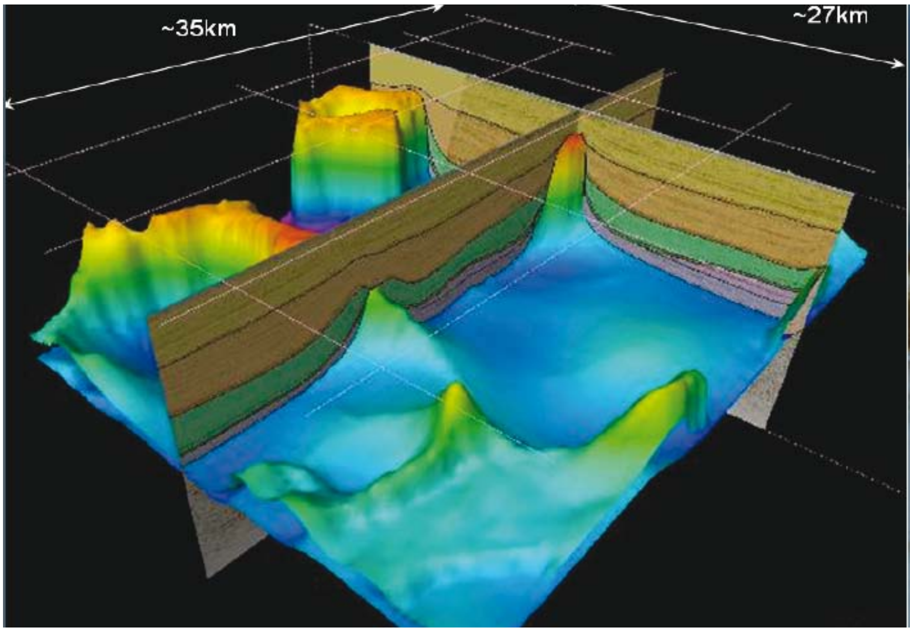
GEOTHERMAL ENERGY

With increasing fossil fuel prices, geothermal energy is an attractive alternative energy source for district heating and industrial heating. In recent years the use of geothermal energy through implementation of low temperature geothermal production systems for both electricity and heating has been growing rapidly. TNO is one of Europe's largest independent research organisations and provides applied science and technical and techno-economic consultancy services for the industry and for governments. TNO can support in exploration and the development of innovative technologies to use the energy the Earth's crust has to offer us.

At present it is generally accepted that the global climate change is a result of increased atmospheric concentration of greenhouse gases such as CO_2. To reduce the CO_2 emissions a lot of effort is put in the development of large scale application of sustainable energy.

Governments and the industry start to become aware that an incredibly large sustainable energy source is available in the subsurface.
Geothermal energy has many advantages as it is unobtrusive and emission free, available 24/7 and operational costs are low and stable. The use of the Earth's heat is therefore increasingly considered in future renewable energy strategies.
The use of geothermal energy resources is not restricted to volcanic regions only. Heat and electricity can also be produced in low enthalpy areas. The development of low temperature geothermal production systems introduces new challenges from both a geological and techno-economical point of view. Being involved in several national and international (EU) projects, TNO has gained more then 20 years experience in the development of low enthalpy geological systems. Due to its extensive knowledge TNO is frequently asked for advise and to perform exploration, techno-economic performance & risk assessment studies by the industry and governmental institutions.
TNO is closely involved in research concerning Enhanced Geothermal Systems (EGS). EGS is a promising development in converting heat into electricity. In low enthalpy regions sufficient temperatures are present at depths of more then 4000 m. To generate electricity the rocks at these depths have to be engineered to sufficiently extract the water. This asks for extensive knowledge in geomechanics, temperature and pressure modeling. In this new field of research TNO participates in the EU program Geisir and has joined the European Energy Research Alliance (EERA) to combine forces with other leading research institutes.
For the development of geothermal energy systems TNO holds extensive knowledge on the complete geothermal energy chain. TNO has developed a variety of applications to simulate and test different scenarios and to deliver in-depth support on individual segments.

RESOURCE MAPPING



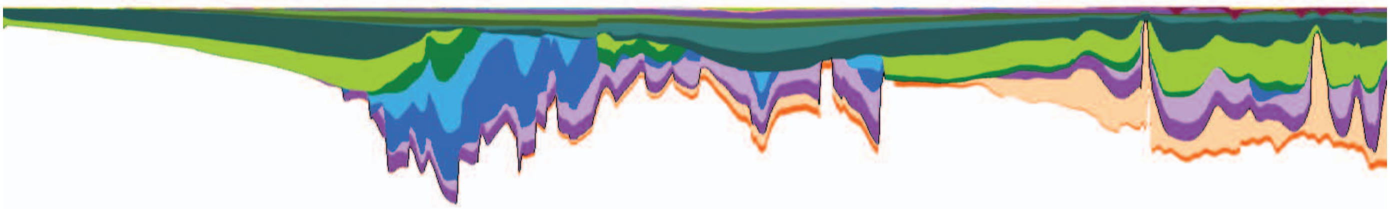
Complementary to structural and stratigraphic mapping, the assessment of properties and dynamic processes in prospective aquifers and fault zones is particularly important. Our methodology features:

- Multi-scale , multi-physics modelling to predict temperature, maximum burial, porosity-permeability relations, chemical signature, natural fracture formation
- Capability to use multiple constraints from well data, seismic data, tectonics and structural analysis, to test and validate models.
- Geostatistical 3D interpolation and updating techniques for stochastic geothermal maps, taking into account parameter and model uncertainty and interpolation variability at various scales.

Geothermal Energy is able to provide a significant share of renewable base load power for electricity, heat and cold around the world. In many countries in continental Europe, geothermal heat and cold is anticipated to grow rapidly from values of a few percent now up to levels of about 5% of the renewable energy mix in 2020. Electricity will accelerate in a somewhat delayed but equally rapid pace, in particular from Enhanced Geothermal Systems (EGS).

In the scope of rapid geothermal growth in the Netherlands, TNO has recently developed novel working approaches for geothermal resource mapping in sedimentary basins, capable to take into account data from thousands of deep wells and densely spaced 3D and 2D seismic.

In mapping of geothermal aquifers, fault structures and suitable rocks for EGS, TNO builds from an extensive track record of applying state-of-the art basin mapping and pre-drill resource assessment techniques to estimate resource potential for oil and gas, coal bed methane, shale gas and CO_2 storage.



RESOURCE ASSESSMENT

Critical subsurface conditions for geothermal applications are production temperature, achievable flow rate, and sustainability of the reservoir. TNO has developed various methodologies to assess the performance of geothermal aquifers and enhanced geothermal systems at the exploration stage. These build on holistic approaches for managing financial risks in oil and gas exploration and production.

Best practices for exploration work flows are marked by properly staged decision tollgates for exploration activities. These should progressively narrow down pre-drill uncertainties which have a high effect on project performance, with acceptable costs for the exploration.

In TNO's approach, a best practice performance work flow benefits from the following key steps:

– Calculation of the distribution of expected production outcome as a function of a quantitative stochastic calculation model (socalled fastmodel).
– Stochastic sensitivity analysis to rank the effect of uncertainty in key parameters in terms of risk and hidden upside for project performance.
– Apply decision, scenario and option analysis to find optimum exploration and production strategies, capable to mitigate the identified risks and to secure upside potential.

The work flow allows to rationally design and optimise exploration and production strategies, in such a way that it is capable to reduce exploration cost and to take full advantage of unexpected upsides of resource potential.

Key to performance assessment are the stochastic fastmodels, capable of integrating uncertainties all along the value chain, from subsurface parameters, technical and cost-engineering options, economic and logistic conditions and public acceptance.

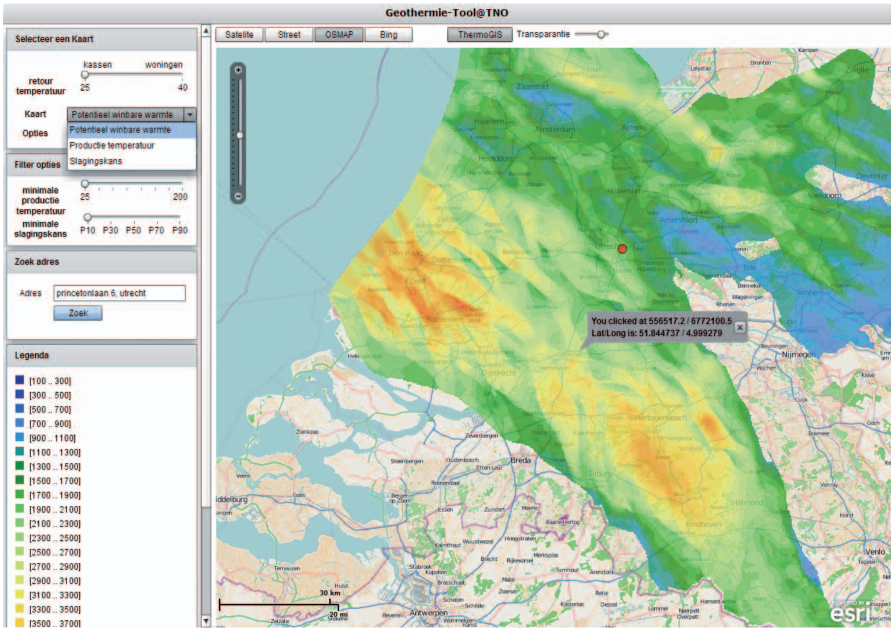
For an agreed exploration and production strategy, expectation curves for technical and economic key performance indicators, can be analyzed interactively on an asset level or presented in map view for regional assessments.

		Reconaissance		Surface exploration		Deep exploration	
Category	Parameter	Uncertainty	Impact	Uncertainty	Impact	Uncertainty	Impact
Resource chracteristic	Temperature	Medium	High	Low	Medium	Low	Low
	Flow rate	High	High	High	High	Low	Medium
	Depth	Medium	High	Low	Medium	Low	Low
	Volume	Medium	High	Low	Medium	Low	Low
	Recovery factor	Medium	Medium	Medium	Medium	Low	Low
	Chemistry	Medium	High	Medium	High	Low	Low
Technology	Energy conversion costs	Medium	Medium	Medium	Medium	Low	Low
	Drilling costs	Medium	High	Medium	Medium	Low	Low
	Plant costs	Medium	Medium	Medium	Medium	Low	Low
	Operational costs	Medium	Low	Medium	Medium	Low	Low
Logistic	Grid connection costs	Low	Low	Low	Low	Low	Low
	Access roads and supplies	Low	Low	Low	Low	Low	Low
Environmental & social	Reserved areas	Medium	High	Medium	High	Medium	High
	Acceptance of exploration	High	High	High	High	Low	Medium
	Acceptance of production	High	High	High	High	Medium	Medium
Market	Energy prices	Medium	High	Medium	High	Medium	High
	Tax and regulations	Low	Medium	Low	Medium	Low	Medium

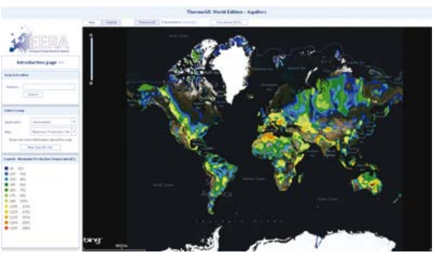
Low Medium High

INFORMATION SYSTEMS

The competence to develop leading-edge geothermal information systems follows from TNO's responsibility for data management of thousands of deep wells and 2D and 3D seismic, collected by the oil and gas industry in the past 30 years. Dutch law prescribes free access to all of these data. Consequently, TNO has developed a range of web-based information systems, to interactively query, display and extract custom-tailored subsurface datasets.



To stimulate the development of geothermal energy from aquifers in the Netherlands, TNO has recently developed a public web-based information system, called ThermoGIS. ThermoGIS provides depth, thickness, porosity and permeability maps of many potential aquifers. Additionally, a stochastic fastmodel based performance module is integrated in ThermoGIS that enables the user to assess the generated power, expected flow rate, the Coefficient Of Performance (COP) and economic variables automatically for any specific location selected (*www.ThermoGIS.nl*).



Key ingredient to web-based geothermal information systems are:

- display/access to subsurface source data (e.g. wells, well data, seismic);
- display of resource mapping products (e.g. geothermal aquifer structures and properties, fault structures);
- display of resource potential maps (e.g. key performance indicators);
- quick scan feasibility tools for local assessment;
- blending with other GIS data in 2D and 3D visualisation environments.

The application of ThermoGIS is not restricted to geothermal energy. It can be easily adjusted to other subsurface applications like storage locations for gas, CO_2, salt mining etc. For governmental institutions an application integrating a balanced score map for the suitability of the underground for different applications can be very useful for subsurface spatial planning.

TNO has also taken the lead in the development of a world aquifer viewer in the framework of the Joint program on geothermal energy (JPGE) in EERA. The world aquifer viewer allows to visualise at glance view the occurrence and suitability of geothermal aquifers for direct use applications.

EERA European Energy Research Alliance

RESERVOIR STUDIES

To extract the available heat from the subsurface aquifers have to satisfy certain geological conditions. The development of a geothermal system at a certain location starts with exploration of suitable water bearing rocks meeting the geological conditions required. Studies do not end here however. Reservoir simulations are necessary to predict temperature and pressure effects in the aquifer. TNO has developed reservoir models to estimate these effects that also can be used for spatial planning.

GEOLOGICAL FIELD STUDIES

Exploration starts with a quickscan to find out if potential permeable strata are present. Next in depth feasibility studies will be performed. TNO has an extensive track record in many geological and reservoir studies. Based on well data and seismic interpretations TNO is able to perform detailed site-specific assessment studies and to estimate geological properties like porosity, permeability, depth and thickness at the location of interest.

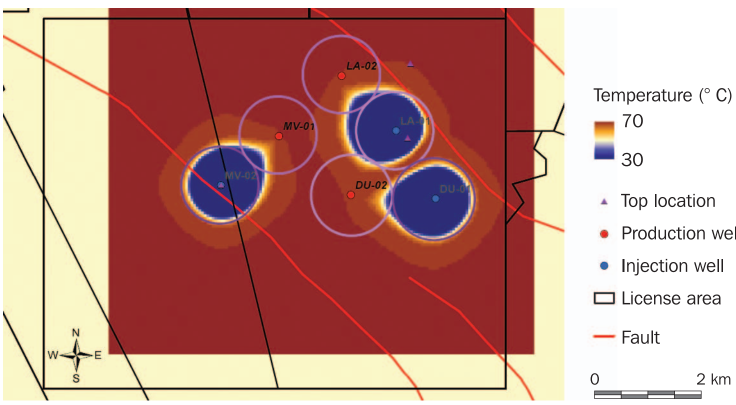
TEMPERATURE MODELLING

The impact of erroneous temperature interpretation can be very significant in geothermal exploration. For direct use applications, including spatial and greenhouse heating, one degree difference in production temperature results in a change in performance of up to 3%. TNO has developed a 3D modelling approach which overcomes this interpolation problem using numerical, thermal models based on tectonic processes. This knowledge can be used in future reservoir studies.

SPATIAL PLANNING

Well layouts can be optimised under uncertainty of the subsurface, adopting state of the art optimisation techniques developed in the oil and gas industry. Key to these techniques is to assess holistically the sensitivity of reservoir performance to particular well design parameters while fully incorporating the effects of subsurface uncertainty on reservoir performance. TNO is using state-of-the-art optimisation techniques for geothermal doublet performance.

These models incorporate the full complexity of geological structural and stratigraphic uncertainty and the practical trade-off of the collective benefits of collective development vs. the risks and additional costs for individual project developers.



GEOCHEMISTRY

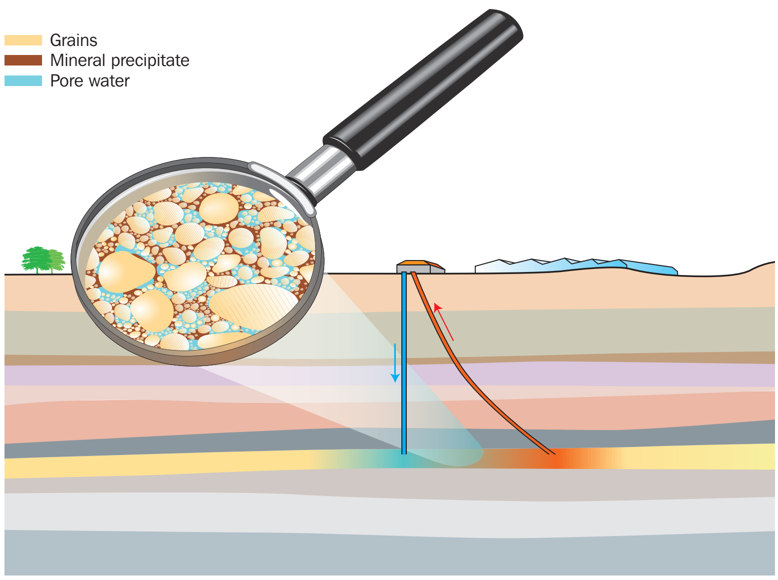
Long term effects caused by temperature changes in the reservoir may reduce the flow and the energy efficiency of a geothermal system. Predicting long term effects and taking preventative measures can overcome future unexpected efficiency reductions.
TNO is performing research in geochemical effects as result of temperature changes in a reservoir due to heat extraction for geothermal purposes.

Deep subsurface reservoir rock contains hot brine, which can be pumped to the surface and exploited as geothermal heat. The reservoir brine is initially in equilibrium with the rock forming minerals. Accordingly, a small amount of these minerals are dissolved in the brine. During brine production and injection the pressure and temperature conditions change, causing a disturbance of the chemical equilibrium. The equilibrium is restored by chemical reactions that involve the precipitation of dissolved elements in the brine forming mineral scales.

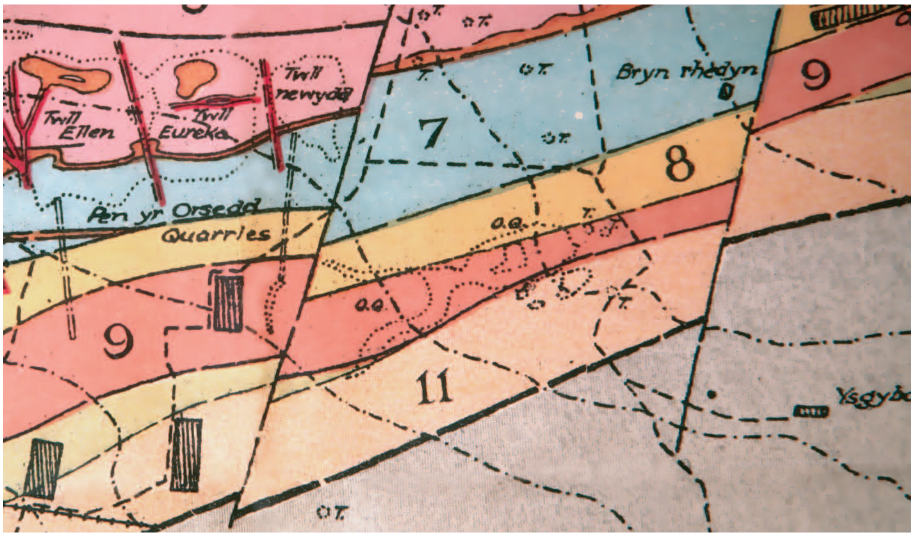
Chemical reactions in the reservoir may also lead to dissolution of minerals. Mineral precipitation in the wells and surface facilities such as pumps, heat exchangers or filters may cause clogging which reduces flow and energy efficiency. Mineral precipitation in the reservoir is important to consider since newly formed minerals can clog pores and flow paths through the reservoir. A permeability decrease results in lower injection and production rates leading to reduced generation of energy.

Geochemistry is required to study the implications on the efficiency and feasibility of a geothermal doublet.

TNO performs feasibility studies to investigate the chemical reactions that affect the flow of water through a geothermal doublet and within the reservoir. Mineral precipitation is computed with changing temperature and pressure conditions using geochemical models. Reactive transport modelling of chemistry and water flow in the reservoir predicts local chemical reactions with time and distance in the reservoir. These studies improve our understanding of geochemical processes concerned with water production and injection and help find a solution for possible upcoming problems in the field of geothermal energy.



GEOMECHANICS



In the near future the developments in Enhanced Geothermal Systems (EGS) will make it possible to start geothermal projects in less favourable geological settings. However, hydraulic stimulation treatments at depths of more then 4000 m are necessary. This introduces new challenges. To face these challenges TNO participates in the 'Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs' project (GEISIR). TNO's extensive knowledge in geomechanics contributes in this research programme addressing issues like the mitigation of induced seismicity to an acceptable level.

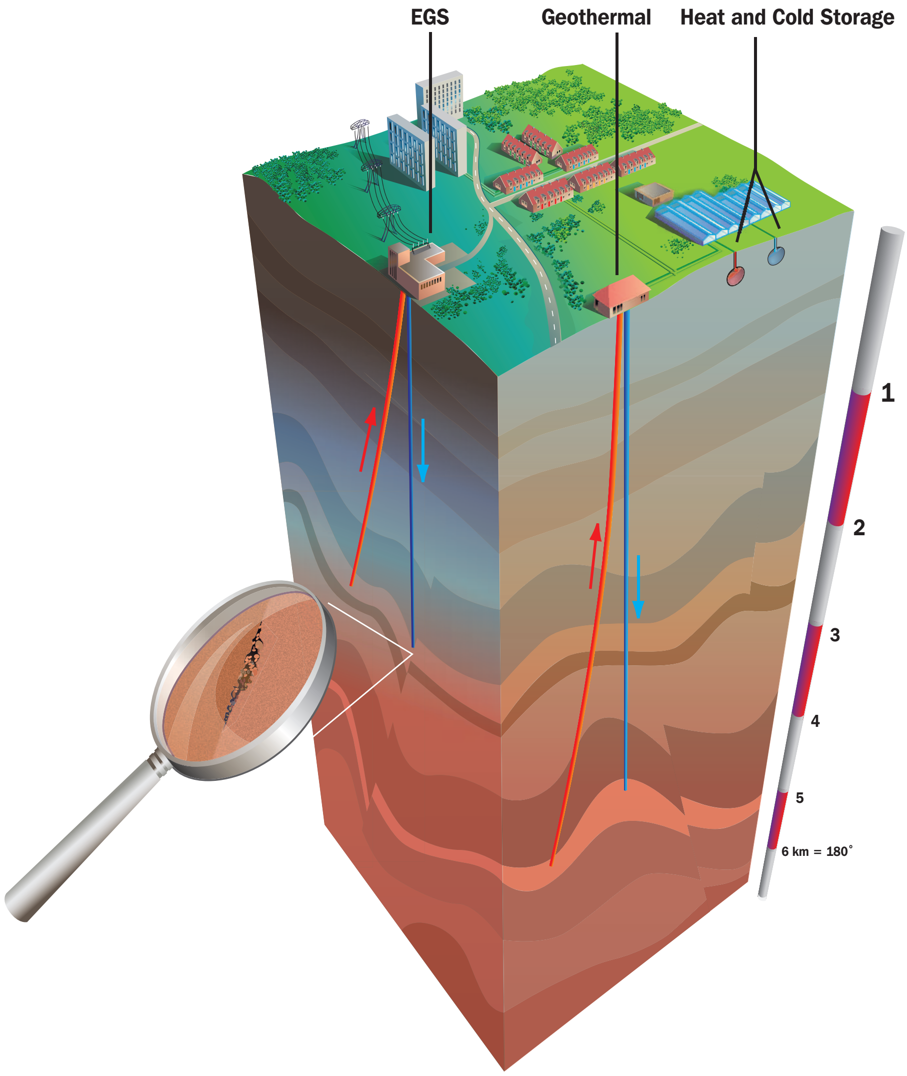
Geothermal energy resources will play an important role in our future energy supply. Geothermal resources are already successfully used in locations with favourable geological conditions. Technologies such as hydraulic stimulation treatments to enhance the productivity of geothermal wells (EGS: Enhanced Geothermal Systems) can be applied to make geothermal projects in less favourable geological settings economically successful.

Hydraulic stimulation (i.e. the injection of fluids to enhance the productivity of a geothermal well) induces micro-seismicity at the location of the geothermal site. In a limited number of geothermal sites, hydraulic stimulation resulted in unwanted larger magnitude seismic events, which caused either damage or public disturbance.

In the EU-granted project GEISER, TNO joins forces with other European research institutions and industrial partners to develop strategies for the mitigation of EGS-related seismicity to an acceptable level. Experience from several geothermal sites, such as the Basel geothermal site and Soultz-sous-forêts (France), is used to improve our understanding of the processes that cause induced seismicity.

The key issues of GEISER are:

- understanding of the geomechanical processes which lead to EGS related induced seismicity;
- quantification of the seismic hazard related to EGS, depending on both geological setting and geographical location;
- development of strategies for the mitigation of induced seismicity, such as 'soft stimulation techniques': hydraulic stimulation without producing larger magnitude seismicity;
- development and use of reliable seismic monitoring networks;
- to formulate guidelines for site selection, site development and the safe deployment of future geothermal plants;
- to formulate guidelines for licensing for local authorities.



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