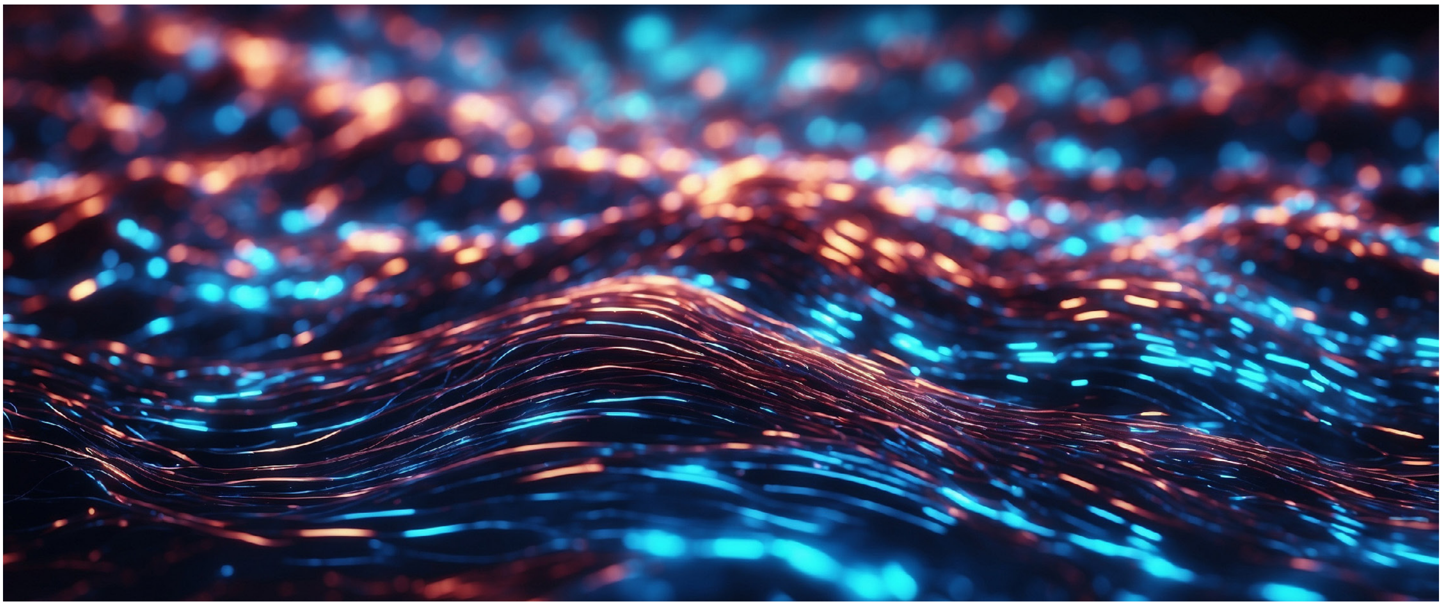


Geosciences Provide a Solid Foundation for the Energy Transition

The shift in energy production infrastructure towards clean energy requires action across multiple sectors. Geological research is playing a critical role in the transition by enabling the use of geothermal energy, identifying new sources of clean and sustainable fuel such as natural hydrogen, and ensuring required infrastructure such as new power plants, underground energy storage, and safe nuclear waste disposal sites are built on solid foundations.

Why do we need to understand the sub-surface?

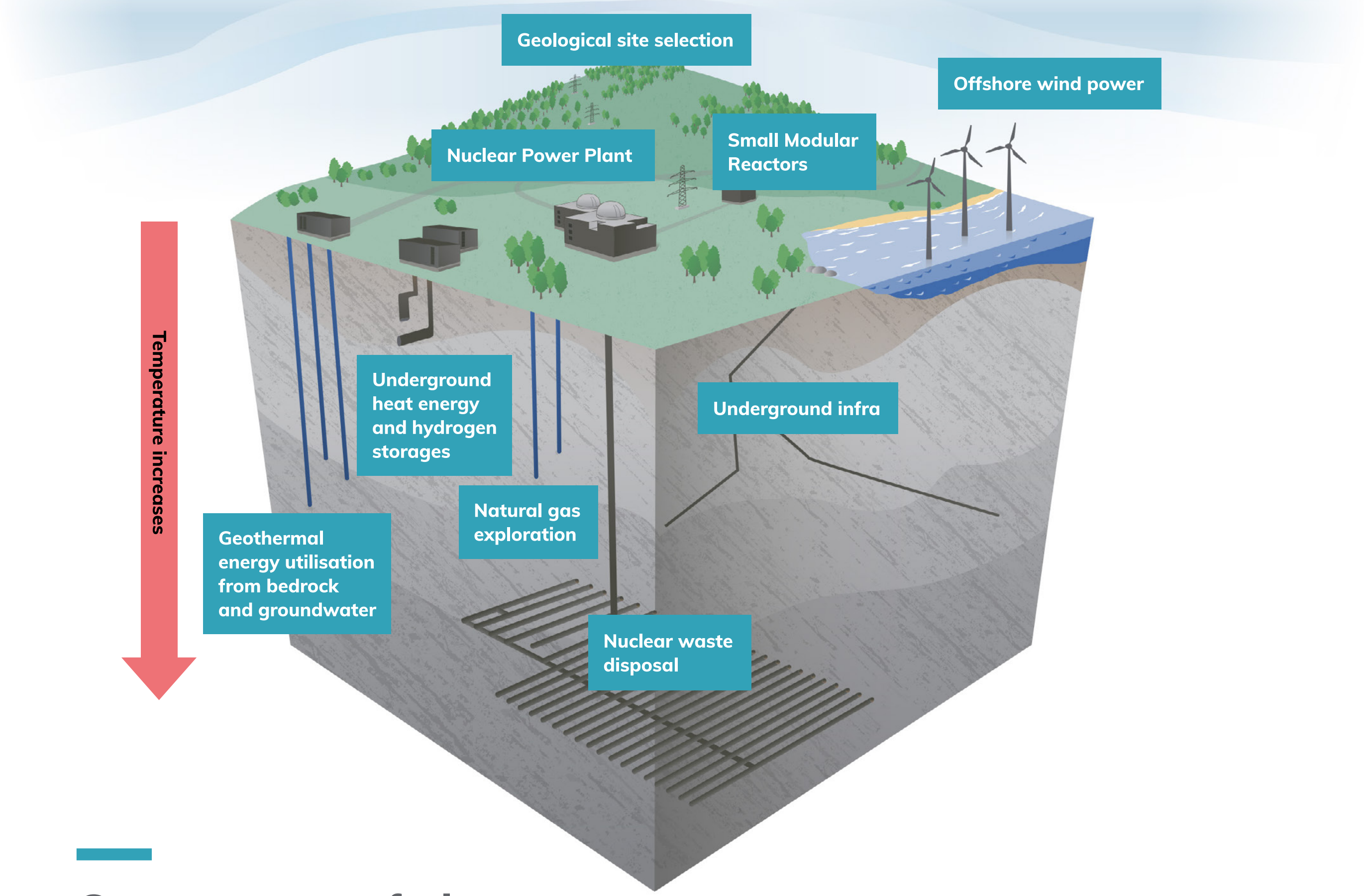
With its decades of experience, Finland is a leader in the field when it comes to utilising the sub-surface to support the energy industry. Geological understanding plays a key role in the optimisation of resource use and leveraging of the underground for various purposes. GTK's activities support the energy transition by focusing on:

- **Geothermal energy and gas exploration**
- **Underground energy storage**
- **The siting and safety of nuclear power plants and radioactive waste disposal**
- **Energy infrastructure planning and development**
- **The availability and circular economy of critical raw materials (see individual Policy Briefs)**

A key challenge is acquiring detailed knowledge of the sub-surface, often to depths of kilometres. From the shallow surface layers to deeper bedrock, properties such as fracturing, groundwater flow and temperature variation can be complex and difficult to interpret. Finland's ancient and heterogenous bedrock makes investigations even more complex. The activities mentioned above rely on continuous development of our understanding of sub-surface properties through the study of geological formations, rock types, sediments and groundwater, and involve building multidisciplinary conceptual models of the sub-surface that can be used to assess the feasibility of new energy infrastructure projects or optimise existing structures.

GTK research presented in this Policy Brief contributes to these United Nations Sustainable Development Goals

Energy and the sub-surface



Current state of play

Geothermal energy and gas exploration

Geothermal energy has played an integral role in Finland's energy system since the 2010s. Despite this early adoption, **only a fraction of Finland's geothermal potential has been harnessed.** For instance, the topmost 300 metres of the ground in Finland could provide enough heating energy for the next 25,000 years based on current utilisation patterns. This highlights the vast untapped potential of our geothermal resources, which are crucial for the country's energy future.

Currently, the majority of new homes in Finland that utilise geothermal energy for heating rely on shallow geothermal systems, with deeper geothermal projects still in development.

The sector is also evolving towards larger installations and centralised energy distribution systems, all of which will make geothermal energy a more significant player in the country's energy landscape in the future. In parallel, exploration for natural hydrogen and other gases is growing, with the hope that these resources will further contribute to clean energy production. Scientific understanding of underground gases is key to the energy transition and requires dedicated research.

Underground energy storage

Underground energy storage is a critical area where innovation is needed to optimise energy management, particularly to **balance the fluctuating energy supply and demand** due to the variable production of renewable energy sources such as wind and solar power.

Underground energy storage is rapidly developing in Finland today. Advances can be seen in new thermal energy storage systems that offer cost-effective solutions for both cooling and storing excess heat, which can then be used for heating in the colder seasons. Additionally, development of underground storage facilities for gases such as hydrogen is ongoing. These advances promise to play a crucial role in Finland's energy strategy as the demand for efficient energy storage grows in the future.

Siting and safety of nuclear power plants and radioactive waste disposal

For over 40 years Finland has been at the forefront of research into the underground disposal of nuclear waste, which requires careful management over long timescales. **Understanding the geological stability of potential sites is critical, not only for waste disposal but also for the siting of surface infrastructure** such as nuclear power plants.

Disposal of low- and intermediate-level radioactive waste is ongoing in semi-deep rock caverns at Loviisa and Olkiluoto. In the near future, deep geological disposal of spent nuclear fuel is expected to begin at Olkiluoto, managed by Posiva Oy, marking a major step forward in Finland's nuclear waste management efforts.

Discussions around the use of Small Modular Reactors (SMRs) as part of government solutions to tackle the energy transition are also gaining momentum. However, these reactors require careful planning and sub-surface knowledge, including underground facility designs. Challenges remain in terms of the development of facility siting criteria as well as issues related to the management and disposal of SMR waste. The geosciences can contribute to cost-effective and seismically safe siting plans for SMRs, for example by identifying structurally weak areas in the bedrock that should be avoided.

Supporting energy infrastructure planning and development

Despite their importance, geological factors are not always prioritised in the planning of new energy infrastructure projects. There is an **increasing need to more fully incorporate geological criteria into the screening process for energy infrastructure projects in order to optimise both site selection and safety, and ensure that Finland's energy systems are as robust and sustainable as possible.**

This also requires smarter area planning as sub-surface environments can be very variable, even within a relatively small area. Smart siting also saves resources and increases the probability that construction will go smoothly. These aspects should be considered by municipalities in the planning stages, and by companies planning to build and operate facilities during the economic and social feasibility assessment stages.

There is also increasing pressure for critical infrastructure to be developed in offshore environments, for example due to ongoing windfarm development.

At sea just as much as on land, geological understanding of sub-surface properties is critically important to ensure the future resilience, safety and security of the built environment.

SMR

Small Modular Reactors (SMR) are being considered by several Finnish municipalities as a potential future energy source for district heating. Globally, electricity-producing SMRs are also being planned and some have already been built.

SMRs can provide energy from sources closer to users and with more flexibility than conventional nuclear power plants. SMRs can vary in size, the biggest being similar in terms of power output to the smallest conventional power plants.

They have variable designs, and hence also variable forms of nuclear waste requiring disposal. Due to the different sized fuel assemblies, alternative disposal methods for some types of SMR waste are being considered, such as deep bore hole disposal of radioactive waste (DBD).

DBD is already planned for other radioactive waste types, e.g. in Malaysia, but its feasibility for high-level radioactive waste is unproven.

Natural Hydrogen

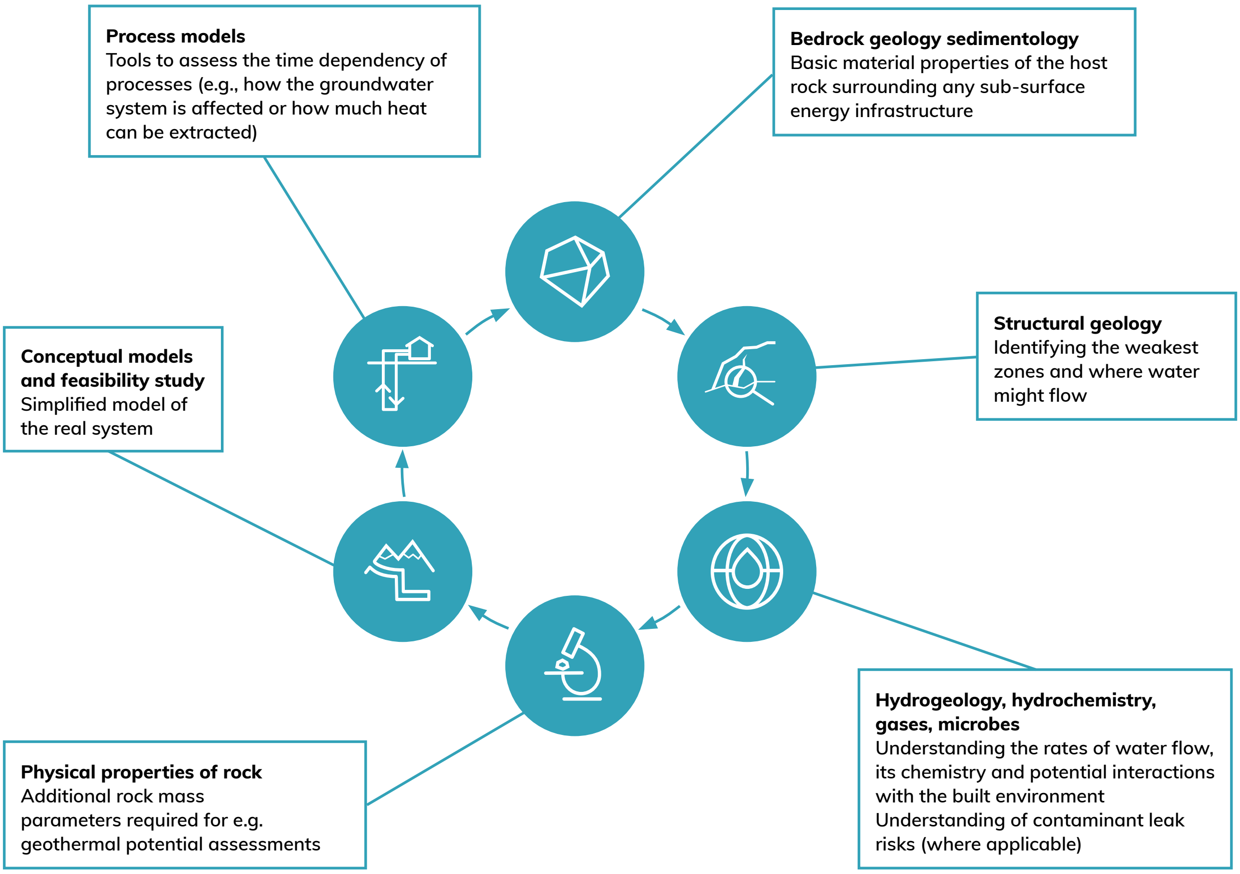
Natural hydrogen (molecular hydrogen, H_2) exists in Finnish bedrock mainly as dissolved gas in deep groundwater that also contains other dissolved gases such as methane, helium and nitrogen.

Hydrogen can form either via reactions between iron-bearing minerals (which require heat) or via radiolysis of water (a process related to the decay of naturally occurring radioactive elements in the bedrock).

To date, no dedicated mapping has been performed in Finland or globally, and the true nature of the potential resources remain largely unknown.

Growing importance of onshore and offshore sub-surface environment exploration

Geoscientific studies support a range of energy infrastructure operations via multidisciplinary workflows that can be tailored and developed for different applications. Geoscience is integral to the conceptualisation of sub-surface environments for system modelling, which enables assessment of factors such as overall system understanding, energy production, safety and the long-term performance of energy infrastructure. Modelling of thermo-hydro-mechanical-chemical-biological (THMCB) processes in various combinations is called for.



An example of a workflow for the study of geological formations, including their physical and chemical properties, to develop conceptual models to be used as the basis for dynamic modelling in energy transition projects.

Several emerging applications for deeper sub-surface areas warrant attention

Geothermal energy: untapped potential

According to geothermal potential maps produced by GTK, there is still significant potential for heating and cooling, making it crucial to enhance research and optimise geothermal energy utilisation. In addition, deeper potential sources for heat extraction are being assessed, which may further support heat delivery to a centralised heating network in the future.
Major advances have been made in understanding the geothermal potential of the deep bedrock.

Natural hydrogen as a novel energy solution

Natural hydrogen is a promising energy source for international markets. GTK has compiled a preliminary collection of natural gas measurements; however, there is an urgent need for a more dedicated survey to comprehensively assess the natural hydrogen capacity of the Finnish sub-surface environment.

Potential deployment of Small Modular Reactors (SMRs)

This equires siting, which involves fulfilling various socioeconomical and scientific criteria including understanding the geological conditions and overall stability of the site. In Finland, existing expertise can be utilised to screen suitable bedrock blocks, as recently pointed out in a dedicated report.

Alternative waste disposal methods for nuclear waste (for example deep borehole disposal)

These are being proposed by many private companies developing SMRs. These ambitions need to be evaluated based on a thorough assessment of the feasibility of such facilities compared to traditional geological cavern-based disposal of nuclear waste. This requires both geological studies at greater depths than today as well as new modelling approaches and long-term safety considerations.

Optimisation of geological disposal of radioactive waste

This is an emerging area of research as disposal programmes develop. This calls for new types of geological analogue studies ranging from investigation of new geomaterials to global scale processes, such as the natural variations within industrial mineral sources and the effects of climate change on disposal safety.

Interaction with other infrastructure

Sub-surface activities are interconnected with other planned infrastructure, including mining operations and other exploration activities. These interactions must be carefully managed to avoid conflicts and facilitate sustainable use of resources. One particular field of potential overlap is the exploration of deeper groundwater reserves. Moreover, there is a shared need to develop methodologies for deep sub-surface characterisation, which would provide great research synergy.

A comprehensive understanding of Finland's onshore and offshore sub-surface environment is critical to support the country's clean energy transition and ensure the responsible use of its geological resources. A multidisciplinary workflow covering various aspects of defining e.g. the geological, structural, and thermal properties of the bedrock as well as groundwater flow properties, geochemistry, and geomicrobiology is required to develop our process understanding. The knowledge gained could be further utilised, for example, in models that seek to describe the future behaviour of energy infrastructures over periods of decades (e.g. energy storage) to millennia (radioactive waste disposal), both in Finland and internationally.

How can we maximise the potential of the geosciences to aid the energy transition?

To maximise the potential of sub-surface geology for the energy transition, the following actions are recommended:

Enhance geoscientific expertise. Strengthen research and expertise in critical areas like geothermal energy and underground storage, ensuring Finland remains a leader in sustainable energy solutions.

Support innovative energy storage solutions. Focus on the development of underground energy storage methods, particularly for heat and hydrogen, to ensure a stable energy supply.

Invest in advanced geological assessments. Develop and deploy cutting-edge techniques for geological site surveys, particularly for energy projects that require high safety standards.

Invest in gas exploration methodologies, mapping and potential modelling. Systematic surveys and mapping are critical to understand Finland's natural hydrogen potential.

Support safety and feasibility in nuclear waste management. Continue to advance geological research to ensure long-term safety, improve our understanding and optimise nuclear waste disposal.

Foster collaboration and knowledge sharing. Encourage partnerships between research institutions, industry and government to drive innovation and share knowledge of sub-surface geology applications.

Account for diverse societal interests in sub-surface investigation. The growing societal interest in sub-surface exploration spans significant depths, from the near-surface environment down to several kilometres deep in the bedrock. Such investigations are linked to and support a range of resource extraction practices – of minerals, groundwater, and energy – with potential for both synergies (for example groundwater energy use) and conflicts between uses (for example waste storage vs. commodity extraction).

Sources and additional information

GTK's research areas, policy briefs and research projects

Energy transition information and research projects

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- Research on the Seafloor's Constructability Properties Supports the Design of Offshore Wind Power
- Geological Expertise Enables Nuclear Energy Generation
- Geology in the Hydrogen Era
- GTK`s Alan Bischoff Believes that Research on Deep Geothermal Energy Deserves a New Endeavour
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The Geological Survey of Finland (GTK) produces impartial and objective research data and services in support of decision-making in industry, academia, and wider society to accelerate the transition to a sustainable, carbon-neutral world. GTK employs more than 400 experts specializing in the mineral economy, circular economy, solutions related to energy, water and the environment, as well as digital solutions. GTK is a research institution governed by the Finnish Ministry of Employment and the Economy, operating in Finland and globally.