Energy
National Research Programmes 70 and 71

Synthesis

Geothermal Energy

Geothermal Energy

Joint synthesis

1. Geothermal Energy

Synthesis of the NRP 70 joint project
“Hydropower and geo-energy”

1.1. Summary

1.1.1. Summary

Near-to-surface geothermal energy with heat pumps is state of the art and is already widespread in Switzerland. In the future energy system, medium-deep to deep geothermal energy (1 to 6 kilometres) will, in addition, play an important role. To the forefront is the supply of heat for buildings and industrial processes. This form of geothermal energy utilisation requires a highly permeable underground area that allows a fluid – usually water – to absorb the naturally existing rock heat and then transport it to the surface. Sedimentary rocks are usually permeable by nature, whereas for granites and gneisses permeability must be artificially induced by injecting water. The heat gained in this way increases in line with the drilling depth: at a depth of 1 kilometre, the underground temperature is approximately 40°C, while at a depth of 3 kilometres it is around 100°C. To drive a steam turbine for the production of electricity, temperatures of over 100°C are required. As this requires greater depths of 3 to 6 kilometres, the risk of seismicity induced by the drilling also increases.

Underground zones are also suitable for storing heat and gases, such as hydrogen or methane, and for the definitive storage of CO_2. For this purpose, such zones need to fulfil similar requirements to those applicable to heat generation. In addition, however, a dense top layer is required above the reservoir so that the gas cannot escape.

The joint project “Hydropower and geo-energy” of the NRP “Energy” focused on the question of where suitable ground layers can be found in Switzerland that optimally meet the requirements for the various uses. A second research priority concerned measures to reduce seismicity induced by deep drilling and the resulting damage to buildings. Models and simulations were also developed which contribute to a better understanding of the underground processes involved in the development and use of geothermal resources.

In summary, the research results show that there are good conditions in Switzerland for the use of medium-deep geothermal energy (1 to 3 kilometres) – both for the building stock and

for industrial processes. There are also grounds for optimism concerning the seasonal storage of heat and gases. In contrast, the potential for the definitive storage of CO_2 in relevant quantities is rather limited. With respect to electricity production using deep geothermal energy (> 3 kilometres), the extent to which there is potential to exploit the underground economically is still not absolutely certain. In this regard, industrially operated demonstration plants are urgently needed in order to boost acceptance among the population and investors.

1.2. Core messages

1.2.1. Core messages

Underground zones can, and in all likelihood will, play a key role in the future Swiss energy system. The following four core messages can be derived from the research work conducted as part of the joint project "Hydropower and geo-energy":

1. **Potential exists** – In recent years, Switzerland has made great progress in the use of near-to-surface geothermal energy, for example through the use of heat pumps. On the other hand, the potential offered by the undisputed heat reservoirs at greater depths (1 to 3 kilometres) has not yet been exploited. These are particularly suitable for feeding into local heating grids and industrial processes. In contrast, the use of geothermal energy for the production of electricity is still in its infancy. It will be able to achieve a breakthrough, however, as soon as the risks of induced earthquakes are controlled. The potential for storing gas and CO_2 is also proven, though limited.
2. **Adopt a holistic approach** – The possible use of underground zones for heating, electricity production and as a storage medium, as well as the geological, hydrogeological and tectonic conditions found underground, must be addressed holistically. This must be undertaken together with all aspects relating to the energy supply and greenhouse gas emissions, taking account of the various dependencies. Only in this way will it be possible to find optimal solutions.
3. **Broad acceptance necessary** – The great potential offered by deep geothermal energy cannot be exploited without the approval of the population. In order to achieve the necessary broad level of acceptance for the relevant technologies and specific projects, the population must be involved in the projects at an early stage and provided with comprehensive information about the advantages and disadvantages. Research shows that – when provided with complete facts that are communicated comprehensibly – citizens are very well placed rationally to weigh up the interests relating to the different options for ensuring an economically and environmentally

sustainable energy supply in the long term.[1]

4. **Set priorities** – To support the fundamental transformation of the Swiss energy system as effectively as possible over the coming decades, clear priorities need to be set for the use of underground zones:
    1. The extraction of heat from medium depths (1 to 3 kilometres) to reduce CO_2 emissions substantially.
    2. The separation of CO_2 at important point sources, such as cement works and waste incineration plants, and the appropriate use of CO_2 or its permanent storage.
    3. The expansion of geothermal electricity generation to meet the increasing electricity demands that will result from sector coupling (e.g. electromobility, heat pumps).

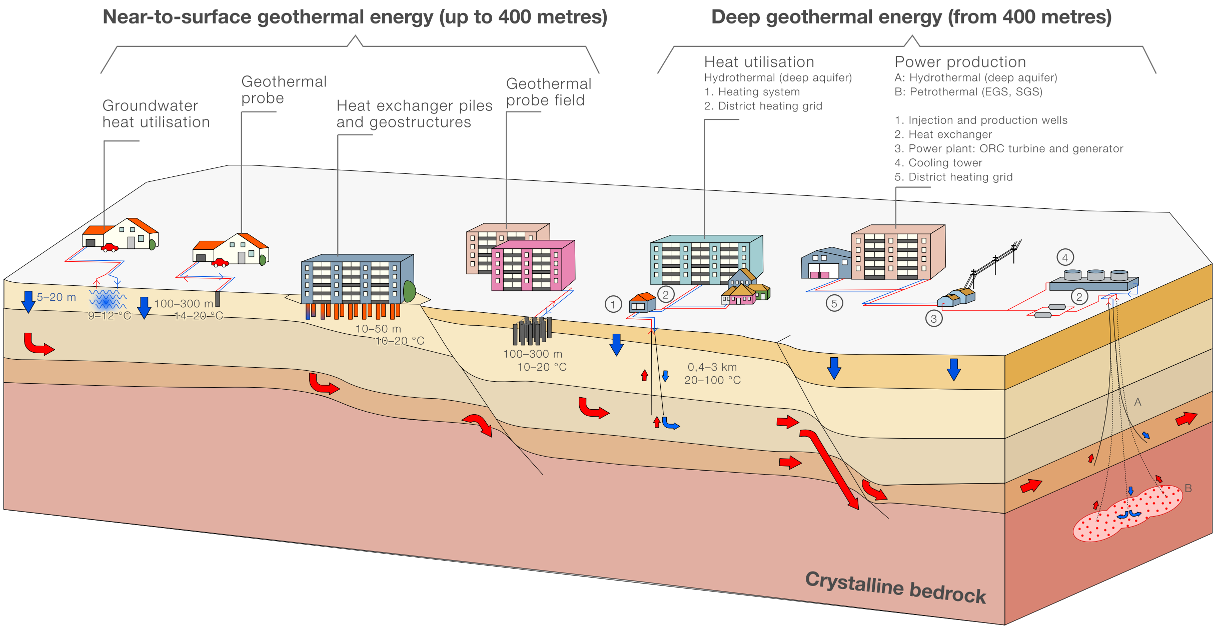
Notes and References

1 Knoblauch, T. A., Trutnevyte, E., & Stauffacher, M. (2019). Siting deep geothermal energy: Acceptance of various risk and benefit scenarios in a Swiss-German cross-national study. Energy policy, 128, 807-816.

1.3. The underground as part of the energy system

Heating # Heat pump # Energy provision

1.3.1. Forms and use of geothermal energy



Possibilities for using geothermal resources for heating and the power supply. *Source: Geothermal Switzerland, modified according to CREGE*

The Swiss underground offers a multitude of opportunities for supporting the objectives of Energy Strategy 2050. To the forefront are heat utilisation, electricity production and the ability of rock formations to store heat and gases.

The heat beneath our feet originates from the early period of the Earth's formation as well as from continuous radioactive decay processes. In the Earth's core, the temperature is probably still up to 6,000°C. It decreases towards the Earth's surface, falling at a gradient of around 30°C per kilometre in the areas directly below us. This so-called geothermal gradient results in a natural stratification of the temperature levels: in the case of near-to-surface geothermal energy, temperatures range between 10°C and 20°C. This energy source can be used with heat pumps for heating and cooling purposes. Deep geothermal energy at a depth of 1 to 3 kilometres provides heat in a temperature range of up to 100°C. This is sufficient for heating grids or industrial processes. To generate electricity, it is necessary, in line with the latest technology and for reasons of efficiency, to access temperatures of over 100°C and thus depths of 3 to 6 kilometres.

Switzerland is – at least in the field of near-to-surface geothermal energy – already a real geothermal country. In 2018, a total of 9.3 PJ[1] of heat was extracted, 85 % of it via borehole heat exchanger fields and heat pumps.[2] On the other hand, direct geothermal heat utilisation without heat pumps and deep geothermal energy for electricity generation only play a niche role. There is great potential here to make sustainable use of existing resources.

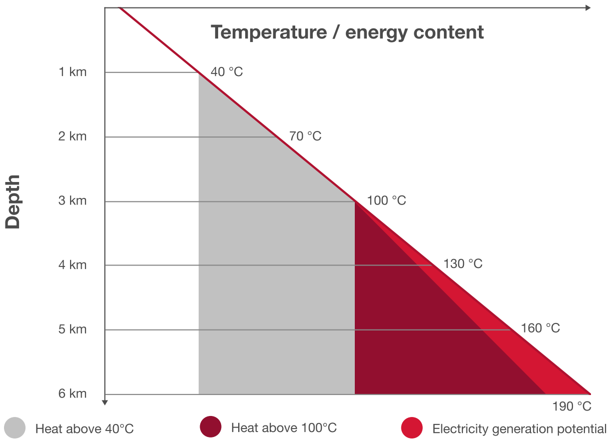
Notes and References

1 1 petajoule (PJ) =10^{15} J, equivalent to approximately 278 GWh, a 1 GWh power plant produces a maximum of 31.5 PJ per year.

2 Swiss renewable energy statistics, 2018 edition

Resources   # Cold / heat   # Sustainability   # Energy provision

1.3.2. Deep geothermal resources have not been tapped



The temperature in the ground increases by about 30°C per kilometre of depth. Considerable amounts of heat are available above a temperature of 40°C (for room heating) or 100°C (for heating grids and industrial processes). If you want to generate power, the latter can be converted into electricity with an efficiency of 12 % to 13 %.

In the case of deep geothermal energy, heat is extracted from an area between 1 and 6 kilometres beneath our feet. Temperatures here can be between 40°C and 190°C. The geothermal energy is available in the form of rock heat. This can be extracted using suitable carrier media – usually water. In Switzerland, the Mittelland region and the Alpine valleys of the major rivers account for 30 % of the total area of around 41,000 square kilometers. It is these regions that are sufficiently densely populated for economic heat utilisation.

The amount of energy theoretically available below this area of approximately 12,000 square kilometres can be roughly estimated. It is initially assumed that for practical reasons only 20 % of the heat can be extracted. If one considers heat above 40°C to be usable in principle (i.e. from a depth of 1 kilometre), this gives rise to a figure of 1,400,000 PJ of stored thermal energy, which corresponds to around 5,000 times the annual heating requirements of the Swiss building stock (as at 2018).[1] If only the heat above 100°C is considered, this figure is still 800,000 PJ. In order to estimate the theoretical potential for electricity generation, the heat quantity must be multiplied by the Carnot factor and the thermodynamic quality of a power plant process.[2] With the resulting average efficiency of 12 % to 13 %, theoretical electricity generation potential of 100,000 PJ or 27,000 TWh[3] is obtained. This corresponds to 130 times the electricity requirements of Switzerland as a whole (as at 2018)[4].

Notes and References

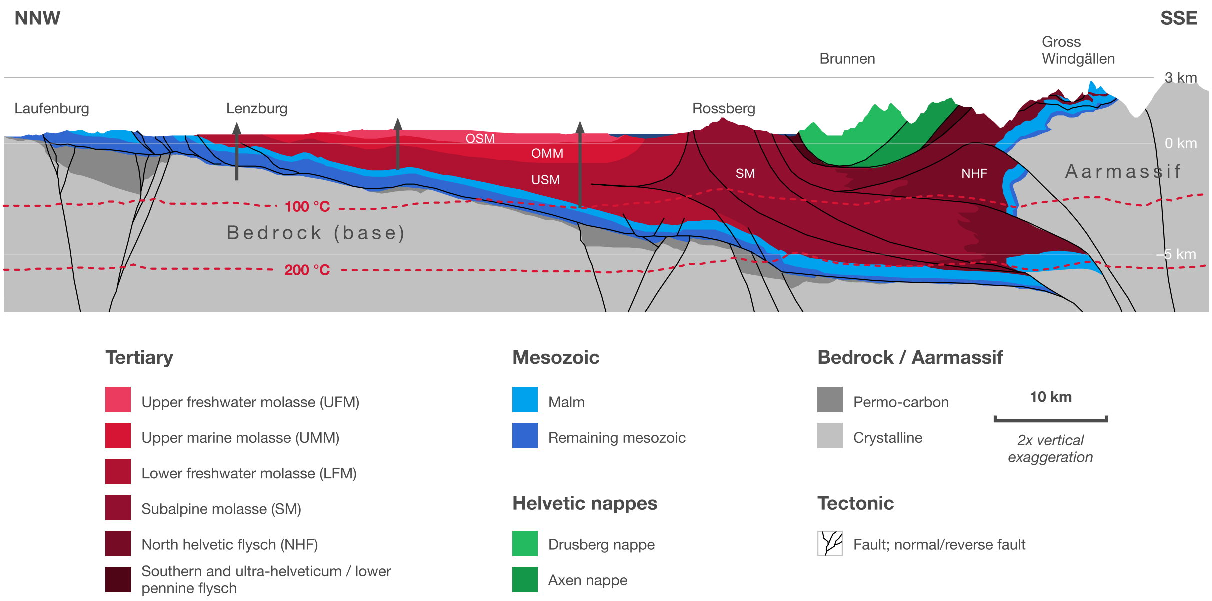
1 SFOE (2019), Analyse des schweizerischen Energieverbrauchs 2000 – 2018 nach Verwendungszwecken, Swiss Federal Office of Energy, Ittigen

2 The Carnot factor represents an upper limit with which heat can be converted into work

(and thus electricity). It depends on the temperature of the heat source. The thermodynamic quality of a power plant process indicates how much of this theoretically producible work is actually obtained. For usual technical processes, it is around 50 %.
3 1 PJ = 0.27 TWh, 1 TWh = 3.6 PJ
4 SFOE (2019), Analyse des schweizerischen Energieverbrauchs 2000 – 2018 nach Verwendungszwecken, Swiss Federal Office of Energy, Ittigen

Resources # Cold / heat # Energy provision

1.3.3. Hydrothermal from permeable rock and petrothermal from dense rock



Geological profile of Central Switzerland *Source: Dr. Roland Wyss GmbH*

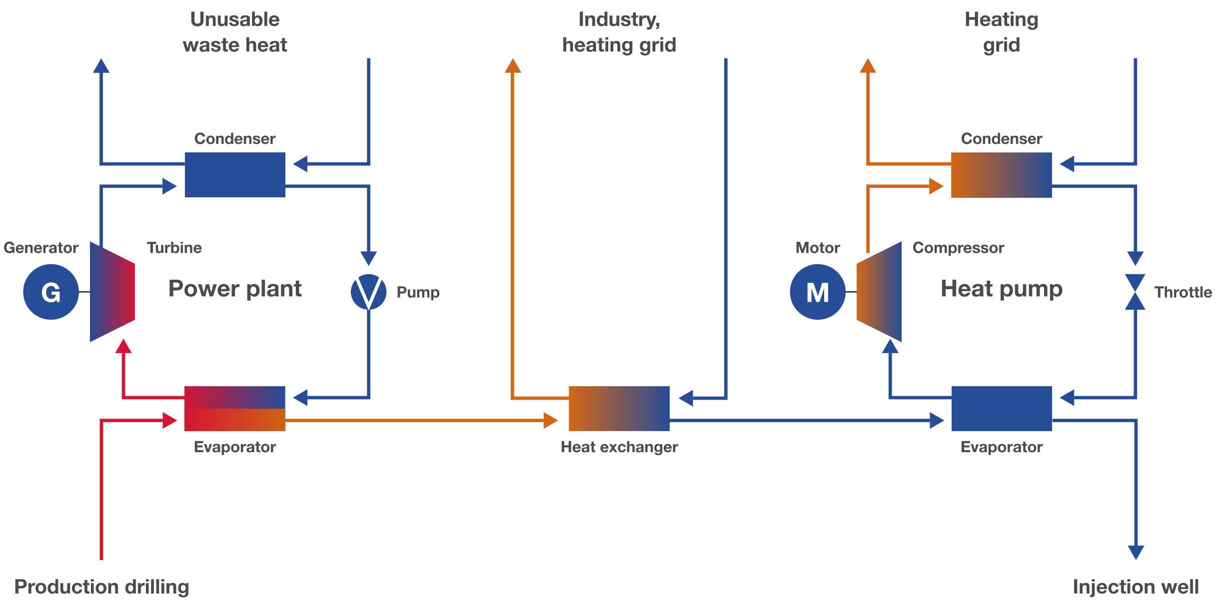
To extract geothermal energy from underground zones, a fluid – usually water – must be able to circulate through the hot rock. It warms up in direct contact with the rock and then transports the geothermal heat to the surface. Such a process requires the rock to be permeable enough for the fluid to move at the required velocity through a sufficiently large volume of hot rock. This permeability is different for different types of rock. While sedimentary rocks such as sandstone and limestone often exhibit natural water permeability, rocks such as granite and gneiss are almost impermeable.

Hot deep water can be transported directly from the porous sedimentary rocks to the surface by drilling into a water-bearing layer – a so-called aquifer (hydrothermal geothermal energy). In Switzerland, water-bearing layers can primarily be found in the Mesozoic (see figure, blue layers), a collective term for a series of rock formations dating back around 70 million to 250 million years that lie close to the surface in the north and at increasing depth towards the Alps and west. The yield is higher close to the surface – but temperatures are lower.

In the case of the less permeable crystalline rock (see figure, bedrock and the Aarmassif), the water permeability has to be increased using engineering methods (petrothermal geothermal energy). This process is referred to as an enhanced geothermal system (EGS). By injecting water, existing fissures in the rock are widened or new fissures are opened up. As the crystalline bedrock is under high tension due to the pressure of the tectonic continental plates, such stimulation causes discharge movements that can be perceived as earthquakes on the surface. A core research topic is the prevention of damage caused by this so-called induced seismicity.

Resources # Cold / heat # Energy provision

1.3.4. The three utilisation stages of geothermal energy



The utilisation stages of geothermal energy electricity generation, direct heat utilisation, heat utilisation via a heat pump.

Depending on the temperature level, geothermal energy can be used in different manners (see figure). If the temperature is above 100°C, electricity can be generated using current technology available on the market, usually via a binary circuit. In the simplest case, this consists of a heat exchanger in which a suitable working medium is evaporated by heat absorption from the geothermal carrier medium. The steam expands via a power turbine that drives a generator. The working medium is then condensed through the releasing of heat to the environment and finally fed back to the evaporator via a feed pump.

If the geothermal carrier medium still has a sufficiently high temperature after heat exchange with the working medium, further heat can be transferred directly to a heating grid or to an industrial process. If the temperature level afterwards is below a directly usable level, additional thermal energy can be extracted from the carrier medium by using a heat pump. Any residual heat can be used in baths or in the agricultural sector.

In practice, each of these three variants is implemented independently depending on the available temperature level. Also conceivable is the combination of electricity generation and downstream direct heat utilisation or direct heat utilisation with the subsequent utilisation of the residual heat via a heat pump.

Cold / heat   # CO2 / greenhouse gases   # Energy provision

1.3.5. The underground as a heat and gas store

Alongside the extraction of geothermal energy, the underground can be used as a storage medium for heat, cold or gaseous substances such as CO_2, hydrogen and natural gas.

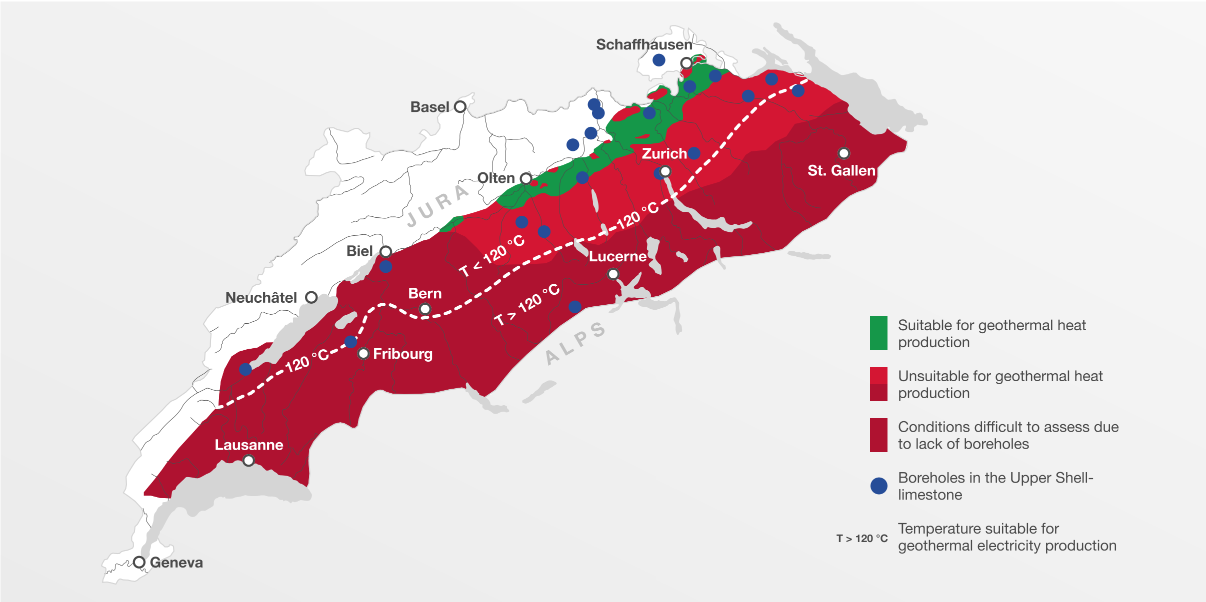
The storage of heat is based on the same principle as the extraction of heat, i.e. via a heat exchange between a fluid such as water and the rock. The difference relative to pure heat extraction is that the process runs in two directions. During heat storage, a hot fluid – usually water – transfers its heat to the rock and cools down in the process. During extraction, a cold fluid absorbs heat from the previously heated rock. The requirements in terms of rock permeability are identical for both processes. The same method can also be used to regenerate a geothermal reservoir that has cooled down due to heat extraction.

One way to reduce the CO_2 content of the atmosphere is to store it permanently underground. This technology – referred to as carbon capture and storage (CCS) – not only requires sufficient permeability, but also rock that is porous enough to be able to absorb the CO_2. Furthermore, the rock must be overlaid by an impermeable rock layer to prevent the injected gas from escaping.

Similar to CO_2, other gases can also be stored in rocks. Of particular importance for the transformation of the energy system is the seasonal storage of hydrogen or natural gas. The latter were not explicitly the subject of the research projects. However, the suitability criteria for these gases are practically identical to those for the storage of CO_2.

1.4. The underground as an energy source

1.4.1. Potential of hydrothermal geothermal energy in Switzerland



Suitability of the Trigonodus Dolomite aquifer in the Upper Shell-limestone for the production of heat and electricity.

In the case of hydrothermal electricity generation or heat utilisation, hot deep water is taken from a water-bearing layer, a so-called aquifer. At the surface, it is fed into a power plant process or the heat is used directly. The cooled water is subsequently returned to the ground. In Switzerland, there are various areas of potential depending on geological formations and structures.

In the project “Deep underground heat reservoirs”[1], the characteristics of a specific aquifer, the Trigonodus Dolomite, were investigated in more detail. This forms a layer within the so-called Upper Shell-limestone with a thickness of between 20 metres and 30 metres. It was found that the porosity of 10 % and permeability of 10 millidarcy required for efficient use is only found at depths of less than 1,130 metres (see figure, green area). This rules out electricity generation, however, as this requires temperatures of over 100°C, which are only found at depths of more than 3 kilometres. The Trigonodus Dolomite is therefore not suitable for hydrothermal power generation.

In contrast the geographically very extensive thermal anomaly found in the Rhone Valley between St. Maurice and Upper Valais, represents one of the sites with the best geothermal energy potential in Switzerland. Here, there is speculation about the presence of sparsely occurring, but all the more productive hot-water filled fracture and fissure systems. These are the target of a hydrothermal electricity project currently underway in Lavey-les-Bains.[2]

In any case, heat utilisation can also make sense at lower temperatures, such as those found at shallower depths (1 to 2 kilometres) – if necessary combined with a downstream heat pump.

Notes and References

1 Project "Deep underground heat reservoirs"
2 https://www.agepp.ch/

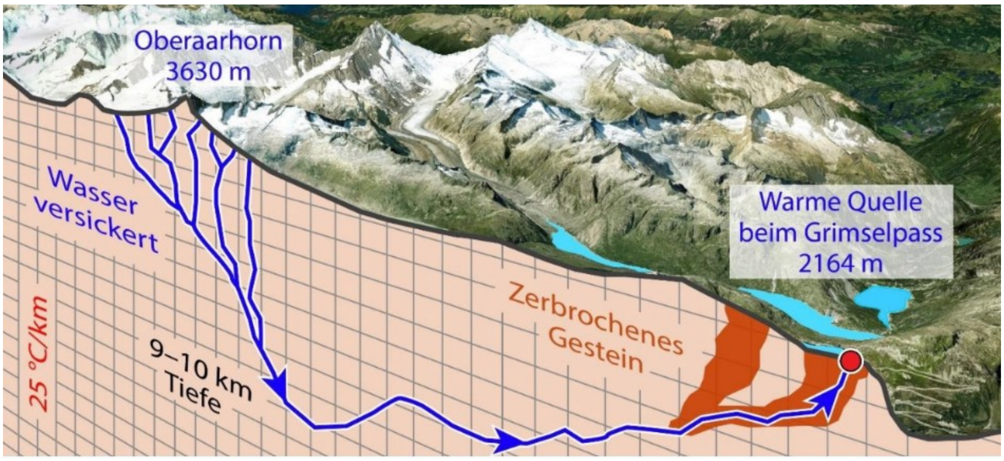
Resources # Geoenergy # Energy provision

1.4.2. Fracture zones with potential for hydrothermal reservoirs

The Swiss underground is not homogeneous in terms of its geological and thermal characteristics. This means that natural fracture zones have developed over the course of Earth's history, along which interesting geothermal sources emerge. One example is the so-called Grimsel Breccia Fault (GBF) near the Grimsel Pass. This formed about 20 million years ago at a depth of 20 kilometres. During the formation of the Alps, a natural circulation of water eventually began. This is fed by surface water near the Oberaarhorn which sinks to a depth of 9 to 10 kilometres where it warms up to between 230°C and 250°C before finally returning to the surface near the Grimsel Pass.

As a result of this fracture system, a so-called geothermal anomaly was formed, in which the temperature rises much faster with depth than is the case in undisturbed rock. The GBF was characterised in the project "Deep underground heat reservoirs"[1] by using a number of geological and geophysical methods. The main finding from these investigations is that fracture zones such as those found in the central Alps and in the area around the Rhone Valley can be promising for hydrothermal geothermal energy. Here, both high temperatures and good rock permeability are found at shallow depths.

Schematic diagram of the geothermal system at the Grimsel Pass.



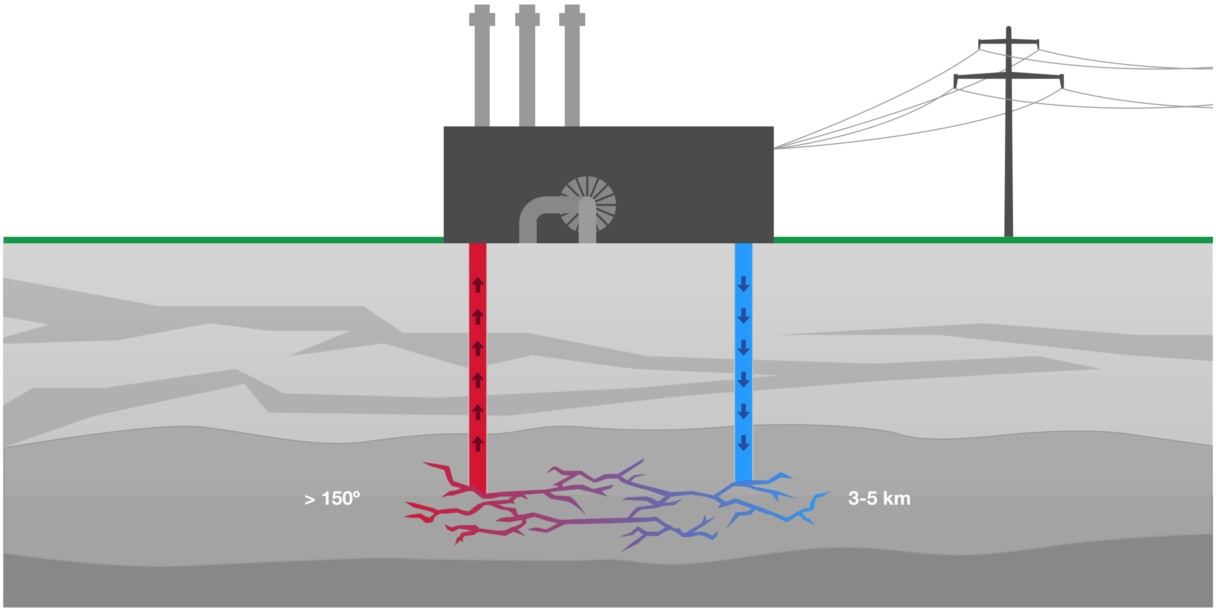
Source: Prof. Larryn Diamond, University of Berr

Notes and References

1 Project "Deep underground heat reservoirs"

Risk # Energy storage # Energy provision

1.4.3. Potential of petrothermal geothermal energy in Switzerland



The realisation of a petrothermal geothermal project is a multi-stage process with the aim of minimising the risk of induced seismicity. *Source: Geoenergie Schweiz AG*

At depths of 4 to 6 kilometres, temperatures can be found in all Swiss underground areas which, at least in principle, allow electricity to be generated using a binary power plant process (petrothermal geothermal energy). However, the rock must first be made sufficiently permeable by injecting water either to widen existing fractures in the rock or to open up new fractures. Fundamental research on this topic has been conducted in recent years within the SCCER-SoE (Swiss Competence Centre for Energy Research - Supply of Electricity). Injection tests were performed at the Grimsel rock laboratory. These showed that the permeability of rock can be increased if the reservoir – based on optimally oriented boreholes – is stimulated and opened up section by section. This also made it possible to limit the earthquakes induced at low levels to the intensity required to produce the required level of permeability. It was also shown that the risk of surface earthquakes can be reduced to a tolerable level by using sophisticated control systems. These findings are currently being expanded with further experiments at the new rock laboratory of ETH Zurich in the Bedretto tunnel – albeit on a scale ten times larger than that on the Grimsel Pass. In addition, a further pilot project “Haute Sorne”[1] has been launched. This has been approved by the canton of Jura, is being co-financed by the federal government and is being run by the industrial sector.

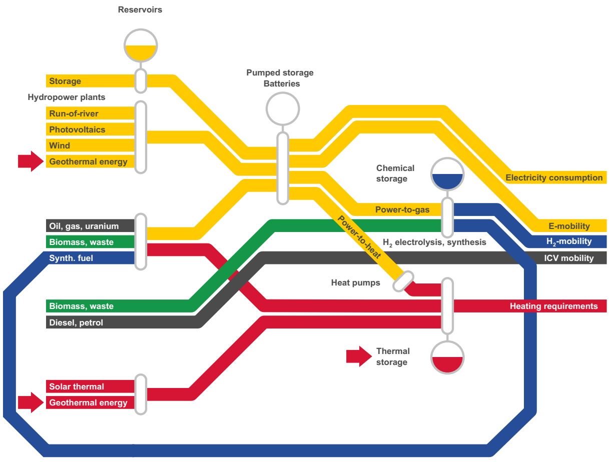
Currently a great deal is going on concerning the use of petrothermal geothermal energy. Where geothermal reservoirs can be developed for electricity generation, there is always the additional possibility of direct heat utilisation for heating grids or industrial processes, especially at temperatures of well above 100°C. The seasonal storage of heat in the temperature range of 100°C to 200°C would also then be possible.

Notes and References

1 https://www.geo-energie-jura.ch/

Resources # CO2 / greenhouse gases # Sustainability # Costs / benefits

1.4.4. Electricity or heat?



Simplified illustration of the energy system. Geothermal energy can make an important contribution both as electricity and heat to the avoidance of fossil fuels.

Petrothermal deep geothermal energy could play an important role for electricity and heating. However, due to the progress still required in terms of research and in the industrial sector itself, it will not be possible to take advantage of this until 2030 at the earliest. Both sectors can benefit from its characteristic features. Generally speaking, it is controllable, flexible and able to deliver base load. It also uses domestic and almost unlimited primary energy. And in operation it causes neither CO_2 emissions nor fuel costs.

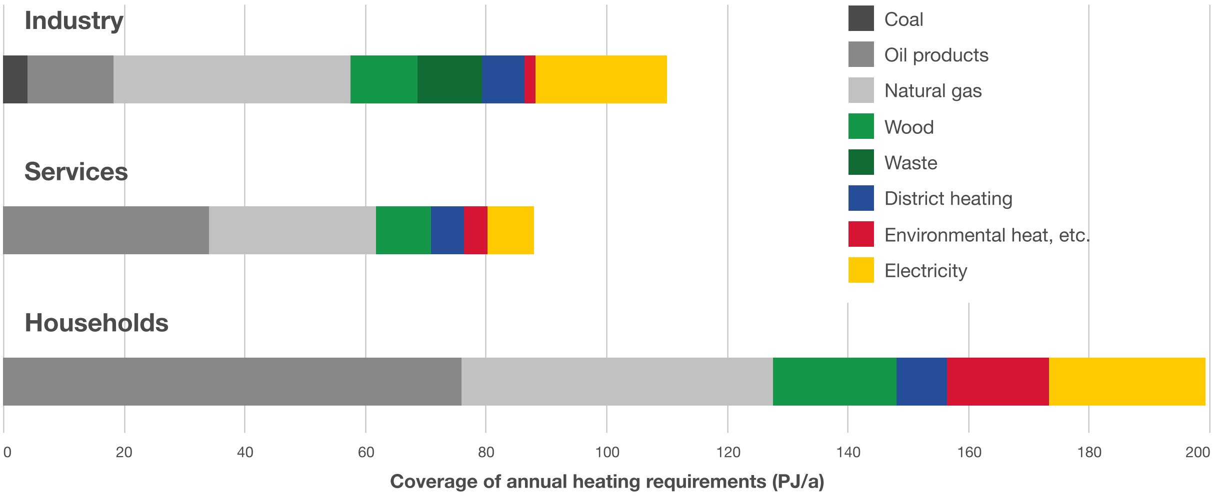
Geothermal electricity can be fed into the power grid without any problems. It thus benefits all electricity consumers, including heat pumps and electric mobility. Furthermore, in the case of petrothermal geothermal energy, the generation of heat is not tied to specific geological conditions. As such, it can be situated in close proximity to the consumer (heating grids or industrial processes).

The extraction of geothermal energy using a combination of injection and production wells that supply at least 50 litres of water a second at over 100°C still poses a challenge. Focus here is being placed on avoiding induced seismicity at greater depths (4 to 6 kilometres). Heat extraction also entails significant investments, although the running costs are relatively low. However, a ratio of high initial investments to low operating costs is typical for almost all technologies of a future CO_2-free energy system (e.g. photovoltaics, heat pumps, electric vehicles).

Given the many uncertainties that currently exist with regard to petrothermal deep geothermal energy, it is not yet possible to determine reliably whether this technology would be better used in Switzerland for the production of electricity or heat – or for both. As things stand, further developments must therefore keep both options in mind. What is certain, however, is that heat extraction from medium depths (1 to 3 kilometres) has a significantly lower earthquake risk and is also more cost-effective.

Cold / heat # Energy grids # Energy provision

1.4.5. Direct use of geothermal energy for local heating grids or industrial processes



At present, 62 % of the heat supply for households, services and industry (space heating, hot water, process heat) is provided by fossil fuels. *Source: Swiss Federal Office of Energy*[1]

In 2018, Switzerland's final energy demand totalled 775 PJ (weather-adjusted). Just over 50 % of this was accounted for by space heating, hot water and industrial process heat.[2] In the building sector, the heat pump (air, water or brine) will be the dominant heat source in future; however, a significant part of heating requirements lie in a temperature range for which deep geothermal energy is ideally suited.

Today, around 19.4 PJ of energy is distributed in Switzerland via heating grids to the consumer sectors households, services and industry. In most cases, the sources of this heat are waste incineration plants. The flow temperatures are greatly dependent on the specific case, but stand at around 80°C to 130°C. With a normal geothermal gradient of 30°C per kilometre, corresponding geothermal heat extraction therefore requires a depth of approximately 3 kilometres. At present, the share of district heating for space heating and hot water stands at around just 5 %. According to estimates by the Swiss District Heating Association, this proportion could rise to about a third in future.[3]

In the area of process heat, total consumption in Switzerland in 2018 was around 95 PJ. Of this figure, about 75 % is currently generated by burning oil and gas. The proportion that could be replaced by deep geothermal energy is smaller, however. Studies show that temperatures below 150°C are common in the food, paper and furniture industries.[4] According to statistics from the Swiss Federal Office of Energy, these areas account for approximately one-third of process heat consumption. In principle, more than 30 PJ of process heat could be supplied by deep geothermal energy, depending on the temperature level from a depth of 3 to 6 kilometres.

Notes and References

1 Swiss Overall Energy Statistics 2018

2 Analyse des schweizerischen Energieverbrauchs 2000 – 2018 nach Verwendungszwecken

3 https://www.fernwaerme-schweiz.ch/fernwaerme-deutsch/News/

4 Ralf Kuder (2010), Technology oriented analysis of the emission reduction potentials in the industrial sector in the EU-27. Institute of Energy Economics and the Rational Use of Energy. Stockholm.

1.5. The underground as a storage medium

Cold / heat # Energy storage

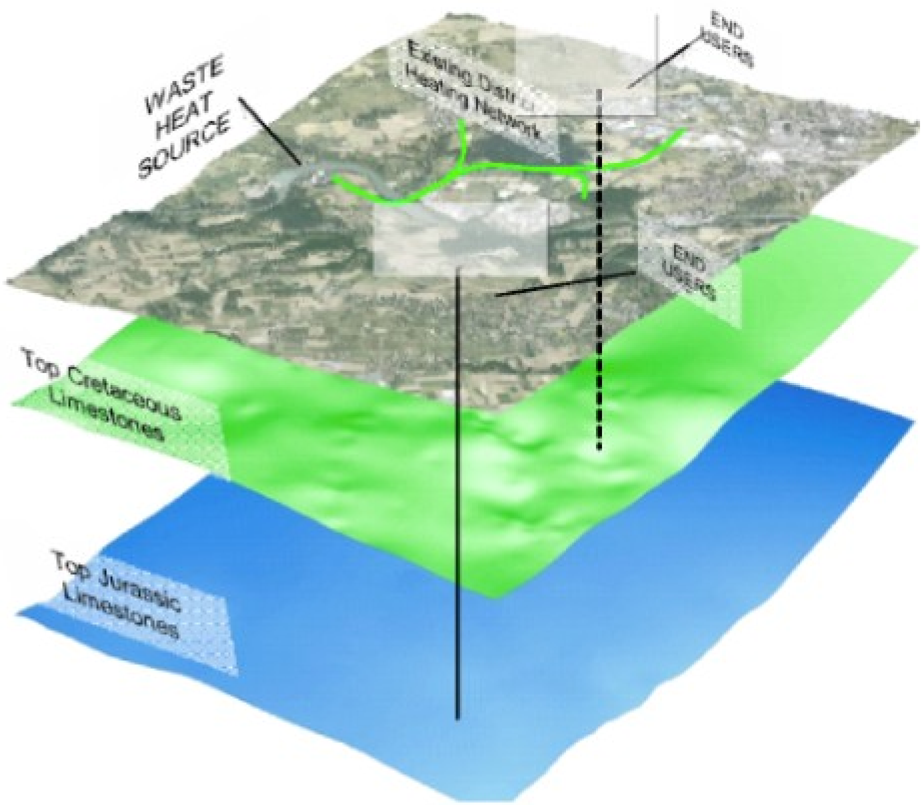
1.5.1. The underground as a heat store for seasonal equalisation

In contrast to electricity, heat can be stored easily. Most heating systems have a type of water storage tank in which the generation of heat and its consumption are decoupled in terms of time over the course of the day. The challenge, however, is to store heat in a cost-effective and seasonal manner. Here, the use of the underground can make an important contribution.

Seasonal heat stores require a correspondingly large volume. In order to meet the heating requirements of a single-family house – approximately 10 MWh – around 170 cubic metres of water (with a temperature rise of 50°C) – are needed.. Large storage solutions of up to 100,000 cubic metres are constructed as ground basins and contain a hole the size of a football pitch up to 20 metres deep. A ground basin such as this with a volume of 75,000 m^3 and a storage capacity of 4,350 MWh was commissioned in Marstal (Denmark) in 2012. Where space is limited, earth probe storage systems are an alternative.[1]

In a similar way to medium-deep geothermal energy, water-bearing rock layers, so-called aquifers, are now also being considered as potential storage media. Technically speaking, this variant is identical to net heat extraction, with the difference that the direction of the heat flow is reversed during the summer months – hot water is injected and cold water is extracted. In Switzerland, this technology is being tested as part of the HEATSTORE project[2] at two domestic locations in Geneva and Bern. Finally, petrothermal geothermal energy can also be used as a storage technology, especially in connection with industrial processes at a temperature range of between 100°C and 200°C.

Two wells are planned as part of the HEATSTORE project near Geneva. Waste heat from a waste incineration plant is to be stored during the summer months and fed into an existing heating grid during the winter months.



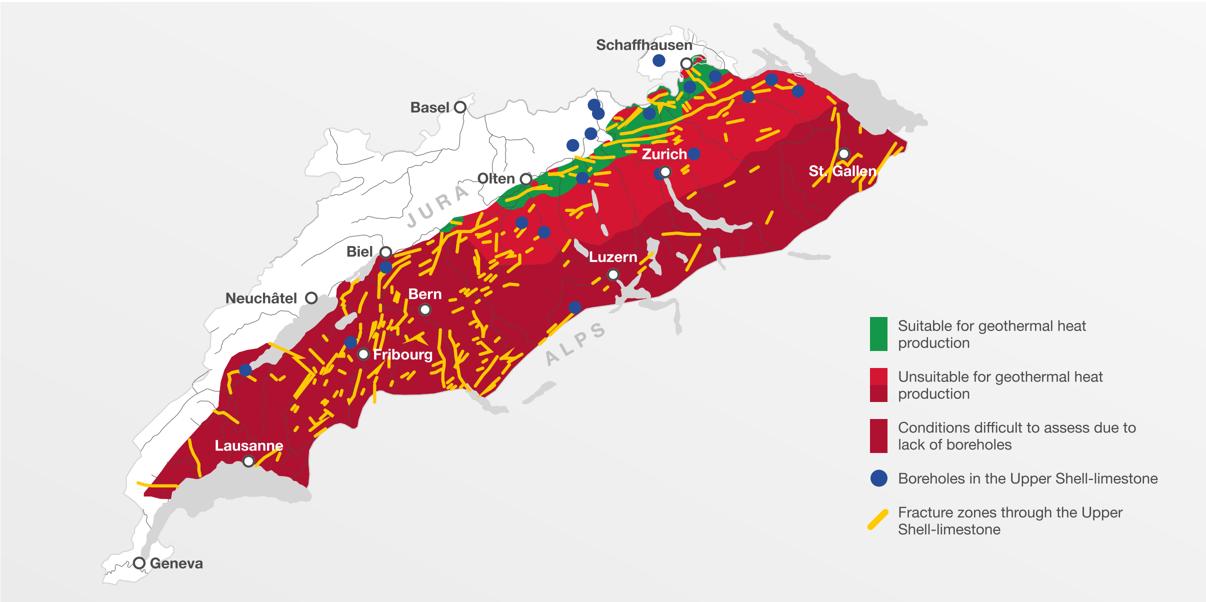
Source: Prof. Andrea Moscariello, University of Geneva

Notes and References

1 Focus study “Saisonale Wärmespeicher – Stand der Technik und Ausblick”, Forum Energiespeicher Schweiz
2 https://www.heatstore.eu/

CO2 / greenhouse gases # Sustainability

1.5.2. Suitability of the Upper Shell-limestone for the storing of CO_2



Suitability of the Trigonodus Dolomite aquifer in the Upper Shell-limestone for the permanent storage of CO_2. Further potential can be found in other rock formations. However, this was not investigated in the sub-project “Deep underground heat reservoirs”. *Source: Prof. Larryn Diamond, University of Bern*

One way to reduce Swiss CO_2 is to capture the gas at its point of origin and then store it permanently underground (carbon capture and storage, CCS). Concentrated sources of CO_2 include cement plants, waste incineration plants and – if they are ever built in Switzerland – gas-fired power plants.

The storing of CO_2 underground requires suitable geological structures. As is the case with hydrothermal geothermal energy, these must have sufficient porosity and permeability. Beneath Switzerland’s Mittelland region, these conditions are most likely to be found in a geological formation called the Trigonodus Dolomite. This forms a layer within the so-called Upper Shell-limestone with a thickness of between 20 metres and 30 metres.

In the project “Deep underground heat reservoirs” , the characteristics of the Trigonodus Dolomite were investigated in more detail. It was found that the characteristics required for CO_2 storage are only found above a depth of 1,130 metres. As permanent CO_2 storage requires depths of at least 800 metres, the suitable area in the Mittelland region is reduced to an area of 640 km^2 between Olten and Schaffhausen (see figure, green area).

The Trigonodus Dolomite is capped at the top by an impermeable layer of Gypsum Keuper. This is broken through in places by fault lines – further reducing the available area to 300 km^2. This reservoir would, for example, allow the fossil emissions of all 30 Swiss waste incineration plants (approximately 2 $MtCO_2$ per year) over 25 years to be stored.

1.6. Managing the underground

Digitalisation # Planning # Innovation # Energy provision

1.6.1. Better understanding of induced fracture networks through simulation

Low-transmissivity	Medium-transmissivity	High-transmissivity
$1.0 \cdot 10^{-11}$ m^3	$2.9 \cdot 10^{-11}$ m^3	$8.3 \cdot 10^{-11}$ m^3

Development of the temperature field in the vicinity of an elliptically shaped fracture zone.[1] **The figure shows for three different transmissivities how the temperature field develops in the vicinity of an elliptically shaped fracture zone.** *Source: Prof. Thomas Driesner, ETH Zurich*[2]

Petrothermal geothermal energy requires hydraulic stimulation to create fracture networks for the subsequent extraction of heat with a fluid. The underlying physical processes are complicated and necessitate close cooperation between different disciplines including fluid mechanics, heat and mass transfer and fracture mechanics. While experiments under real conditions are possible, they are very expensive. For this reason, numerical simulations are being used to further develop the technology.

In the project “Deep-heat mining”[3], various effects within a fracture network such as this were investigated using numerical simulations. Among other things, it was shown that the natural convection of water can lead to temperature anomalies of up to 20°C. Such anomalies make it possible, for example, to identify already existing fracture networks and thus to find them more easily.

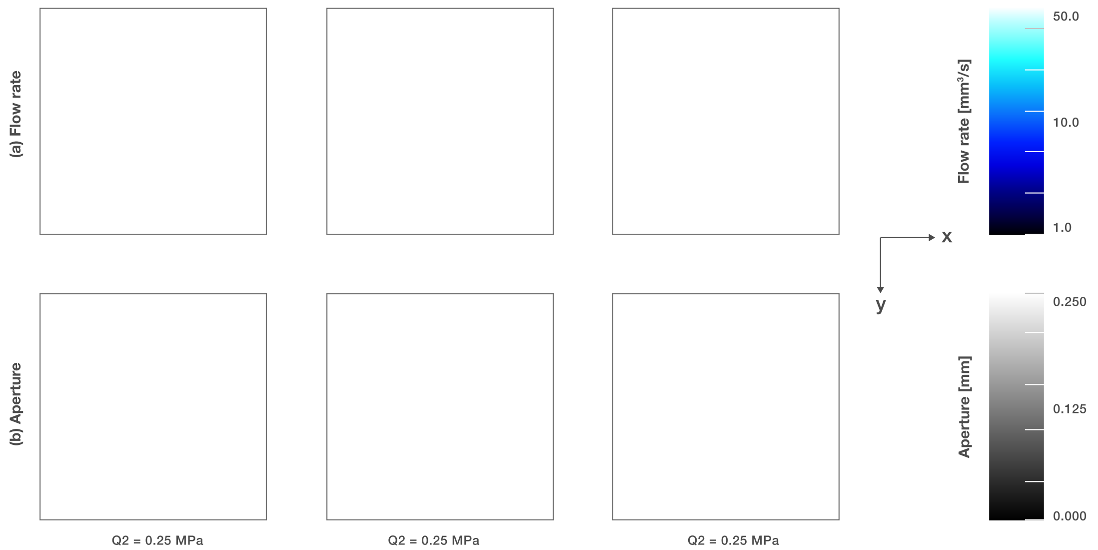
It was also found that the injection of cold water for the purpose of heat extraction can influence important characteristics of the fracture network such as its permeability. Finally, initial evidence was found that cold water can lead to the growth of fractures due to thermoelastic effects. To date, such a mechanism had only been suspected.

Notes and References

1 Transmissivity is the ability of an aquifer to transport water.
2 Patterson et al., 2018, https://doi.org/10.1002/2017JB015363
3 Project "Deep-heat mining"

Digitalisation   # Innovation   # Energy provision

1.6.2. Simulation of the change in permeability during hydraulic stimulation



The simulation shows how an increase in the vertical stress leads to a closing of the gap and a corresponding decrease in permeability.[1]

The breaking up of deep rock during so-called hydraulic stimulation is a complicated multi-stage process. The rock is initially broken up by increasing the water pressure. Due to existing shear stresses, the rock then shifts in a tangential direction, similar to the movement seen during an earthquake. This displacement means that the opposite sides no longer fit together, creating a gap with permanent narrow channels through which water can now circulate.

The detailed numerical simulation of such a process must take into account the linking of the mechanical deformation of the rock and the flow through the gap. Most important is the efficient representation of the geometry of such a rough fracture surface. The geometries of the rocks are approximated by grids, with the result that the grids on opposite sides of the gap no longer match. This situation leads to numerous problems in the simulation. The project “Deep-heat mining”[2] has shown how this complex problem can be resolved efficiently by means of “variational transfer operators”.

The figure above shows the flow field and opening width in a gap whose geometry is based on a real rock sample. It was shown how an increase in the rock stress perpendicular to the gap (left: 0.25 MPa, middle: 8 MPa, right: 20 MPa) leads to a closure of the gap and a corresponding reduction in permeability. Such methods provide a better understanding of the processes underpinning hydraulic stimulation.

Notes and References

1 Planta, C., Vogler, D., Chen, X. et al. Comput Geosci (2019) 23: 1125.
https://doi.org/10.1007/s10596-019-09873-0

2 Project "Deep-heat mining"

Innovation

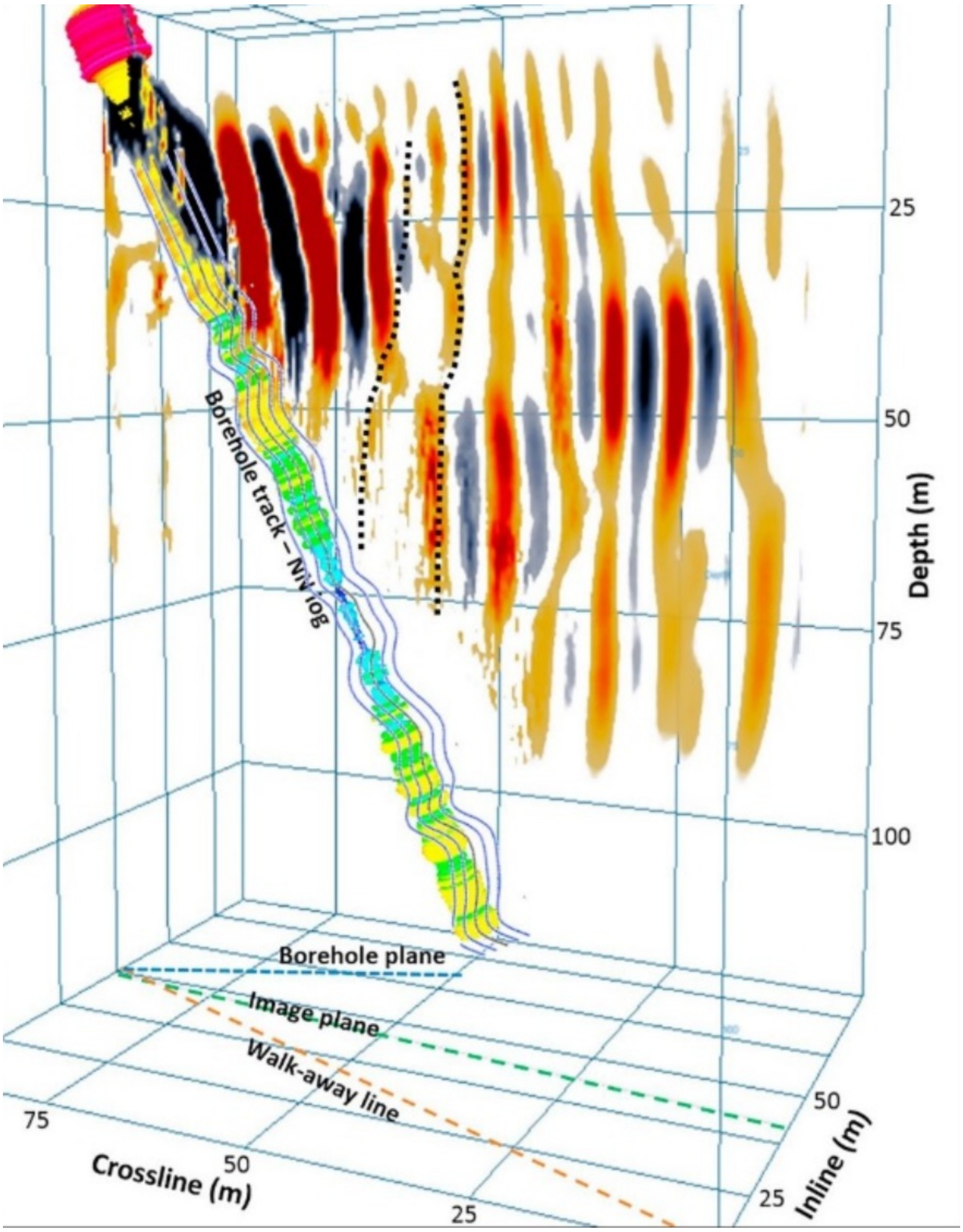
1.6.3. Characterisation of geothermal reservoirs

To extract geothermal energy from the underground, there must be sufficient permeability for the circulation of water. Alternatively, this must be generated by hydraulic stimulation. In any case, measurement and analysis processes are necessary in order to characterise the properties of existing or newly created fracture networks.

As part of the project “Deep underground heat reservoirs”[1], investigations were conducted to determine which indirect measurement methods can map the distribution of fractures in the rock around a borehole. To this end, various measurements of the physical rock properties were carried out along the 125-metre borehole. Among other things, the area surrounding the borehole was caused to vibrate by powerful hammer blows at the Earth’s surface (comparable to the vibrations of a guitar string) and the seismic noises were recorded using pressure sensors located in the borehole.

The computer analysis of this data generated a quasi-three-dimensional image of the fractured rock around the borehole. Using this technique, it will in future also be possible to better localise fractures in the rock around deep boreholes, which in turn will allow the more targeted stimulation of underground areas through the introduction of water into certain zones of a borehole. It is hoped that this will make it possible in future to minimise palpable earthquakes such as those observed during the geothermal projects in St. Gallen (2012) and Basel (2006) which were jointly responsible for the discontinuation of both projects. The prevention of such earthquakes will be decisive for the success of geothermal energy.

Quasi three-dimensional seismic image of the surroundings of the borehole on the Grimsel Pass. The coloured vertical structures correspond to seismic energy backscattered from fractures. The two dotted lines indicate the boundaries of the large-scale fault zone known as Grimsel Breccia Fault.



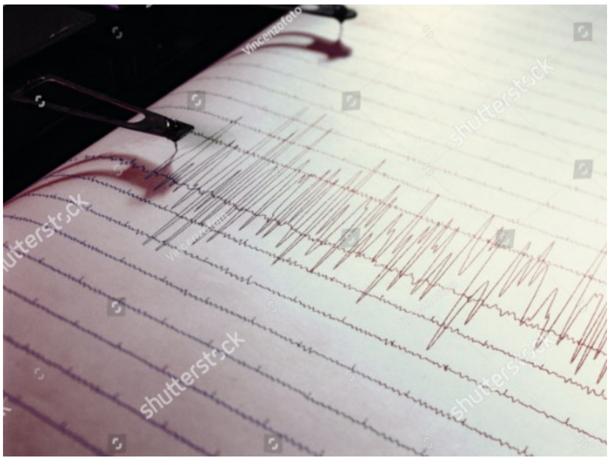
Source: Dr Andrew Greenwood, formerly University of Lausanne, now University of Leober

Notes and References

1 Project “Deep underground heat reservoirs”

Risk # Acceptance # Innovation

1.6.4. Improved analysis of weak induced seismicity

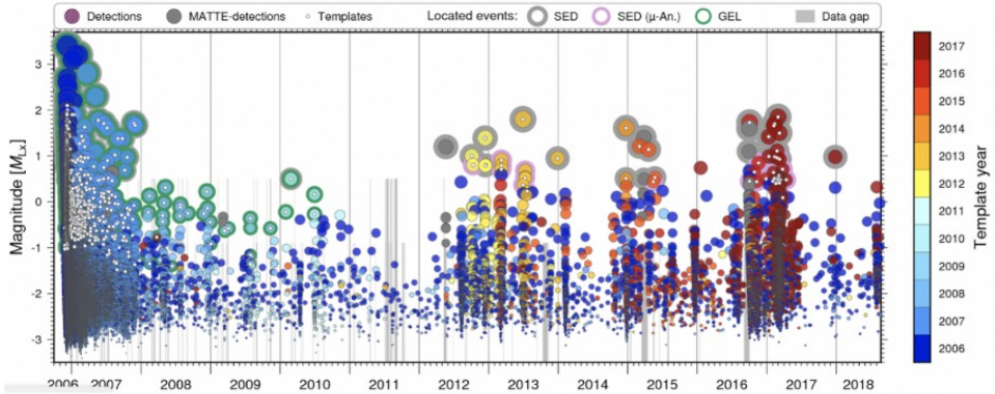


As part of an enhanced geothermal system project conducted in December 2006 in Kleinhüningen near Basel, test drilling was completed to a depth of 5,000 metres. Water was subsequently injected to increase the permeability of the rock – the borehole was open to the rock from a depth of around 2,500 metres. In contrast to the procedure as planned in Haute-Sorne, the entire 2.5-kilometre-long open borehole section was stimulated here, rather than in sections.

As part of the project “Risk management for geothermal power and hydropower”[2], a 12-year time series of the Basel earthquakes comprising a total of 280,000 results was evaluated in detail. These were recorded by a seismometer placed at a depth of 2.7 kilometres. By applying an improved matched filter, the sensitivity was increased by two orders of magnitude, down to a magnitude[3] of MLx = -3.4. The matched filter is based on the cross-correlation of the measured signal with the waveforms of known seismic events.

The concepts developed at the Swiss Competence Centre for Energy Research - Supply of Electricity (SCCER-SoE) for dealing with the risk of induced seismicity are largely based on so-called earthquake catalogues and their statistical distribution. Therefore, the number of earthquakes detected – especially those that are not palpable – must be massively increased. This will enable the development of the seismic risk during the opening up and later operation of a geothermal reservoir to be assessed in real time. The application of the newly developed assessment method makes it possible to detect such significantly weaker seismic events.

Time series of seismic events following the hydraulic stimulation in Basel. The colour scale indicates the year in which each of the seismic events used for the cross-correlation took place.



Source: Swiss Seismological Service[1]

Notes and References

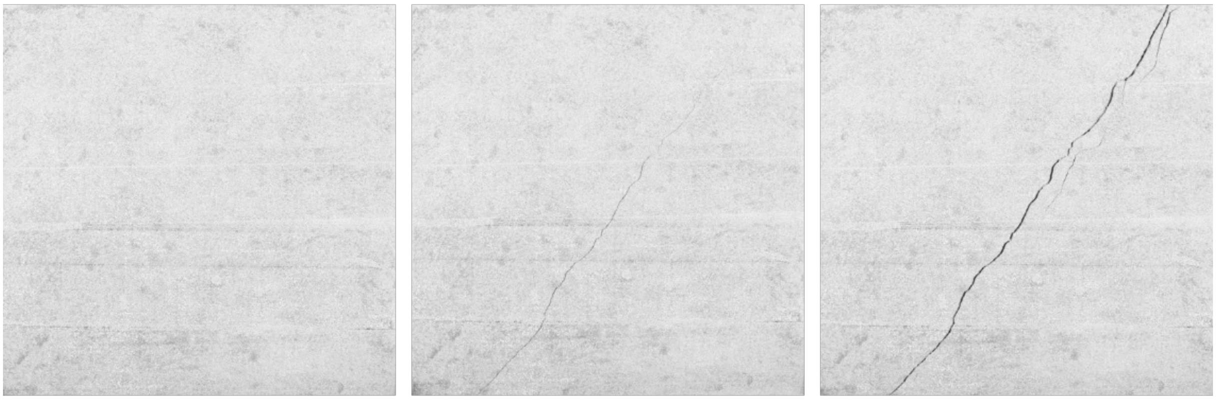
1 Herrmann, M., Kraft, T., Tormann, T., Scarabello, L., & Wiemer, S. (2019). A consistent high-resolution catalogue of induced seismicity in Basel based on matched filter detection and tailored post-processing. Journal of Geophysical Research: Solid Earth,124, https://doi.org/10.1029/

2 Project "Risk governance for geothermal and hydro energy"

3 The local magnitude ML,x corresponds to the Richter scale. As this is a logarithmic scale, negative magnitudes can also occur, which accordingly stand for very weak earthquakes.

Risk   # Innovation

1.6.5. Improved description of building damage in the case of weak induced seismicity



Observed damage to the masonry: no cracks (left), visible cracks (middle), flaking of plaster (right).[1]

A fragility function describes the relationship between the intensity of a triggering event (e.g. an earthquake) and the probability of certain damage. Standard seismic fragility functions only take into account damage ranging from highly visible damage to building structures to collapse. However, in order to be able to assess minor damage such as cracks in the plaster, a much finer measurement scale is required that links changes in the masonry to the strength of seismic events.

As part of the project “Risk management for geothermal power and hydropower”[2], plastered, unreinforced masonry was subjected to cyclic loads in a test set-up at ETH Zurich. These loads corresponded to long series of weak to medium seismic events. The stress and deformation fields of the wall sections were measured directly during the tests via digital image correlation. Based on the distribution of the shape changes measured as von Mises stresses, two damage indicators were defined which quantify the damaged area of the plaster and the length of the cracks.

Three observable cases of damage were defined for the assessments: (1) no cracks, (2) visible cracks, (3) flaking of plaster. The damage indicators were linked to the three cases of damage by means of mathematical calculations. On this basis, a probability model for the damage with a correlation between the deformation amplitudes and the calculated damage ratios was developed. This approach ultimately made it possible to establish a link between the strength of a seismic event and the damage to the masonry.

Notes and References

1 Didier, M. (2018): Seismic Resilience of Communities and of Their Civil Infrastructure Systems, doctoral thesis, ETH Zurich, Switzerland. Didier, M., Henken, J., Hefti, F., Blagojevic, N., Stojadinovic, B. (2019): Resilience Assessment of a Community and its Interdependent Civil Infrastructure Systems, World Congress on Resilience, Reliability and Asset Management WCRRA, July 28-31, Singapore.
2 Project "Risk governance for geothermal and hydro energy"

1.7. Want, can, do

The subject of "geothermal energy" affects a wide range of stakeholders – these actually include everyone involved in the energy system, namely the overall population, all businesses, energy providers, professional associations, public administrative bodies and politicians.

However, the following recommendations are aimed at those stakeholders who could exert a direct influence on the future shaping of energy provision and the energy consumption of Switzerland's building stock. In particular, these include the following:

- Politicians (federal government, cantons, municipalities)
- Energy suppliers
- Businesses
- Investors
- Public administrations
- Associations

Furthermore, recommendations have primarily been formulated that can be derived from the research work conducted in the joint project "Hydropower and geo-energy" as well as the areas identified in which action is required. The recommendations are relevant with a view to the transformation of our energy system.

Public administration # Energy suppliers # Businesses # Politics (federal government, canton, municipality)

1.7.1. Switzerland needs a national strategy for the deep underground!

In order to support the transformation of the Swiss energy system as effectively as possible, a comprehensive strategy needs to be formulated for underground areas – taking account of geothermal energy and all other uses.

Geothermal energy is the extraction of heat from underground. However, the joint project Hydropower and geo-energy" and the complementary Swiss Competence Centre for Energy Research - Supply of Electricity (SCCER-SoE) have made it clear that this narrow definition does not do justice to the possibilities offered by areas deep underground.

The first priority is always the net extraction of the heat stored beneath our feet. Depending on the depth, temperature level and geological conditions, this can be either used directly or converted into electricity using suitable processes. However, underground zones can also be used as seasonal heat stores. This can take place in different geological structures and at different depths depending on the temperature level.

In addition to heat, underground areas can also be used to store gases such as hydrogen and natural gas or for the permanent storage of CO_2. Such zones require an appropriate level of porosity and an impermeable layer of rock above them. In addition to all of these possibilities, it must not be forgotten that underground areas are also used as a resource for the disposal of highly radioactive waste and that transport systems are also being located at ever greater depths.

It is therefore clear that Switzerland needs a long-term strategy that optimally links all forms of use of the deep underground. As these are always linked to corresponding systems on the surface, this also requires long-term infrastructure planning at this level.

Investors (outside creditors) # Politics (federal government, canton, municipality)

1.7.2. Use all possibilities for long-term CO_2 storage!

In order to achieve the net zero target for greenhouse gas emissions, CO_2 must be removed from the biosphere, converted in an appropriate manner or permanently stored underground.

The Federal Council has set itself the goal of reducing Swiss greenhouse gas emissions to net zero by 2050. As there are sectors such as cement production and agriculture in which it will be very difficult to reduce emissions, Switzerland must either compensate for its domestic emissions abroad or remove CO_2 from the biosphere over the long term. The first option will no longer be possible in the longer term. This is because every country around the world will contribute to the complete avoidance of greenhouse gas emissions and optimise their own environmental balance to this end.

In the project "Deep underground heat reservoirs"[1], the potential of geological CO_2 storage in a specific geological structure was assessed This could absorb the emissions from Swiss waste incineration plants for around 25 years. In order to dispose of even greater quantities of CO_2 permanently, alternatives need to be developed. One option is to convert CO_2 into methane or aviation fuel. The creation of a European CO_2 transport infrastructure is also conceivable. This collects the CO_2 via pipelines and transports it to exploited oil and gas deposits.

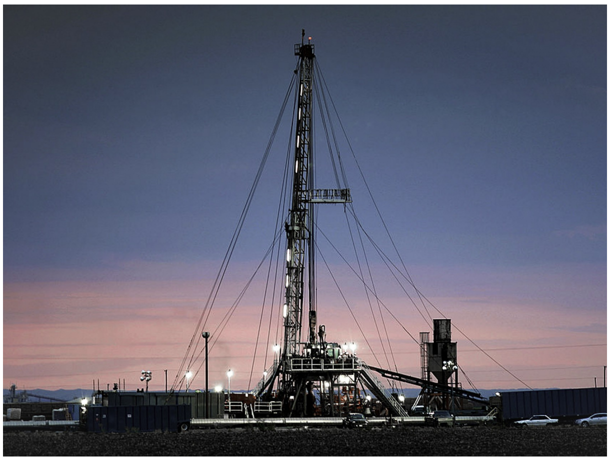
It is urgently necessary for Switzerland to address intensively the issue of CO_2 disposal, analyse all of the available options in an integrated manner, become active in this area, including at an international level, and implement solutions that are feasible in the medium term. The research work has shown that an optimal solution for achieving net zero cannot be found at purely a national level.

Notes and References

1 Project "Deep underground heat reservoirs"

Associations and NGOs   # Politics (federal government, canton, municipality)

1.7.3. Demonstrate geothermal power generation as a matter of urgency!



Two pilot projects are underway for hydrothermal and petrothermal geothermal energy: Lavey-les-Bains (VD) and Haute-Sorne (JU). These projects must now be used to demonstrate in practice the major progress that has been made in recent years in terms of the research work aimed at minimising seismic risks.

Research and industry work hand in hand on the fundamentals of hydraulic stimulation with the clear objective of achieving efficient stimulation with minimal seismic risk. Traffic light systems have been developed and tested that combine the permanent monitoring of induced seismicity during the stimulation process with clear decision-making criteria as to when stimulation needs to be interrupted. All of these findings are being incorporated in the Haute-Sorne project. Following a successful feasibility study, the hydrothermal geothermal project in Lavey-les-Bains (VD) is also taking shape.[1]

Direct heat utilisation must also be promoted. In densely populated areas with a high heat demand density or for larger heat consumers from the agricultural and industrial sectors, medium-deep hydrothermal geothermal energy can supply heat at a temperature level of around 30°C to 100°C at attractive production costs (see geothermal energy plant in Riehen[2]). At higher temperatures and where no hydrothermal heat sources are available, petrothermal geothermal energy can be used again.

These options need to be made more widely known among the stakeholders involved, including municipalities, project developers and industrial companies. Pilot and demonstration projects are urgently required to this end.

Notes and References

1 http://www.agepp.ch/
2 https://www.erdwaermeriehen.ch/erdwaerme-riehen.html

Associations and NGOs # Energy suppliers # Politics (federal government, canton, municipality)

1.7.4. Public promotion measures are important and appropriate!

In many areas, deep geothermal energy finds itself at an early stage of development and is therefore not yet able to generate the required level of investment on the free market. To accelerate its further development, targeted support from the federal government and the cantons is essential.

Public promotion measures will continue to be necessary in future in order to develop the potential offered by geothermal energy. The investment risk will remain too high for private-sector players in many projects for some time to come.

At present, the federal government is offering a geothermal guarantee for geothermal electricity projects. Under this scheme, up to 60 % of the eligible investment costs can be covered under a risk guarantee if the search for a suitable geothermal reservoir fails. Pilot and demonstration projects can also be funded by the Swiss Federal Office of Energy. Feed-in compensation is likewise available for geothermal electricity production.

Within the framework of Energy Strategy 2050, further promotion measures have been adopted. These include exploration contributions of up to 6 % of the investment costs for projects aimed at generating electricity. One such contribution was granted for the project in Haut-Sorne in September 2019. Up to CHF 50 million will be made available here. Since 2018, heating projects have also been funded with exploration contributions of up to 60 %.

With the foreseeable transition from petrothermal pilot projects to the first productive plants, the way in which public support is provided will also have to be adjusted. Instead of guarantees and exploration contributions, start-up financing and investments by the cantons will then have the optimal effect. As such deep geothermal energy plants will be important cornerstones of the energy infrastructure in future, it is logical that they should be co-financed by the public sector – as is the case with rail and road infrastructure.