing abandoned oil storage caves, but Vantaa plans to build new underground spaces for this purpose and store energy in water heated up to 140 °C temperatures. Similar system could be a future option also for Tallinn but would require big investments. Building of underground caves would evidently be somewhat more expensive in the geological conditions in Tallinn compared to areas of exposed crystalline rocks. Projects in the Helsinki region should anyway be benchmarked.

7.2. Steps forward

A government supported project or larger program would be a pragmatic way to study and demonstrate the feasibility of versatile geoenergy applications in Estonia, as an integral part of the energy transformation. This would be the way promote geoenergy for developers and energy companies and speed up commissioning of geoenergy applications in Estonia.

Relevant geoscientific and geoenergy related knowhow from Estonian organisations should be combined with expertise in applied geoenergy studies, engineering, and technical implementation acquired, e.g., from Finland, Sweden, and other EU countries. This would accelerate knowhow building in Estonia and help choosing the best available applications and technologies for various needs.

The core team should select in cooperation with the Ministry of Economic Affairs and Communications and relevant other parties from the business and public sectors at least 4 to 6 test areas for detailed studies of different types of geoenergy applications. The studies should lead to building of demonstration geoenergy wells and pilot plants to proof the concept of geoenergy using real-world examples for the investors, developers, and decision makers. This would be a pragmatic and the most viable way to speed up investments for geoenergy applications. Possibilities for applying different types of public – private – partnerships should be considered.

The Project should combine various aspects of applied geosciences (bedrock geology, hydrogeology, geochemistry, geophysics, environmental geology), thermogeology (petrophysics, down-hole testing and modelling), geoenergy engineering, and economic scoping. All these studies are important to optimise parameters of geoenergy systems to different applications and areas, such as, number, depth and distance of individual wells, and sustainable yield of energy.

Geoenergy studies are highly site specific because thermogeological properties may vary considerably in a kilometre scale. Therefore, test site selection is a critical phase of the project. The proof of concept should be demonstrated within the area or adjacent to possible geoenergy plants.

Furthermore, various permitting/legal and environmental issues, possibilities for public support, and geoenergy PR and promotion are integral tasks of the project.

Acknowledgements

Discussions with several people from the academia, research centres and companies helped in understanding current geoenergy applications. The Geological Survey of Estonia kindly provided geoenergy and geology related data and drafted related diagrams for this study. I am grateful for Sirli-Sipp Kulli and Heikki Bauert for their help. Discussions with Teppo Arola and Sami Valli from the Geological Survey of Finland were important to learning about geoenergy potential of Finland and Estonia, and about various practical geoenergy applications. They also made preliminary modelling on selected Estonian data. Alvar Soesoo (Taltech) kindly provided data and diagrams on previous geoenergy studies in Estonia, and Urmas Lips (Taltech) unpublished data on seawater temperature monitoring in the Keri area.

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