MSc Program
Renewable Energy in Central and Eastern Europe

Utilisation of Geothermal Energy in Turkey using Hot Dry Rock Technology - does this make sense for OMV from a technological and economic point of view?

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, November 30th, 2012

Affidavit

I, **Dr. Michael Graf**, hereby declare

1. that I am the sole author of the pages 54 to 93 and the co-author of the pages 1 to 12 and 101 to 177 of the present Master's Thesis, "Utilisation of Geothermal Energy in Turkey using Hot Dry Rock Technology – does this make sense for OMV from a technological and economic point of view?", 177 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 30.11.2012

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Signature

I, **Ing. Peter Trupp**, hereby declare

1. that I am the sole author of the pages 13 to 53 and 94 to 100 and the co-author of the pages 1 to 12 and 101 to 177 of the present Master's Thesis, "Utilisation of Geothermal Energy in Turkey using Hot Dry Rock Technology – does this make sense for OMV from a technological and economic point of view?", 177 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Hot Dry Rock is a technology utilizing geothermal energy, which may be at the beginning of a possible widespread commercial use and it potentially might play a major role in the future global energy supply. Turkey has promising sites for the application of HDR, fulfilling geological and geothermal prerequisites. Further due to an increasing economy in Turkey also the energy demand is growing. Based on these statements the main research question which shall be addressed within this study is whether or not the utilization of geothermal energy in Turkey using Hot Dry Rock technology makes sense for OMV from technological and economic point of view.

This study explains systematically the principles and correlations how Hot Dry Rock technology works and how such reservoirs are created, what the prerequisites for a potential application in Turkey are, describes OMV´s suitability to HDR in Turkey and the project economics as well as analyzes involved risks and chances of success. The knowledge and information collected within this paper was gained through secondary research of the relevant scientific literature, expert interviews with professionals from the geothermal industry and within OMV, as well as data collected from OMV internal studies and site visits to geothermal power plants in France and Germany.

One of the key findings of this study is that the technology at the current state of development is controllable. However, the technology implies high exploration risk and high economic uncertainties and is still in its infancy.

Secondly, Turkey is a suitable location for geothermal projects, although better results with less risk involved may be achieved when applying other EGS technology at first rather than starting geothermal activities in Turkey with an HDR project.

A third finding is that due to OMV internal prerequisites, it is recommended to enter the Turkish geothermal market together with a suitable partner.

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Acronyms

BHA	Bottom Hole Assembly
BOP	Blow out Preventer
BWR	Boiling Water Reactor (Nuclear)
CIA	Central Intelligence Agency
EBRD	European Bank for Reconstruction and Development
EGS	Enhanced Geothermal System or Engineered Geothermal System
EMRA	Energy Market Regulatory Authority
EPC	Engineering, Procurement, Construction
E&P	Exploration and Production
FIT	Feed In Tariff
GIS	Geographic Information System
GDP	Gross Domestic Product
HDR	Hot Dry Rock
HFR	Hot Fractured Rock
HT	Hydrothermal
HWR	Hot Wet Rock
ID	Inside Diameter
IEA	International Energy Agency
MTA	Mineral Research and Exploration Institute
NGCC	Natural Gas Combined Cycle (Power Plant)
OD	Outside Diameter
PV	Photo Voltaic
PWR	Pressurized Water Reactor (Nuclear)
R&D	Research & Development
Rig U/D	Rig Up / Down (Drilling)
ROP	Rate of Penetration (Drilling)
SWOT	Strength, Weakness, Opportunity, Threats
TEIAS	Turkish Electricity Transmission Company
WH Ops	Well Head Operations

1 Introduction

1.1 Objective

Hot Dry Rock is a technology utilizing geothermal energy, which may be at the beginning of a possible widespread commercial use and it potentially might play a major role in the future global energy supply as it is not limited to some few preferential locations in the world as conventional, hydrothermal geothermal plants are.

Turkey has promising sites for the application of HDR, fulfilling geological and geothermal prerequisites. Further due to an increasing economy in Turkey also the energy demand is growing.

These statements given above lead to the main motivation to write this Master Thesis, as the chance that the core objective of this work – HDR in Turkey – to be realized in future seems to be possible.

OMV supports this Master Thesis with expertise, internal studies and knowhow and has a vital interest in the final conclusions.

1.2 Core Objective of the Work

The core objective of this Master Thesis is to assess whether or not HDR technology in Turkey is feasible and makes sense from technological and economic point of view.

Currently, the knowledge of OMV in the area of Hot Dry Rock technology and its application to Turkey is limited, since no project has been realized to date, neither in Turkey, nor anywhere else. In this context, this study should analyze the energy extraction based on Hot Dry Rock technology and explain the principles of its methodology. It further should highlight potential improvements in the technology, supporting to make HDR more feasible in future.

This Master Thesis attempts to assess the geothermal potential of Turkey based on existing literature and outlines the future development of this segment. Further the economics of a development project in Turkey as well as the potential risks and chances will be analyzed in this study.

Turkey is one of the defined focus areas of OMV and therefore this study should be a base for OMV´s strategic planning whether or not HDR shall be realized in practice in Turkey.

1.3 Structure of the Work

The structure of this Master Thesis comprises generally of a technological part, Turkey related chapters including not only geography, constitution, economy and the energy sector, but also the legal framework and the auction system for geothermal projects in Turkey, further a section specifically addresses OMV related topics including economics and a part that deals with risks and chances of HDR projects. The technological disquisition starts with geothermal basics, leads through potential resource evaluation and other main technical metrics relevant to HDR as well as methodologies involved in the creation of a respective reservoir. Further it reflects existing installations of the present and the past including lessons learned. Finally also technological research and developments in progress are introduced.

Further Turkey as a potential market applicable to HDR installations is analyzed concerning suitability to HDR required prerequisites and electric power related issues.

In the chapter related to OMV, the strategic fit of HDR is investigated and conclusions from an economic point of view are drawn.

Finally the involved risks and the chances related with applying this technology in Turkey are evaluated.

Split of Work and Investigation:

Since the scope contained in this study is too comprehensive to be covered by one person, this work is a joint effort of Peter Trupp and Michael Graf. In order to allow separate evaluation of the work, the scope was split as following:

Peter Trupp worked out chapter 2 – Hot Dry Rock (HDR) Technology and 7 – SWOT Analysis, and Michael Graf wrote the chapters 3 – Geothermal Energy in Turkey, 4 – Legal Framework in Turkey for Geothermal, 5 – Auction system for Geothermal in Turkey and 6 – Strategic fit of HDR.

The chapters 1 – Introduction and 8 – Conclusions are a joint work although the core question whether it makes sense or not from technological point of view is answered by Peter Trupp and the core question whether or not it makes sense from economic point of view is concluded by Michael Graf.

1.4 Description of Method of Approach applied

The technological part of this study was investigated by secondary research in relevant scientific literature. In addition, expert interviews were held with Richard Artley (GP International) and Julia Davies (OMV Geothermal Team) to supplement and clarify the findings, respectively to identify additional areas of investigation.

Moreover the European Test Site in Soultz-sous-Forêts in France was visited, as well as the geothermal power plants based on EGS in Landau and Insheim, both in Germany. These site visits and the personal conversation with Bernd Melchert in Soultz-sous-Forêts as well as Jörg Baumgärtner in Germany gave additional added value to the information contained in the Study.

Data collected from research in relevant literature were building the base for the chapters about Turkey. In addition the findings where substantiated with internal studies of the OMV geothermal team and the Gas & Power Group, as well as interviews with OMV experts.

The section related to OMV relevant topics is based on an analysis of expert interviews and relevant secondary data research.

The chapter concerning risks and chances as well as the SWOT analysis was built on the information collected during the site visits to France and Germany as well as relevant literature research and an interview with Walter Brunner from OMV E&P to get the OMV internal strengths and weaknesses.

2 Hot Dry Rock (HDR) Technology *(Peter Trupp)*

2.1 Introduction to Geothermal Energy

Taking a look inside the planet earth as shown in Figure 1, it can be seen that the earth is structured in layers, called the earth´s crust, the mantle and the core, listed from the out- to the inside. While the solid crust, with a thickness of about 30 km onshore and about 5 km beneath the oceans, consists of solid rock material and sediments, the material below the crust more and more becomes ductile. 99% of the planet earth has a temperature at levels higher than 1.000°C.[1]

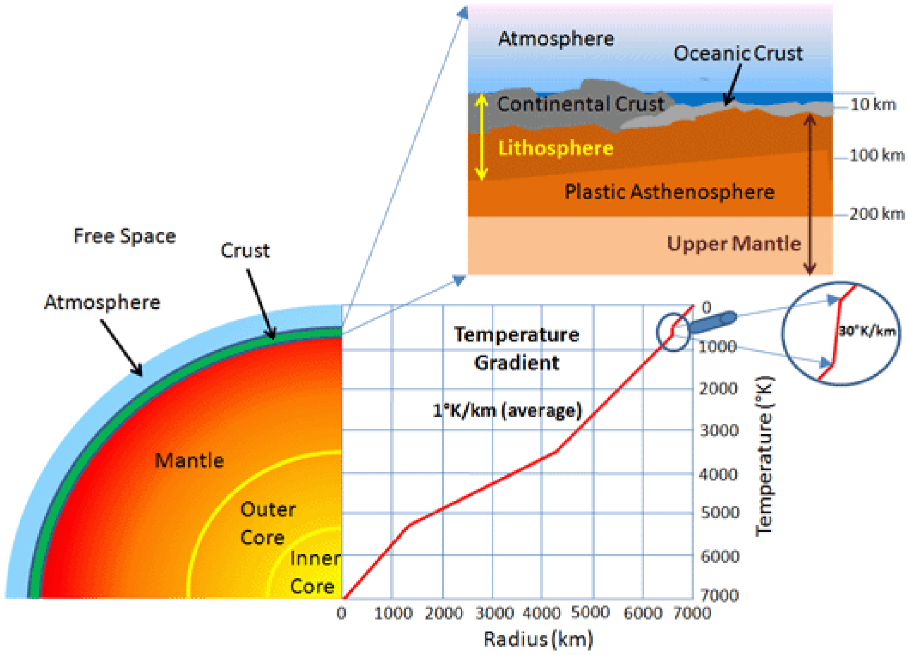

Figure 1: Structure of the earth and Temperature Gradient[2]

The temperature is increasing from the outer crust towards the inner core to levels of more than 6.000°C as it was modelled. The energy contained in the earth in the form of thermal respectively heat energy is called geothermal energy.

The major source of this vast geothermal energy potential is a process of radioactive decay of isotopes that naturally appear in the layers of the earth, such as

[1] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

[2] http://www.mpoweruk.com/geothermal_energy.htm, 25.04.2012.

Potassium-40, Uranium-235, Uranium 238 and Thorium-232. When thinking about usable geothermal energy as a fraction of the total geothermal energy, the limitation mainly is given by the depth in the earth that can be reached with technology available today (deepest borehole on earth is 12,3 km deep) and the limitation due to economic feasibility[3]. According to an estimation, the geothermal energy stored in the earth´s crust is in the range of 5,4 billion EJ, where the annual global consumption of primary energy is about 400 EJ, which leads to an estimated availability of geothermal energy for 13.500 years if only 0,1 % of the total geothermal energy stored in the crust is extracted[4].

2.2 Classification of Geothermal Resources

Geothermal Resources can be structured and classified according various criteria, described as following:

2.2.1 Classification according to Enthalpy

Classification of geothermal resources according to their enthalpy helps in evaluating the potential use of the water and / or steam produced from a reservoir. While vapour and dry steam, respectively hot water above 200°C dominated high enthalpy resources are perfectly suitable for electricity generation, low and medium enthalpy resources that are liquid dominated are energetically inefficient for electricity production and therefore are better suitable for direct heat use.
Although there is no uniform, standardized limitation for low, medium and high enthalpy resources, according different scientists the limits are quite similar.

Table 1: Classification of Geothermal Resources acc. to Enthalpy[5]

	Muffler & Cataldi, 1978	*Hochstein, 1990*	*Benderitter & Cormy, 1990*	*Haenel, Rybach & Stegena,1988*
Low Enthalpy	< 90C°	< 125C°	< 100C°	< 150C°
Medium Enthalpy	90-150°C	125-225°C	100-200°C	-
High Enthalpy	> 150°C	> 225°C	> 200°C	> 150°C

[3] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[4] Milics, Gabor: Script Geothermal Energy. MSc Program “Renewable Energy in Central and Eastern Europe”, 2011.
[5] Milics, Gabor: Script Geothermal Energy. MSc Program “Renewable Energy in Central and Eastern Europe”, 2011.

2.2.2 Classification according to Extraction System

2.2.2.1 Borehole Heat Exchanger

When geothermal energy is utilized through a borehole heat exchanger, water is circulated down a casing, installed in the borehole, where the water is heated from the surrounding soil and rock, and further flows up again through a tubing string, which is installed within the casing. The heated water, on the surface can be used for space heating or domestic hot water heating as well as industrial purposes. A characteristic feature of this system is that the water is not in direct contact with the rock itself.

2.2.2.2 Hydrothermal Systems

A hydrothermal system is distinguished by an aquifer, where naturally occurring thermal liquids circulate and are heated from hot solid rock or magmatic heat sources. As preferentially the aquifer spreads out over a big flow channel network, the thermal water circulating through the aquifer gets access to vast heat sources. The thermal fluids finally are available as hot water and sometimes steam. Hydrothermal systems appear in regions of volcanic activity, at the boundaries of tectonic plates and in areas of deep reaching geologic fault systems and consequentially are limited to specific regions on the globe.

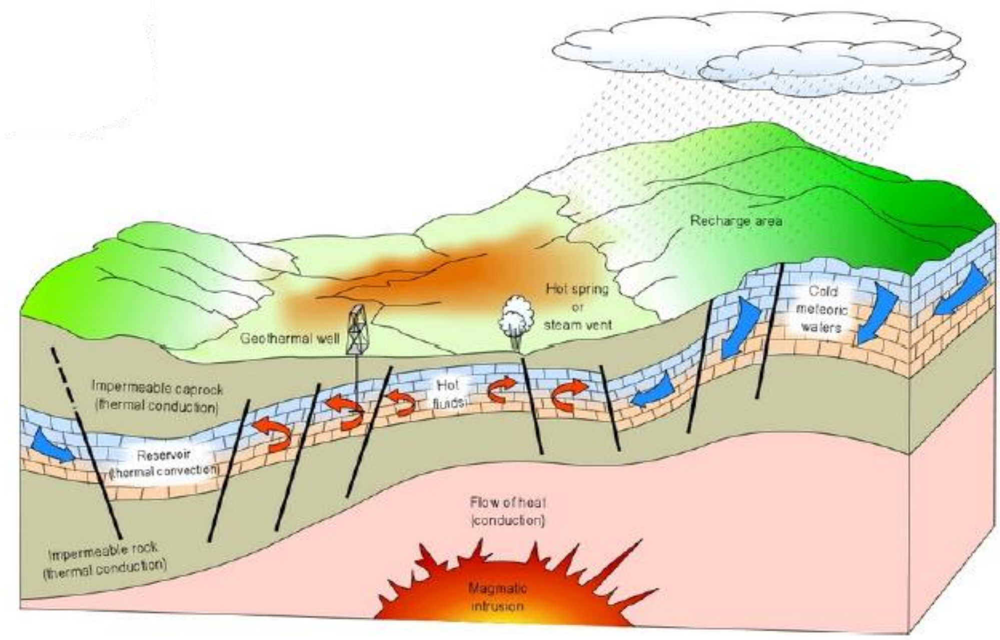

Figure 2: Hydrothermal System with Aquifer, Cap rock and Heat Source[6]

[6] Milics, Gabor: Script Geothermal Energy. MSc Program "Renewable Energy in Central and Eastern Europe", 2011.

Depending on the enthalpy of the thermal fluid, the heat is used directly or to generate electric energy. Where the thermal liquid doesn´t find its way to the surface on its own, wells are drilled through the cap rock into the aquifer to produce the hot water and steam[7].

2.2.2.3 Petrothermal Systems

The energetic utilization of a geothermal reservoir is called petrothermal system, when the reservoir does not bear water or contain only little amounts of natural liquids. As this type of geothermal system is not strictly bound to the prerequisite of in situ water, the global potential of energy extractable from petrothermal systems is much larger than from hydrothermal systems. Hot dry rock reservoirs, as well as other types of enhanced geothermal systems fall within petrothermal[8].

2.3 Definition of Hot Dry Rock (HDR) Technology

In a Hot Dry Rock geothermal system heat is extracted from a dry mass of rock that is characterized as homogeneous and crystalline, having low or even no permeability and having a reasonable high temperature allowing heat mining[9]. To utilize this energy contained in a confined[10] HDR (Hot Dry Rock) reservoir, artificially flow channels have to be created in the rock and due to the absence of substantial amount of naturally occurring geothermal liquids, external fluid has to be circulated through these manmade fractures to extract heat from the rock mass[11].

The subsurface fluid flow paths typically are created by drilling into the hot rock mass that is intended to be mined, until temperatures are reached at a reasonable high level. This well usually is used for fluid injection. By stimulation of this well, preexisting fractures in the rock are widened and kept open, as well as new fractures are created to a network of interconnected flow channels within the HDR

[7] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

[8] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

[9] Sass, John H.: Potential of Hot-Dry-Rock Geothermal Energy in the United States, A Report to the United States Congress under Section 2502 of Public Law 102-486. U.S. Geologic Survey in collaboration with the U.S. Department of Energy, 1993.

[10] Brown, Donald W.: Hot Dry Rock Geothermal Energy: Important Lessons from Fenton Hill. Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University Geothermal Program, Technical Report SGP-TR-187, 2009.

[11] Dickson, Mary H. and Fanelli, Mario: What is Geothermal Energy? Instituto di Geoscienze e Georisorse, CNR, Pisa, Italy, 2004.

reservoir. Further wells, which will be used for fluid production, then have to be drilled, intersecting the fracture network to enable fluid to be circulated through the injection well into the reservoir and back to the surface through the production well(s). The subsurface fracture network acts as a huge heat exchanger, where the injected fluid is heated passing the HDR formation, whilst the rock mass is cooled over time of operation[12].

The heat extracted from the reservoir further can be used for space heating or to satisfy hot water needs in private houses, agricultural businesses or the industry, respectively can the energy be converted from heat into electricity, where the hot water and/or steam produced, feeds electricity generating power plants[13].

The primarily concept of HDR technology, since it was invented by a group of scientists and engineers from the Los Alamos National Laboratory in the 1970s[14], developed and today appears with different names, such as “Hot Dry Rock (HDR)”, “Hot Wet Rock (HWR)”, “Hot Fractured Rock (HFR)”, “Enhanced Geothermal System (EGS)”, “Engineered Geothermal System (EGS)” or “Heat Mining”[15] where finally also reservoirs are covered at the edge of hydrothermal fields.

The major differences between these denominations are in the extent of permeability respectively preexisting fractures, and the extent of geothermal liquid naturally existing in the formation. While Hot Dry Rock (HDR) is a confined system with least permeability of the different methods and no fluid in place, Hot Fractured Rock (HFR) has a higher permeability, but still is confined with no insitu liquid. Hot Wet Rock (HWR) is a partly open system with an even higher permeability than the two before mentioned and consequentially already naturally exchanges fluids with more remote rock masses. All of the three categories need enhancement as permeability improvement and fluid has to be added to produce the reservoir for a reasonable time, and consequentially fall into the group Enhanced or Engineered Geothermal System[16].

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[12] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

[13] Dickson, Mary H. and Fanelli, Mario: What is Geothermal Energy? Instituto di Geoscienze e Georisorse, CNR, Pisa, Italy, 2004.

[14] Brown, Donald W.: Hot Dry Rock Geothermal Energy: Important Lessons from Fenton Hill. Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University Geothermal Program, Technical Report SGP-TR-187, 2009.

[15] Friedleifsson, Gudmundur Omar et al: Deep Unconventional Geothermal Resources: a major opportunity to harness new sources of sustainable energy. http://www.worldenergy.org/documents/congresspapers/P001099.pdf, 2006

[16] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.

To extract heat from the earth´s crust using HDR technology for an extended time at commercial rate, according to a very basic definition of the HDR concept, the following conditions must be met. As Baria[17] puts it

- *"A substantial mass of hot rock should be available at a reasonable depth*
- *A fluid flowpath and heat exchanger or a permeable zone must be created in the rock mass, having*
- *A low flow resistance, enabling high fluid throughputs to carry the required amounts of thermal energy to the surface power conversion system*
- *A sufficiently large heat exchange surface between rock and circulating fluid to enable transfer of thermal energy"*[17]

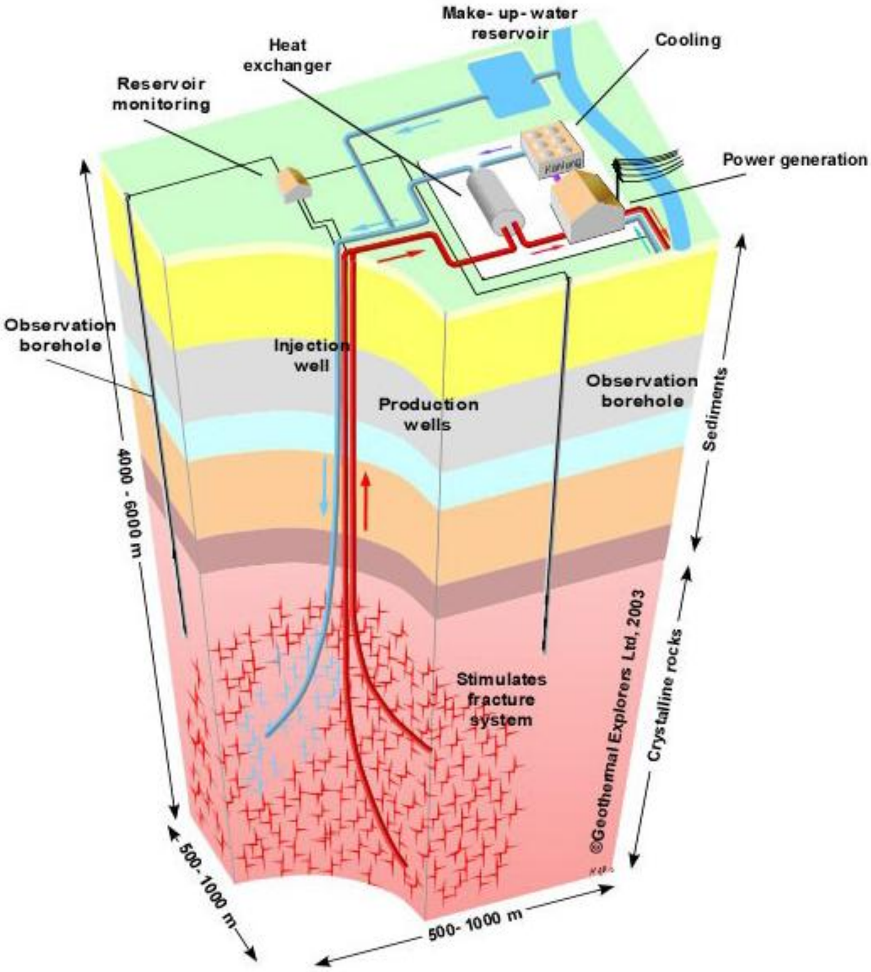

Figure 3: Principle of HDR technology[18]

[17] Baria, Roy et al: HDR/HWR reservoirs: concepts, understanding and creation. In: Geothermics 28, Elsevier Science Ltd., 1999.
[18] http://www.ifd.mavt.ethz.ch/research/group_pj/project_geotherm, 10.04.2012

2.4 HDR Basic Conditions and Technical Framework

2.4.1 Essential Parameters characterizing HDR thermal energy resources

As the primarily purpose of HDR technology is the provision of energy for human utilization, at first it is important to know what the energy content is, that is stored in a mass of rock in accessible depths, above a minimum reference temperature, e.g. the ambient temperature on surface where the contained heat potentially can be released to atmosphere.

The following formula describes the quantity of heat contained in rock material, relative to a reference environment:

$$Q = \rho \cdot C_p \cdot V \cdot \Delta T$$

Where ρ = rock density (kg/m³)

C_p = rock specific heat capacity (kJ/kg-K)

V = rock volume (m³)

ΔT = Temperature difference between mean initial rock temperature and a reference temperature (e.g. ambient surface temperature or a temperature to that the rock mass is cooled down) (K)[19]

The definition of the reference temperature today is not yet fixed uniform. While in the study of the Massachusetts Institute of Technology from 2006 it is suggested to use the ambient surface temperature, other literature refers to a reference temperature of 80°C above ambient surface temperature[20].

Taking as an example a rock density of 2.550 kg/m³, a rock specific heat capacity of 1.000 J/kg-K, an initial rock temperature of 250°C and a reference temperature of 50°C, to which the rock mass is cooled down in this example, as well as a rock volume of 14 km length, 14 km width and 1 km thick, the heat possibly released from the rock mass equals to 100 EJ.

As the rock specific heat and the density are material specific given facts, the major parameters characterizing energy content in place in HDR reservoirs are the initial temperature and the volume of the rock mass.

To assess heat content in place over a specified territory, the information about the temperature at depth is needed. The main mechanism how heat is distributed

[19] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

[20] Beardsmore, Graeme et al: A Protocol for Estimating and Mapping Global ESG Potential. Presented at: Australian Geothermal Conference 2010.

through solid bodies as the earth is conduction where heat flows from the point of higher temperature to the point with lower temperature. The heat flow caused by the conduction is measured in Watt per Square meter (W/m^2). Related to the earth this means that there is heat flow from the hot center of the planet to the surface where temperature is lowest, corresponding to the second law of thermodynamics. The rate of heat flow in earth depends mainly on a material specific thermal conductivity, measured in Watt per Meter and Kelvin (W/mK), which represents a measure for the ability to transfer heat. These relations show that high temperatures in shallow depths are a consequence of high heat flow in this area. Of course also the presence of radioactive elements gives its contribution to energy in place due to the radioactive decay, generating thermal energy where these elements occur. Another important parameter is the geothermal gradient, indicating the temperature increase per depth, which is measured in Kelvin per kilometer (K/km). It can be calculated by dividing the heat flow through the thermal conductivity, respectively it is measured during drilling operations[21].

2.4.2 Essential Parameters affecting HDR energy recovery

Where in the previous chapter purely the heat content of a mass of rock was considered referring to a minimum reference temperature, it is further important to know what the recoverable fraction of this is and what the influencing metrics are.

The main mechanisms responsible for the amount of energy that can be extracted from a given mass of rock are the quality of heat transfer from the rock to the fluid that is injected, heated and produced, and consequentially the speed at which energy is extracted, and how good the access is to the whole rock that is considered to be mined[22].

2.4.2.1 Fractured Rock Volume

Although rock has very good heat storage capacity, the ability to transmit heat is poor due to relatively low thermal conductivity. If there is insufficient access to the whole mass of rock that is considered to be produced, some of the heat will remain in place in areas where no circulation fluid access is given. The volume that is

[21] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

[22] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

accessible for the fluid to be circulated through the created fracture network is referred to as the fractured rock volume.

In sensitivity analysis to the recoverable energy of a reservoir, that were performed to model the impact of the various parameters such as fractured volume and spacing, fluid mass flow and others, it showed that the single most important value influencing the recovery rate is the fractured volume.

It also was found that for a variety of temperatures, well set ups and spacing, even assuming power requirements of a power plant, the net electric power that can be generated is about 0,026 W_{el}/m^3 fractured rock volume, which means it is directly proportional to the fractured volume within limits.

Another finding is that it always is beneficial to have more than one producer well, to reduce the dead fractured volume, as the fractures do not expand in one direction only from the well the fractures originated from.

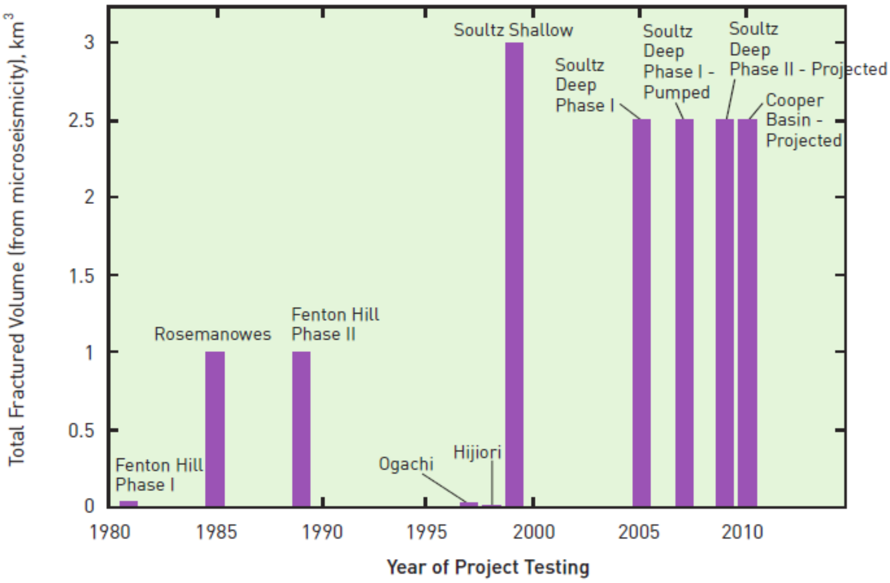

Figure 4: Fractured Rock Volume (Information from microseismics) achieved in existing HDR / EGS test facilities[23]

2.4.2.2 Temperature and Fluid Flow

When heat is extracted from a given rock mass with a given initial energy content, the temperature in the rock will decrease over time, as long as there is more energy released to the production fluid, than is absorbed through heat flow into the rock

[23] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

from rock below the reservoir. As typically the energy extracted from a HDR reservoir is converted into electricity, and the efficiency of a heat to electricity converting power plant decreases with temperature, at a certain rock temperature it doesn´t make sense any more from economic point of view to continue heat extraction from this reservoir. At this point in time the power generation is ceased. The mean rock temperature where the heat extraction is discontinued is called the abandonment temperature. The lower the abandonment temperature related to the initial rock temperature will be, the bigger is the total amount of heat extracted from a reservoir over its lifetime as the life then is extended[24].

The rate at which energy is extracted from a reservoir - the power - can be defined as a product of enthalpy difference between fluid entering and fluid leaving the reservoir and the liquid mass flow circulated through. The total energy recovered is the time integral of all power extracted per time unit over the life time of the reservoir. Both the power and the total energy recovered are wanted to be high, as the power determines the current sales revenues per time unit and the total energy recovered leads to the total revenues over the lifetime of a reservoir that justifies the whole investment.

Another important relation is that the rate at which energy moves from the rock to the fluid gets bigger, the bigger the temperature difference is between rock and fluid. This means if fluid is circulated through the rock at a very low mass flow, due to a long retention time of the fluid in the reservoir, the fluid temperature will increase to or almost to the rock temperature which gives high enthalpy difference between injected and produced fluid, but still the power is low due to low mass flow of fluid. If the energy extracted per time unit is equal or even less than the heat flow into the reservoir from below, there would be no decline in rock temperature and the life time would be maxed, although the heat extraction would be economically inefficient.

When fluid mass flow is increased to a maximum, the retention time of fluid within the reservoir is reduced and the power output would be increased, as there is in average a bigger temperature difference between rock and liquid. The total heat that can be extracted over lifetime in this case is reduced, due to the fact that the temperature drawdown will happen quicker and the reservoir will significantly cool down, especially close to the injection well where the temperature of the fluid is coldest.

[24] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

The goal should be to maximize the total energy mined before the abandonment temperature is reached, at the same time optimizing the power output to be economically efficient but still to enable a reasonable life time of 20 to 30 years for the reservoir.

2.4.2.3 Fracture Spacing

The distance between fractures in a HDR reservoir that is produced is called fracture spacing. It has shown in simulations that the fracture spacing has also an important impact on the total energy recovery possible. In modeling the total energy extractable at different fracture spacing between 3 and 300 m it was found out that for very large fracture spacing the recovery factor decreases as there is insufficient access to all the rock mass. At smaller spacing the recovery factor increases, although within a range of 30 m and smaller, the recovery factor did not further improve. Even when modeling with the assumption of homogeneous fractures within the rock, which is not realistic as the fractures exist or are created in a heterogenic distribution, the influence of fracture spacing to the recovery of energy in place is important to be understood.

2.4.2.4 Fracture Surface Area

The contact surface between hot rock and fluid, which is the active fracture surface area, virtually behaves as a heat exchanger. The heat moves through the rock due to conduction to the fracture surface and then is transferred by convection to the fluid. If there is insufficient fracture surface area, also the magnitude of heat that is transferred is limited and consequentially the total energy recovery out of a given rock mass is reduced.
The fracture surface area is determined by the well distance, which assimilates with the length of the fractures, the width of the fractures, the number respectively the spacing between the fractures and the well configuration, whether there is one, two or more producer wells per injection well[25].

2.4.2.5 Recovery Factor for HDR

The recovery factor is defined as heat extracted divided by the heat in place, and is expressed in percent. It is crucial for economic investment decisions, whether a project makes sense or not. The major parameters finally determining the recovery

[25] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

factor are described above. Based on modeling and field test at the various test sites the latest estimation of realistic recovery factors are from below 2% to about 3 to 4%[26].

2.4.3 Sustainability and Renewability

When heat is extracted from a confined HDR reservoir at a rate which is higher than conductive heat resupply from deeper hot regions in the earth, the mean temperature of the reservoir will decline and the energy content will decrease as well. The heat resupply in this case reduces the speed of temperature drop, but nevertheless the energy contained in the reservoir will exhaust[27]. After a formation is ceased to be produced, due to the evidence of heat flow, the reservoir will recover in less than 100 years as it was modeled, and consequentially heat extraction from a HDR reservoir can be considered as sustainable and renewable, although the time scale for renewability is quite different than for other renewable energy sources as biomass, wind or solar[28].

2.5 Creation of a HDR reservoir

2.5.1 Drilling Technology

Drilling generally is an operation which is well known from the oil and gas industry, although there are a couple of very specific peculiarities, such as the bigger drill diameters used in geothermal drilling projects compared to oil and gas drilling, the potential corrosive property of naturally existing geothermal fluids, the high temperatures occurring when drilling for a HDR reservoir and the harsh mechanical properties of the hard and abrasive rock, that the wells drilled for HDR reservoirs typically are deeper than oil and gas wells, and last but not least, drilling for a potential HDR reservoir almost always demands directional drilling. As drilling costs involved in HDR and also other geothermal projects are in the magnitude of 40 to 60% of the total investment, they can be the crucial factor whether a project is economically feasible or not.

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[26] Grant, Malcolm A. and Garg, Sabodh K.: Recovery Factor for ESG. Proceedings, Thirty Seventh Workshop on Geothermal Reservoir Engineering, 2012.

[27] Antics, Miklos and Ungemach, Pierre: Presentation Insight into Modern Reservoir Engineering and Management Practice. At: Conference Geothermal Energy and CO2 Storage: Synergy or Competition, 2010

[28] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

According to currently used drilling methodology, the main equipment is the drilling rig (see figure 5), that drives the drill bit down hole through the drilling string. During the process, while the drill bit makes its way down to the target zone, the drilling string is extended by installation of more and more drill pipes. To protect the borehole against collapsing, protective pipes, the so called casing, are inserted into the hole and cemented to the surrounding rock. As the drill bit has to pass the casing before continuing the drilling operation, the borehole is produced in a tapered shape, reducing diameter the deeper to hole gets.

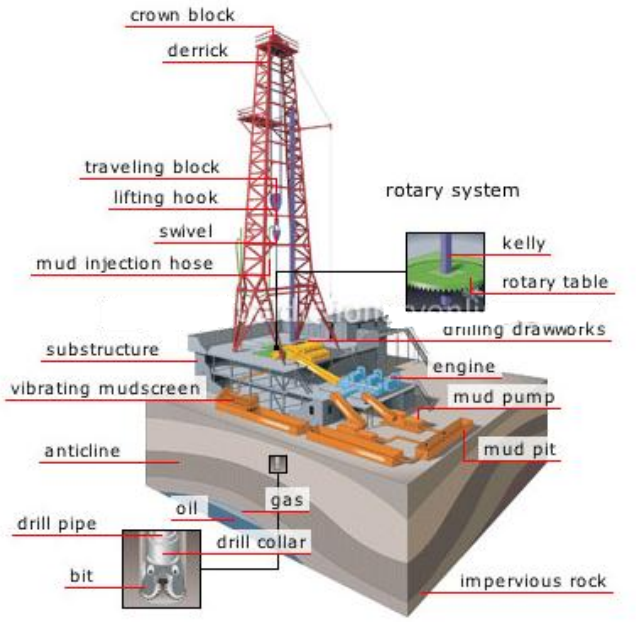

Figure 5: Drilling Rig[29]

During drilling, so called drilling mud is flushed down the drilling string, as Huenges[30] puts it, to

> "*cool the drill bit, transport the cuttings away to the surface, stabilize the borehole wall, exert hydraulic pressure (via the hydrostatic head of the mud column) to prevent gas and fluids from entering the borehole and to power own hole drilling motors for directional drilling".*[30]

The drilling mud reaches surface again through the annulus between drilling string and borehole to be recycled in a way that the cuttings are removed, and again is pumped back down hole. There is several types of drilling mud, such as water based muds, oil based muds which are used when penetrating water sensitive formations, foam based muds, used for low pressure gradient formations, and also

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[29] http://visual.merriam-webster.com/energy/geothermal-fossil-energy/oil/drilling-rig.php, 02.06.2012

[30] Huenges, Ernst: Geothermal Energy Systems – Exploration, Development and Utilization. Wiley-VCH Verlag GmbH & Co.KGaA, 2010.

air can be used as drilling fluid, typically for drillings where stability of the borehole is not an issue.

As the goal in drilling for HDR reservoirs is to get quick, cheap and reliable access to the hot rock formation with only little risk involved, the choice of equipment and methodology is crucial. While with every change of the drill bit the whole drilling string has to be pulled to get access to the bit, whereat this so called tripping causes unproductive time which involves costs, the life time of the drill bit is essential. As challenges for the bits are increasing the harder and hotter the material to be drilled is, especially boreholes in abrasive hot basement rock as in HDR reservoirs need careful selection of the drill bit materials, where typical life time spans in a range from 30 h to 60 h. Depending on the depth reached already, the tripping might last as long as 24 h, which shows that the portion of unproductive time is high related to net drilling time. The fact that the ratio of drilling time vs. unproductive time is declining with depth, is one of the reasons why drilling costs grow exponentially the deeper the borehole is.

Air drilling, where the drilling fluid is air instead of mud, potentially decrease costs involved, as the rate of penetration (ROP) can be as high as ten times the ROP with conventional mud. Nevertheless, air drilling has its limits as heavy muds are needed when formations are penetrated containing gases or liquids under pressure, to prevent these liquids and gases from entering the borehole.[31]

A representative cost breakdown for EGS wells (see figure 6) shows that about 75% of the overall costs involved are from drilling, cementing, casing and tripping, which actually indicates already the future saving potentials.

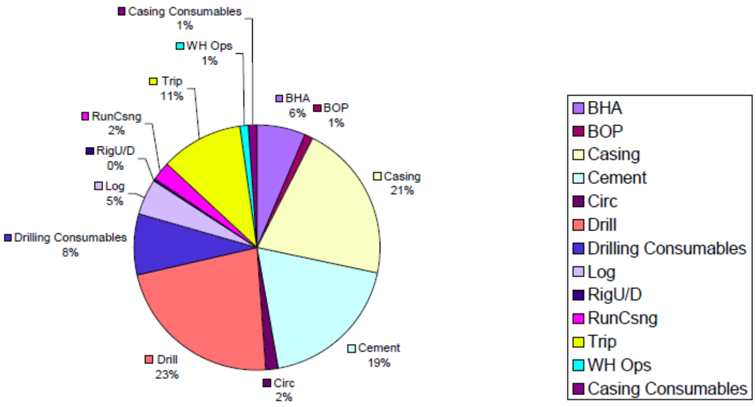

Figure 6: Well Cost breakdown to Categories for EGS Wells[32]

[31] Huenges, Ernst: Geothermal Energy Systems – Exploration, Development and Utilization. Wiley-VCH Verlag GmbH & Co.KGaA, 2010.

[32] Polsky, Yarom: Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report. Sandia National Laboratory, 2008.

The development under way today to make drilling into deep hot rocks cheaper is mainly concentration on automation of the drilling procedure to reduce manpower involved, development of more efficient methodologies as for drill bits and drilling muds, as well as new casing concepts (e.g. with a single diameter from surface to the bottom of the hole) and new revolutionary drilling methods.[33]

2.5.2 Enhancement

Due to the fact that, contrary to hydrothermal reservoirs where waterways already exist, HDR energy resources are within rock mass with little or no permeability, artificial fluid flow paths have to be created or at least have to be enhanced by stimulation. While thermal and chemical stimulation improve permeability near the wellbore, hydraulic fracturing respectively shearing is the only methodology creating fractures long enough to develop an economically feasible HDR reservoir.[34]

2.5.2.1 Hydraulic Fracturing

Hydraulic fracturing is a process, where water is injected into a borehole, and due to increasing water pressure open fractures within the rock are created. This generally is a technology which is well known from the oil and gas industry, although the fractures required to enhance oil and gas production typically are created in sedimentary rocks and have a length of a few meters, which is sufficient to improve the oil and gas inflow performance to a well. Contrary when creating a HDR reservoir, the material that should be fractured is brittle basement rock, and the length that should be achieved reaches out to several hundred meters to get sufficient fractured rock volume and fracture surface area. Hydraulic fracturing in basement rock is dependent on the existing stress regime within the rock. As there is stress in each direction, as shown in Figure 7, the vertical stress S_V and the two horizontal stress components S_H and S_h, the orientation of created fractures is dependent from the order of magnitude of the stress components in relation to each other.

[33] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[34] Huenges, Ernst: Geothermal Energy Systems – Exploration, Development and Utilization. Wiley-VCH Verlag GmbH & Co.KGaA, 2010.

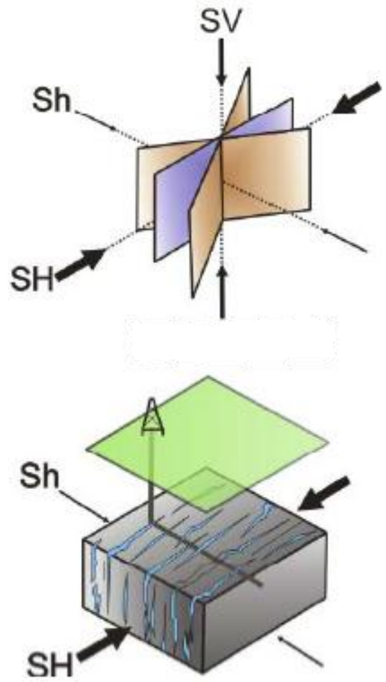

Figure 7: Stress Regime and Orientation; Shear Failure and Tensile Fractures[35]

Stress forces within the rock are transmitted through mechanical contact of solid material and through fluids that are contained in the rock. When water is injected into the rock that is intended to be fractured, the water finds its way into preexisting fissures and pore volume. By increasing the pressure of the water injected, also the hydraulic pressure within these preexisting fissures and pores, the so called pore pressure, is increased and an increasing portion of the stress forces is transmitted by the fluid contained in the rock, respectively a declining portion of these forces is received by solid contact. Consequentially the shear strength of the rock is reduced. When the pore pressure exceeds the least stress of the three directions, a fracture opens, with increasing aperture in the least stress direction. At the same time the biggest stress moves the parted rocks and props the fracture open as the faces of the fracture will not match any more, as shown in figure 8. While tensile fracturing (blue in figure 7) occurs along the plane oriented along the maximum stress direction, shear fractures (brown in figure 7) appear at ±30° related to the maximum stress direction.

[35] Huenges, Ernst: Forschungsplattform Groß Schönebeck, Technologieentwicklung für eine effiziente Wärme- und Strombereitstellung aus tiefer Erdwärme. In: System Erde, GFZ Journal 2, Deutsches GeoForschungszentrum, Potsdam, 2011.

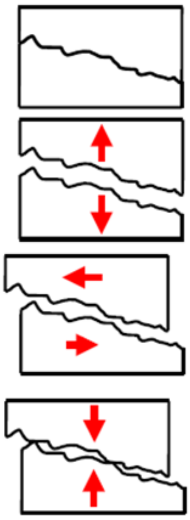

Figure 8: Mechanism during Hydraulic Stimulation[36]

It has shown that the most important mechanism in creating fractures in crystalline basement rock is shear failure. A potentially negative side effect that needs careful planning of hydraulic stimulation is that the induced seismicity possibly can be felt as an earthquake on the surface.[37]

2.5.2.2 Chemical Stimulation

Chemical stimulation is a process where chemical substances are injected into the borehole to disperse material that restricts the flow of geothermal water that is intended to be produced or injected, within close proximity to the well bore. The flow restrictions can be precipitations, that sometimes occur after producing a well, or can the aperture of a flow channel be increased when acidized. The chemicals used and their concentration depends on the geochemistry of the rock material that is intended to be solved. Typically the process consists of three stages, pre flushing, main acid stage and post flush, where hydrochloric acid (HCl), hydrofluoric acid (HF), citric acid or other substances respectively mixtures of the various chemicals, as concentration of 3 to 15%, are injected.

2.5.2.3 Thermal Stimulation

Thermal stimulation, as also chemical stimulation improves the permeability in close proximity to the well bore. While cold water is injected into the hot rock, due to the relatively big temperature difference to the rock, the rock cools and consequentially

[36] Sass, Ingo: Presentation Seismizität und mögliche Probleme – Darstellung am Beispiel Basel. Held at: 2. Tiefengeothermie-Forum Darmstadt on 04.09.2007.
[37] Huenges, Ernst: Forschungsplattform Groß Schönebeck, Technologieentwicklung für eine effiziente Wärme- und Strombereitstellung aus tiefer Erdwärme. In: System Erde, GFZ Journal 2, Deutsches GeoForschungszentrum, Potsdam, 2011.

contracts, while generating tensile stress. Supported by pulsing hydraulic pressure which is applied through the well head, near well bore fractures develop. Thermal stimulation is typically applied on high temperature wells.[38]

2.6 Existing Installations

Since the idea of Hot Dry Rock technology, based on an artificially created subsurface fracture network to extract geothermal energy, first was started to be realized in Fenton Hill, New Mexico in the early 1070ies, a number of further test projects where implemented in Europe, the USA, Australia and Japan. In the following chapters an overview is given about these, including conclusions derived from the work at these projects. As the number of real HDR projects in the world is very limited, this overview also contains other EGS projects and test installations that do not strictly comply with the definition of HDR, but still contribute to the gain of knowledge in HDR development due to similar approach in creating and producing a reservoir.

2.6.1 Overview of realized Projects

A chronological overview about the various projects is shown in Figure 9 below.

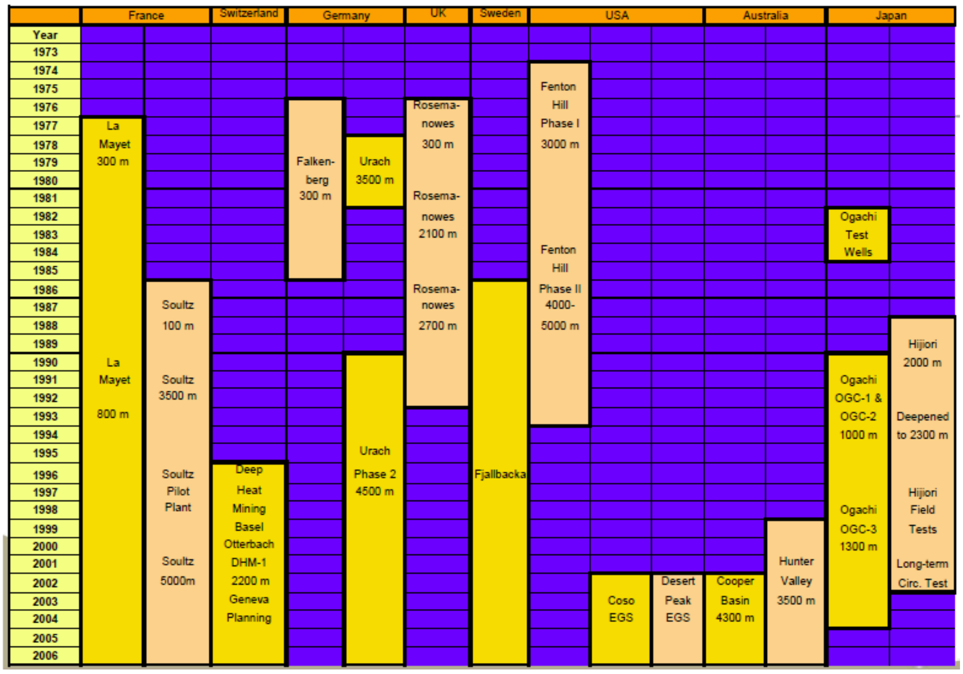

Figure 9: Overview of realized HDR / EGS projects until 2006[39]

[38] Huenges, Ernst: Geothermal Energy Systems – Exploration, Development and Utilization. Wiley-VCH Verlag GmbH & Co.KGaA, 2010.
[39] Alta Rock Energy Inc.: Presentation Status and Achievements, EGS Reservoir Creation. At: Technical Workshop, Reykjavik, Iceland, 2008.

Further the main technical characteristics are summarized in Table 2 below.

Table 2: Main technical characteristics of some HDR / EGS projects realized[40]

Project	Fenton Hill	Fenton Hill	Hijiori	Rose-manowes	Soultz	Soultz	Soultz
Country	USA	USA	J	UK	F	F	F
Phase	1	2			1	Antici-pated 2	2011
Rock Temperature (°C)	195	232	270	80	170	200	200
Reservoir Depth (m)	2800	3500	2200	2000	3500	5000	5000
Well Separation (m)	100	150-300	130	160-270	450	600	600
Production Flow (l/s)	6	7	12	15	25	60	23
Water Loss (%)	<10	<10	25	25	0	0	0
Flow Impedance (Mpa*s/l)		2,5	0,3	0,6	0,23		
Thermal Output (MW)	3-5	5	7	3	11	25	9
Breakthrough Volume (m³)		80-100	50-150	200-300	6000		
Source other than in Title	41					42	43

2.6.2 Description of some realized projects

Following some of the past and ongoing projects are described including some of the major lessons learned during the project execution are mentioned. This listing is not complete as there are a couple of further projects that were or are realized in the world.

2.6.2.1 Fenton Hill, Los Alamos, New Mexico / USA

The Fenton Hill Project was initiated to first test the viability of creating a confined HDR reservoir within crystalline, hot basement rock and further to test the flow and

[40] Tischner, T et al: Hot Dry Rock Projekt Soultz: Erste Phase der Erstellung einer wissenschaftlichen Pilotanlage, Abschlußbericht. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 2006.
[41] Brown, Donald W.: Hot Dry Rock Geothermal Energy: Important Lessons from Fenton Hill. Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University Geothermal Program, Technical Report SGP-TR-187, 2009.
[42] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.
[43] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.

thermal behavior of the reservoir while heat is extracted from the reservoir. Fenton Hill was selected as a test site because of the high temperature gradient, the rock characteristics and the close proximity to the Los Alamos National Laboratory, which was leading the project. The project consisted of two phases, in which each one reservoir was created and tested.

In Phase 1 a reservoir was formed at a depth of approximately 2.800 m, where rock temperatures where found at about 195°C. At this early stage of development of HDR technology it was tried to get 2 drilled wells connected through fractures that where artificially created. As several attempts failed and after redrilling of the second well directionally into the rock area where most of the seismic events happened during stimulation and therefore fracture intersection was expected, a sufficient connection to allow reasonable liquid flow was achieved. During a final flow test of the reservoir, the temperature of the produced fluid dropped significantly at a constant mass flow and therefore the testing at the Phase 1 was abandoned due to the fast drawdown of the reservoir temperature. The reason for this decline in temperature was that the fracture surface was too small and the fractured rock volume was little by commercial standard. Consequentially the mass of rock ready to release heat to the fluid was very limited.

During Phase 2 of the project another reservoir was created at a depth of about 3.500 m, where the rock temperature was around 235°C. Similar as in Phase 1, the attempt to reasonably connect two boreholes through hydraulic fracturing failed and a directionally drilled hole, intersecting the created fractures enabled hydraulic connection. Due to a lack of additional funding, the site was decommissioned in the year 2000.

Some of the main outcomes of this project are:

- It was confirmed that it is possible to create a permeable fracture network in hot dry rock where it did not exist before stimulation and further fluid can be circulated through the fracture network to extract energy from the rock mass[44].
- It is nearly impossible to drill a set of boreholes and hydraulically connect them by stimulation. The proper procedure is to drill one hole to the depth where the temperature is appropriate, stimulate the rock, map the resulting fracture system and then directionally drill into the fracture system to get the set of wells connected.

[44] Duchane, Dave and Brown, Donald W.: Hot Dry Rock (HDR) Geothermal Energy Research and Development at Fenton Hill, New Mexico. In: GHC Bulletin, December 2002.

- The fracture network created will be aligned according to the direction of least principle stress and it will grow from the point stimulation is originated (first borehole) in either direction. To increase productivity of the reservoir and to keep the ratio of liquid flow over pressure drop high, it is beneficial to intersect the fracture system on two opposite ends of the fracture system and further to drill the wells furthest away from each other possible to make the reservoir larger. As shown in Figure 10, there is substantial reservoir volume south of the injection well, where no fluid is circulated due to the absence of another production well[45].

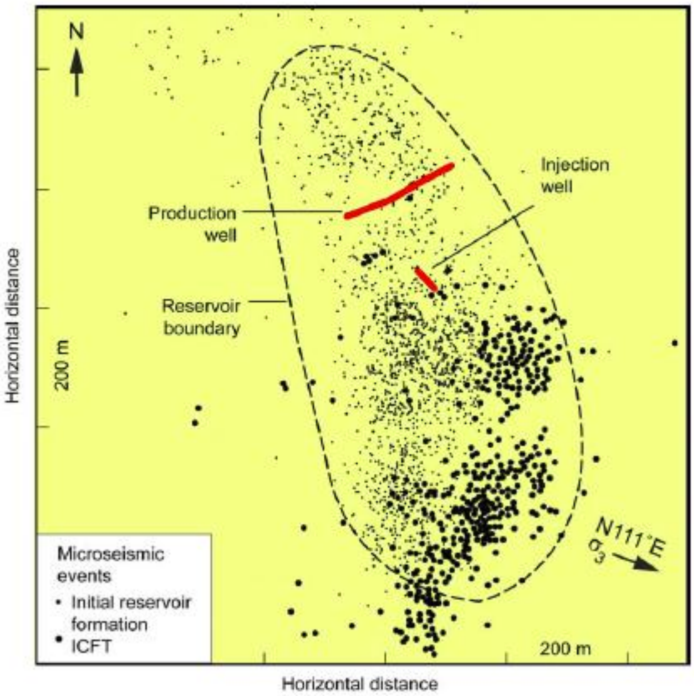

Figure 10: Location of seismic events related to Injection and Production Well at Fenton Hill and Direction of least principal Earth Stress (σ_3) [46]

- It was found that the hydraulic pressure implied on the rock at depth does not stimulate mainly because of new fractures are cracked, but because of joints that are existing already and blocked by secondary mineralization are opened[47].

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[45] Brown, Donald W.: Hot Dry Rock Geothermal Energy: Important Lessons from Fenton Hill. Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University Geothermal Program, Technical Report SGP-TR-187, 2009.

[46] Brown, Donald W.: Hot Dry Rock Geothermal Energy: Important Lessons from Fenton Hill. Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University Geothermal Program, Technical Report SGP-TR-187, 2009.

[47] Duchane, Dave and Brown, Donald W.: Hot Dry Rock (HDR) Geothermal Energy Research and Development at Fenton Hill, New Mexico. In: GHC Bulletin, December 2002.

- Measurements showed that the majority of pressure drop occurs near the production well – the so called near wellbore outlet impedance. By maintaining high pressure, the outlet flow joints can be dilated and therefore pressure drop can be reduced over time[48].

2.6.2.2 Rosemanowes / UK

The project in Rosemanowes, which was started in 1977 never was initiated to generate electricity, but the main intention was to experiment with the techniques to create a down hole heat exchanger.

Some major outcomes of the project were:

- The main mechanism creating a permeable reservoir is to open existing but closed fractures by hydraulic stimulation until they fail in shear and consequentially are permanently kept open as after shearing the surfaces do not match any more.
- When the pressure applied on the reservoir is too high while circulating liquid through, the fractures might grow, which leads to water loss due to growth of the ineffective volume of the reservoir.
- An important parameter for usability of a created reservoir is the flow impedance which might create a high hydraulic pressure drop when the reservoir is produced. Caused by this, the power consumption of the circulation pump might increase and therefore the parasitic power loss related to power produced in a power plant that would be installed in a commercial plant gets high. Another negative impact of high pressure drop again is that the reservoir will grow uncontrolled and water losses are increased.
- When a formation gets overstimulated, this might lead to short circuits and consequentially to temperature drawdown more rapid than expected. The reason is that most of the circulated fluid will pass the short circuit and energy will be extracted around this predominant fracture whereas other portion of the rock mass remains nearly untouched.

[48] Brown, Donald W.: Hot Dry Rock Geothermal Energy: Important Lessons from Fenton Hill. Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University Geothermal Program, Technical Report SGP-TR-187, 2009.

- Once fractures that are propped open due to hydraulic stimulation this process is irreversible. The rock mass that moved will not return into its original position and close the fracture again.[49]

2.6.2.3 Hijiori / Japan

The Hijiori project was initiated primarily to test whether the techniques acquired during Japans participation on the Fenton Hill project to create a subsurface heat exchanger could be applied at conditions available in Japan or not. The site was selected because of the high thermal gradient at the flanks of a volcano. There were two reservoirs created. The first one at a depth of about 1.600 m including one injection well and three producer wells. After some testing the wells were deepened and a reservoir at below 2.000 m was created by hydraulic fracturing. The project was ceased due to high drop of the reservoir temperature.
Some of the main outcomes of the project are:

- If the distance between injector and producer well is too little, the risk of short circuits, especially when a dense preexisting network of fractures is present, is increased, which makes the reservoir inefficient. To reduce this risk of short circuits, the well separation should be chosen as large as possible, of course still having sufficient connectivity.
- As already found out in Fenton Hill, it was proven true that the right procedure for creating a reservoir is to drill and stimulate a well first, and then to map the created network and directional drill other wells into the fractures, rather than first completing all the wells and then connect by stimulation.
- If stress regime changes within a reservoir, as it was found in Hijiori, it might be nearly unpredictable in which direction the reservoir might grow by stimulation.[50]

2.6.2.4 Soultz-sous-Forêts / France

The tests in Soultz-sous-Forêts where started as a joint effort of Germany, France and the European Union in 1987 and today still are in progress funded by Germany and France. The major goal of this test was to demonstrate the creation of a HDR

[49] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.
[50] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

reservoir available for scientific and experimental research as well as further development into a commercial viable plant including surface power plant. The site was selected because geology is well known until a depth of about 1.500 m as the location is in the area of the former Pechelbron oilfield, and the temperature gradient is high with more than 110°C/km within the depths familiar from oil production.

The project passed various phases and started in 1987 with single well tests on a shallow well drilled to a depth of 2.000 m. Further phases in the project where the flow tests with 2 wells at a depth of about 3.800 m, the testing of the performance of the wells after they were deepened to about 5.000 m, the construction and operation of an electric power plant and finally the scientific and technical monitoring which still is in progress. During the various phases, not only circulation tests and hydraulic fracturing attempts to create a reservoir where made, but also experiments with chemical stimulation and material tests[51].

Although the Soultz reservoir was thought to be a HDR formation, it was found out that there is an open connection to the sedimentary layers and that natural flow of hydrothermal liquids occur. This information was achieved due to significant reduced thermal gradient in depths between 1.200 m and 3.200 m due to convection, and further core analysis of granite from depths of 3.000 m showed, that it was altered already from formation fluids circulated through[52].

Modeling the drop of rock temperature over time in the reservoir as illustrated in Figure 11 showed, that it is beneficial to have connectivity to the rock further away from the created fractured network, as this connection creates access to heat in remote places which is an additional energy source and prevents rapid cooling of the reservoir rock itself[53].

[51] Schindler, M et al: Hot Dry Rock Projekt Soultz: Zweite Phase der Erstellung einer wissenschaftlichen Pilotanlage, Abschlußbericht. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 2009.

[52] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.

[53] Genter, Albert: EGS Pilot Plant, Publishable final activity report. GEIE Exploitation Minière de la Chaleur 2009.

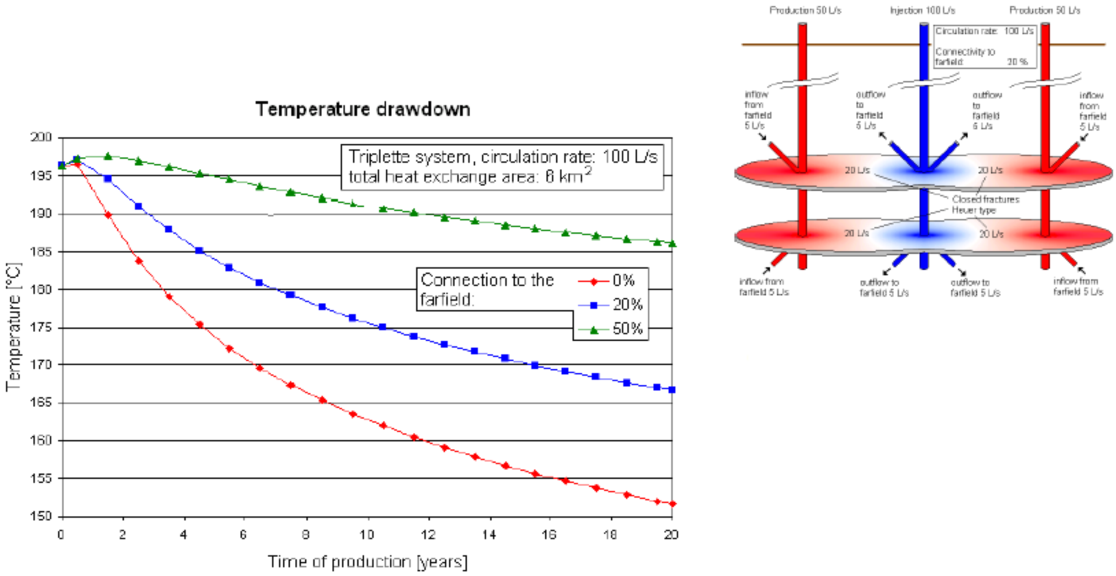

Figure 11: Modeling of Temperature Drawdown within the Reservoir over Time depending on connectivity and Fluid exchange to far field[54]

Some of the major technical outcomes of this project are:

- The creation of the reservoir in depth during hydraulic fracturing was mainly caused by failure in shear of preexisting, but closed fractures, rather than breaking new fractures.
- While fractures will open mainly in the direction of least stress in the rock, the alignment of the fractures will be most likely along the direction of the maximum stress, which then is also the orientation of the wells to maximize the active volume of the reservoir.
- As the created fracture network in reality is not a homogeneous system, but a heterogeneous arrangement of fissures the chance of short circuits can be reduced by large well separation. The separation of 450 m in the shallow reservoir and 650 m in the deeper reservoir was sufficient to avoid flow short circuits.[55]
- There is a direct relation between the amount of fluid pumped into the formation during hydraulic fracturing and the number of seismic events as shown in Figure 12 below.[56]

[54] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.
[55] Baria, R. et al: European HDR research program at Soultz-sous-Forêts (France) 1987-1996. In: Geothermics 28 (1999) 655-669, Elsevier Science Ltd., 1999.
[56] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.

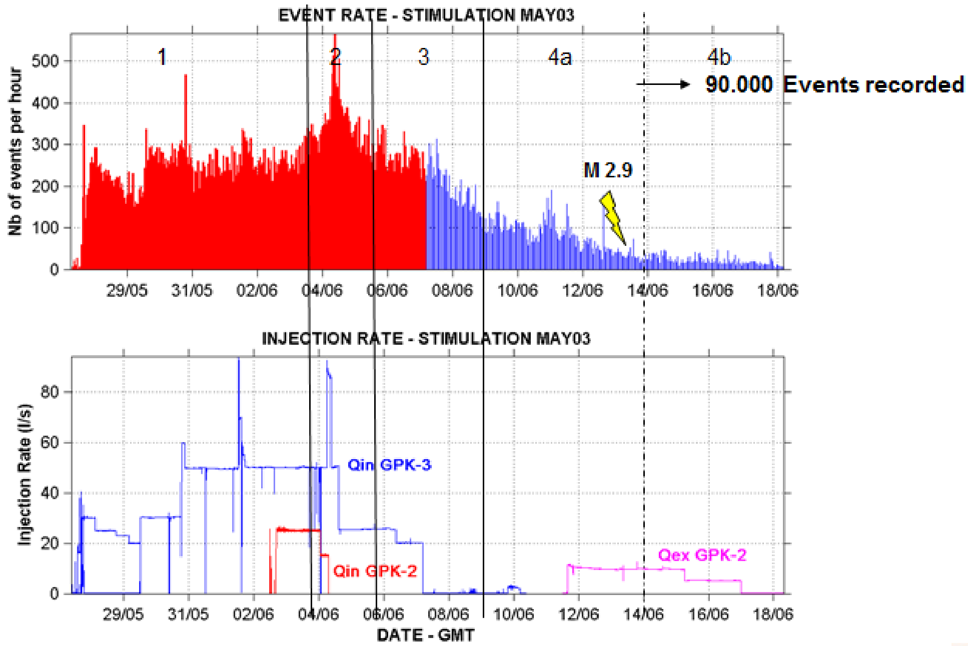

Figure 12: Seismic Events during hydraulic stimulation of the Reservoir in 5000m depth[57]

- Scale from water circulated through deep reservoirs as the one in Soultz might contain radioactive elements which have to be treated with care. It has shown that the precipitation of scale in the surface installation could be reduced dramatically by maintaining the pressure in the system above 18 bar.

Figure 13: Scale formed in the Surface Plant at Soultz

- In the Soultz setting it was possible to control whether the lower or upper part of the open hole completion is fractured, depending on the gravity of the injection fluid, meaning if fresh water or brine was injected.[58]

[57] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.

- To avoid uncontrolled growth of a reservoir, which leads to increased water loss, it is beneficial to circulate the fluid through the system not only with one injection pump, but to use one production pump per producer well in addition. This reduces the pressure in the system, which possibly grows the reservoir.[59]

2.6.2.5 Basel / Switzerland

The “Deep Heat Mining Basel” project was started in 1999 with the goal to generate electricity from Geothermal Energy. The location was selected because of its high temperature gradient. First some exploration boreholes and observation wells where completed, and then one deep well down to a depth of 5.009 m was drilled in 2006. After testing and measurements, massive hydraulic stimulation began, but had to be stopped again after 6 days only, because an earthquake with a magnitude of 3,4 acc. Richter was induced, which could be felt at the surface.
The project is aborted meanwhile due to resistance of the local population and politics, but nevertheless it could be demonstrated that even with the incomplete stimulation the hydraulic transmissibility was increased by a factor of 400.
Another interesting fact was that even months after the stimulation was abandoned, aftershocks occurred at even a similar magnitude as the main earthquake.[60]
According to an article of Welt Online from 09.01.2007 it was stated that the energy implied to the rock by stimulation was much less than the energy that was released with the earthquake and as a consequence the hydraulic stimulation only triggered the massive seismic event. This in fact was stated as a positive effect as this sudden release of energy prevented the region from a much stronger earthquake at a later time.[61]

2.6.2.6 Cooper Basin / Australia

The Cooper Basin project, probably the largest and most ambitious project currently engaged with HDR, was started with drilling operations in 2003. The main objective

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[58] Melchert, Bernd: Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012.
[59] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.
[60] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[61] www.welt.de/wissenschaft/article707547/Kuenstliche-Erdbeben-in-Basel-gerechtfertigt, 03.05.2012

of the project is to create an enhanced geothermal reservoir that can be successfully tested, demonstrate feasibility with a 1 MW_{el} pilot plant and then to extend the project to commercial size with modular reservoir-power plant segments in the order of 50 MW_{el} or even bigger and finally to supply electric energy at competitive prices.[62]

The company Geodynamics Ltd., who is developing this project, was choosing the site because of high temperature gradient, which is known from oil and gas related drilling activities in the region.[63]

The current status of the project is that five wells were drilled to depths of up to 4.900 m with bottom hole temperatures of more than 260°C[64], reservoir was created and flow tests confirmed ability to use the reservoir for heat mining as it was published by Geodynamics in the companies proof of concept completed statement.[65] Currently another well is drilled and the commissioning of the 1 MW_{el} pilot plant is coming up soon. After successful operation of this pilot plant and further stimulation and test proceedings the roll out of the commercial size power generation is planned.[66]

2.6.3 Lessons Learned

There was a lot of information and experience gathered in the last decades experimenting with Hot Dry Rock and EGS, but also from producing hydrothermal reservoirs where experiences hold true for HDR applications. Some of the findings are very site specific, but others can be used for future general approach for developing HDR sites:

- To achieve economically feasible reservoirs that can be produced for reasonable period of time, high flow rates needs to be maintained at moderate pressure drops to avoid excessive parasitic power losses for fluid circulation. At the same time big heat exchange areas are needed, preferably through a multiple layer fracture system with long pathways, resulting in large well separation down hole.

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62 Chen, Delton: Concepts of a Basic EGS Model for the Cooper Basin, Australia. Proceedings World Geothermal Congress, 2010

63 Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

64 http://www.geodynamics.com.au/IRM/content/projects_innadeep.html, 05.05.2012

65 Grove-White, Gerry: ASX Announcement 31 March 2009, Stage 1 – Proof of Concept Complete. Geodynamics Ltd., 2009.

66 http://www.geodynamics.com.au/IRM/content/projects_innadeep.html, 06.05.2012.

- To effectively create a HDR reservoir, it is essential to at first drill one well, stimulate the rock from this well and to identify the extent and direction of the reservoir that was grown, and finally to intersect the fractured volume by directionally drilling into the fracture network.
- It was proven a qualified technique to monitor the acoustic emissions indicating the seismic activity during hydraulic stimulation to quantify the growth of a reservoir and to target potential drill zones for further wells to connect to the reservoir.
- It is understood today, that the major mechanism creating a HDR reservoir in crystalline basement rock by hydraulic fracking, is not tensile failure but the failure in shearing that props open preexisting fractures in the granitic rock. The orientation of the fractures that are stimulated and the magnitude of their openings depends on the regional stress field within the host rock.
- It is beneficial to circulate the fluid through the reservoir not only by injection, but to use in addition to the injection pump also circulation pumps at the production wells. This will lead to a decreased overall pressure in the reservoir and therefore decreases the chance of unwanted growth of the reservoir during production. As a consequence water losses are reduced and also the chance of overstimulation causing short circuits within the reservoir, leading to rapid temperature drawdown due to preferential pathways, is reduced.
- Models where developed that help in prediction of the development of a reservoirs parameters while it is produced.
- Induced seismicity due to hydraulic fracturing caused shearing of the rock mass can lead to surface felt earthquakes which is an issue if HDR power plants are applied in close proximity to populated areas.[67]

2.7 Preferential Conditions and Limitations of HDR Technology, benefits and disadvantages

2.7.1 Preferential Conditions for HDR Technology

Beside several factors as e.g. risk and the environmental aspect, where the CO_2 saving of a geothermal power plant versus a hydrocarbon powered power plant

[67] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

comes into the picture, one of the main success elements of a power plant generating electricity from a hot dry rock reservoir is whether or not the power sales justifies the investment, respectively the installation is economically feasible. According to an economic approach, the three main performance factors for the development of a reservoir are according to Augustine[68]:

- *"Temperature gradient / temperature as a function of depth,*
- *Reservoir temperature, and*
- *Reservoir productivity / production well flow rate."*[68]

The temperature gradient leads to the depth the wells have to be drilled to find sufficiently high rock temperatures and the depth that has to be drilled further end up in costs for drilling. The reservoir temperature is a criterion for the efficiency of the surface power plant converting heat energy into electricity and consequentially the higher the reservoir temperature and the efficiency is, the smaller and cheaper a power plant could be designed still having the same output. And the reservoir productivity has an impact on required stimulation efforts and costs, as well as on the temperature drawdown and therefore on the lifetime of the reservoir before abandonment temperature is reached. This is also the crucial factor for the overall recovered energy out of the reservoir.[68]

The economics of a HDR reservoir with an electricity generating power plant can be modeled taking into account every applicable parameter, where also electricity market price, predicted for the future, plays an important role, as this price indicates also the future sales revenues.[69]

As an indicative target of preferential conditions to meet economic feasibility criteria, the following shall be reached or exceeded according to Baria[70]:

- *"A total circulation flow rate of around 100kg/s*
- *Not more than 10% overall fluid losses*
- *The parasitic losses to drive the fluid through the system to be about 0,1Mpa/kg/s*
- *The mean reservoir temperature to be in the range of 190°C*

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[68] Augustine, Chad R.: Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems. Massachusetts Institute of Technology, 2009.

[69] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

- *The life of the reservoir without re-stimulation to be in the range of 15-20 years with a temperature drawdown of around 10% at the end of its life*
- *An effective heat transfer area greater than 2 x $10^6 m^2$*
- *The rock volume of the reservoir to be more than 2 x $10^8 m^3$"* [70]

2.7.2 Limitations of HDR technology

There is a couple of limitations to HDR technology with technical know-how of today, although most of them are related with economy, as even the least efficient power plant as long as it produces more power than the parasitic losses are, would pay off if only the energy price would be high enough. With new or existing but improved technology, respectively if due to mechanism of a learning curve investment costs go down, these limitations might alter accordingly. Where metrics mentioned in the chapter 2.7.1 are not met or exceeded, non-economic feasibility might turn down a project as long as there is no sufficient support scheme in place. Further some of the limiting factors are:

- Restricted areas in parks, nature reserves, and where infrastructural facilities are as e.g. freeways, refineries, and the like.
- The limitation of drilling depth with current technology is in the order of 10.000m.
- A lack of interest and investment in R&D would limit the progress, as it is proposed that one billion US$ has to be invested until about 2020 in EGS (including HDR) technology, to make it a viable technology supplying the US with 100.000 MW of geothermal energy in 2050.[71]
- The proximity to cities might be a limit, respectively the resistance of the community, due to induced seismicity and the consequentially felt earthquakes, as the project in Basel, which after the earthquakes was abandoned, has shown.[72]

[70] Baria, Roy et al: HDR/HWR reservoirs: concepts, understanding and creation. In: Geothermics 28, Elsevier Science Ltd., 1999.
[71] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.
[72] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

2.7.3 Benefits and Disadvantages of HDR Technology

The utilization of geothermal energy, no matter if hydrothermal, HDR or other EGS has some advantages compared to other energy generation technologies that implies that geothermal might play a major role in future energy supply. All geothermal power plants have the unique advantage amongst all renewable energy sources, that geothermal energy is available all year long independent from season, daytime or weather and it does not need energy storage. Geothermal energy can be produced depending on demand what makes it a high quality energy source. Geothermal resources further are classified as renewable and sustainable and are not considered to run short within the next couple of 1000 years, based on today's worldwide energy consumption. Looking into space requirements compared to other power generation technologies it shows that geothermal is on the low requirements end as shown in table 3.[73]

Table 3: Comparison of land requirements for typical power generation technologies[74]

Technology	Land use m^2/MW	Land use m^2/GWh
110 MW geothermal flash plant (excluding wells)	1,260	160
20 MW geothermal binary plant (excluding wells)	1,415	170
49 MW geothermal FC-RC plant [(1)] (excluding wells)	2,290	290
56 MW geothermal flash plant (including wells, [(2)] pipes, etc.)	7,460	900
2,258 MW coal plant (including strip mining)	40,000	5,700
670 MW nuclear plant (plant site only)	10,000	1,200
47 MW (avg) solar thermal plant (Mojave Desert, CA)	28,000	3,200
10 MW (avg) solar PV plant[(3)] (Southwestern US)	66,000	7,500

(1) Typical Flash-Crystallizer/Reactor-Clarifier plant at Salton Sea, Calif.
(2) Wells are directionally drilled from a few well pads.
(3) New land would not be needed if, for example, rooftop panels were deployed in an urban setting.

Emissions such as noise and exhaust gas for geothermal are also low compared to other technologies, especially the CO_2 saving potential is large when geothermal power plants would replace fossil fuels.

[73] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[74] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

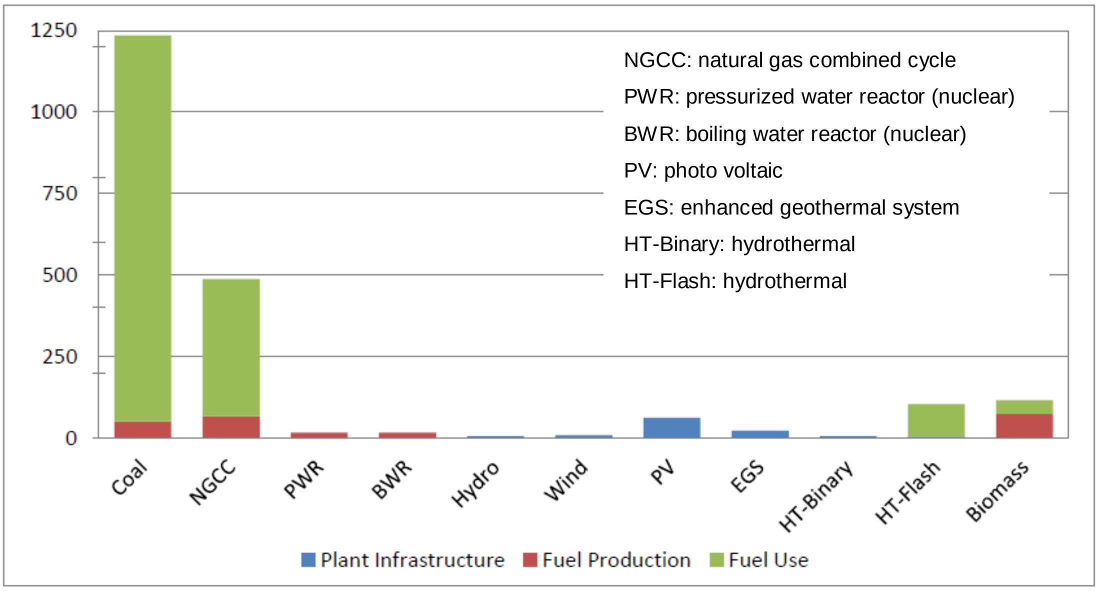

Figure 14: GHG Emissions (gCO_{2e}/kWh) by Life Cycle Stage for various Power Generating Technologies[75]

Comparing hydrothermal with HDR and other EGS resources, the major advantage of HDR and EGS is that for hydrothermal the resources are much smaller and most importantly it is limited to few locations in the world like the ring of fire, while the electricity generation from HDR and EGS virtually is possible everywhere in the world.

The major downside of hot dry rock and other EGS technologies compared to conventional energy generation, other renewables but also to hydrothermal is the relative high economic risk, as there will be uncertainty about the success of a project remaining until a reservoir is drilled, stimulated and tested, which already involves a major portion of the investment.[76]

2.8 Value Creation Chain of a HDR based Power Plant

To better understand the risks involved in the development of a HDR based power plant project, it is essential to know what the value creation chain engaged in this development is and what the major steps are in developing a HDR site.

[75] Sullivan, J.L. et al: Life-Cycle Analysis Results of Geothermal Systems in Comparison to other Power Systems. Argonne National Laboratory, 2010.

[76] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

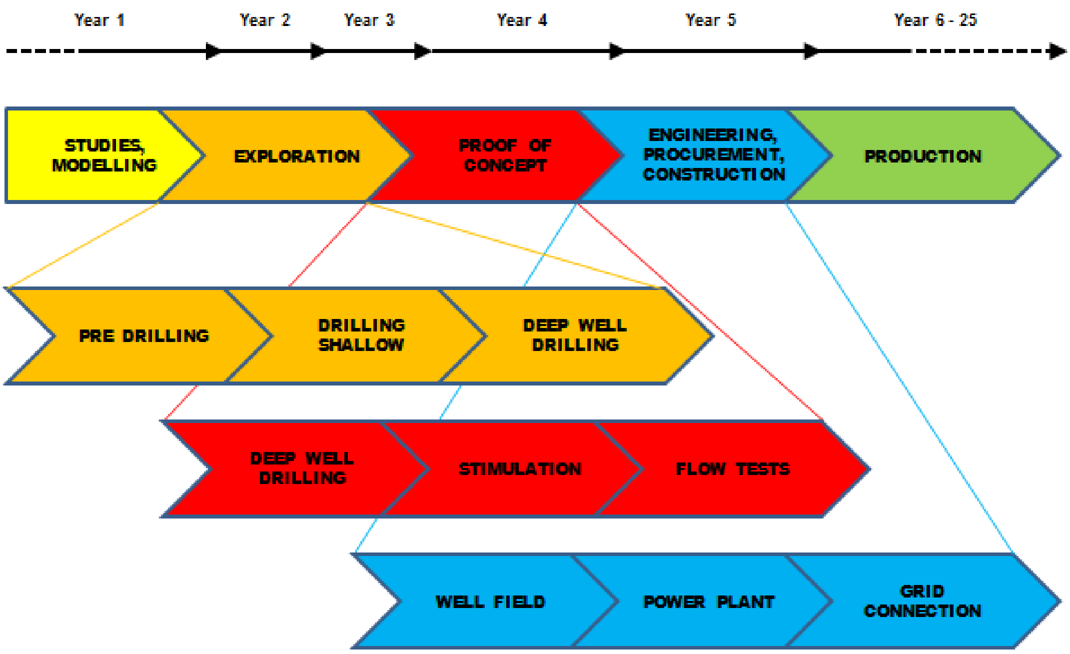

Figure 15: Value Chain in HDR Power Plant Development with estimated Timing[77] [78]

2.8.1 Studies, Modelling

This initial phase of a geothermal development project is mainly office based and consists of collection and evaluation of existing information from e.g. Geographic Information Systems (GIS), previous geologic studies as well as oil and gas exploration and geothermal exploration in the target region.[79]

2.8.2 Exploration

When once the phase of studies and modeling of existing data is completed and some sites are preselected to a shortlist, the preselected sites are further investigated in depth. There are some methods available, that can be applied even before a time and cost intensive licensing procedure has to be targeted. One of these methods is an airborne hyper spectral survey, which can measure surface heat flows, which further can be mapped and evaluated. Another commonly used methodology is the LiDAR technology (Light Detection and Ranging), which scans

[77] Goldstein, Barry A. and Hill, Tony: Presentation: Australia´s Update to the IEA´s GIA Executive Committee April 2008. Australian Geothermal Energy Group, 2008.
[78] Jennejohn, Dan: Research and Development in Geothermal Exploration and Drilling. Geothermal Energy Association, 2009.
[79] Deloitte Development LCC: Geothermal Risk Mitigation Strategies Report. Deloitte Department of Energy – Office of Energy Efficiency and Renewable Energy Geothermal Program, 2008.

the topography of a target zone to identify fault systems, which can be beneficial for creating a reservoir.

When the investigated site after the first investigations still looks promising and the land use rights are secured as well the license for geothermal exploration is obtained, as the next steps geochemical and geophysical surveys are conducted. Typical geophysical exploration methods are 3D Seismic Surveys, where existing fractures can be mapped, or Magnetotelluric (MT) Surveys, giving information about already existing aquifers and indirectly detect temperature patterns.

As a next step to get more confidence in the potential of a site some exploration wells have to be drilled as thermal gradient holes and to gain more knowledge about the rock properties core drillings usually are performed. Again measurements are done as stress measurement in depth, borehole imaging and others. When all the previous steps show positive results, a first deep well is drilled, that again is analyzed in detail.[80]

2.8.3 Proof of Concept

The next steps after a first deep well is successfully drilled, completed and tested typically are hydraulic stimulation of the well, mapping of the created fractures and directionally drilling into the edge of the fracture system, as well as stimulation of the second well to improve connectivity. This created system then is subject of extended flow tests to proof that HDR energy extraction works in the selected location to a high probability of economic feasibility.[81]

2.8.4 Engineering, Procurement, Construction

After evaluating all information gained and after remodeling the reservoir and its heat extraction, the further development of the exploitation of the formation and the design of the power plant, the grid connection and the switch gear are engineered. Along with engineering, permissions have to be obtained as e.g. extended land use permission, power plant operation permit and agreements have to be entered like power purchase agreement, subsidy agreements if any and grid connection agreement. When after procurement of equipment and services as well as the construction of the power plant is completed and all permits are obtained,

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[80] Jennejohn, Dan: Research and Development in Geothermal Exploration and Drilling. Geothermal Energy Association, 2009.

[81] Goldstein, Barry A. and Hill, Tony: Presentation: Australia´s Update to the IEA´s GIA Executive Committee April 2008. Australian Geothermal Energy Group, 2008.

respectively agreements are concluded, the power plant is ready to feed in electricity.[82]

2.8.5 Production

During the phase of power production the major disciplines involved are monitoring and maintenance of the equipment, monitoring of the reservoir and reservoir management, as well as planning ahead for an extension of the well field.[83]

2.9 Future Development of HDR Technology

Today there are some HDR or related test sites and pilot plants in operation, and there is one full size hot dry rock geothermal power plant project currently being developed in the Cooper Basin / Australia, but there is no commercial size HDR installation running in the world for the time of writing. This is because of technical shortcomings and the currently high specific energy costs for the energy produced of HDR power plants. Some of the most important focus areas where the technology of HDR needs enhancement and further development acc. to Roegiers[84] are:

- *"Lower cost drilling*
- *Zonal isolation / packers*
- *High temperature tools*
- *Stimulation procedures*
- *Modeling*
- *Exploration technologies*
- *Induced seismicity"*[84]

Developments for all involved technologies are under way from scientists and engineers around the world to make energy generation from EGS and consequentially HDR more efficient from technical point of view and consequentially economically feasible.[85]

Following some of the potential innovations are described.

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[82] Kraml, Michael and Walzer, Marissa: Geothermie, Wertschöpfung und Wirtschaftlichkeit von Geothermieprojekten in Deutschland. Forseo GmbH, 2008.

[83] Bracke, Rolf et al: Analyse der Wertschöpfungskette Geothermie in der Metropole Ruhr. Hochschule Bochum, GeothermieZukunftBochum, 2008.

[84] Roegiers, Jean-Claude et al: Stimulation procedures-IPGT High Priority Topic Area. International Partnership for Geothermal Technology, 2012.

[85] Tester, Jefferson W. et al.: The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology, 2006.

2.9.1 Drilling and Well Completion

As drilling and well completion causes costs in the order of 50% of the total investment, the saving potential is rather big. There are concepts investigated where the degree of automation of the drilling is increased, as the drilling costs beside material involved are about 50% rig rental and 50% manpower. Other concepts focus on long life drill bits to reduce tripping, revolutionary drilling technology as e.g. spallation drilling and new casing concepts with a mono diameter casing.[86]

2.9.1.1 Spallation Drilling

At spallation drilling the penetration of rock is effected by rapid, directed heating of a rock surface locally, that due to the induced thermal stress, rock chips spall off the remainder of the rock, as shown in figure 15.[87]

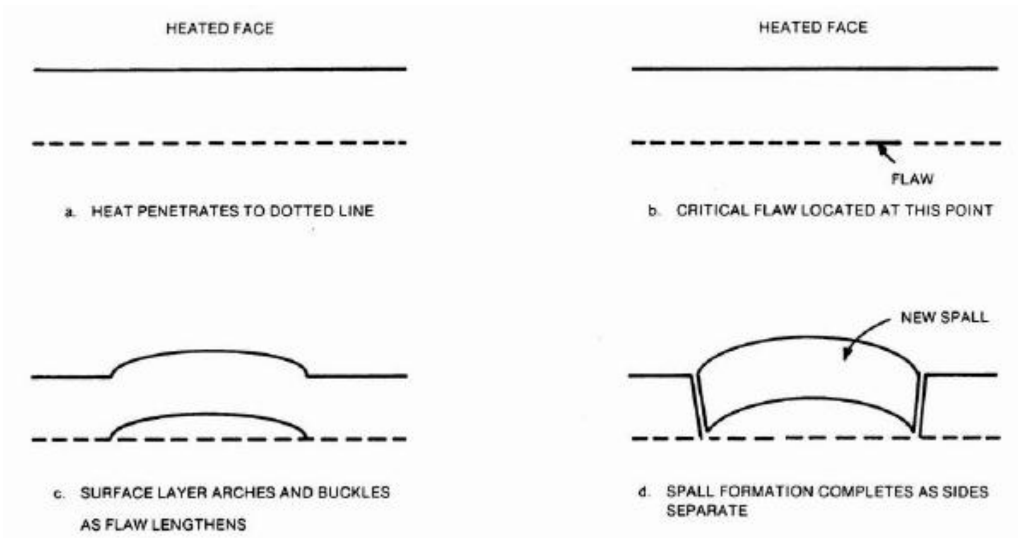

Figure 16: Mechanism of Spall formation due to rapid heating of a rock surface[88]

Due to the fact that rock has a low thermal conductivity, the directed heat generates this stress as long as the heat flux implied is bigger than the heat can be conducted to surrounding material. Tests have demonstrated, that the rate of penetration could be in the order of five times higher than with rotary rig drilling, which implies that due to shorter drilling procedure the costs for drilling can substantially being reduced. A

[86] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[87] Heinzelmann, Elisabeth: Geothermie – Energiepotential unter unseren Füssen, Neue Ansätze zur Nutzungsoptimierung. Electrosuisse, Bulletin 3/2010.
[88] Augustine, Chad R.: Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems. Massachusetts Institute of Technology, 2009.

further big advantage of this technology is that there is virtually no physical contact between the rock to be drilled and the "drill head", which saves tripping time involved in conventional drilling due to wear of drill bits that is occurring less in spallation drilling.

The technique is already in use since the 1940ies, where it was used for ore mining, although in shallow depths only, and without applying any drilling mud to the borehole, where the flushing of the cuttings occurred due to the high flame jet velocity in air. When drilling into potential HDR reservoirs, due to requirement to effectively remove the spalls away from the drill head to the surface from deep under, and to secure borehole stability, drilling mud has to be introduced, this due to the great depths and the consequential high hydrostatic pressure would appear as supercritical fluid.

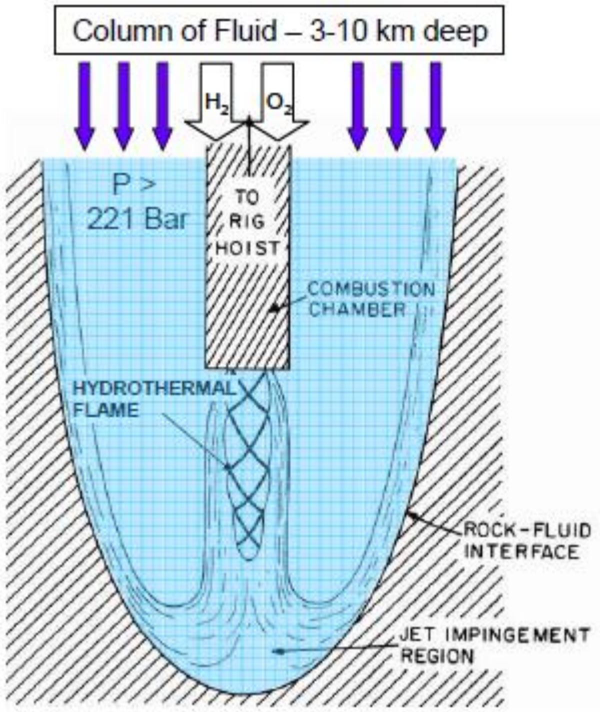

Figure 17: Depiction of Spallation Drilling at HDR conditions[89]

Within experiments it has shown that the heat fluxes to be applied are in the magnitude of 0,5 to 10 MW/m² and temperatures of the hydrothermal flame is up to 1.000°C. The fuel that is used could be Methane, Ethane, Methanol or Hydrogen. The use of Hydrogen compared to the other proposed fuels would be least problematic related to emissions, as the combustion of Hydrogen will not create CO_2, but water only as combustion product.

[89] Augustine, Chad R.: Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems. Massachusetts Institute of Technology, 2009.

Promising research is going on in several countries and commercial use of this technology from today's point of view is scheduled for 2015, but the stage of development is still experimental for this technology.[90]

2.9.1.2 Mono Diameter Casing

During the drilling process, depending on stability of the rock layers penetrated, casing sections have to be installed and cemented into the borehole to protect the borehole from collapsing. When once a casing string is installed, the drill bit has to pass this casing section to continue drilling and consequentially must be smaller in OD than the ID of the last installed casing. As a result to achieve a specific down hole casing diameter which is required according expectedly produced geothermal liquid, the diameter of each the shallower casing section has to be larger and the surface casing typically is sizes bigger than required by the amount of fluid. Drilling, casing and cementing for bigger diameters is more expensive than for smaller diameters and consequentially this before described procedure increases drilling and well completion costs, especially for wells that are deep as HDR wells typically are.[91]

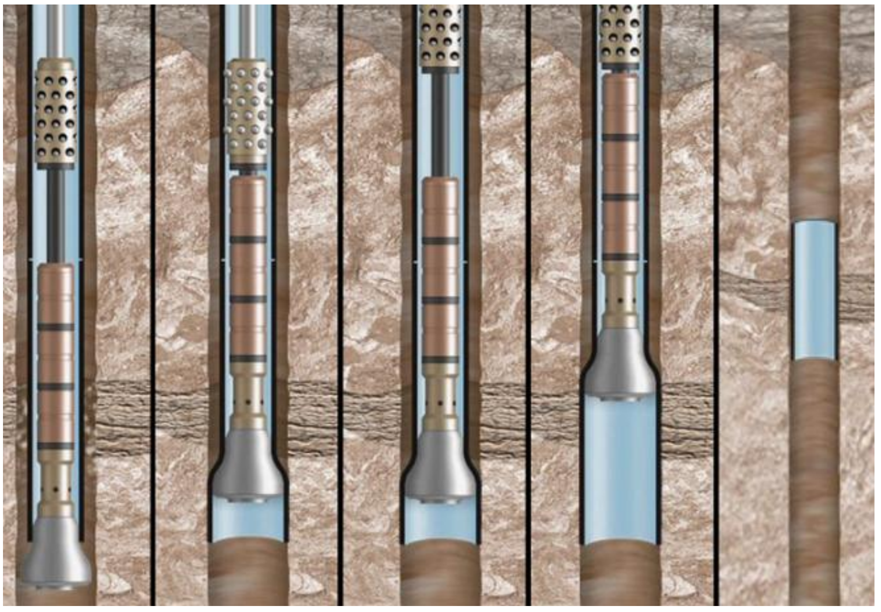

Figure 18: Expanding Process of a Casing to install a Mono Diameter Casing String[92]

[90] Augustine, Chad R.: Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems. Massachusetts Institute of Technology, 2009.
[91] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[92] http://www.drillingcontractor.org/no-longer-niche-expandables-finally-going-mainstream-9915, 30.05.2012.

The concept of mono diameter drilling and casing works in a way, that a casing joint is set to depth where it is intended to be installed and an expansion tool expands the casing in diameter, and the joint is then cemented. An expandable drill bit can move through the installed casing to continue drilling underneath.
This technology is already available as the equipment is offered from several specialized companies and currently is mainly applied in off shore oil and gas industry with substantial savings in well costs.[93]

2.9.2 Stimulation

One of the main problems when stimulating a well by hydraulic fracturing respectively hydraulic shearing is that when at first water is injected, to open preexisting fractures, most permeable zones in the rock will take most of the fluid and are stimulated, while other zones are least or not stimulated. This can cause irreversible overstimulation of preferential zones which further leads to short circuits and rapid cooling of the surrounding rock and a poor recovery factor.

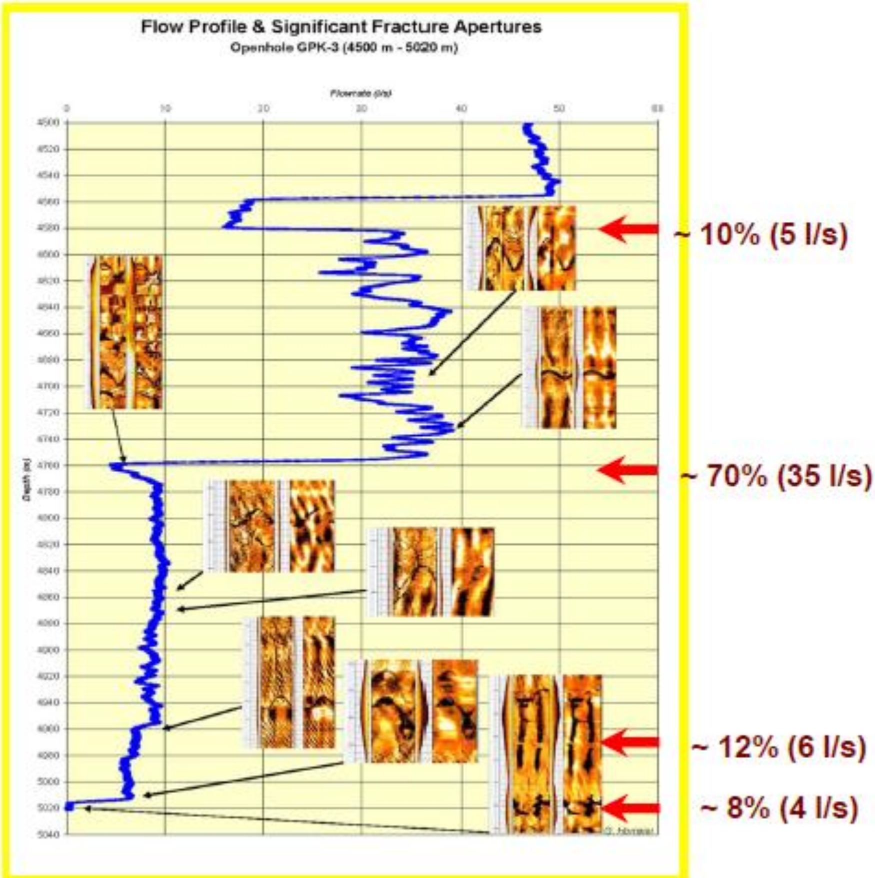

Figure 19: Flow Profile open hole section of Well GPK 3 in Soultz-sous-Forêts[94]

[93] Kerbart, Yves: Monodiameter Drilling Liner – From Concept to Reality. In: Journal of Petroleum Technology, a publication of the Society of petroleum Engineers, February 2004.

A solution is to temporarily isolate such preferential zones to sufficiently stimulate least preferential fractures. This can be done by either open hole packer, although there is also still a need of development as the packers known from oil and gas industry do not perform that good in the hot environment as seen in an HDR reservoir, or temporary diverters that degrade after time at high temperatures. The company AltaRock Energy developed a product called TZIM or Thermo degradable zonal isolation material which is pumped as slurry into the preferential fractures to seal them off.

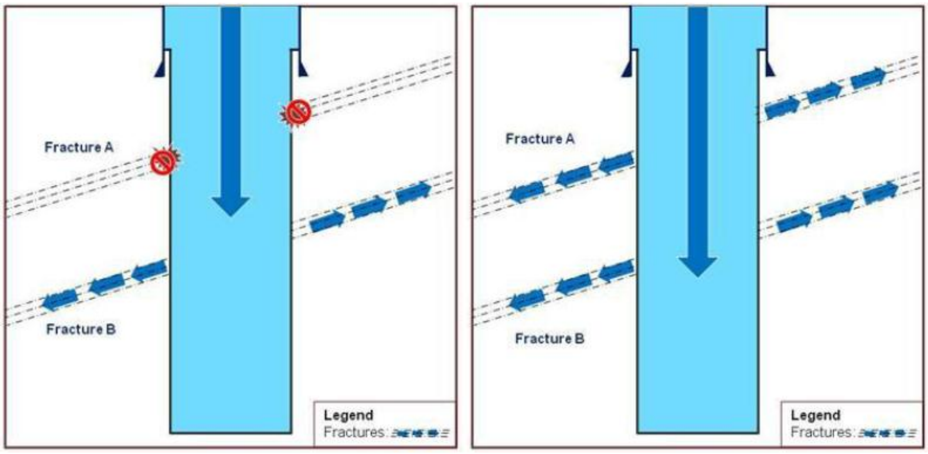

Figure 20: Principle of temporary sealing off Fractures while others are stimulated[95]

After the well heats back up subsequent to cooling during stimulation, the temporary sealing degrades to non-damaging products. This innovation leads to more focused stimulation and consequentially an increased fracture surface area and fractured volume, both ingredients for extended life time of a reservoir and increased heat recovery, which improves economy of a reservoir.[96]

[94] Petty, Susan: Presentation „Using EGS Technology in Geothermal Energy Development“. AltaRock Energy, 06.12.2011.

[95] Petty, Susan et al: Presentation “Multiple Zone Stimulation of EGS Wells – Key to Reservoir Optimization”. AltaRock Energy, 15.06.2011.

[96] Petty, Susan et al: Presentation “Multiple Zone Stimulation of EGS Wells – Key to Reservoir Optimization”. AltaRock Energy, 15.06.2011.

3 Geothermal Energy in Turkey *(Michael Graf)*

In the following chapters, an overview on Turkey - in particular the Turkish economy and constitutional and political aspects - shall be given. This is followed by an analysis of the Turkish energy sector, whereas the development of the demand of electricity, oil & gas, and coal is provided. Furthermore, an outlook into the next decade is provided, which intends to enhance the understanding, in which any potential geothermal in general, or HDR project in particular is set. Following this, specific attention will be dedicated to the global geothermal electricity market in order to set the scene where the Turkish market is located compared to other players in the world. The next chapter will elaborate specifically on geothermal resources in Turkey, providing a brief history on geothermal activities in Turkey and describe the geological prerequisites. Moreover, statistical data drawn from secondary research will be presented in order to provide an overview on geothermal fields and realized projects. This overview is supplemented by geographic maps that also allow assessing the proximity to relevant load centers in Turkey. Last, the chapter is concluded with an outlook in possible future development in geothermal in Turkey.

3.1 Geography of Turkey

Turkey, officially the Republic of Turkey, enjoys a favorable geographic position by connecting the European sphere to the Asian sphere. Neighboring countries are Bulgaria, Greece, Armenia, Iran, Iraq, Syria, Georgia and Azerbaijan. Turkey is surrounded by the Black Sea, Sea of Marmara, the Aegean Sea and the Mediterranean Sea and possesses a sea cost of roughly 8.300 km[97].

The country is divided into 81 administrative provinces and seven regions, which exhibit significant economic disparity. The strongest region of Turkey is the Marmara region, which includes Istanbul, Izmir and Bursa and comprises roughly 30% of the economy in terms of GDP.

[97] http://en.wikipedia.org/wiki/Turkey accessed on 11.08.2012

Figure 21: Map of turkey

The majority of the people of Turkey are Muslim and the official language is Turkish. However, Kurdish and Zazaki languages are spoken by 18-25% of the people, comprising the Kurds and Zazas part of the population.

The size of the whole Turkish population amounts to 69 million people out of which an estimated 75,5% live in urban areas. The largest cities are Istanbul (13,3 million inhabitants), Ankara (4,3 million inhabitants), Izmir (2,7 million inhabitants), Bursa (1,7 million inhabitants) and Adana (1,6 million inhabitants)[5]. The population may be considered as young and fast growing since almost 30% of the population is below the age of 15. Moreover, according the United Nations[98] the growth rate of the population amounts to 1,26% and is expected to reach 92 million in 2025.

3.2 Constitution and politics

In 1923 the Treaty of Lausanne resulted into the international recognition of the newly formed "Republic of Turkey" as the successor of the Ottoman Empire. One major building block of this treaty stipulates that that a population exchange between Greece and Turkey shall take place, in which 1.1 million Greeks had to leave Turkey and 380,000 Muslims were transferred from Greece to Turkey in exchange (Clogg 1992). The first president of the Republic of Turkey was Mustafa Kemal, who

[98] United Nations, World Populations Prospects, 2006 Revision

implemented many radical reforms with the target of transforming Turkey into a modern secular state out of its Ottoman past (Shaw and Shaw 1977).

3.3 Turkey's accession to the European Union

In line with the reforms of Mustafa Kemal, Turkey turned its political orientation towards the West by joining the UN in 1945 and the NATO in 1952. Furthermore, since 1959 Turkey strives for integration into the European Union[99]. One milestone is represented by the Ankara Association Agreement in 1963, which aimed at the progressive establishment of a Customs Union that was finally put into force in 1995. The Delegation of the European Union[100] to Turkey point out that additionally the "continuous improvement in living conditions in Turkey and in the European Economic Community through accelerated economic progress and the harmonious expansion of trade, and to reduce the disparity between the Turkish economy and … the Community" was central to the Ankara Association Agreement.

In 1987 Turkey submitted its application for full membership and in 1999 Turkey was granted the candidate status. Since then accession negotiations with the European Union are ongoing. The accession negotiations require Turkey to adjust a significant part of its national legislation to EU standards. Due to the discrepancies between both parties in this regard this will imply a fundamental change of the Turkish society and will touch all sectors of the country covering environmental, judiciary and economic matters[101].

Despite the positive impact of the accession negotiations in recent times accession to the European Union may seem less important to the Turkish population, mainly due to the economic crisis the European Union faces currently. In contrast to its European counterparts, Turkey has enjoyed reasonable economic growth in the last years. For example, in 2004 polls estimated the support for the accession of Turkey to the European Union to be roughly 75% of the population. In 2012 this figure dropped to a mere 50%[102]. Despite these recent downsides of the current political state, the close collaboration with Europe is expected to remain central to both parties, Turkey and the European Union.

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[99] European Commission, http://ec.europa.eu/enlargement/countries/detailed-country-information/turkey/index_en.htm accessed on 29.10.2012

[100] Delegation of the European Union to Turkey, http://www.avrupa.info.tr/en/turkey-the-eu/history.html accessed on 29.10.2012

[101] Delegation of the European Union to Turkey, http://www.avrupa.info.tr/en/turkey-the-eu/accession-negotioations.html accessed on 29.10.2012

[102] Der Spiegel, http://www.spiegel.de/international/europe/turkey-and-the-eu-turks-question-advantages-of-eu-membership-a-849982.html accessed on 29.10.2012

3.4 Economic overview

In order to describe the structure and current condition of the Turkish economy, in the following table will be shown that has been compiled based on economic data from the Central Intelligence Agency (CIA)[103]. To enhance the understanding, a comparison will be made between Turkey, Austria and Germany. Moreover, the comparison will be made based on leading key economic indicators, such as GDP growth rate, distribution of GDP across economic sectors, inflation rate, unemployment rate, investment and current account balance.

Indicator	Turkey	Austria	Germany
Population	79,8 million	8,2 million	81,3 million
GDP per capita	$ 14.700	$ 42.400	$ 38.400
GDP 2011 (purchasing power parity)	$ 1,1 trillion	$ 356,5 billion	$ 3,1 trillion
GDP 2010 (purchasing power parity)	$1 trillion	$ 345,8 billion	$ 3,0 trillion
GDP 2009 (purchasing power parity)	$ 920 billion	$ 338	$ 2,9 trillion
GDP growth rate 2011	8,5 %	3,1 %	3,1 %
GDP growth rate 2010	9 %	2,3 %	3,6 %
GDP growth rate 2009	- 4,8 %	- 3,8 %	- 5,1 %
GDP composition per sector 2011			
agriculture:	9,3 %	1,5 %	0,8 %
industry:	28,1 %	29,4 %	28,6 %
services:	62,6 %	69,1 %	70,6 %
Unemployment rate 2011	9,8 %	4,2 %	6 %
Investment (gross fixed) of GDP	21,8 %	21 %	18,2 %
Inflation rate 2011	6,5%	3,5 %	2,3 %
Current account balance 2011	$ - 77, 2 billion	$ 8,2 billion	$ 188,6 billion

Figure 22: Comparison of economic key indicators between Turkey and Austria

Turkey is one of the largest and fasted growing economies in the world. Real GDP (Gross Domestic Product) amounts to 1,1 trillion USD dollars based on purchasing power parity making it the 15th largest economy in the world in 2011[104]. Moreover,

[103] Central Intelligence Agency (CIA), https://www.cia.gov/library/publications/the-world-factbook/geos/au.html accessed on 29.10.2012

[104] World Development Indicators database, World Bank, 1 July 2011

Real GDP Growth rate amounts to roughly 9% in 2010/11[105]. Austria and Germany are far below in this regard, although it needs to be pointed out that the economies of those countries is considerably more developed. In terms of GDP Germany is leading due to its size of the population and strong economy. $ 3,1 trillion compared with Austria's GDP amounting $ 356,5 billion. Regarding GDP per capita Austria ($ 42.400 in 2011) is about three times above the Turkish level ($ 14.700 in 2011) closely followed by Germany with about $ 38.400 in 2011. As regards the distribution of GDP across economic sectors it can be stated that all three of them are fairly close, whereas Turkey still has the highest share of agriculture amounting to 9,3%. Therefore Germany and Austria may be considered as more industrialized countries, since the share of industry and services is contributes more to the economy with roughly 30% for the industrial sector respectively 70% for the services sector. Traditionally, the unemployment rate is Austria is low amounting to 4,2% in 2011, whereas in Turkey it is rather high with 9,8%. Germany lies in between with 6%. Room for improvement can also be observed in the inflation rate that persists in Turkey. 6,5% may be considered as high and therefore price stability is threatened. Furthermore, the current account balance required improvement, since the deficit is quite high with $ 77,2 billion. Austria and Germany enjoy a current account balance surplus due to their strong industrialized sector, although Germany by far outperforms Austria – in absolute but also in relative terms. Interestingly, the share of GDP that is invested is the highest in Turkey compared to Austria and Germany, which is a further indication of the dynamic economic conditions in Turkey.

3.5 Energy sector overview

In line with its impressive overall economic growth in recent years Turkey possesses one of the fasted growing energy markets in the world. As can be seen in the graph below the level of the Turkish consumption showed a continued growth until 2008 amounting to 102 million tons of oil equivalent. However, due to the global economic crisis energy consumption fell down by approximately 5% to 97 million of oil equivalent in 2009, but is expected to increase again by 2,5% until 2013.

[105] Economic Survey of Turkey 2012, OECD, http://www.oecd.org/turkey/economicsurveyofturkey2012

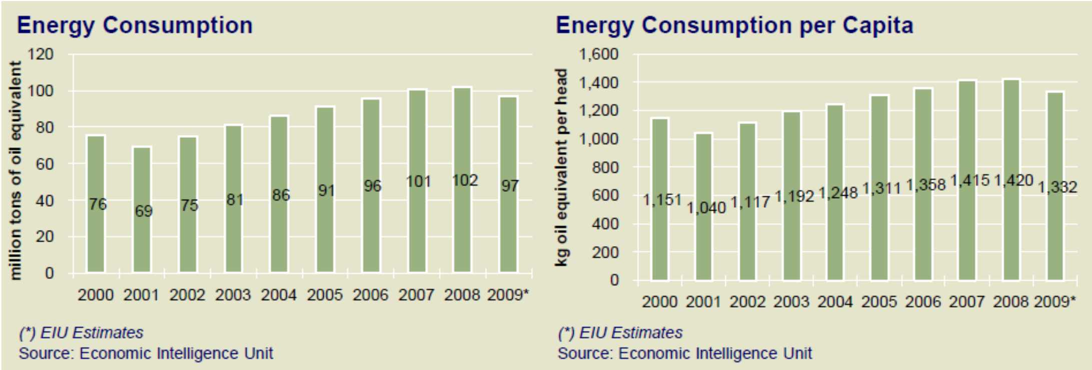

Figure 23: Energy consumption in Turkey[106]

Moreover, it is important to note that energy consumption per capita is still well below Western standards.

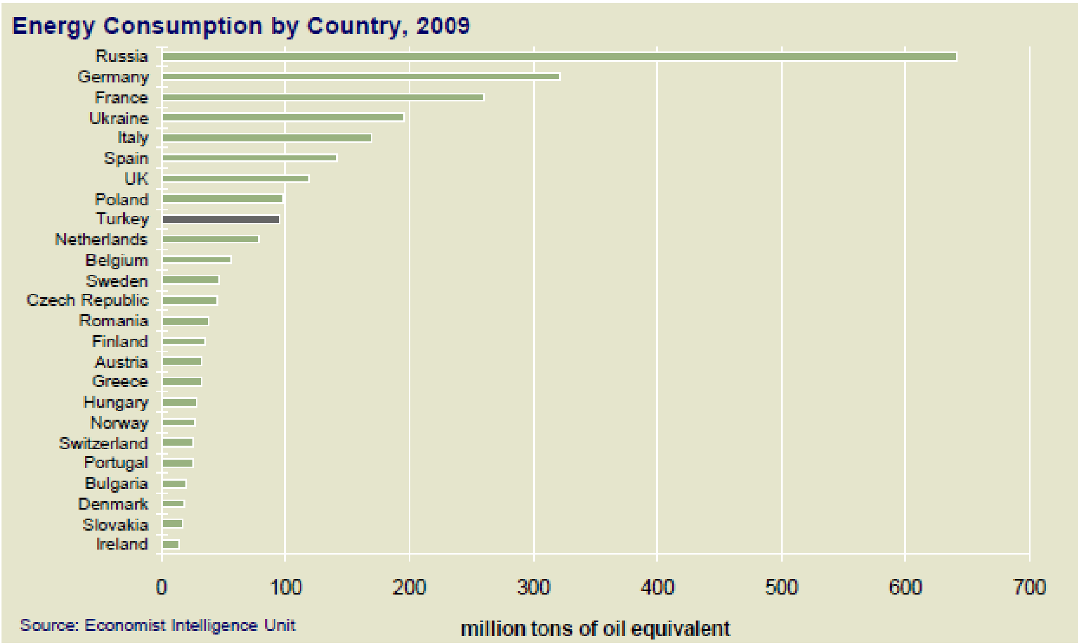

Figure 24: Energy consumption per country[107]

For example, as can be seen in the figure above the energy consumption amounts to roughly 102 million tons of oil equivalent in total, far below Western countries which are comparable in size. In relative terms, 1,332 kg oil equivalent per capita have been consumed in Turkey in 2008, which implies a clear upward trend in the long term also taking the economic outlook into consideration.

[106] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010

[107] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010

3.5.1 Electricity

Due to increasing levels of urbanization and industrialization, electricity demand grew steadily ranging from 6,3% to 8,8% until 2008. However, also electricity generation was affected by the global economic downturn. It decreased by approximately 2,2% and leveled out at 194,1 TWH in 2009. Nonetheless, driven by the growth of the Turkish economy higher levels of electricity demand may well be expected again for the future.

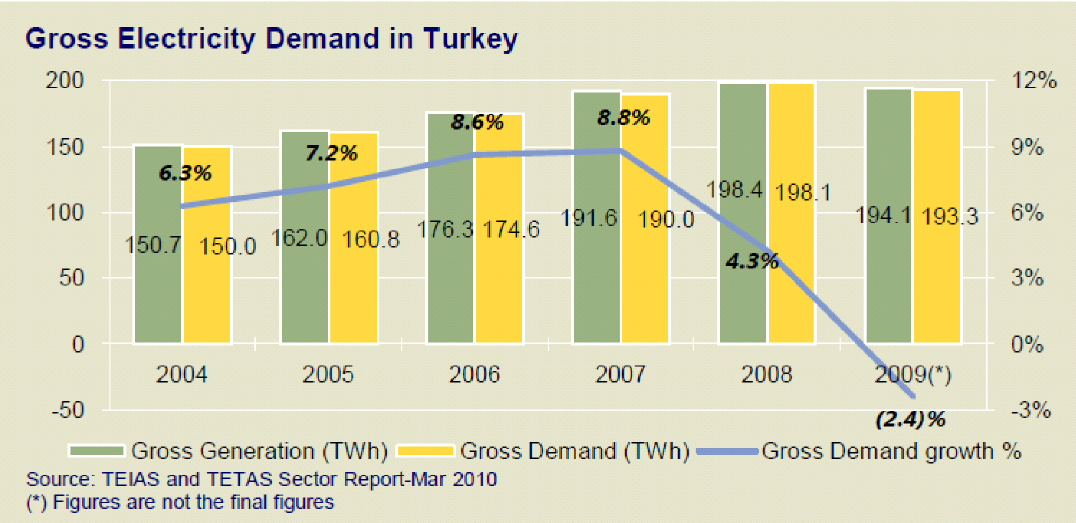

Figure 25: Gross electricity demand in Turkey[108]

Looking at the installed capacity of electricity generation in the graph below a continued rise can observed from 1998 until 2009 from 23,354 MW to 44,766 MW[109]. Hydro power and natural gas fired plants have the highest share of total capacity amounting to roughly 34% each and these technologies could even extend their contribution continuously over the last decade. Hard coal and lignite based plants follow with a share of 24%. It is interesting to note that fuel-oil and diesel driven plants declined their contribution considerably in 2008 onwards. Further, as can be seen in the graph below, plants fired with other renewable resources still play a minor role to date in Turkey. However, this will be analyzed in more depth in the following chapters.

Installed capacity is expected to grow further. For example, the Turkish Electricity Transmission Company puts forward that domestic demand for electricity will grow on an annual compound growth rate of 6% between 2009 and 2023. The total

[108] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010

[109] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010

investments needed to cover the increasing electricity demand in Turkey until 2023 is estimated around USD 130 billion[110].

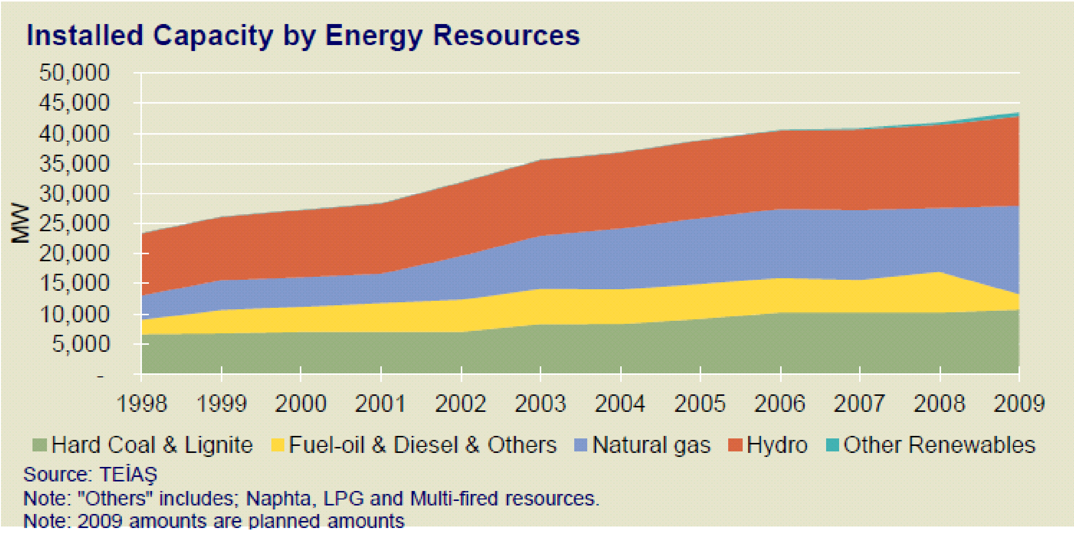

Figure 26: Installed capacity by energy resources[111]

3.5.2 Oil and gas

According to the Crude Oil and Natural Gas Sector Report of Turkey 2,5 million tons of oil and 726m3 natural gas were produced in 2010. During the last ten years a decline of Turkish oil production of 2,2% was observed. However, due to increased investments in new oil fields and redevelopment programs the decline could be stopped and in 2010 an increase of 4% was noted. The graph below depicts the crude oil production by years[112].

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[110] http://www.invest.gov.tr/en-US/sectors/Pages/Energy.aspx accessed on 11.08.2012
[111] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010
[112] Turkish Petroleum Corporation General Directorate, Oil and Natural Gas Sector Report August 2010

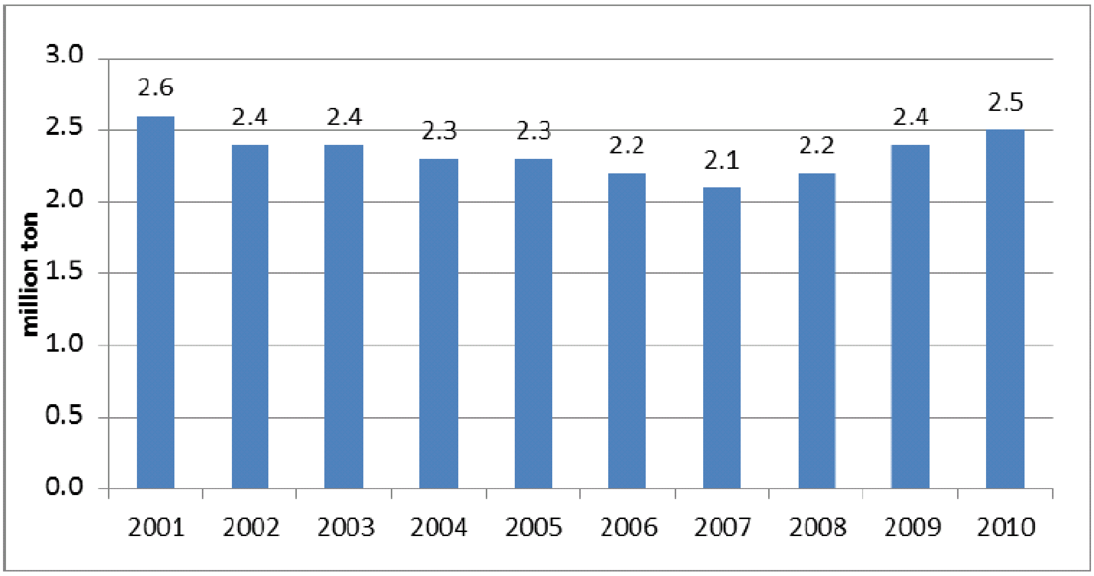


Figure 27: Crude oil production per year[113]

Gas production, as graphically shown below, reached its peak in 2008 with 1,014 million m3 of gas. However, starting in 2009 gas production fell and amounts to 726 million m3 in 2010.

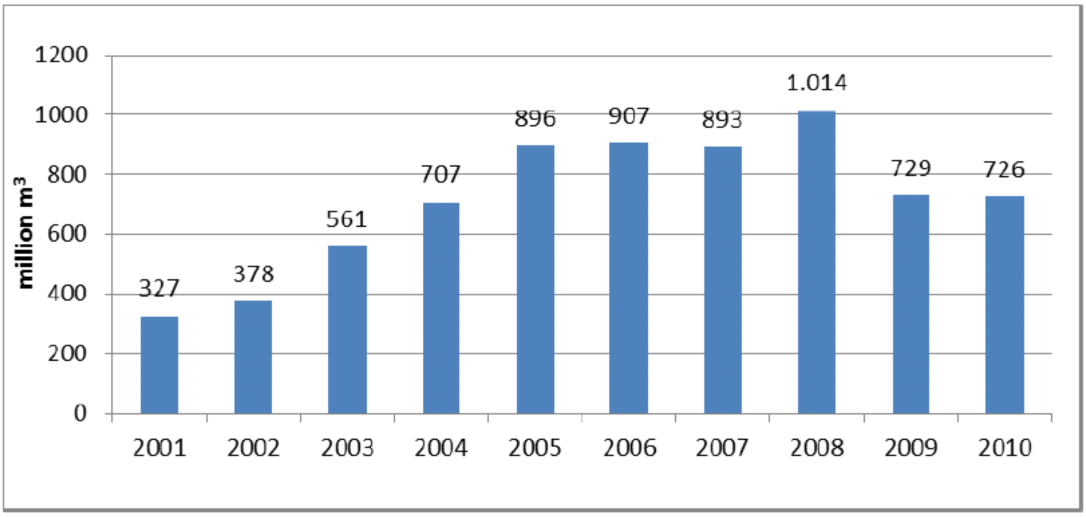


Figure 28: Gas production per year[114]

Taking the current level of production and the proven reserves into account, oil would last another 17,2 years whereas the gas production would be depleted in 8,6 years in case no new discoveries are made or no new production technologies are

[113] Turkish Petroleum Corporation General Directorate, Oil and Natural Gas Sector Report August 2010
[114] Turkish Petroleum Corporation General Directorate, Oil and Natural Gas Sector Report August 2010

utilized to exploit unconventional gas from shale for example[115]. In addition, it has to be noted that the domestic production of oil and gas covers merely 3% of Turkey's energy demand making it a major importer, mainly from Saudi Arabia, Iran, Iraq and Russia.

3.5.3 Coal

Coal makes up a major building block of Turkey's primary energy demand amounting to 30% in 2009. As can be seen below from 2005 until 2007 coal consumption grew from 22,794 ktoe to 29,385 ktoe and declined to 28,204 ktoe in 2009. In contrast, coal production increased continuously from 10,806 ktoe in 2005 to 15,069 ktoe in 2009 (Turkish Energy Industry Report August 2010). Thus, roughly 50% of the total coal consumption can be covered by domestic coal production, but at the same time this induces a rather high dependency on coal imports.

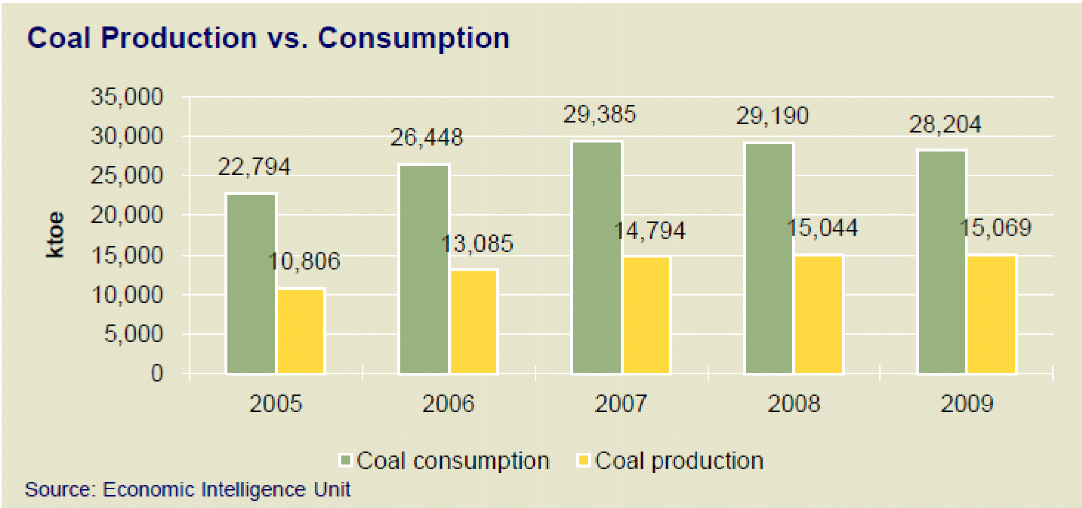


Figure 29: Coal production vs. consumption[116]

3.5.4 Outlook

Due to the ongoing urbanization and industrialization of Turkey, the growing population and the economic development the increase in energy demand is expected to continue and be even stronger compared to European peers. This hypothesis is substantiated by the projections of the Turkish Electricity Transmission

[115] Turkish Petroleum Corporation General Directorate, Oil and Natural Gas Sector Report August 2010
[116] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010

Company (TEIAS) which assumes a compounded annual growth rate of electricity generation and demand of 7% until 2018 resulting in 357 TWh[117].

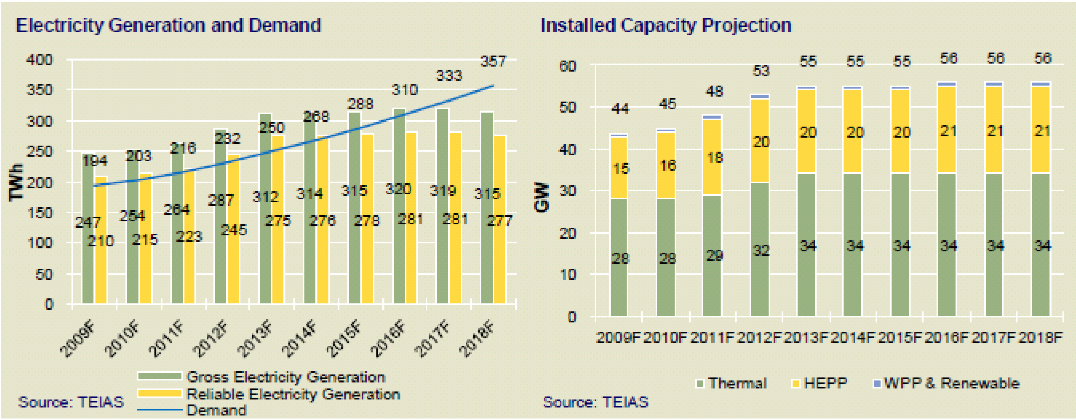


Figure 30: Electricity generation and demand[118]

In line with this oil consumption is expected to increase steadily to approximately 740,000 bbls/day in 2014, whereas natural gas consumption rises to 46 bcm in 2014.

	2009	2010F	2011F	2012F	2013F	2014F
Oil consumption ('000 b/d)	663	676	693	707	728	740
Natural gas consumption (bcm)	35	37	40	44	46	46
Oil prices (US$/bbl)	59	83	85	90	90	90

F: Forecasts; Source: BMI

Figure 31: Outlook oil consumption[119]

Further, coal consumption – a large contributor to Turkey's energy resources - is expected to increase slightly by 1% reaching 29,573 ktoe in 2014.

	2009E	2010F	2011F	2012F	2013F	2014F
Coal consumption (ktoe)	28,204	28,496	28,963	29,351	29,675	29,573

E: Estimated; F: Forecast, Source: Economist Intelligence Unit

Figure 32: Outlook coal consumption[120]

As said, the energy consumption today in Turkey is still below compared to Western European countries and, as shown above, the domestic energy production does not cover domestic energy demand making Turkey a major energy importer at the moment. In addition, the increase of energy demand is well above the increase of

[117] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010
[118] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010
[119] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010
[120] Republic of Turkey Prime Ministry, Investment Support and Promotion Agency of Turkey "Turkish Energy Industry Report", 2010

production capacities. This means that significant investment in the energy sector will be needed in the near future in order to close this gap and reduce Turkey's dependency of energy imports.

3.6 Geothermal electricity generation

Geothermal electricity generation has first been put into operation for commercial use in 1911 in the Larderello fields in Italy, with an electricity generation capacity of 250 kW. Since then geothermal electricity generation has seen continued growth. According to Bertani (2010) installed capacity from geothermal electricity generation plants has increased from 200 MW in 1950 to 10.715 MW in 2010 on a global basis. Even higher growth rates are expected in the coming years as shown in the table below.

Year	Installed Capacity MW	Produced Energy GWh
1950	200	
1955	270	
1960	386	
1965	520	
1970	720	
1975	1,180	
1980	2,110	
1985	4,764	
1990	5,834	
1995	6,833	38,035
2000	7,972	49,261
2005	8,933	55,709
2010	10,715	67,246
2015	18,500	

Figure 33: Geothermal electricity capacity and production[121]

The following table provides a good overview of the countries generating geothermal electricity today.

[121] Bertani, Ruggero: Geothermal Power Generation in the World 2005–2010 Update Report. *Proceedings World Geothermal Congress 2010*

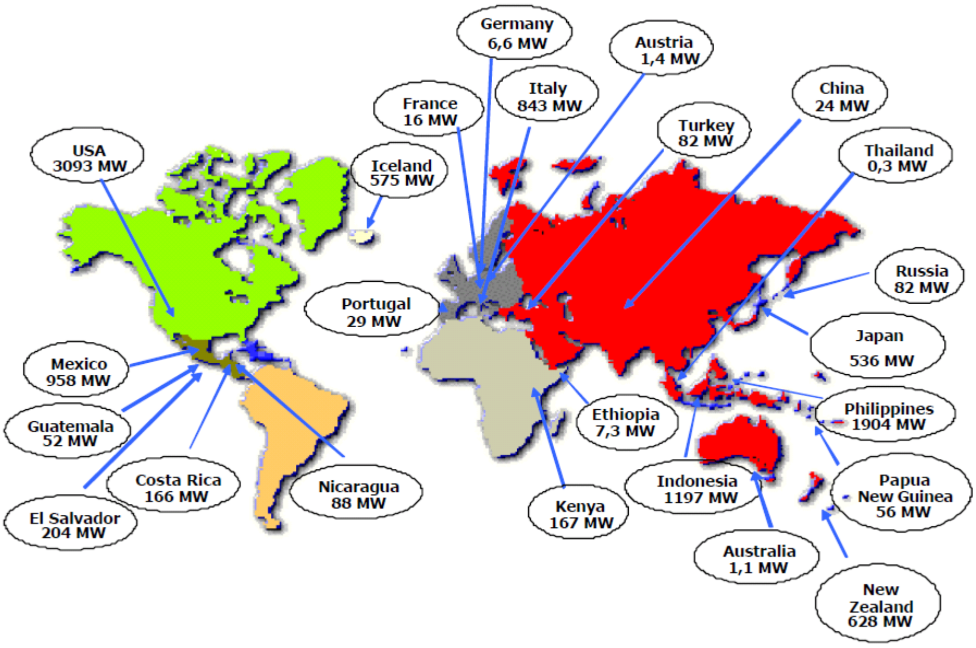


Figure 34: Overview of countries producing electricity from geothermal resources[122]

As can be seen there is a natural concentration of activity in countries which possess vast geothermal resources, be it from volcanism or active tectonism or both. Based on installed capacity in 2010 the USA is leading with 3093 MW, followed by the Philippines with 1904 MW and Indonesia with 1197 MW. In Europe Italy has most of the installed capacity with 757 MW installed and on the second rank Ice with 575 MW can be found. Moreover, it is interesting to note that Turkey's installed capacity was rather low until 2005 with 20 MW, but picked up strongly and quadrupled to 82 MW in 2010[123]. However, until 2015 growth is expected to slow down and result in 200 MW installed capacity. Below an overview from Bertani's study (2010) on the global geothermal capacity is provided.

[122] Bertani, Ruggero: Geothermal Power Generation in the World 2005–2010 Update Report. *Proceedings World Geothermal Congress 2010*

[123] Bertani, Ruggero: Geothermal Power Generation in the World 2005–2010 Update Report. *Proceedings World Geothermal Congress 2010*

COUNTRY	Installed in 2005	Energy in 2005	Installed in 2010	Energy in 2010	Forecast for 2015	Increase since 2005			
	MW	GWh	MW	GWh	MW	MW	GWh	Capacity %	Energy %
ARGENTINA	0	0	0	0	30	0	0		
AUSTRALIA	0.2	0.5	1.1	0.5	40	1	0	633%	-5%
AUSTRIA	1.1	3.2	1.4	3.8	5	0	1	27%	19%
CANADA	0	0	0	0	20	0	0		
CHILE	0	0	0	0	150	0	0		
CHINA	28	96	24	150	60	-4	54	-13%	57%
COSTA RICA	163	1,145	166	1,131	200	3	-14	2%	-1%
El SALVADOR	151	967	204	1,422	290	53	455	35%	47%
ETHIOPIA	7.3	0	7.3	10	45	0	10	0%	
FRANCE	15	102	16	95	35	2	-7	10%	-7%
GERMANY	0.2	1.5	6.6	50	15	6	49	2,774%	3,249%
GREECE	0	0	0	0	30	0	0		
GUATEMALA	33	212	52	289	120	19	77	58%	36%
HONDURAS	0	0	0	0	35	0	0		
HUNGARY	0	0	0	0	5	0	0		
ICELAND	202	1,483	575	4,597	800	373	3,114	184%	210%
INDONESIA	797	6,085	1,197	9,600	3,500	400	3,515	50%	58%
ITALY	791	5,340	843	5,520	920	52	180	7%	3%
JAPAN	535	3,467	536	3,064	535	1	-404	0%	-12%
KENYA	129	1,088	167	1,430	530	38	342	29%	31%
MEXICO	953	6,282	958	7,047	1,140	5	766	1%	12%
NEVIS	0	0	0	0	35	0	0		
NEW ZEALAND	435	2,774	628	4,055	1,240	193	1,281	44%	46%
NICARAGUA	77	271	88	310	240	11	39	14%	15%
PAPUA-NEW GUINEA	6.0	17	56	450	75	50	433	833%	2547%
PHILIPPINES	1,930	9,253	1,904	10,311	2,500	-26	1,058	-1%	11%
PORTUGAL	16	90	29	175	60	13	85	78%	94%
ROMANIA	0	0	0	0	5	0	0		
RUSSIA	79	85	82	441	190	3	356	4%	419%
SPAIN	0	0	0	0	40	0	0		
SLOVAKIA	0	0	0	0	5	0	0		
THAILAND	0.3	1.8	0.3	2.0	1	0	0	0%	11%
THE NETHERLAND	0	0	0	0	5	0	0		
TURKEY	20	105	82	490	200	62	385	308%	368%
USA	2,564	16,840	3,093	16,603	5,400	530	-237	21%	-1%
TOTAL	**8,933**	**55,709**	**10,715**	**67,246**	**18,500**	**1,783**	**11,538**	**20%**	**21%**

Figure 35: Geothermal capacity per country[124]

[124] Bertani, Ruggero: Geothermal Power Generation in the World 2005–2010 Update Report. *Proceedings World Geothermal Congress 2010*

3.6.1 Outlook on geothermal electricity generation

Until 2035 electricity generation is expected to grow continuously. For example, the International Energy Agency (IEA) states in its 2011 International Energy Outlook that electricity generation will expand from app. 20.000 TWh as of today to roughly 35.000 TWh in 2035. However, it is interesting to note that the share of fossil and nuclear energy sources will decline from 81% to 77% in 2035. The difference will be made up renewable energy forms such as solar, biomass, wind and geothermal, which is expected to grow to 7%.

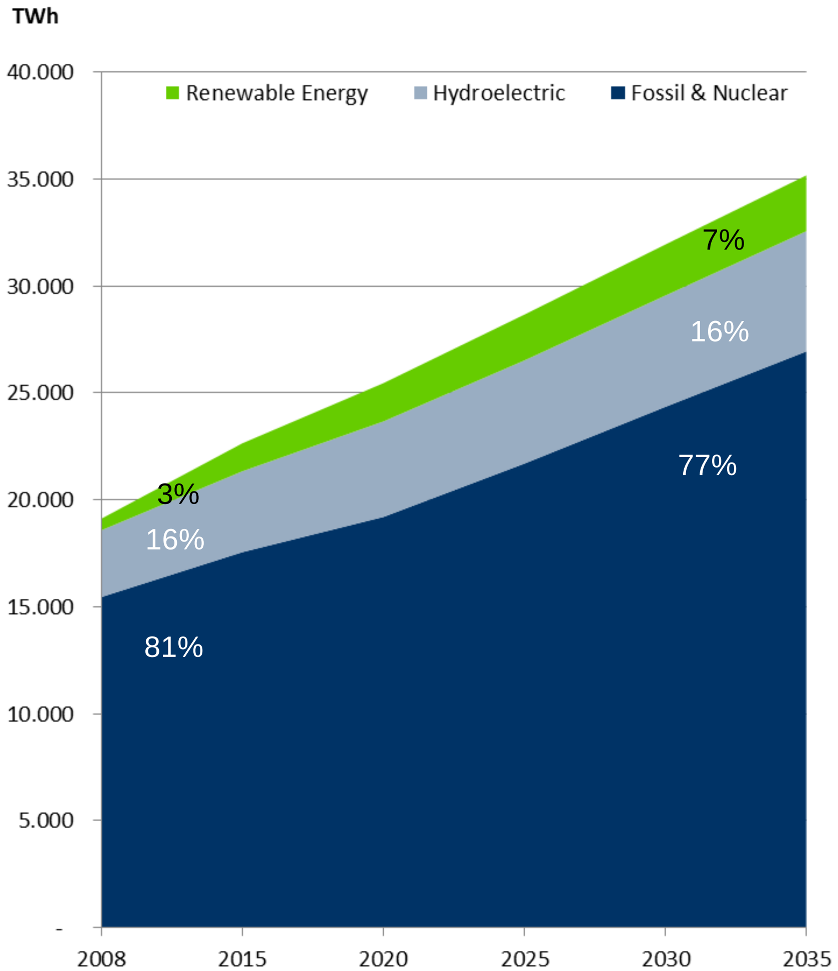


Figure 36: Electricity generation per energy carrier[125]

[125] U.S. Energy Information Administration: International Energy Outlook 2011, 2011

However, looking at the share of renewables in electricity generation more closely it has to be stated that the biggest contribution are likely to come from wind power. Electricity generation based on geothermal resources is likely to stay small in size amounting to roughly 7% of the renewables in total. So in total the worldwide contribution from geothermal to electricity generation is likely to make up app. 0,5% meaning it will stay small in size compared to other technologies. This means geothermal will remain a niche market on a global basis.

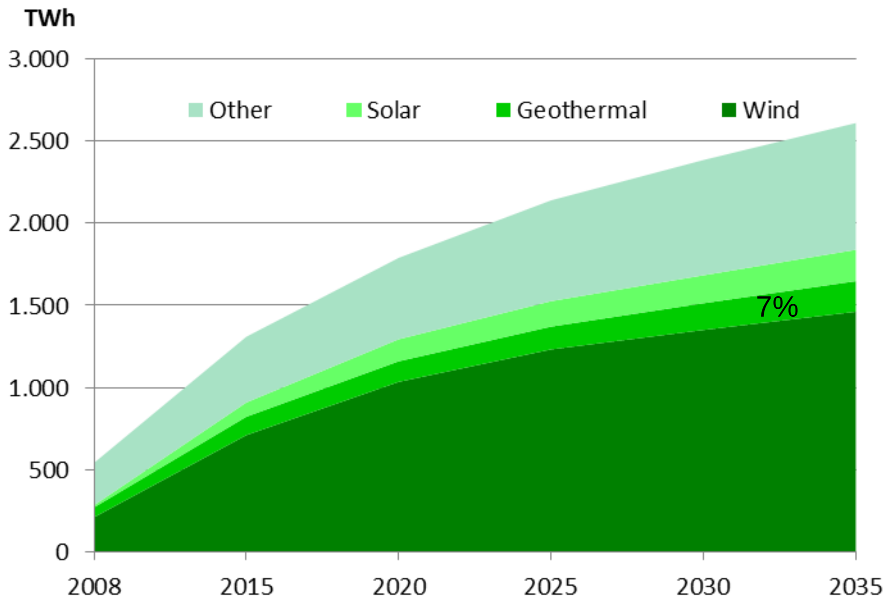


Figure 37: Share of geothermal in renewable energy forms of electricity generation[126]

3.7 Geothermal resources in Turkey

Since 1962 extensive efforts have been conducted by the Mineral Research and Exploration Institute (MTA) in order to assess the geothermal resources in Turkey. Based on this more than 170 fields have been identified to be useful at an economic scale. In addition, roughly 1500 hot and mineral resources have been found that have temperatures between 20°C and 242°C[127]. As can be seen in the figure below these occurrences are located to the largest extent along the major grabens at the Western Anatolia, along the Northern Anatolian Fault Zone, and the Central and Eastern Anatolian volcanic regions.

[126] U.S. Energy Information Administration: International Energy Outlook 2011, 2011
[127] Simsek, Mertoglu, Bakir, Akkus, Aydogdu 2005, Geothermal Energy, Utilization, Development and Projections – Country Update Report (2000 – 2004) of Turkey; *Proceedings World Geothermal Congress 2005*

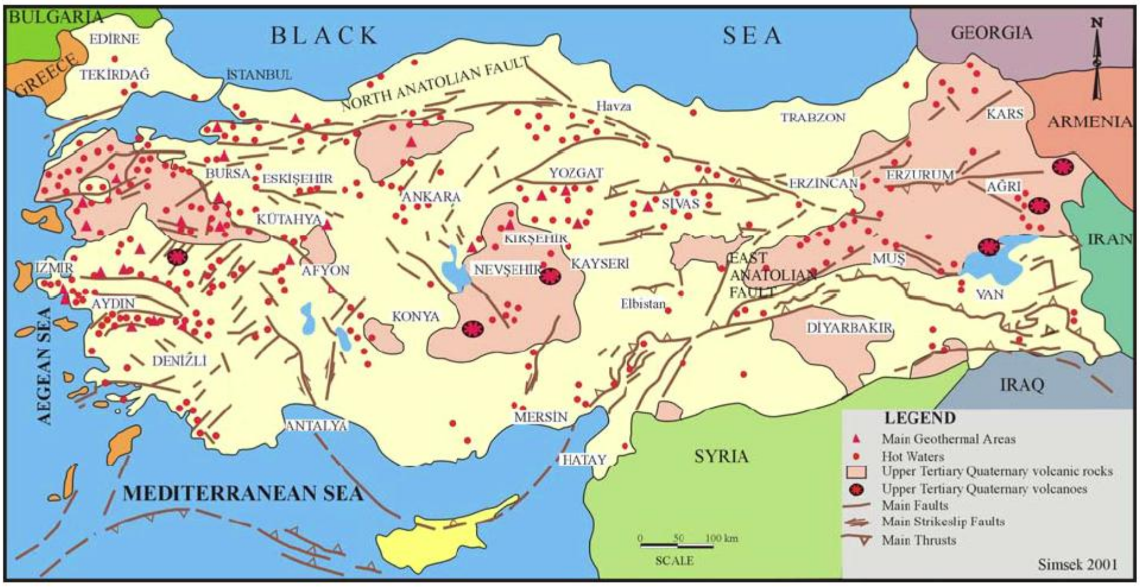


Figure 38: Geothermal regions in Turkey[128]

These regions are also the most promising areas for future development of geothermal projects. The MTA (2005) report depicts three geothermal areas in particular. For example, when looking at their inventory a map of hot spring temperatures is shown, which employs an absolute scale for the hot spring temperatures, however a relative scale for the distribution of temperature.

128 Simsek, Mertoglu, Bakir, Akkus, Aydogdu 2005, Geothermal Energy, Utilization, Development and Projections – Country Update Report (2000 – 2004) of Turkey; *Proceedings World Geothermal Congress 2005*

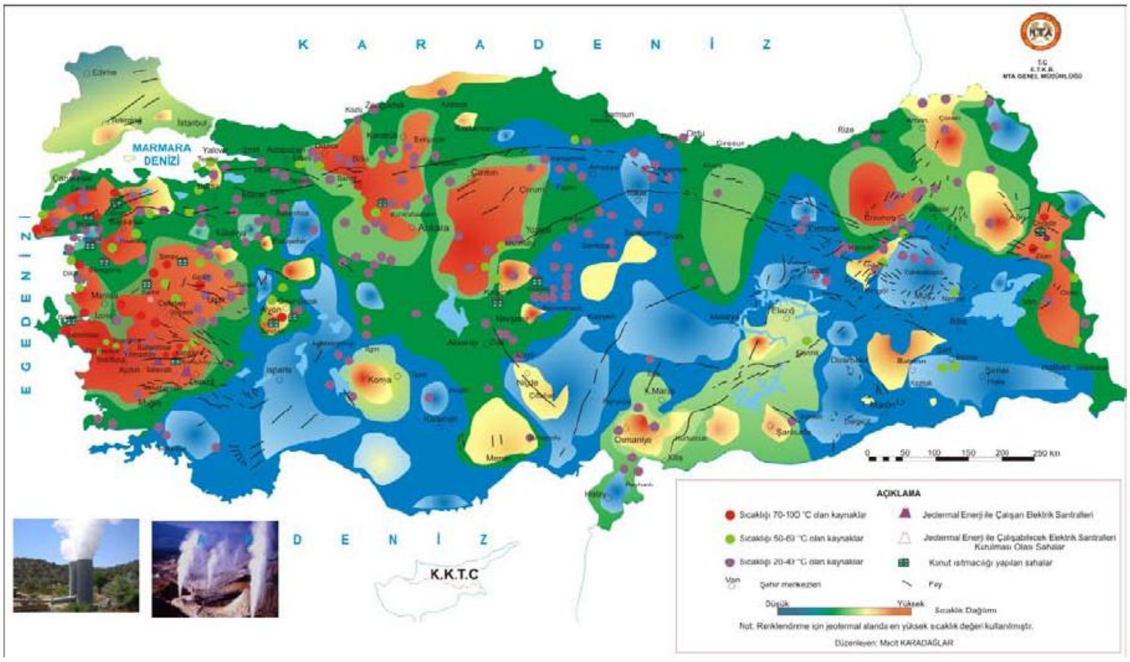


Figure 39: Inventory map of hot springs in Turkey[129]

The figure below illustrates the number of geothermal fields per province. Out of 81 provinces 61 have proven geothermal resources[130]. As can be seen the provinces in the Western part of Turkey has the highest density of geothermal resources. However, the Central and Eastern part of Turkey also exhibit significant amounts of geothermal resources. Obviously, the Western part of Turkey has the highest number of plants, both in operation and under construction, and most district heating systems. This corresponds with the fact that the highest maximum observed temperatures in °C are found in this region.

[129] MTA (2005), Turkey Geothermal Resource Inventory. In MTA, Turkey Geothermal Resource Inventory. MTA.

[130] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

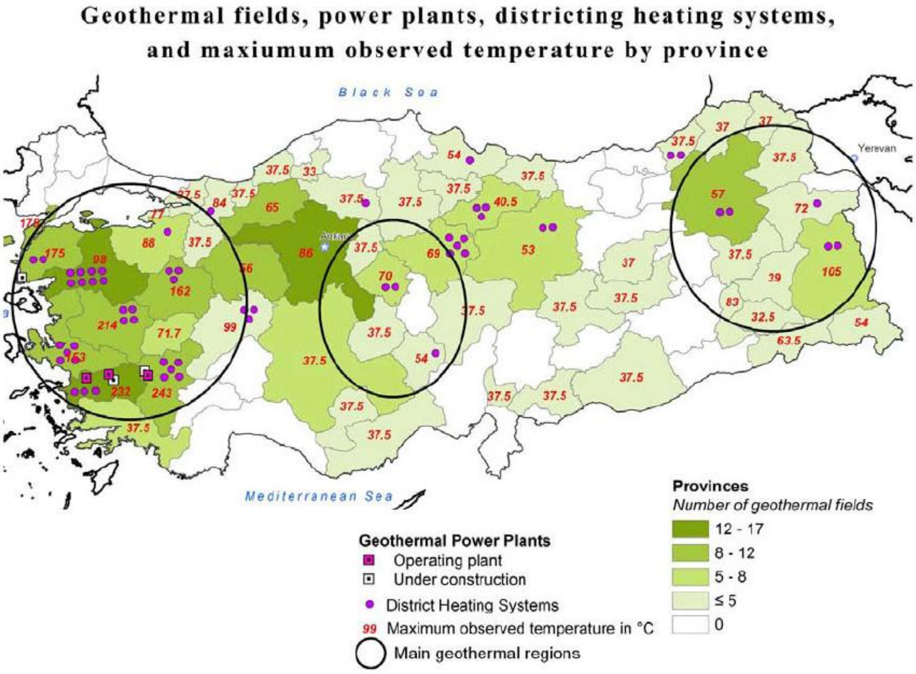


Figure 40: Geothermal fields, power plant, district heating system and maximum observed temperature by province[131]

Also the maximum number of fields is to be found in the West. The table below lists all provinces with more than 5 occurrences of geothermal resources and depicts additional key statistics. However, also central and eastern Turkey have an considerable amount of geothermal potential. In this context it needs to be pointed out that the data generated mainly by MTA may be biased by the fact that MTA drilled most of the wells in the Western part and therefore higher temperatures are more likely to be reported in this region, since measured temperatures in deep wells can be considerably higher compared to measured hot spring temperatures for a given resource area[132].

[131] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[132] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

PROVINCE	REGION	MAXIMUM TEMP. (ºC)	NUMBER OF FIELDS	NUMBER OF POWER PLANTS	NUMBER OF DISTRICT HEATING SYSTEMS
Balikesir	Western Turkey	98	17		8
Aydin	Western Turkey	232	13	2	3
Izmir	Western Turkey	153	12		5
Kutahya	Western Turkey	162	11		3
Canakkale	Western Turkey	175	10	1	2
Denizli	Western Turkey	243	10	2	5
Eskisehir	Western Turkey	56	10		
Bolu	Western Turkey	65	9		
Manisa	Western Turkey	282	9		4
Bursa	Western Turkey	88	8		1
Mugla	Western Turkey	37.5	6		
Usak	Western Turkey	72	6		
Elzurum	Eastern Turkey	57	12		2
Bingol	Eastern Turkey	68	7		
Van	Eastern Turkey	105	6		2
Ankara	Central Turkey	86	14		
Konya	Central Turkey	37.5	8		
Silvas	Central Turkey	53	8		2
Yozgat	Central Turkey	69	8		2
Kirsehir	Central Turkey	70	7		5
Tokat	Central Turkey	40.5	6		2
Kayseri	Central Turkey	37.5	5		3

Figure 41: Geothermal field statistics for provinces with 5 or more identified geothermal fields[133]

Further, another important consideration of MTA was to be close to the load centers of Turkey and the electric grid to lower the total costs of geothermal energy. This is shown in the figure below where it can be observed that the main lines and the power grid of Turkey are passing the main geothermal regions. Also important load centers are relatively close.

[133] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

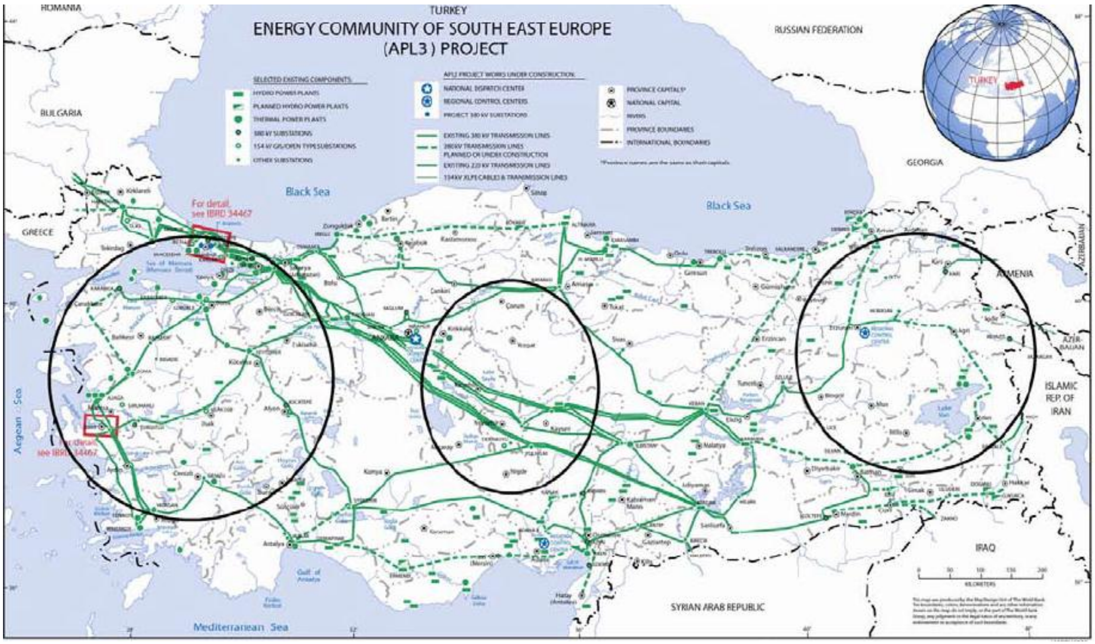


Figure 42: Power lines in Turkey[134]

As said the maps presented so far do not allow differentiating along the method of measurement, that is to say whether the temperature was taken in a hot spring on the surface, or a geothermometer was employed or whether the measurement took place in a deep drilled well. This potentially implies a bias since the distribution of drilled wells across Turkey is not even[135]. In contract, most of the wells have been drilled to the largest extent in the West of Turkey and if in other parts of Turkey an equal amount of wells would have been drilled the overall picture would likely to be different. In order to make up for this deficiency only temperatures from hot springs measured at their discharge point is shown below. In addition, this map depicts different areas with different colors representing different geological settings. Moreover. the volcanos and the geologic faults are shown, whereas the black triangles are representing the volcanos and the red lines depict the geologic faults. Both of them are important in this context, because permeability and temperature are key in order to exploit geothermal resources. Volcanic regions and tectonically active regions have therefore a good chance to host attractive geothermal resources. In Turkey both phenomena can be found. As shown in map below one Quaternary volcano can be found in the Western part of Turkey in Anatolia. In addition a chain of Quaternary volcanoes is found in central Turkey and in eastern Turkey near the Armenian border[136].

[134] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[135] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[136] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

In this context it has to be stated that Quaternary volcanoes were active in the Quaternary period, which was about 1.8 million years ago to today[137]. Such volcanos are considered as young in geological terms and in general the presence of magma at relatively low levels in the crust may be expected there. Hence, such regions containing magma are likely to provide heat to the upper structures of that region.

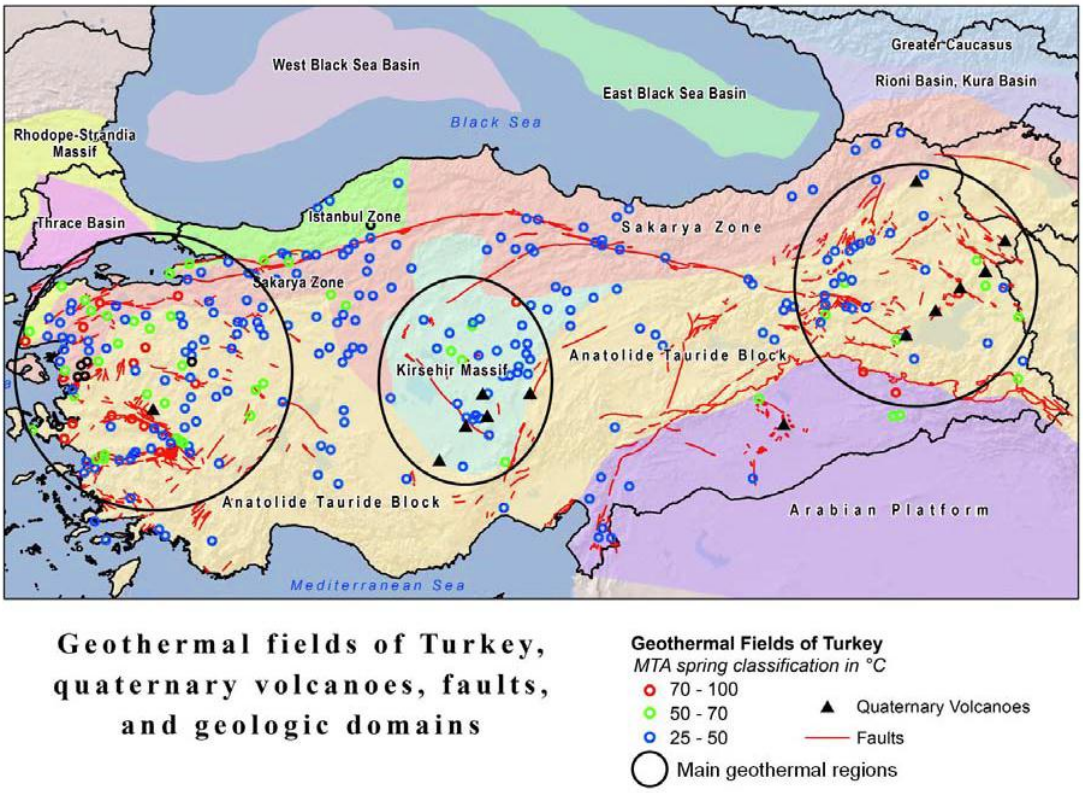


Figure 43: Geothermal fields of Turkey, quaternary volcanoes, faults, and geologic domains[138]

A further indication where geothermal potential may be found is given by investigation heat flow measurements[139]. The map below shows the major faults and Quaternary volcanoes on the one hand, but also heat flow values which are represented by the shaded areas. Further, it depicts the location were heat flow data was measured with black points. These data points stem from wells drilled for the purpose of exploiting oil and gas reserves. Again the similar picture arises, i.e. high heat flow is present in the West of Turkey, which emphasizes its geothermal potential. In the central part only limited data is available, i.e. only 4 wells and in the

[137] http://en.wikipedia.org/wiki/Category:Quaternary_volcanoes accessed on 07.10.2012
[138] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[139] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

East no data at all is there. This may explain why no heat flow can be shown in this area[140].

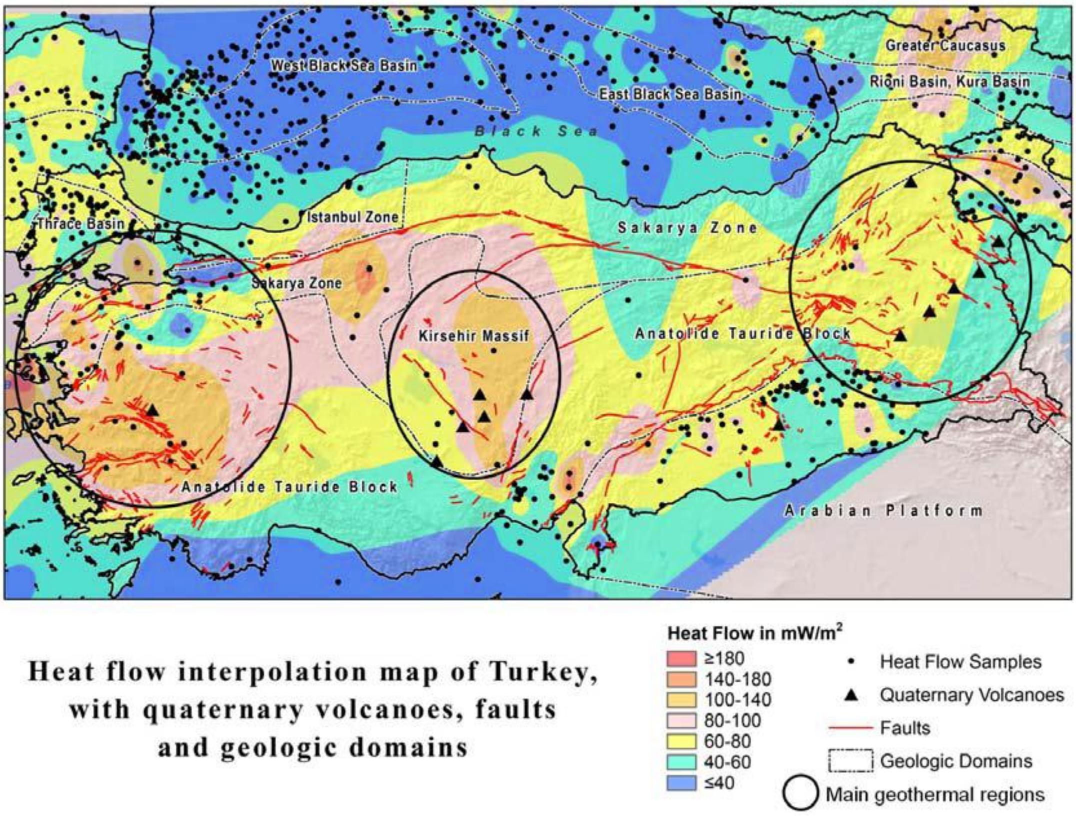


Figure 44: Heat flow interpolation map of Turkey with quaternary volcanoes, faults and geologic domains[141]

Last, another indicator for high geothermal potential is provided by a special geologic phenomenon which is referred to as a metamorphic core complex. This structure is found in West Turkey[142] and it is considered to host large blocks of deep, hot rocks which stretch upwards in the crust and effect regions characterized by significantly higher temperature close to the subsurface. In addition, constantly occurring faulting of these areas causes a higher degree of permeability. One of such extremely favorable structures can be found again in the West of Turkey and is referred to as the Menderes metamorphic core complex[143]. This is shown in the figure below. Furthermore, it is important to note that In this region all except one

140 EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
141 EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
142 EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
143 EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

power producing plants utilizing geothermal resources are to be found.

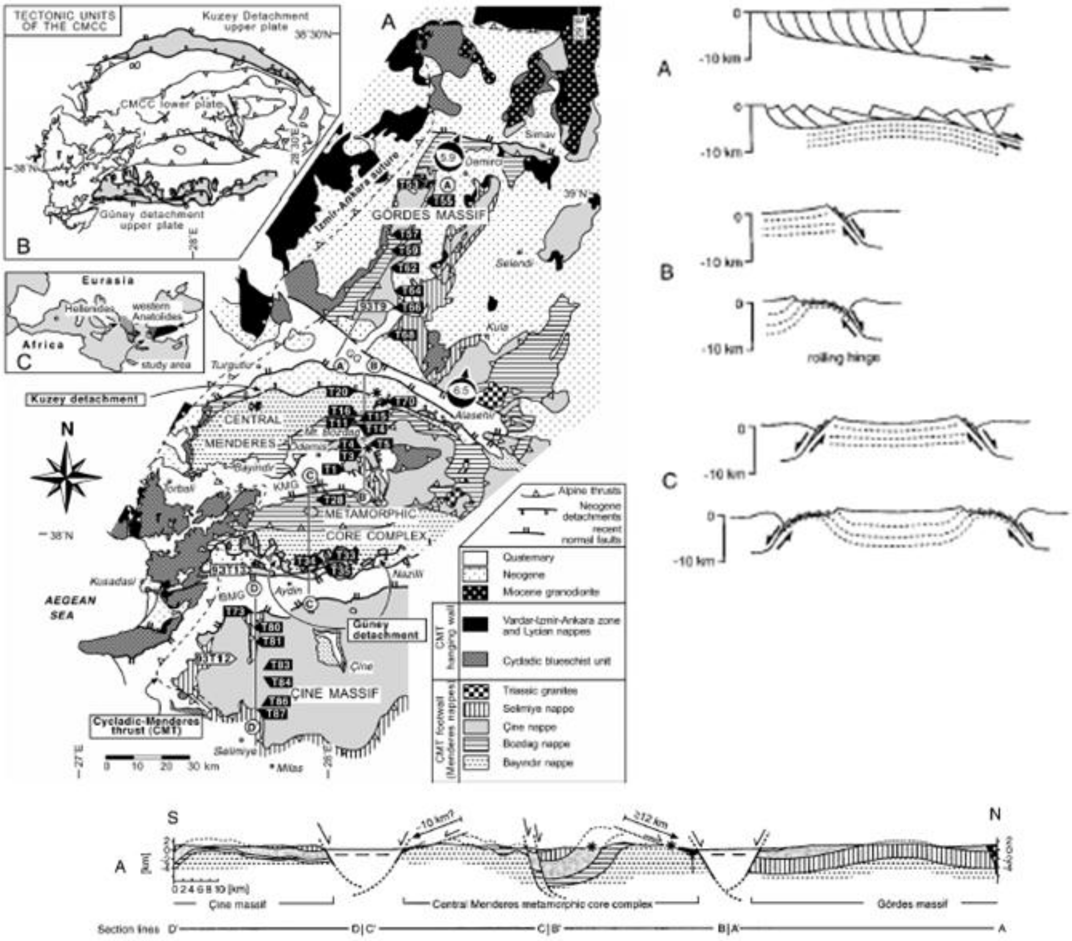


Figure 45: Metamorphic core complex[144]

3.8 Geothermal power generation in Turkey

In the following the key geothermal power generation projects currently installed will be outlined. The two hottest sites– Kizildere and Germencik – will be investigated in more detail by giving a brief historic background.

3.8.1 Kizildere

According to the EBRD report (2011) the first commercial power generation unit from a geothermal resource was installed in 1984 at Kizildere. Net capacity of this plant amounts to 17,5 MWel. However, it is reported that continuous operational problems related to scaling by deposition of calcite (CaCO3) and high CO2 content led to a decline of power output to 7,8 MW in 2000. Wells drilled until 1998 were rather shallow with depth amounting to approximately 1.100 m. In order to avoid

[144] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

cooling of the reservoir deeper wells were drilled to more than 1.600 m and considerably higher temperatures of geothermal fluids were found, i.e. 242°C. This was the hottest well at that time[145]. Finally, in 2008 Kizildere was acquired by Zorlu Doğal Elektrik Üretim A.Ş. Zorlu performed well deepening programs and work overs and achieved to double the output by 2010.

3.8.2 Germencik

Germencik was said to be one of the hottest and largest geothermal fields in Turkey for many years with temperatures reaching 232°C. This field was first explored by MTA in the 1970s and further developed in the 1980s with an extended drilling program as reported in the EBRD report (2011). In the course of the regulatory reforms in the early 2000s in Turkey the private sector was encouraged to further develop the geothermal potential. A Turkish consortium consisting of Güris and Ormat (Gürmat) acquired 49-year resource license from MTA. After in-depth investigations of this field the largest geothermal electricity generation plan was constructed, whereas net capacity amounts to 47,4 MWel[146].

3.8.3 Additional geothermal electricity generation projects

In the table below a complete list of geothermal electricity generation projects is shown. Interestingly, most of the capacity in Turkey has been installed during the last decade. It amounts to 100 MWel in total.

[145] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[146] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

PLANT NAME (LOCALITY)	YEAR COMMISSIONED	OPERATOR	NET INSTALLED CAPACITY (MWe)	POWER CYCLE, TEMPERATURE
Kizildere (Denizli)	1984	Zorlu	17.5	Single Flash, 242°C
Dora I Salavatli (Aydin)	2006	Menderes Geothermal	7.35	Binary, 170°C
Sarakoy (Denizli)	2007	Bereket Enerji	7.5	Binary, 140°C (effluent from Kizildere)
Gurmat Germencik (Aydin)	2009	Gurmat	47.4	Dual-Flash, 232°C
Tuzla (Canakkale)	2009	Enda Enerji	7.5	Binary, 170°C
Dora II Salavatli (Aydin)	2010	Menderes Geothermal	9.7	Binary, 170°C

Figure 46: List of geothermal electricity generation projects[147]

The Salavatli area consists of two sub-fields, i.e. Dora I and Dora II, and are operated by Menderes Geothermal Elektrik Üretim A.Ş. Four production wells power a 7.4 MW unit at Dora 1 making use of the 167°C geothermal fluid and three wells supply the second station, a 9.4 MW power plant at Dora 2[148].

The Tuzla field is operated by Egenda Ege Enerji Üretim A.Ş. and announced to commission an power plant with an initial capacity of 7,5 MWel in 2010. The site is intended to be expanded by installing another 7,5 MWel unit.

Last, since 2007 the effluent from the Kızıldere plant is used to supply an additional 6.9 MW plant (Bereket Kızıldere-Sarayköy project).

Below two pictures provided by MTA[149] (General Directorate of Mineral Research and Exploration) from installation in the Aydin field are shown for exemplary purposes.

[147] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[148] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[149] http://www.mta.gov.tr/v2.0/daire-baskanliklari/enerji/jeotermal_calisma_eng.pdf accessed on 26.10.2012

Aydın-Pamukören-AP-3

Aydın-Sultanhisar SH-1

Figure 47: Aydin field installations SH1, AP3

3.9 Geothermal fields suitable for electricity generation in Turkey

Based on the study by Mertoglu, Simsek and Dagistan (2010) a number of additional fields, which are suitable for electricity generation have been identified in the past. Field above a temperature of 170°C are most promising from an economic point of view, however existing technology also allows economically feasible solutions for lower temperature fields. The EBDR report (2011) further states that Balkova and Dikili which is suitable for electricity generation according to their view has not been taken into account in the Mertoglu, Simsek and Dagistan (2010) study. Below the complete list of fields is shown.

PROVINCE	GEOTHERMAL FIELD	RESOURCE TEMPERATURE (°C)
Denizli	Kizildere	217-242
Aydin	Germencik-Omerbeyli	220-232
Manisa	Kavaklidere	213
Aydin	Pamukoren	187
Manisa	Salihli-Gobekli	182
Canakkale	Tuzla	160-174
Aydin	Salavatli	157.5-171
Kutahya	Simav	145-162
Manisa	Salihli-Caferbeyli	150-155
Aydin	Umurlu	155
Izmir	Seferihisar	144-153
Izmir	Balcova	142
Aydin	Yilmazkoy	142
Aydin	Sultanhisar	145
Aydin	Hidirbeyli	143
Nazilli	Bozyurt-Guzelkoy	140

Figure 48: Geothermal fields suitable for electricity generation in Turkey[150]

It is also estimated that a couple of hundreds megawatts will be put into operation within the next decade whereas capacity increases in existing fields and new projects will likely be in the range of 10 – 50 MW[151].

[150] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[151] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

4 Legal Framework in Turkey for Geothermal *(Michael Graf)*

In the following relevant information with regard to the relevant legal framework under which any geothermal project in Turkey needs to be carried out, will be presented.

In the past, Turkey has undergone significant moves towards new structures and governance principles the energy sector, which has led to a complete change of the whole industry. In particular, the legal and regulatory framework has changed fundamentally. The main concern that these regulations intended to tackle was to encourage private investment in the energy sector in order to meet growing demand[152]. Furthermore, House (2004) states that another objective was to downsize the state's balance sheet and to enforce competition to lower consumer prices of energy. Regulatory efforts started back in 1984 through Law No. 3096 which allowed private companies to build and operate power plants and to sell the electrical output to the state-owned Turkish Electricity Authority. However, the law did not provide more private capital for the energy sector due to the unfavorable interpretation of the law by the Constitutional Court[153]. In 1993 the Turkish Electricity Authority was split up into generation and transmission plus wholesale entity (the TEAS) and a distribution entity (TEDAS). Along with this the Turkish Parliament issued a new regulatory framework (Law No. 3996) which provided for guarantees for the obligations of the off-taker and even tax exemptions. However, again the Constitutional Court deemed this law as unconstitutional[154].

Finally, in 2001 the Turkish Parliament passed due to the high cost of power the Electricity Market Law, which fundamentally changed the power market and the Energy Market Regulatory Authority (EMRA) was established. The purpose of this law was to foster a financially sound and transparent electricity market with the goal

[152] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
[153] Joshua House, E. C. (2004). IPP Investment in Turkey's Electric Power Industry. Accessed on 26.10.2012, Stanford University: http://pesd.stanford.edu/publications/ipp_investment_in_turkeys_electric_power_industry/
[154] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

to provide sufficient and low cost electricity to the consumers[155]. Moreover, based on this law TEAS was separated into a generation, wholesale, and transmission part[156]. Further, in 2005 the Renewable Energy Act (Law 5346) was issued. Among other, the law intends to expand the utilization of renewable energy resources with the goal to generate electricity, to enhance the diversification of energy carriers, to lower greenhouse gases and to incentivize the private sector to reach these objectives (MTA 2011).

The EBDR report (2011) points out that the initial Renewable Energy Act was not that effective since the market prices for electricity was higher than the tariffs set out in the law. Based on this the law has been amended in 2011. With regard to pricing the law provides for geothermal a 10 years fixed feed-in tariff (FIT) amounting to 10,5 US $ cents per kWh for installations which are put into operation between 2005 and 2015. However, a yearly cap of 600 MW was set. Moreover, the law sets forth that the FIT may be higher up to 2.4 US $ cents per kWh for a period of five year if certain Turkish-made components in the generation plant are installed.

In addition, retailers of electrical energy have to purchase a certain amount of electrical energy from generators using renewable energy carriers. Interestingly, the license holder of renewable energy can also erect additional plants in the same area in case the energy transferred to the system does not exceed the specified amount (follow-on capacity). Further, renewable energy generating plants can also be put in even environmentally sensitive areas, such as natural parks based on prior approval of the relevant authorities (Atayilmaz 2011). Next, TEIAS and/or legal entities holding distribution licenses has to provide a connection of generation facilities to the system (EBDR report 2011).

Last, with regard to the relevant legal framework regarding geothermal in Turkey the Law on Geothermal Resources and Natural Mineral Water (Law No. 5686) as passed in 2007 needs to be mentioned. The objective of this law is to *"set forth the procedures and principles regarding effective exploration, research, development, production and protection of geothermal and natural mineral water resources, holding rights on these resources and devolution of the rights, economic utilization of the resources in a compatible way to the environment, and abandonment of these resources"* as cited by MTA (2011).

[155] MTA (2011), Geothermal energy study, http://www.mta.gov.tr/v2.0/daire-baskanliklari/enerji/jeotermal_calisma_eng.pdf accessed on 26.10.2012

[156] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

5 Auction system for Geothermal in Turkey *(Michael Graf)*

As outlined previously in order to exploit geothermal resources in Turkey a license is required. These licenses can be either of a non-competitive nature issued by the local government (provincial or municipal authorities) or can be obtained based on a competitive auction, in which bids are submitted by interested parties for those fields that have previously been explored and drilled by MTA157.

In order to promote the usage of geothermal resources in Turkey, MTA has performed auctions for the required licenses. The results of two of them, i.e. the September 2008 and April 2009 auctions, are publicly available and shall be reported in the following.

GEOTHERMAL SITE	ESTIMATED IPC (MW)	TENDER DATE	BID BOND	NUMBER OF THE APPLICANT COMP.	BIDDER	BID PRICE (WITHOUT VAT)($)	BID PRICE (WITH VAT) ($)
Aydin-Sultanhisar	20	11/4/2008	450	27	Gokkale Organik Urunler TIC.Ltd.Sti	19,050	22,479
Aydin-Merkez-Kosk-Umurlu-Sercekoy	25	11/5/2008	550	23	Karkey Karadeniz Elektik Uretim A. S.	20,150	23,777
Aydin-Germencis-Bozkoy-Camur	10	11/6/2008	400	19	Maren Maras Elektric Ure San.ve Tic. A. S.	15,100	17,818
Aydin-Sultanhisar-Atca	5	11/7/2008	300	19	Santral Enerji Uretim A. S.	10,300	12,154
Manisa-Alasehir-Kavaklidere	30	10/10/2008	600	17	Aktif Enerji San. Ve Tic. A. S.	21,310	25,146
Manisa-Salihli-Caferbeyli	20	11/11/2008	350	13	Permak Enerji Uretim ve Dagitim A. S.	11,300	13,334

Figure 49 Results of September 2008 auction[158]

157 EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch
158 EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

In total, 110 MW have been auctioned and for each lot between 13 and 27 applications have been received. All the fields are located in the Menderes and Gediz Grabens and the wells have all been drilled by MTA in previous times. The total sum of all bids amounts to roughly 100 Mio TL (~ 43 Mio EUR) according to the EBDR report.

In 2009 13 geothermal fields have been offered via a public auction in addition to the previous ones. As can be seen in the table below, all of them include a significant amount of acreage and are located all across Turkey.

NUMBER	MTA TENDER FILE NUMBER	PROVINCE	GEOTHERMAL FIELD	BID PRICE AMOUNT (US DOLLARS)	AREA (HECTARES)	GEOTHERMAL CHARACTERISTICS
1	2009/JA-07-SH	Kirsehir	Kirsehir-Cicekdagi-Mahmutlu	30,000	1,325	70°C Spring
2	2009/JA-08-SH	Kirsehir	Kirsehir-Mucur	15,000	330	Low temperature spring and wells
3	2009/JA-09-SH	Izmir	Izmir-Aliga-Samurlu	40,000	1,113	96°C in 1,246m well
4	2009/JA-10-SH	Izmir	Izmir-Aliaga-Ilicaburun	30,000	1,642	Moderate temperature wells
5	2009/JA-11-SH	Balikesir	Balikesir-Balya-Ilica	30,000	2,000	60°C spring
6	2009/JA-12-SH	Kutahya	Kutahya-Gediz-Saphane	50,000	2,790	97°C in 543 m well
7	2009/JA-13-SH	Van	V an-Ozalp-Caybagi	35,000	1,500	87°C in 452 m well
8	2009/JA-14-SH	Van	Van-Ercis-Zilan-Sorkoy	40,000	2200/4080	98°C in 255 m well, 105°C in 1,172 m well; temperature reported at over 200°C (no confirmation)
9	2009/JA-15-SH	Konya	Konya-Seydisehir-Kavakkoy	25,000	888	Low temperature springs
10	2009/JA-16-SH	Konya	Konya-Tuzlukcu	20,000	1,813	No data
11	2009/JA-17-SH	Mersin	Mersin-Silifke-Keben	30,000	3,500	No data
12	2009/JA-18-SH	Siirt	Siirt-Billuris	20,000	1,428	Low temperature springs
13	2009/JA-19-SH	Karabuk	Karabuk-Eskipazar	15,000	3,000	Low temperature springs

Figure 50 Results of April 2009 auction[159]

Next, in 2010 MTA auctioned 16 additional fields in March 2010. Relevant data can be seen in the table below.

[159] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

MTA TENDER FILE NUMBER	CLOSING BID DATE AND TIME	PROVINCE	GEOTHERMAL FIELD	BID PRICE AMOUNT (US DOLLARS)	GEOTHERMAL CHARACTERISTICS
2010/JA-20-SH	March 10, 2010, 11:00 am	Afyon	Afyon-Bozhuyuk	35,000	No data
2010/JA-21-SH	March 10, 2010, 11:00 am	Ankara	Ankara-Cubuk-Meliksah	15,000	3 wells; 61°C in 1296m well
2010/JA-22-SH	March 10, 2010, 11:00 am	Aydin	Aydin-Pamukoren	450,000	Proven electrical generation potential
2010/JA-23-SH	March 10, 2010, 11:00 am	Aydin	Aydin-Nazilli	250,000	Proven electrical generation potential
2010/JA-24-SH	March 10, 2010, 11:00 am	Aydin	Aydin-Sultanhisar	450,000	Proven electrical generation potential
2010/JA-25-SH	March 10, 2010, 11:00 am	Erzurum	Ezurum-pasinler-Uzunahmet (Hamamderesi)	25,000	Low temperature springs and wells
2010/JA-26-SH	March 10, 2010, 11:00 am	Izmir	Izmir-Torbali	25,000	No data
2010/JA-27-SH	March 10, 2010, 11:00 am	Kayseri	Kayseri-Cicekdagi-Mahmutlu	15,000	Low Temperature Well
2010/JA-28-SH	March 10, 2010, 11:00 am	Kirsehir	Konya-Cihanbeyli-Bozdag	15,000	Low Temperature Well
2010/JA-29-SH	March 10, 2010, 11:00 am	Kirsehir	Manisa-Kula-Emir-Sehitli	30,000	64°C and 70°C springs
2010/JA-30-SH	March 10,	Konya	Konya-	20,000	Low Temperature
2010/JA-31-SH	March 10, 2010, 11:00 am	Konya	Konya-Cihanbeyli-Bozdag	20,000	No data
2010/JA-32-SH	March 10, 2010, 11:00 am	Manisa	Manisa-Kula-Emir-Sehitli	25,000	Moderate Temperature springs; 163°C in 132m well
2010/JA-33-SH	March 10, 2010, 11:00 am	Mersin	Mersin-Tarsus-Guneyyolu	25,000	No data
2010/JA-34-SH	March 10, 2010, 11:00 am	Siirt	Siirt-Billuris	20,000	Low Temperature Springs
2010/JA-35-SH	March 10, 2010, 11:00 am	Van	Van-Caldiran-Ayrancilar	25,000	61°C spring and other low temperature springs

Figure 51 Results of March 2010 auction[160]

[160] EBDR (2011). Assessing the geothermal market in Turkey. Black & Veatch

Although most of the fields are located in the Western part of Turkey it is interesting to note that applications have also been received for licenses in the presumably less interesting locations in the central and eastern part of Turkey

6 Strategic fit of HDR *(Michael Graf)*

In the following paragraphs the strategic fit of HDR technology with the defined corporate strategy of OMV shall be investigated.

In this context three key questions arise:

- **Choice of country**

  With regard to geothermal, what differentiates Turkey from other countries within the defined geographic operating radius of OMV?
- **Leverage of core competencies**

  Can OMV leverage from its core competencies that will allow a competitive edge?
- **Economics**

  Could geothermal become a profitable business for OMV?

6.1 Choice of country for geothermal projects

In order to answer the first question, the official website of OMV has been searched for the geographic spread of its operations. The Investor Relations department provided a helpful power point presentation[161] that included a map showing OMV's current core markets. Those are marked in green color. In addition, the current upstream business, Exploration & Production, and the defined extended exploration focus radius is depicted. Moreover, the geographic area of Gas & Power, in which integrated gas will represent the leading strategic intent, is circled in blue. In this context in needs to be pointed out that integrated gas refers to the objective to fully integrate gas across OMV group. This means specifically that OMV strives to tackle the overall supply chain of gas, i.e. from gas production, to transportation and finally to use gas in power plants as feed for electricity production. Last, the downstream business, i.e. Refining and Marketing, is represented by the inner circle.

[161] http://www.omv.com/portal/01/com/omv/OMV_Group/Investor_Relations/Download_Center/Presentations access on 27.10.2012

Moreover, together with the OMV geothermal team and based on the information presented in chapter 3.6 – Geothermal electricity generation, countries with no or low electricity generation from geothermal potentials or with geothermal potential for direct heat only have been marked with a red cross (x), i.e. Tunisia, Libya, Egypt, Bulgaria, Romania, Czech Republic, Norway, Great Britain, Scotland, Hungary, Croatia, Pakistan, Yemen, and Kazakhstan. As outlined by Bertani (2010) out of those countries only Romania and Slovakia is expected to have some 5 MW installed capacity by 2015. This is clearly negligible in terms of size taking OMV's requirements into consideration. However, since Romania is one of OMV's core countries, it should remain on the watch list regarding future developments. To the extent known in the literature the other countries are very likely to not possess relevant geothermal potential at all.

Second, those countries which possess electricity production potential from geothermal and lie within the defined geographic operating radius of OMV are marked with a red flag, i.e. Austria and Germany.

Finally, the regions with high temperature geothermal fields and high electricity potential from geothermal are marked with a black check mark, i.e. Turkey, New Zealand, and Italy. As Bertani (2010) states New Zealand is forecasted with 1240 MW geothermal capacity installed in 2015, Turkey with 200 MW installed in 2015 and Italy with 920 MW installed in 2015.

All of them have favorable conditions for geothermal. However, it they differ significantly when looking at the degree of market development. New Zealand and Italy can be considered as rather established markets with 843 MW in Italy respectively 682 MW in New Zealand installed capacity based on the study of Bertani (2010). In contrast, Turkey may rather be characterized as emerging market, since geothermal is by far not that relevant with 82 MW installed capacity in 2010. However, the growth rates are higher in Turkey compared to New Zealand and Italy. Bertani states in his 2010 study that geothermal electricity capacity in Italy will grow is expected to grow by 9% and New Zealand by 197% until 2015, whereas Turkey will grow by 243% within the same period.

In addition, OMV has invested in recent years significant amounts in the Turkish retail market, when it acquired additional shares of Petrol Ofisi (97% in total), Turkey's leading fuel marketing company. Furthermore, OMV has a 40% stake in Enerco Energy, which is the second largest gas sales company. Last, the gas-fired power plant in Samsun is under construction. Moreover, OMV considers Turkey as a bridge to important neighboring countries, which are essential in particular for the

Nabucco project. Hence, Turkey is considered as a core market of OMV, which means that it is from the strategic point of view attractive to expand the Turkish business portfolio of OMV also by geothermal projects.

Moreover, it can be stated that also from a practical point of view, Turkey as a location for geothermal projects makes more sense compared to New Zealand simply because of its geographic proximity to the other operations, in particular in Austria and Romania. For example, New Zealand bears disadvantages due to time differences and higher travel efforts which makes steering and implementing potential geothermal projects more difficult.

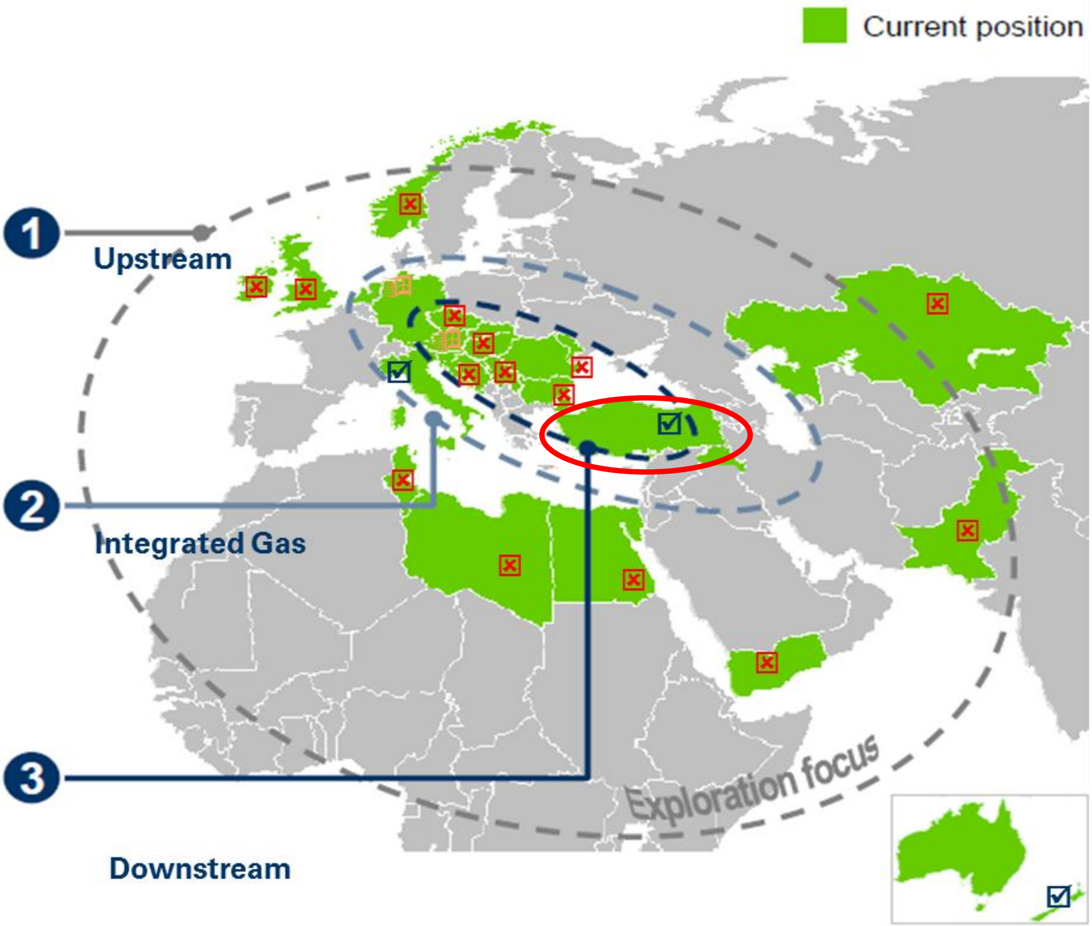


Figure 52: Operating radius of OMV and geothermal potential[162]

[162] OMV Investor Presentation http://www.omv.com/portal/01/com/omv/OMV_Group/Investor_Relations/Download_Center/Presentations access on 27.10.2012 and amended accordingly for the purpose of this thesis

Hence, taking all the above outlined facts into consideration it may be stated that Turkey is the most interesting candidate for geothermal projects within the defined operating radius of OMV.

6.2 Leverage from core competencies

In order to provide guidance for the second questions, i.e. can OMV leverage from its core competencies that will allow a competitive edge, one needs to assess OMV's capabilities in the single disciplines that are necessary to realize a geothermal projects. This task was performed by conducting expert interviews[163] within OMV and drawing on internal studies. Two dimensions were deemed as of particular interest, i.e. whether or not and to what degree the required expert know how is available within OMV and whether the required level resources may be dedicated to geothermal projects. The assessment was done on a three point scale ranging from high to low. Five key areas were identified: Geology, Drilling, Reservoir Management, Engineering and Construction and Operation and Maintenance. These dimensions have been discussed in depths with OMV experts and internal studies have been taken to substantiate and to supplement the findings. The results of this analysis are summarized in the table below.

Table 4: Availability of know-how and resources in the various disciplines within OMV

Discipline	Availability of know how	Availability of resources
Geology	Low – Medium	Low
Drilling	Low – Medium	Low
Reservoir Management	Low	Low
Engineering & Construction	Medium	Low
Operation & Maintenance	Medium	Low

[163] Brunner, Walter: Expert Interview held on 28.06.2012
Davies, Julia: Expert Interview held on 06.03.2012, 08.05.2012, 24.09.2012

The analysis clearly shows that in four out of those five dimensions relevant know how is available, however not to the required level of expertise. OMV has expert know how in Geology, Drilling, Engineering & Construction and Operation & Maintenance matters, however this know how is related to the traditional oil business and may not be transferred without additional training for the very specific requirements of geothermal projects. Since OMV has to date not realized any geothermal project, in particular Reservoir Management requires special attention, since this discipline differs to the largest extent from the traditional oil business compared to the other disciplines.
Moreover, it was found that the availability of internal resources represents a severe limiting factor to the realization of geothermal projects. In all five dimensions investigated the required level of resources is only to a low degree available within OMV.

6.3 Economics

The decision to implement a geothermal project is to a large degree driven by the estimation of the costs and revenues of a certain project, which finally determine whether or not a project makes sense from an economic point of view.
Therefore, this study also aims at presenting an economic decision model for geothermal projects in Turkey. For this purpose a business case was calculated by the geothermal team within OMV. It considers on the one hand the typical costs of geothermal projects in Turkey, such as geothermal reservoir exploration costs, drilling costs, or the costs related to the construction of the power plant, but on the other hand it also allows assessing whether such project meets the minimum returns that OMV requires.
In general, the costs for a geothermal project may vary significantly across different locations due to differences in labor costs for example. Therefore, in order to define a valid economic model for Turkey it is necessary to consider such differences. The EBDR report (2011) provides valuable input data for the business case with regard to the idiosyncrasies of cost factors in Turkey. It outlines for example that in Turkey power plant costs are typically fall into the lower range of possible costs. For example, it states that flash plants cost usually between 2000 US $ per kW and 4500 US $ per kW. In Turkey it is valid to consider the lower end of that range. One of the most important cost driver of geothermal projects are drilling costs. The EBDR report (2011) finds that those costs usually amount to one-third to one-half

compared to Europe or the United States. For example, in the United States costs per meter are about 2500 US $ whereas in Turkey 1000 US $ is a valid assumption. Considering such information three cases have been calculated, a low cost, medium cost and high cost case. Below the results of this analysis are shown[164].

Phase	Details		low cost	medium cost	high cost
Greenfield	Reservoir identification	m€	1	2	2
Exploration	Field evaluation prodcution & injection wells	m€	4	6	9
Development & construction	Field development	m€	16	27	43
	Power Plant EPC + OE	m€	39	42	45
Total Capex		m€	**60**	**78**	**100**
Operation	Net power output	MWh/a	208050	201480	197100
	Opex (ap.. 3% of capex)	m€	3	3	4
	Revenues at FIT (78,6 €/MWh)	m€	21	20	19
Economics after tax	**IRR**	**%**	**17,36%**	**14,93%**	**11,28%**
	NPV@7%	**m€**	**93**	**78**	**50**
	Pay back period	**years**	**10**	**13**	**17**
		€/MW	2,4	3,1	4,0

Figure 53: Generic business model for geothermal projects in Turkey

As can be seen the costs per MW range between 2,4 and 4,0 Mio EUR. The internal rates of return are 17,36% in the low cost case, 14,98% in the medium case and 11,28% in the high cost case. Hence of them meet the internal return requirements of OMV, which are 11% - 15% in the Exploration & Production division. However, in this context it needs to be pointed out that the decision to allocate finanical resources to a single project does not soley depend on whether or not a project meets the minimum requirements. Since financial resources are not endless, but limited, projects are competing within OMV for such resources. Therefore, the final investment decision will always consider also other opportunities for investment within OMV.

[164] Please note that due to confidentiality reasons specific data cannot be provided within this thesis

7 SWOT Analysis *(Peter Trupp)*

7.1 Involved Risk

For a development project with the goal that electricity is fed into a power grid using a HDR reservoir as an energy source, potential risks are from technical respectively technological nature, there is market risk, political risk, management risk and financial risk involved.[165]

Following an overview about the main HDR specific and Turkey related risks is given, on top to the risks involved already in conventional geothermal energy projects.

7.1.1 HDR Technology related Risks

7.1.1.1 Exploration Costs

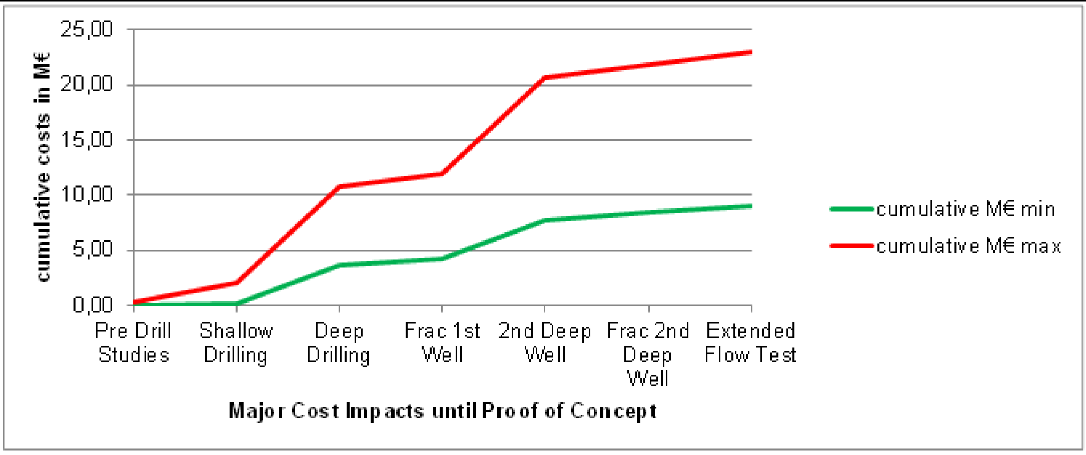
One of the biggest barriers in developing a technological and economic successful HDR project is that exact conditions underground are largely unknown at the beginning of a project, and only predictions can be used to simulate the life cycle of a power generating installation. While the probability at the start is poor, the feasibility is increasing with progress of exploration, although a conclusive assertion to which extent a potential HDR reservoir can be utilized, can be done only after extended flow tests with a pair of stimulated wells are completed. Until this point in time, the risk for the project to fail is big, and there is already substantial investments needed prior to reaching the milestone “Proof of Concept”.[166]

[165] McVeigh, J. et al: Preliminary Technical Risk Analysis for the Geothermal Technologies Program, Technical Report NREL/TP-640-41156. NREL National Renewable Energy Laboratory, 2007.

[166] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

Table 5: Rough Cost Estimate until Milestone "Proof of Concept" reached[167]

	M€		cumulative M€	
	min	max	min	max
Pre Drill Studies	0,05	0,30	0,05	0,30
Shallow Drilling	0,15	1,75	0,20	2,05
Deep Drilling	3,50	8,70	3,70	10,75
Frac 1st Well	0,60	1,20	4,30	11,95
2nd Deep Well	3,50	8,70	7,80	20,65
Frac 2nd Deep Well	0,60	1,20	8,40	21,85
Extended Flow Test	0,60	1,20	9,00	23,05
TOTAL PROOF OF CONCEPT	**9,00**	**23,05**	**9,00**	**23,05**



7.1.1.2 Seismic Risk

The seismic risk involved in the creation of a HDR reservoir came into public awareness in December 2006 during the Deep Heat Mining Project in Basel / Switzerland. During hydraulic stimulation of a well in a depth of around 5.000 m, earthquakes occurred that were felt at the surface with a magnitude of 3,4 acc. Richter. Aftershocks at an almost equal magnitude even happened weeks after the hydraulic stimulation was abandoned. Due to this incident, the whole project had to be ceased. As measurements and analysis have shown in Basel and also at other locations, it is obvious that frac fluid pressure and amount of fluid alone do not necessarily lead to earthquakes, but also time is of essence, in which the suggested amount of fluid is injected, as well as other influencing issues.

Today the qualitative correlation is understood, but not the quantitative influence to seismicity of pressure, fluid flow, total fluid volume, rock properties, rock stress and consequentially the probability and the magnitude of any potentially resulting seismic event. Development projects in nearly unpopulated areas, like the one in the

[167] Goldstein, Barry A. and Hill, Tony: Presentation: Australia´s Update to the IEA´s GIA Executive Committee April 2008. Australian Geothermal Energy Group, 2008.

Cooper Basin / Australia, where there is least risk of destruction and injuries or even fatalities, could help to further investigate these correlations with seismicity.[168]

7.1.1.3 Refusal of Technology by local Population

Due to induced seismic during stimulation and incidents that already happened as the one in Basel in December 2006, there is a risk that local population and other stakeholder, such as local authority forms a protest movement and consequentially refuses the technology involved in HDR, where artificial flow paths are created deep under the surface. This can lead even to abortion of a development project. It is recommended to involve and educate all possible stakeholders well ahead of any stimulation.[169]

7.1.1.4 Risk of Short Circuits and Water Loss

When a well is subject of hydraulic stimulation, risk exists that predominant existing fractures take most of the fracture fluid and will be stimulated more than other preexisting fissures. This consequentially leads to short circuiting through the over stimulated preferred water ways which causes rapid temperature drawdown of the reservoir and inefficient as well as incomplete energy extraction of energy from the targeted rock mass.

Another risk involved is that if a fracture system grows during production in an uncontrolled manner, this can lead to water losses due to the fact that the newly created fractures take fluid, although they do not contribute to the heat extraction as they are possibly out of the flow circuit from injection well through reservoir and back to the surface through the production wells.[170]

7.1.2 Country related Risks in Turkey

Due to the fact that Turkey is used already to geothermal projects, no additional risk specifically coming along with HDR technology in Turkey was identified.

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[168] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

[169] Kohl, T. et al: ENGINE Coordination Action: Best Practice Handbook for the development of Unconventional Geothermal Resources with a focus on Enhanced Geothermal System. Orleans BRGM Editions, 2010.

[170] Cooper, G. T. and Beardsmore, G. R.: Geothermal Systems Assessment: understanding risks in geothermal exploration in Australia. PESA Eastern Australasian Basins Symposium III, 2008.

7.2 Chances of Success

7.2.1 Chances related to Technology

7.2.1.1 Base Load Power

One of the major chances related with HDR power plants is, contrary to any other renewable energy source, that it is available independent of daytime, season, climatic condition and weather. Further this technology can be applied virtually everywhere, which implies that electricity out of a HDR reservoir can be produced locally which leads to short distances to feed in points into the grid, reduced transmission losses and high supply security as it is not dependent on political sensitive regions in the world as this is obvious for oil and gas. These aspects together with the possibility to easily control a HDR power plant in capacity, makes the technology an excellent candidate for substituting currently existing base load power plants running on fossil fuels or nuclear.[171]

7.2.1.2 Environmental Friendly, nearly free of CO_2 and other emissions

HDR power plants, like all other geothermal power plants are considered an environmental friendly technology. The low emission of noise in relation to noise emissions of equally sized fossil fueled power plants and the small footprint in relation to other power plants, especially other renewable based power plants as wind power and photovoltaic plants, is an advantage. Further due to the fact that there is no combustion engaged in geothermal power plants in general, keep the emissions of NO_x, SO_2, particulate matters and CO_2 very low or even at cero.[172]

7.2.1.3 Sustainability

Due to the fact that geothermal resources are much bigger than the need, it is considered as sustainable and consequentially the utilization of geothermal energy does not lead to a shortage for future generations. There will be a local cooling of a

[171] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.
[172] Kagel, Alyssa et al: A Guide to Geothermal Energy and the Environment. Geothermal Energy Association, 2007.

reservoir due to exploitation of geothermal energy, but the reservoir will reheat after the energy extraction is ceased.[173]

7.2.2 Chances related to Turkey

As Turkey is one of OMV´s identified core markets, the country is used to geothermal projects, the evidence of favorable conditions for geothermal projects as high temperature gradient and also the rapidly growing economy and consequentially the growing demand of energy, Turkey seems to be a good starting point for OMV to step into the geothermal business and to develop skills to successfully launch a first HDR project within the OMV Group.

7.3 Assessment of Strengths and Weaknesses of OMV

7.3.1 Strengths

The Exploration and Production part of the oil and gas business, which is the core activity of OMV, has a very similar approach as it is for HDR and geothermal projects in general. When an oil or gas reservoir is developed, at first the activity starts with studies and modeling as well as evaluation of existing data and information. In a further step, the target area is to be explored, which mainly consists of a 3D seismic survey and the drilling of exploration wells that are further analyzed. As long as the evaluation of the data collected as described shows promising results, production wells are drilled and completed according to the defined lifting methodology. Further a surface gathering station is constructed to collect the produced fluid. Depending on the productivity of the wells, chemical stimulation and or hydraulic fracturing are applied for improvement.

Although the majority of the field works involved in the development of OMV´s oil and gas fields are performed with contracted labor and equipment, OMV has the know-how involved in the disciplines described before, and is planning, designing, supervising and evaluating each the steps involved. These OMV internal competence centers include the faculties seismic surveys, geology, drilling, completion, reservoir management, well stimulation such as chemical stimulation and hydraulic fracturing. As this OMV internal expert knowledge can be applied to

[173] Häring, Markus O.: Geothermische Stromproduktion aus Enhanced Geothermal Systems (EGS), Stand der Technik. Geothermal Explorers Ltd. per order of EWZ (Elektrizitätswerk der Stadt Zürich), 2007.

HDR and the development of a power generating HDR project as well, this is an essential asset of OMV.
Further strengths are the strong financial position of OMV and consequentially the capability to realize projects in the magnitude of hundreds of million Euro, as well as the fact that OMV is a well-known company in Turkey with a good reputation due the engagement in Petrol Ofisi and the current market entry into the Turkish power generating world through the currently ongoing construction of the gas power plant in Samsun.[174]

7.3.2 Weaknesses

Although OMV has a major portion of the required know how in house, the capacity in these disciplines is very limited and there is no resources available to cover a possible market entry into HDR in Turkey on top of the currently ongoing business in oil and gas. In case that no additional capacity is built up, it could lead to a conflicting situation of allocating the available resources to oil and gas or to geothermal.
A further weakness of OMV is the lack of experience in realizing a geothermal power plant, as this was not done before on projects in noteworthy size, and especially was no HDR project developed by OMV ever before. There is also very limited experience in the Turkish power market. Although OMV´s first power plant in Samsun, Turkey had its start of construction in the year 2010, it is not supplying power to the grid yet.[175]

[174] Brunner, Walter: Expert Interview held on 28.06.2012.
[175] Brunner, Walter: Expert Interview held on 28.06.2012.

7.4 SWOT Matrix

As a result of the evaluation of the value creation chain as per chapter 2.8 – Value Creation Chain of a HDR based Power Plant and the opportunities and threads involved in the technology and the country, as well as the OMV internal strengths and weaknesses, the SWOT matrix below is concluded, whereat the highlighted items are on top of the strengths, weaknesses, opportunities and threads of a conventional geothermal project in Turkey:

Table 6: SWOT Matrix

	STRENGTHS	WEAKNESSES
OMV INTERNAL ORIGIN	• E&P know how and skills involved in developing HDR projects are available • Strong financial position; economic capability to realize HDR project • OMV is well-known on Turkish market; good reputation	• Lack of capacity in E&P disciplines required to develop a HDR project • No experience in realizing HDR projects • Limited experience in Turkish power market
	OPPORTUNITIES	**THREATS**
EXTERNAL ORIGIN (HDR, TURKEY)	• Engagement in new power generating technology from beginning can lead to technology leadership • Technology (HDR) portable to other regions on the globe • Environmental friendly, sustainable base load power • Turkey is good starting point for OMV to develop geothermal, EGS and further HDR skills and experience	• High investment cost before "proof of concept" • High exploration risk • Risk of induced earthquakes during hydraulic stimulation • Risk of refusal of technology by local population • Possible short cuts and consequentially inefficient heat mining • No long term commercial HDR project realized to date

8 Conclusions

Hot Dry Rock is a technology utilizing geothermal energy, which may be at the beginning of a possible widespread commercial use and it potentially might play a major role in the future global energy supply.

Based on the statement above, the Thesis started out with a definition of HDR Technology and an introduction of geothermal energy generation including a classification of geothermal resources. Moreover the basic conditions of Hot Dry Rock technology and the relevant technical framework have been given. Special attention was dedicated on characterizing HDR thermal energy resources and energy recovery from such a resource. This was followed by practical guidance on creation of a HDR reservoir. Based on an overview of realized projects and lessons learned for future HDR applications have been drawn. In addition possible avenues for future development of HDR have been shown.

Moreover Turkey was introduced as a possible location for geothermal projects, also giving an insight into the constitutional, the political and economic setting. In particular an overview of the energy sector in Turkey was provided delineating the current status of electricity, oil & gas and coal, but also focused on the future development. Furthermore geothermal electricity generation was described on a global base and for Turkey in particular. Realized geothermal power generation projects in Turkey have been described and geothermal fields suitable for electricity generation in the future have been identified. The relevant legal framework in Turkey was introduced as well.

The next chapter focused on the strategic fit of HDR in Turkey with OMV. In particular the possible leverage of core competences has been shown as well as insights of economics.

Last, a SWOT analysis was performed drawing on previous chapters.

The key findings of this study are that first of all HDR is a technology that still is in its infancy although it seems to be a controllable technology. In particular the currently ongoing project in the Cooper Basin / Australia might justify this expectation in the near future. In addition ongoing research and development programs, especially in drilling and exploration techniques, may lead to significant cost and risk reduction, to make such HDR projects more economic. However it must be clearly pointed out

that from today’s point of view substantial risks are involved, in particular the high level of upfront investment and the high exploration risk as such.
As regards to Turkey it is concluded that it is suitable for HDR projects, due to the favorable geological conditions, in particular the high temperature gradient, but also the growing energy demand. Moreover, this is substantiated by the fact that geothermal projects in general have also been realized in the past and that the growth of geothermal energy in Turkey is amongst the highest in the world.
Referring to OMV in the context to HDR in Turkey it can be stated that OMV has relevant know how and skills originated from the conventional oil & gas business. However the required level of expertise and experience for HDR in particular is not available. Neither are there sufficient idle human resources currently available in house.
In addition it is concluded that geothermal (including HDR) will remain a niche market in the global energy supply, at least for the next 20 years. Moreover fossil energy carriers, in particular oil & gas will retain its significant share of primary energy, which is well above 50%. In absolute terms even the growth rate of geothermal energy compared to oil & gas is expected to be lower until 2035. Although geothermal projects in Turkey are likely to meet the required level of returns, the investment in oil & gas projects generates higher returns. Thus, it is concluded that any project in HDR may not be solely evaluated with economic considerations, but requires justification from a sustainability point of view.

Recommendations:

- Since geothermal projects may not solely be justified by economic considerations, a fundamental decision whether or not to pursuit this technology and to integrate it into OMV´s strategy must be taken by the management and shareholders of OMV.
- Based on the fact that HDR is the most complex and the least developed geothermal technology, it is recommended to make the initial step into geothermal energy generation with EGS rather than HDR.
- Moreover taking the available internal resources and level of geothermal related expertise into consideration it is recommended to enter Turkey with the geothermal business by looking for a suitable partner, having already experience from realized geothermal projects in Turkey as well as having a promising portfolio of geothermal licenses in Turkey for future development.

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Expert Interview

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Annexes

- Presentation Soultz Geothermie Melchert April 2012 OMV, held on April 27th, 2012 by Bernd Melchert
- Site Inspection Report for the site visits in Soultz-sous-Forêts / France, Insheim / Germany and Landau / Germany, on April 27th, 2012.

Das Geothermieprojekt Soultz -

- auf dem Weg zur Stromerzeugung

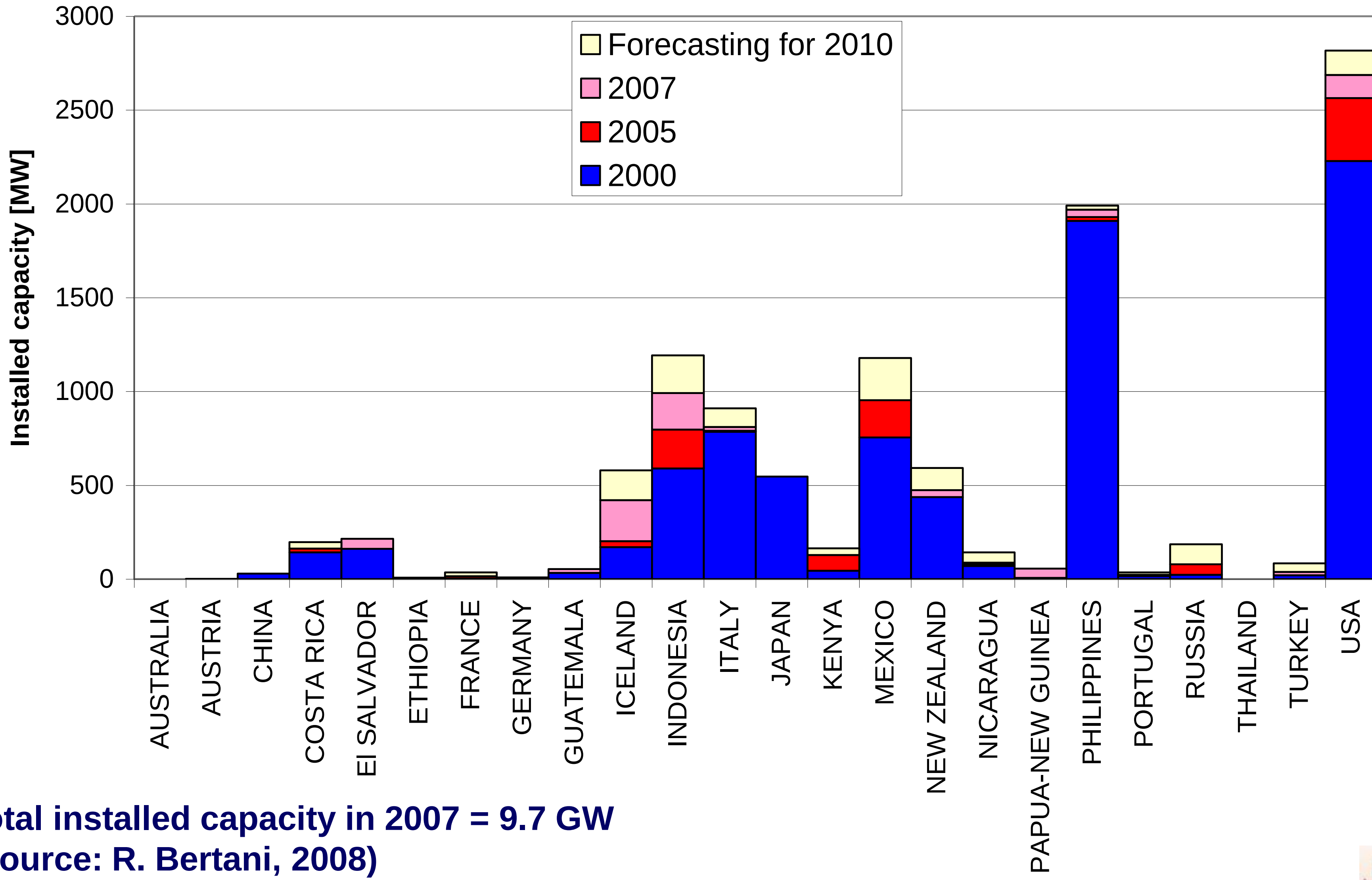
Das Konsortium

Private Finanzierung und Betrieb

Öffentliche Finanzierung

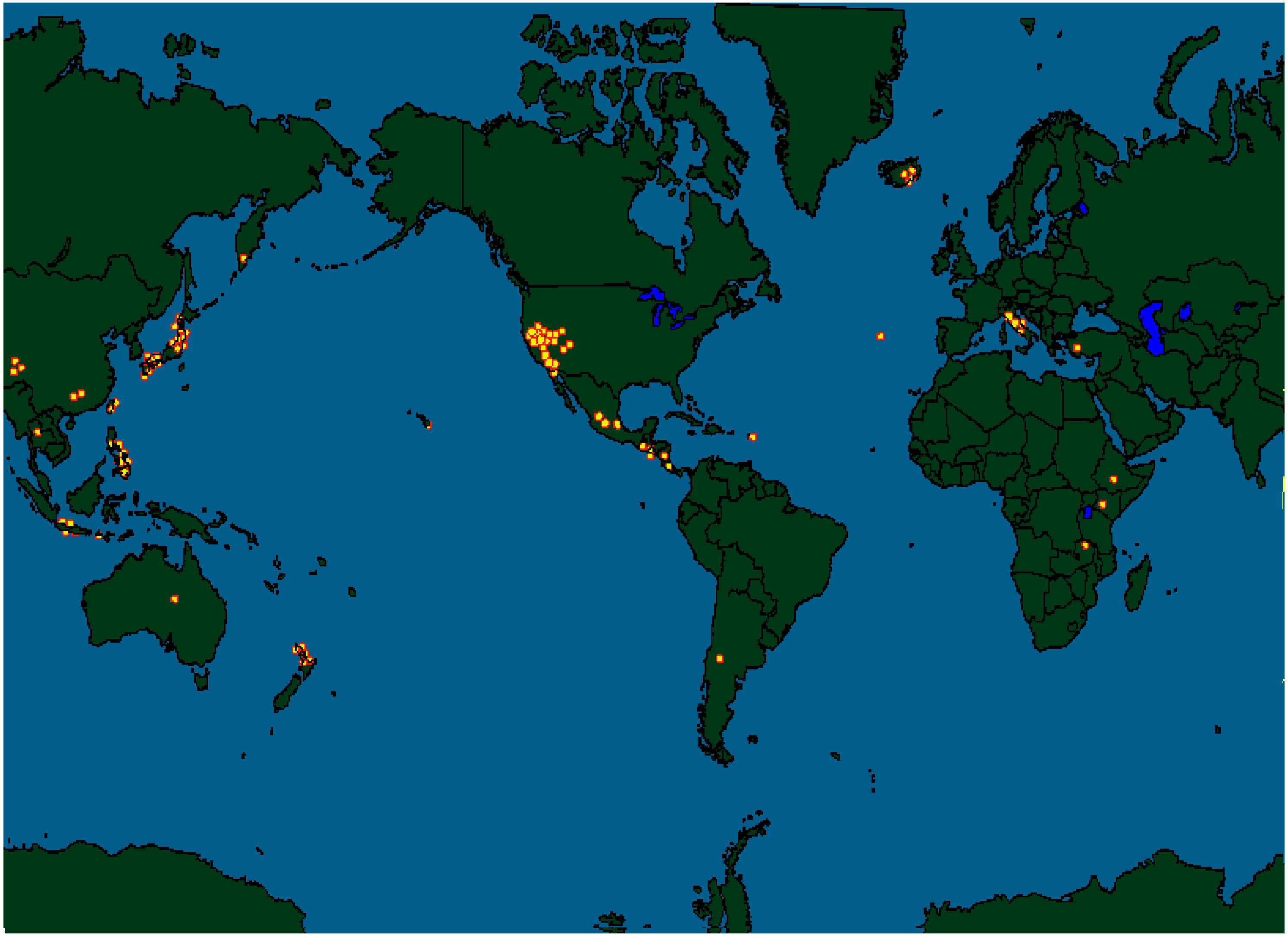
Wissenschaftliche Partner

Weltweite Nutzung der Geothermie



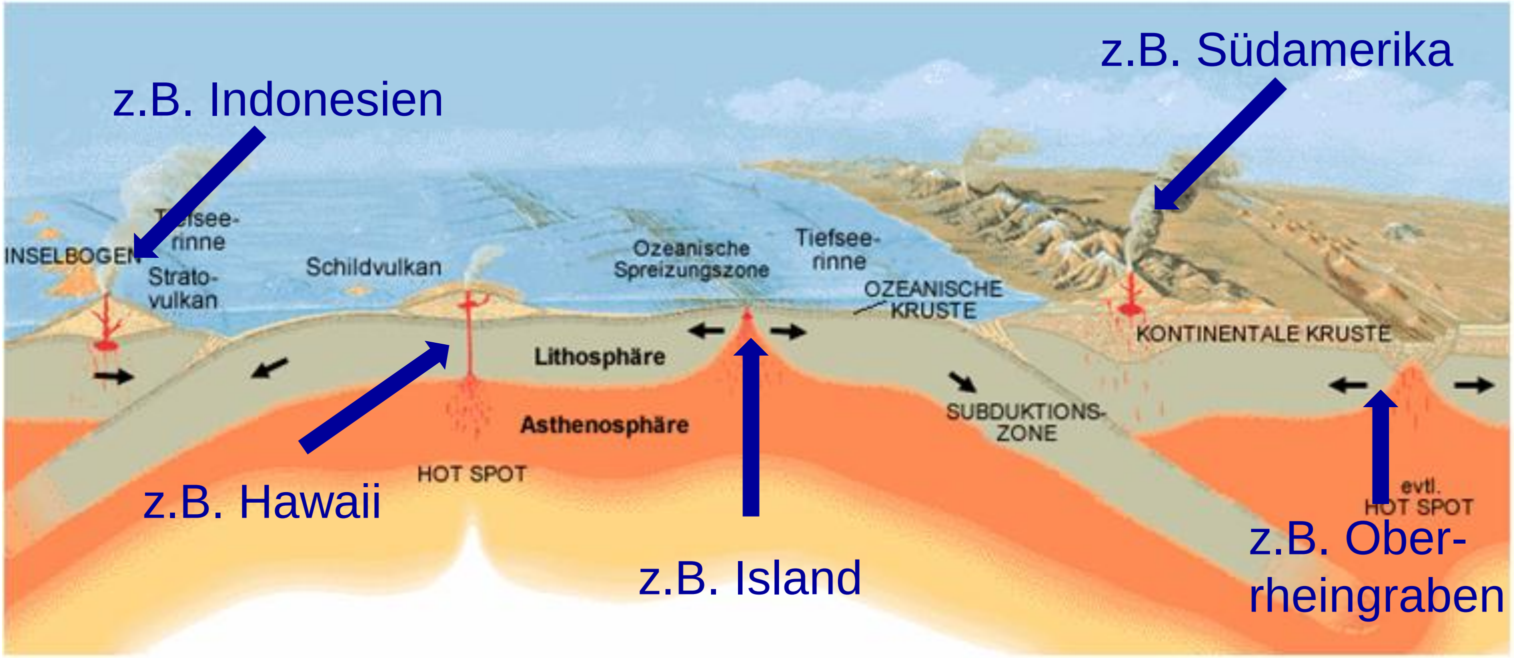
Total installed capacity in 2007 = 9.7 GW
(Source: R. Bertani, 2008)

Verteilung geothermaler Systeme



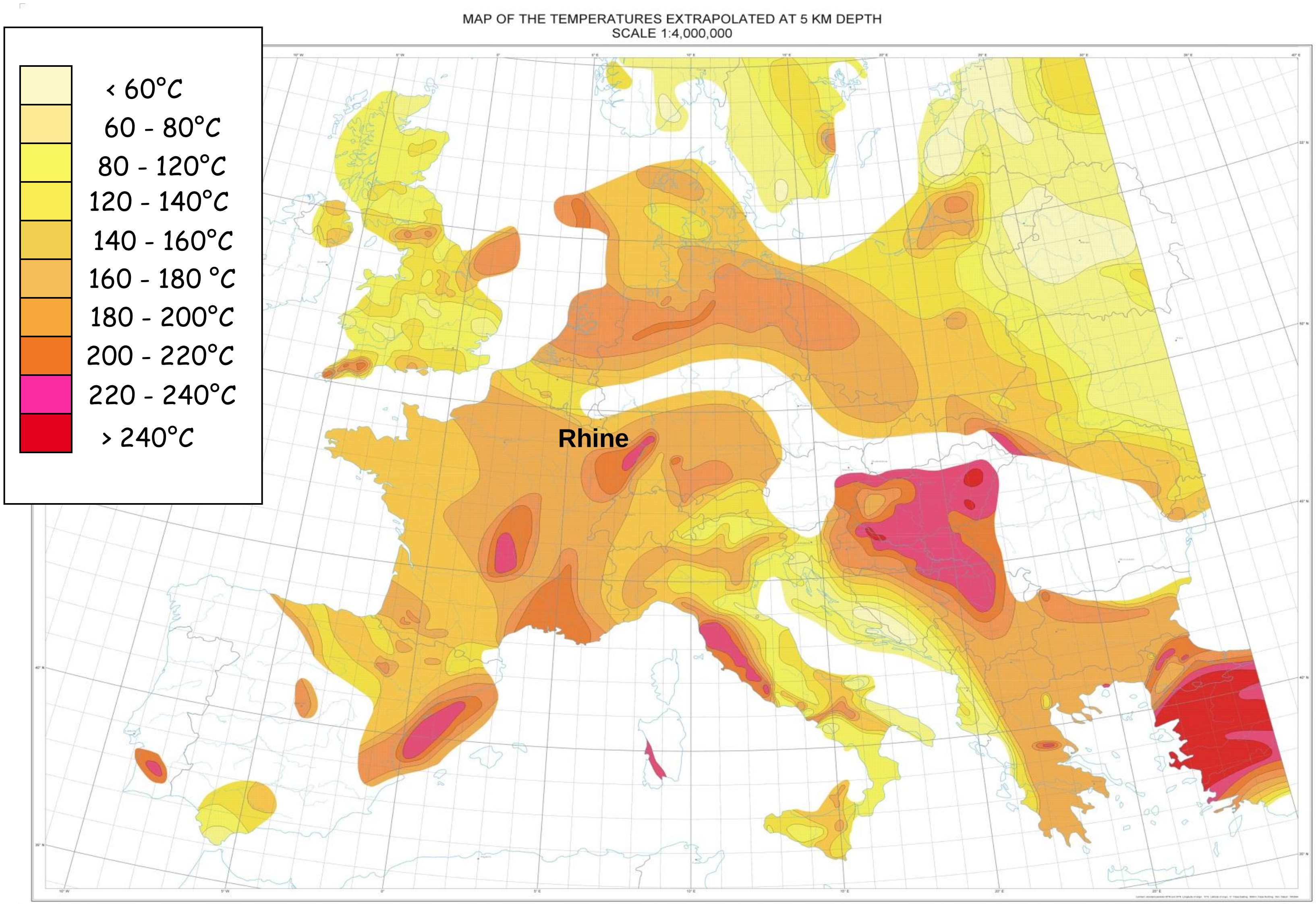
Mancherorts ist es heißer…

- sehr hohe Temperaturen an den Grenzen tektonischer Platten
- aber auch: Seismizität und Vulkantätigkeit besonders ausgeprägt



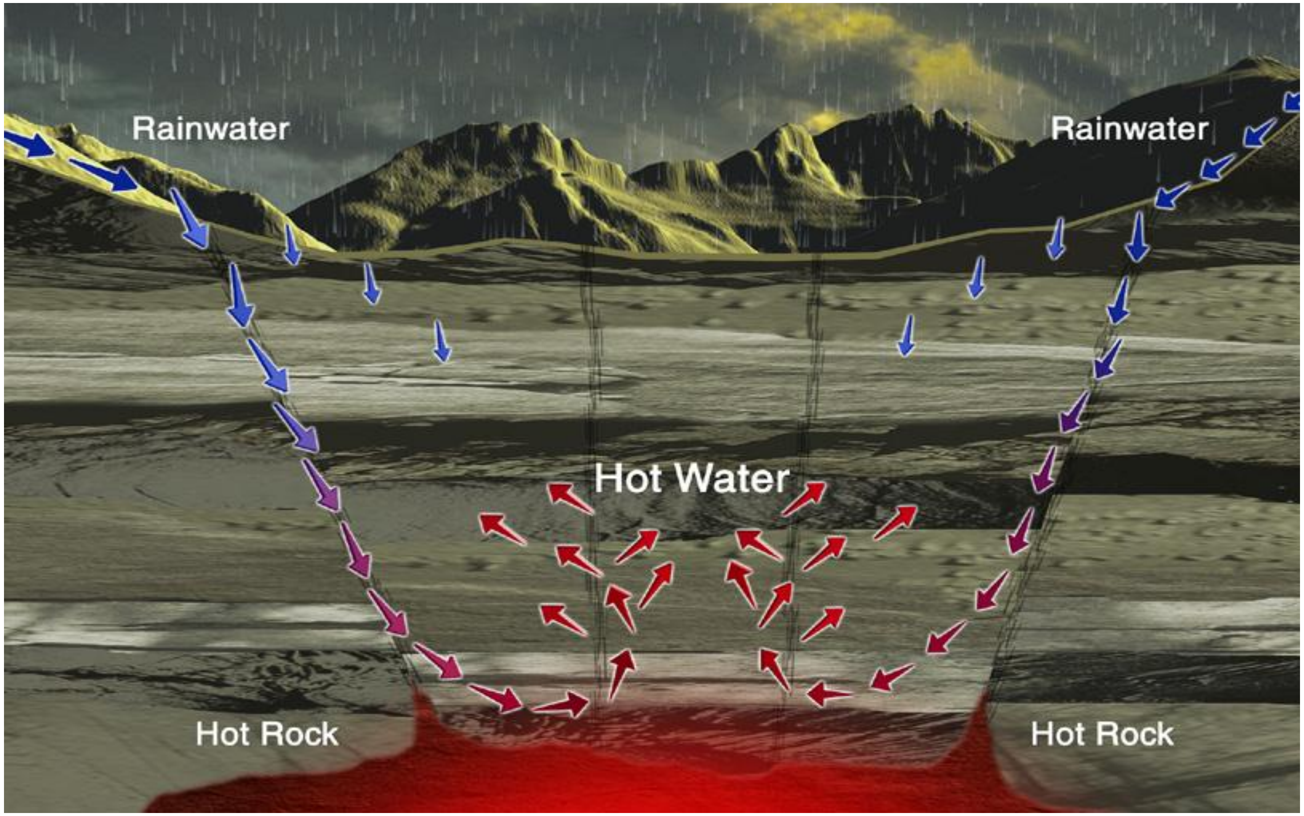
Quelle: US Geological Survey, 1999

Tiefen-Temperaturen in Europa



Géothermie Soultz

Geothermale Systeme



Geothermale Systeme bestehen aus:

Einer Wärmequelle

~~**Einem permeablen Kluftnetzwerk**~~

~~**Wärmetransportmedium, Thermalwasser**~~

Géothermie Soultz

EGS-Technologie (HDR, HFR, HWR)

Nutzung des natürlichen Riss- und Kluftsystems im heißem Tiefengestein

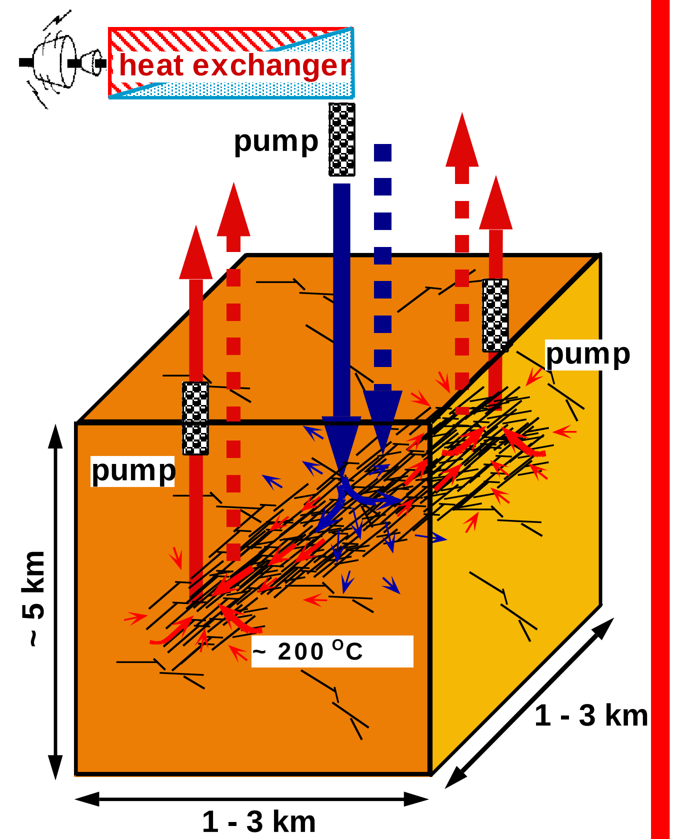
Erweitern des natürlichen Riss- und Kluftsystems durch Stimulation (Injektion von Wasser unter hohem Druck)

Ortung der Ausdehnung des unterirdischen Riss- und Kluftsystems durch Aufzeichnung der Mikroseismizität

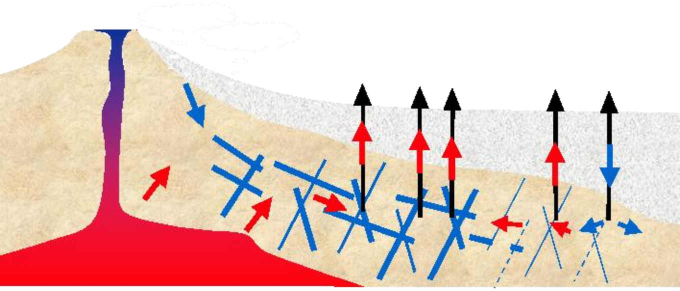
Installation eines Multi-Well-Systems und Verbindung der Bohrungen durch weitere Stimulationen

Durch den Einsatz von Injektions- und Tauchpumpen wird das Wasser gezwungen in einem geschlossenen Kreislauf an dem unterirdischen Wärmetauscher entlang zu strömen

Entnahme der Wärme des Tiefenwassers durch einen sekundär Kreislauf und Stromerzeugung



Geothermal offers a wide range of ressources



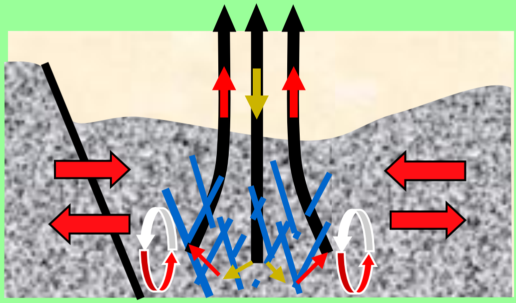
Hydrothermal Systems
Natural resources
Water & Steam

> 90% of the world wide activity

Enhanced Geothermal Systems

weniger permeabel,
schwieriger zu gewinnen

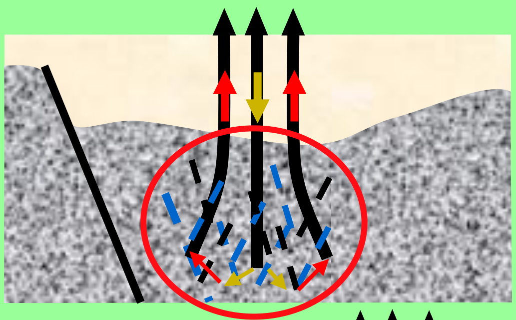
Only partly open hydraulic system, convection, fluid exchange with far field



HWR: Hot Wet Rock

Landau (D)

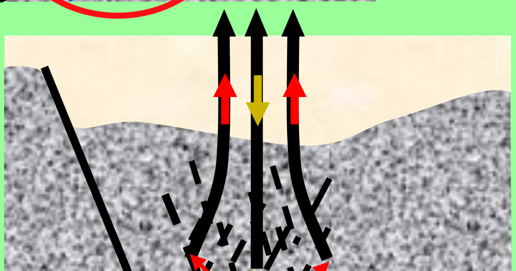
Fractured rock, contained hydraulic system !



HFR: Hot Fractured Rock

Soultz-sous-Forêts (F)

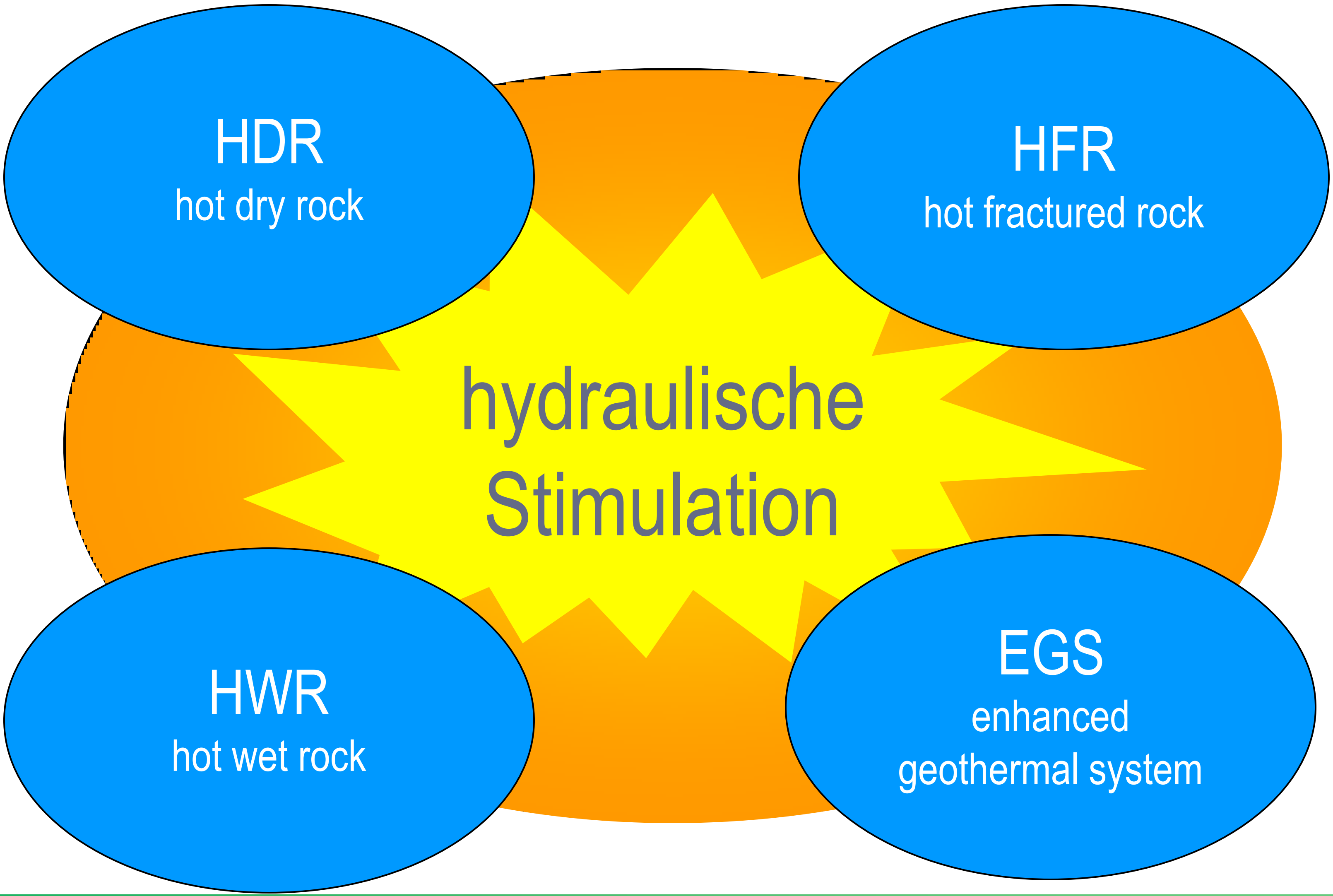
Tight rock, artificial fracture system



HDR: Hot Dry Rock

Los Alamos (USA)

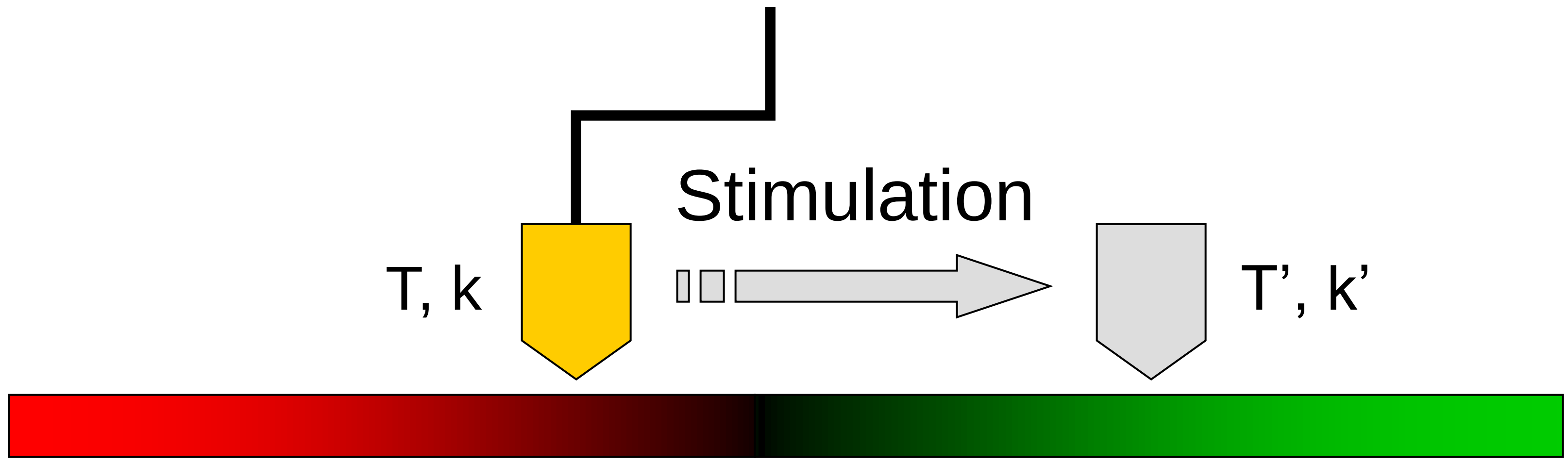
VIELE NAMEN FÜR EINE TECHNOLOGIE...



DIE SCHLÜSSELPARAMETER

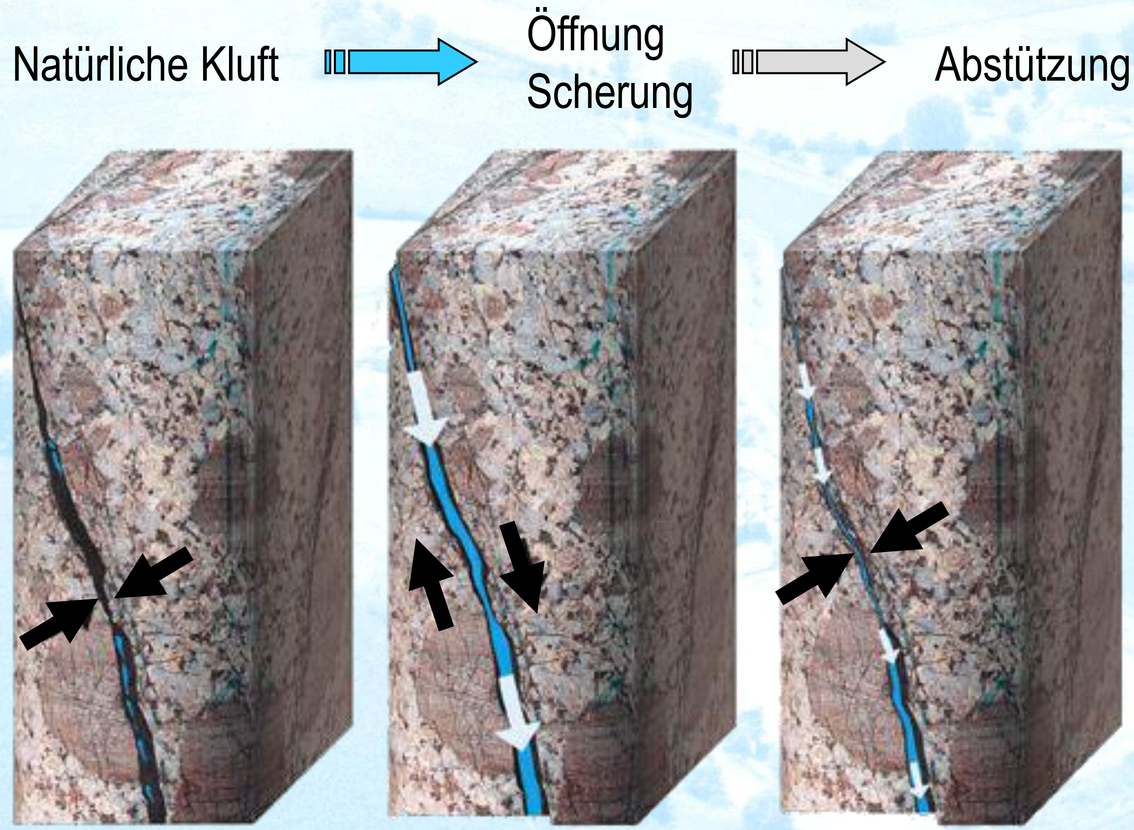
POTENTIELLES GEOTHERMISCHES RESERVOIR:

Temperatur T Permeabilität k



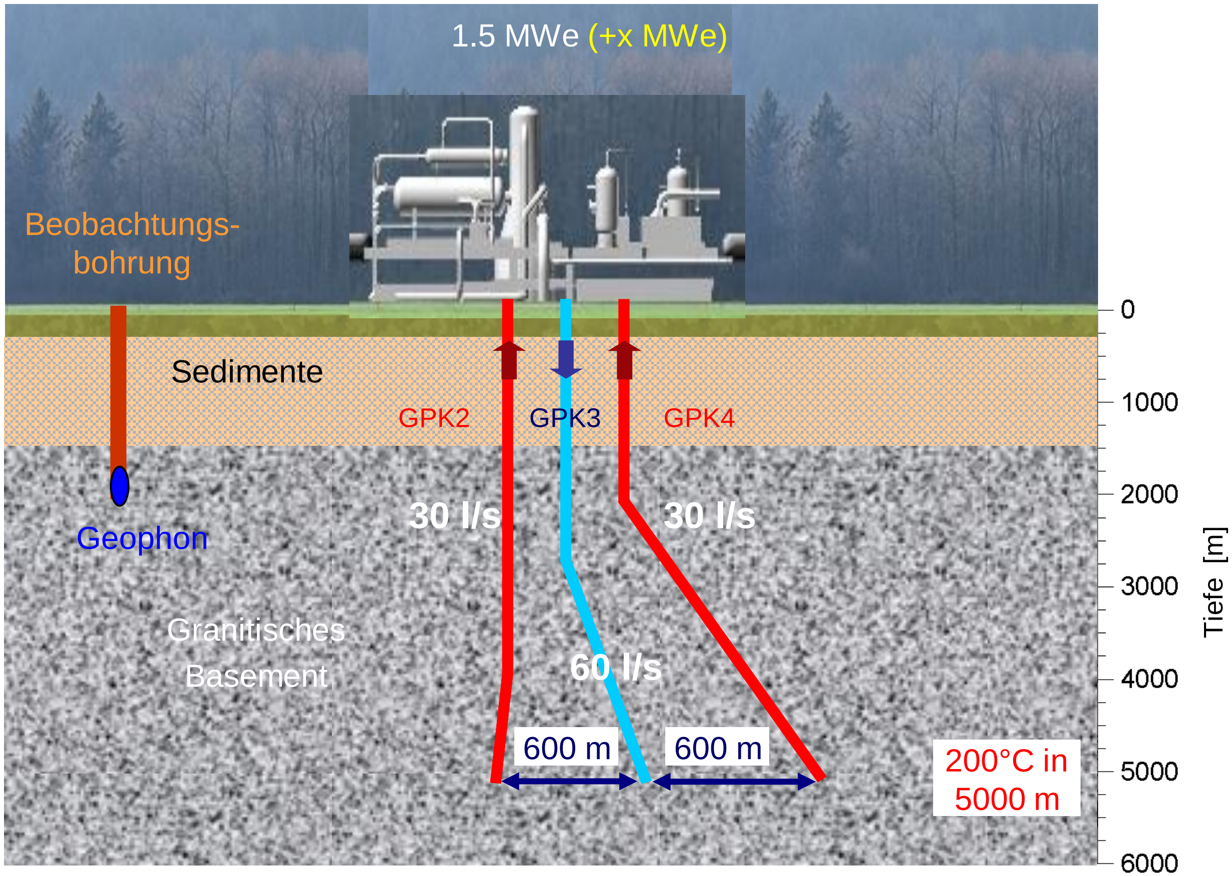
unwirtschaftlich wirtschaftlich

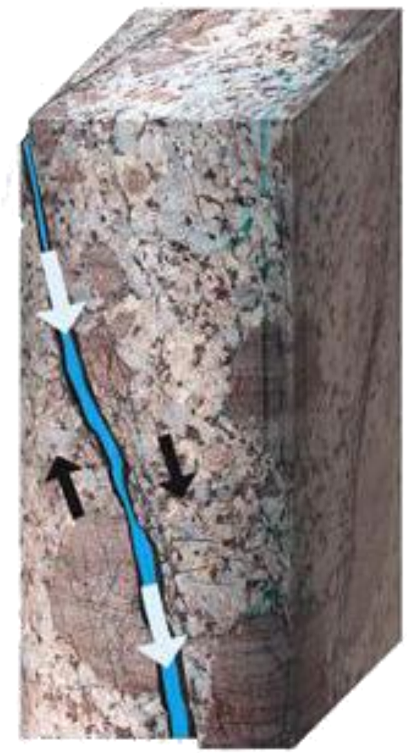
DAS KONZEPT – Stimulation / Erzeugung eines Wärmetauschers



Hydraulic Fracturing / Einpressen von Wasser unter Druck

Konzept





Errichtung einer wissenschaftliche und experimentellen Pilotanlage zur geothermischen Stromerzeugung aus kristallinen Formationen.
Großräumige Permeabilitätserhöhung durch Stimulation.

Förderungs-Phasen des Projektes

2001 Phase I 2005

Deep Drilling & Stimulation
29 Mio.€

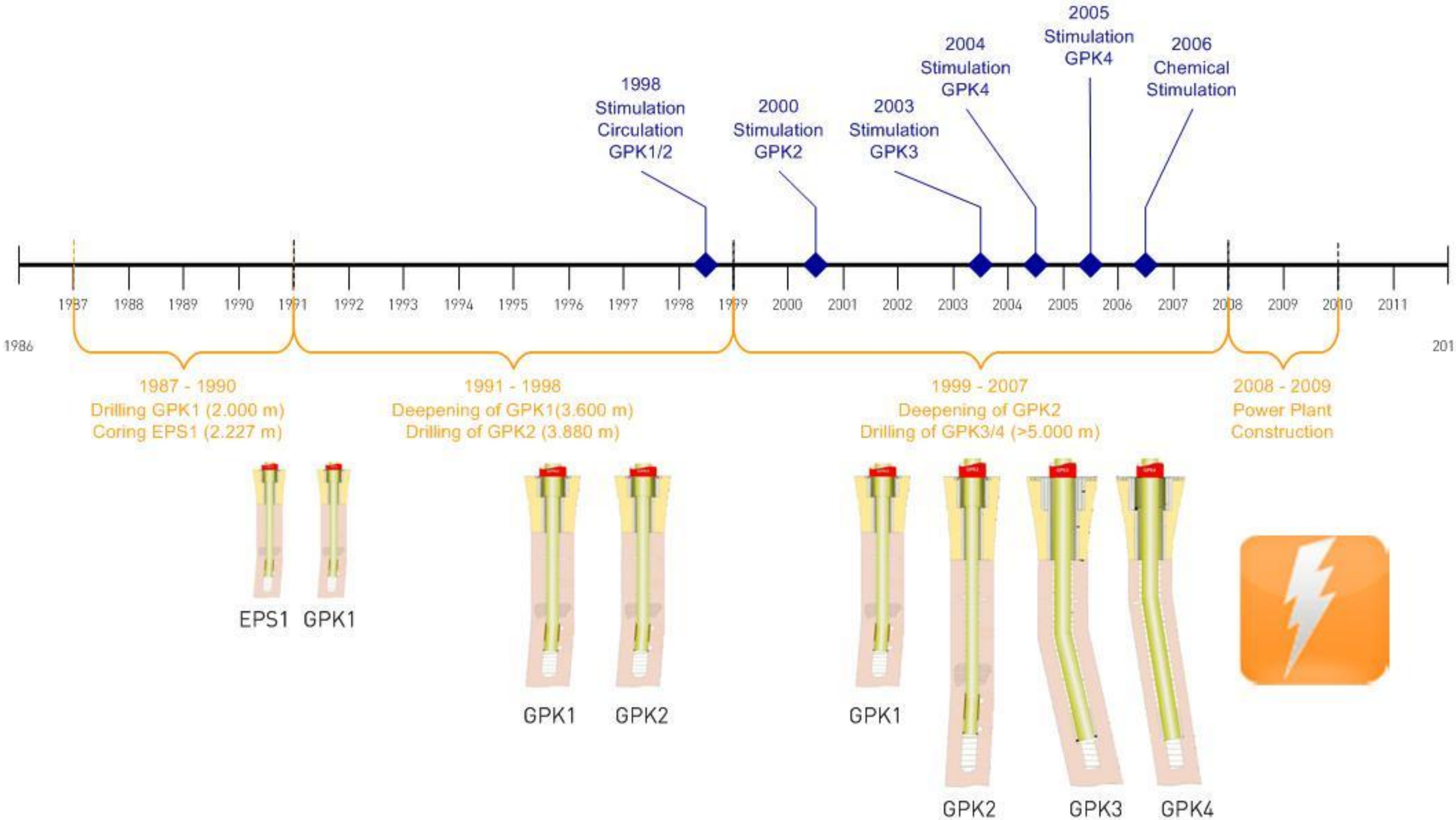
2004 Phase II 2009

Power plant construction
25 Mio.€

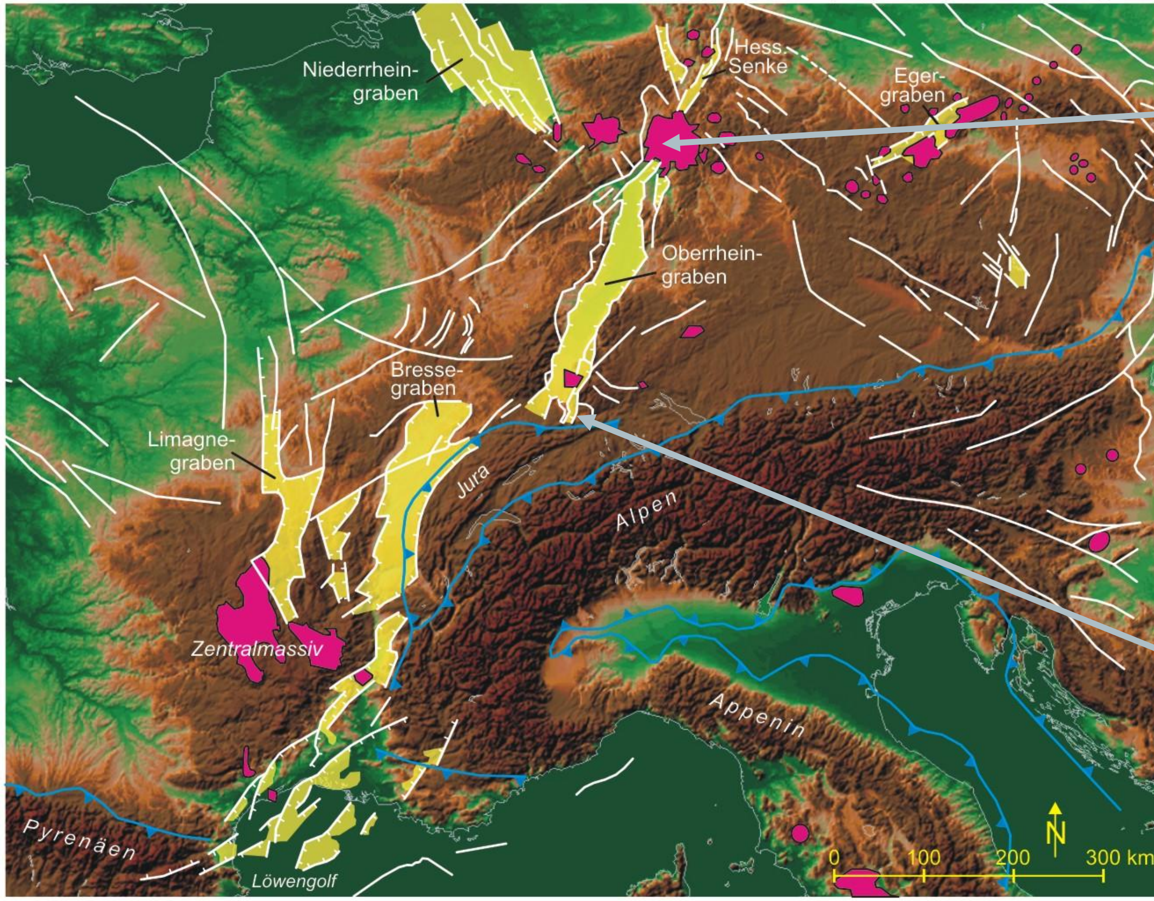
2010 Phase III 2012

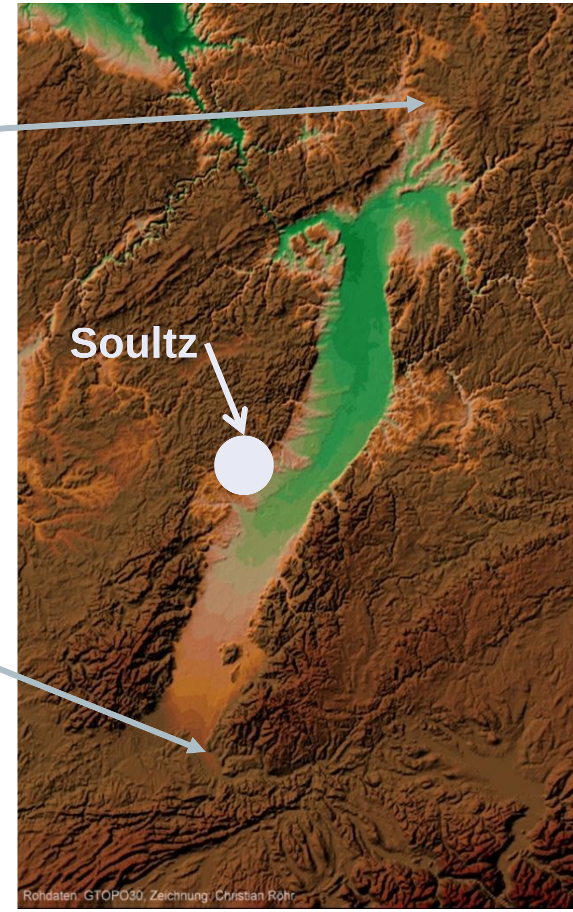
Scientific and Technical monitoring
5 Mio.€

Projektverlauf



Der Oberrheingraben



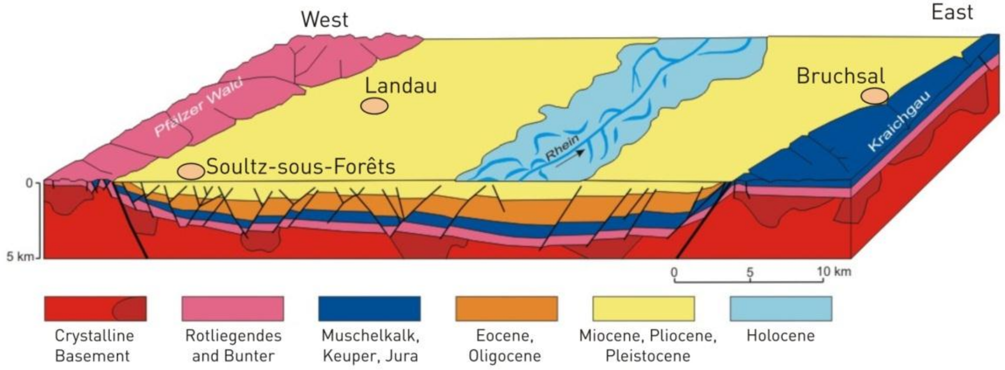


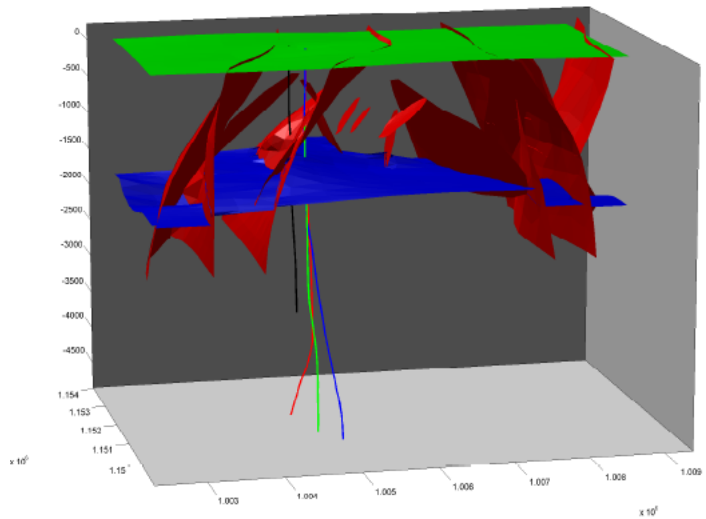
Topographie: GTOPO30

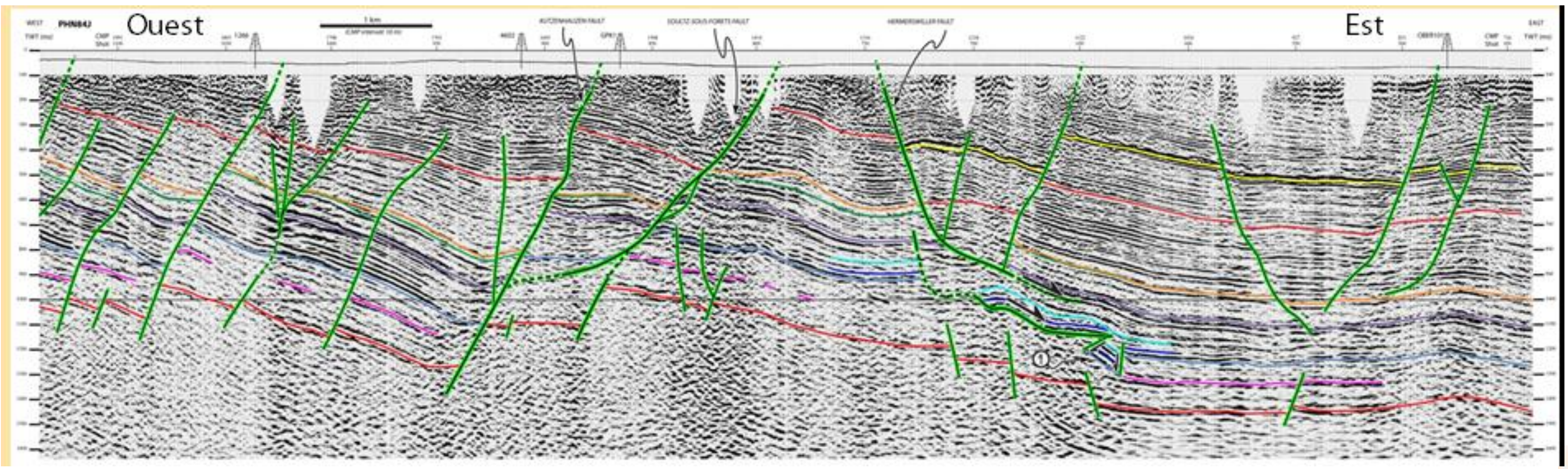
Ref.: Röhr, 2007

Cenezoic Faults | Cenezoic Sediment Basins | Cenezoic Volcanites | Alpine Faults

Der Oberrheingraben

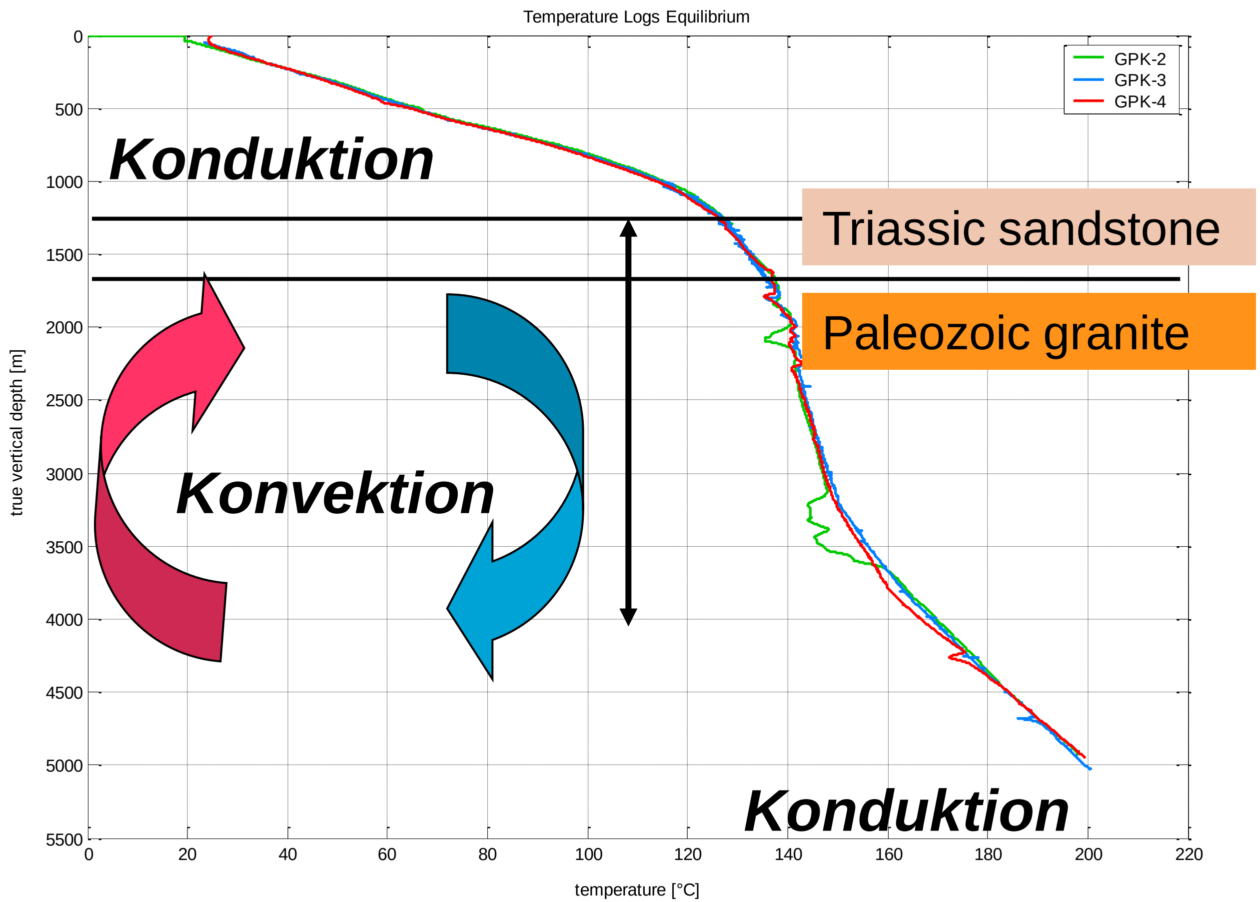






Thermal profiles in the Soultz wells

Fractured
Altered
Granite



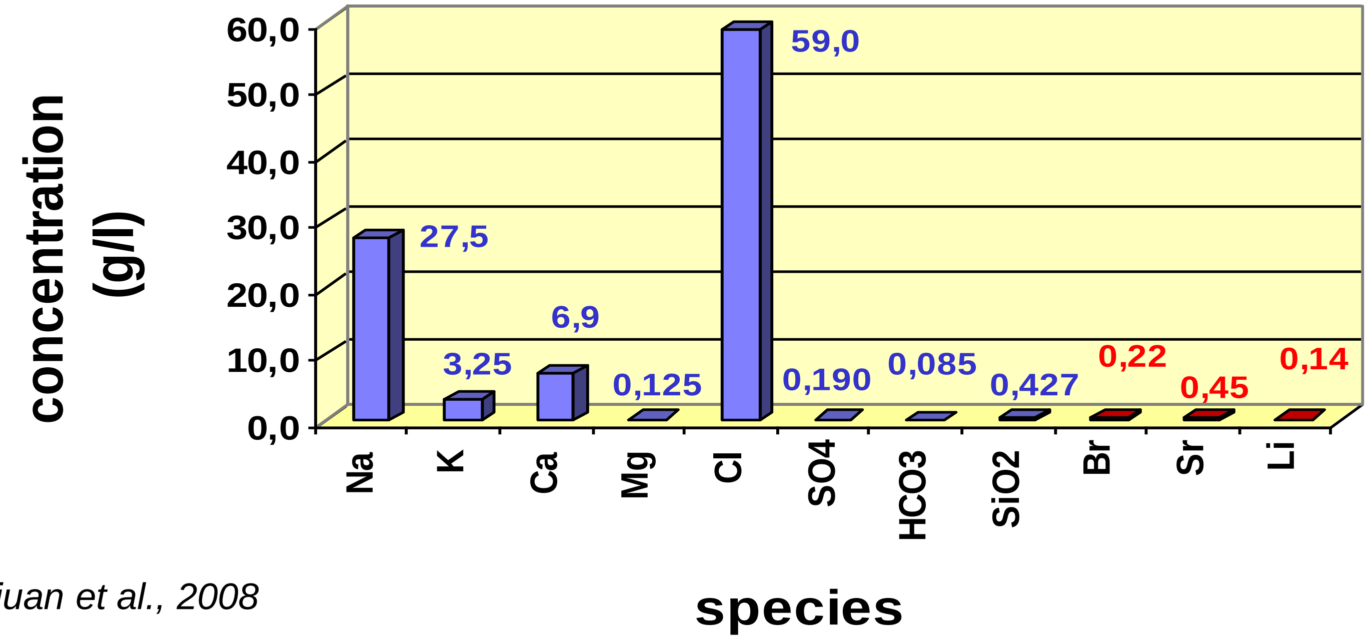
Fractured
Sandstone

Natürliche Zirkulation in hydrothermal alterierten und gestörten Zonen

-> Formationswasser mit 100 g TDS/l

NATIVE BRINE COMPOSITION

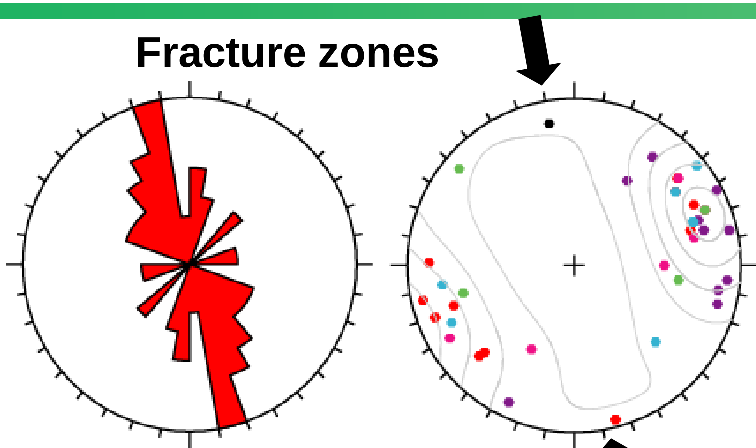
- Representative chemical composition: Na-Cl brine, pH ≈ 4.8-5.0
- TDS ≈ 97 g/l and density = 1.065 g/cm^3 (20° C)



Sanjuan et al., 2008

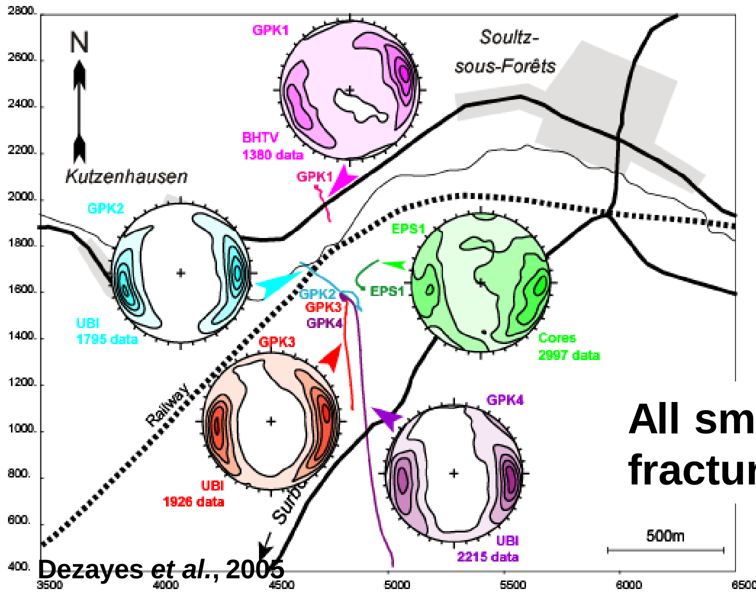
Orientierung der Störungszonen

Fracture zones



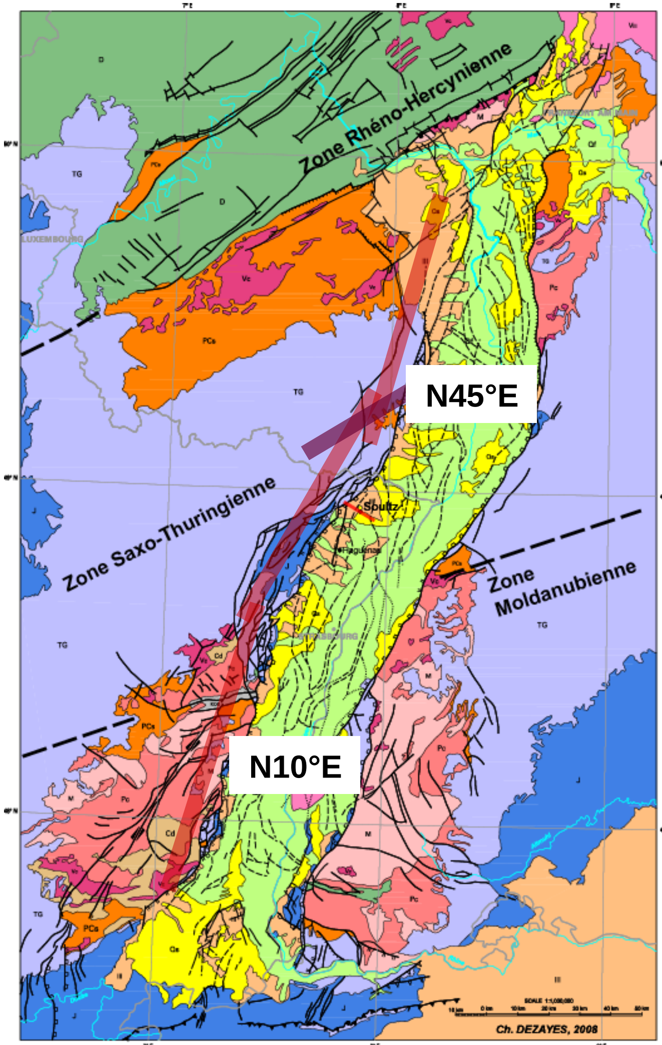
N160°E±10°

σ_H **N170°E**
(Klee & Rummel, 93)

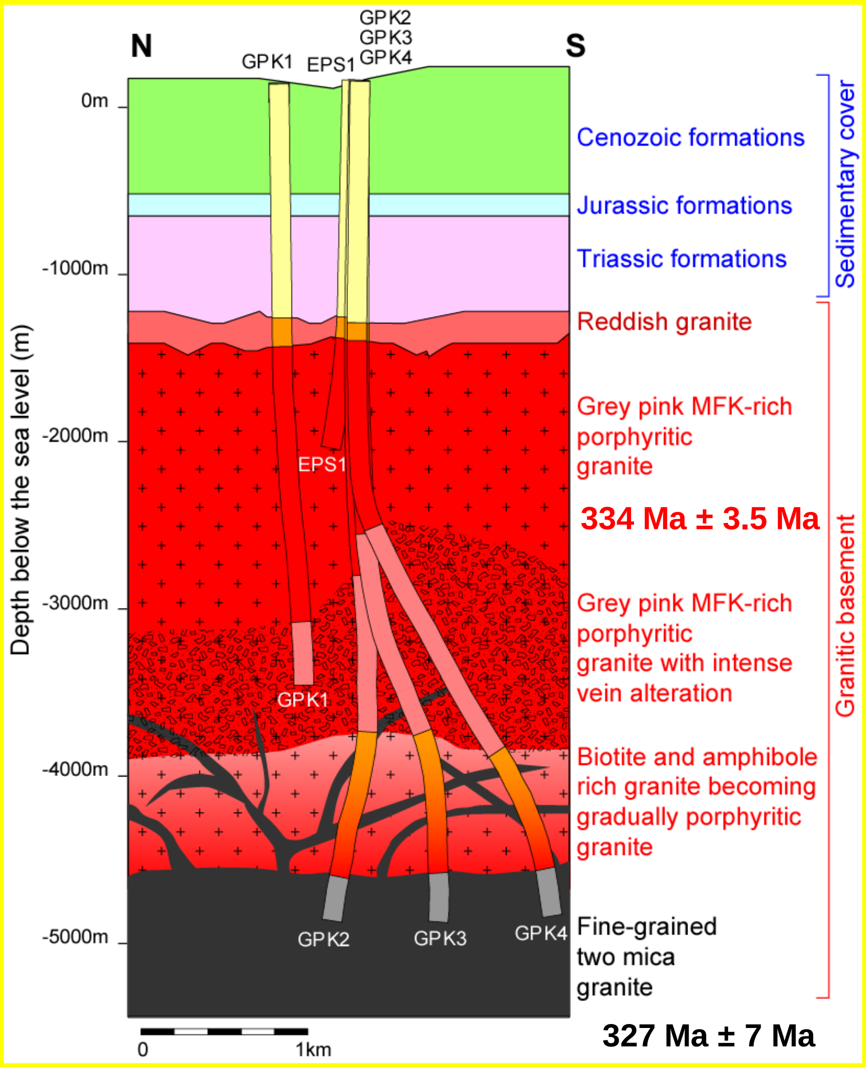


Dezayes *et al.*, 2005

All small-scale fractures



Synthetisches Geologisches Profil



Geologisches Modell Soultz

2 Kristallintypen

2-Glimmer Granit jünger und intrusiv

Zerklüftung und Alteration im tiefen Teil der Bohrungen

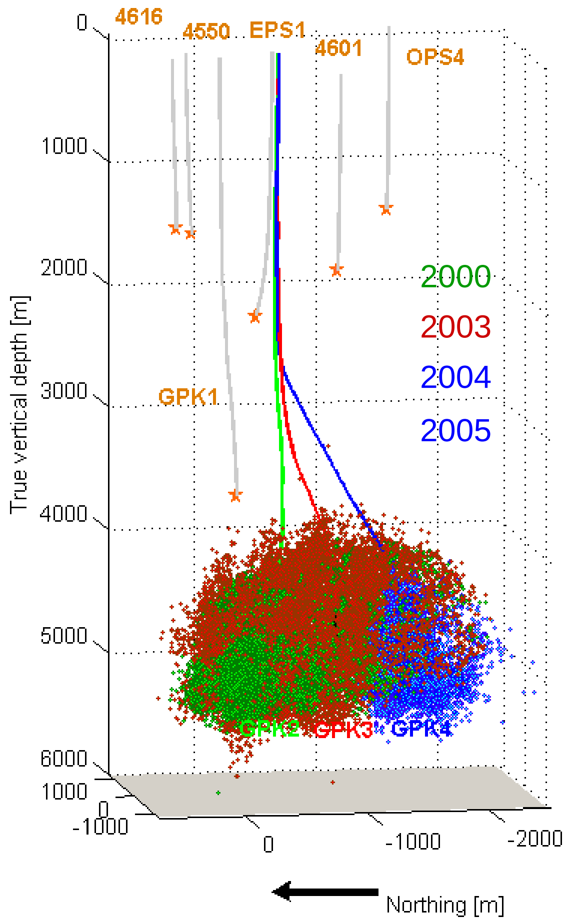
In alterierte Zonen ist Uran angereichert

‚Tiefes Reservoir‘

1999 – 2007

Triplette
GPK2/GPK3/GPK4
5000 m Tiefe

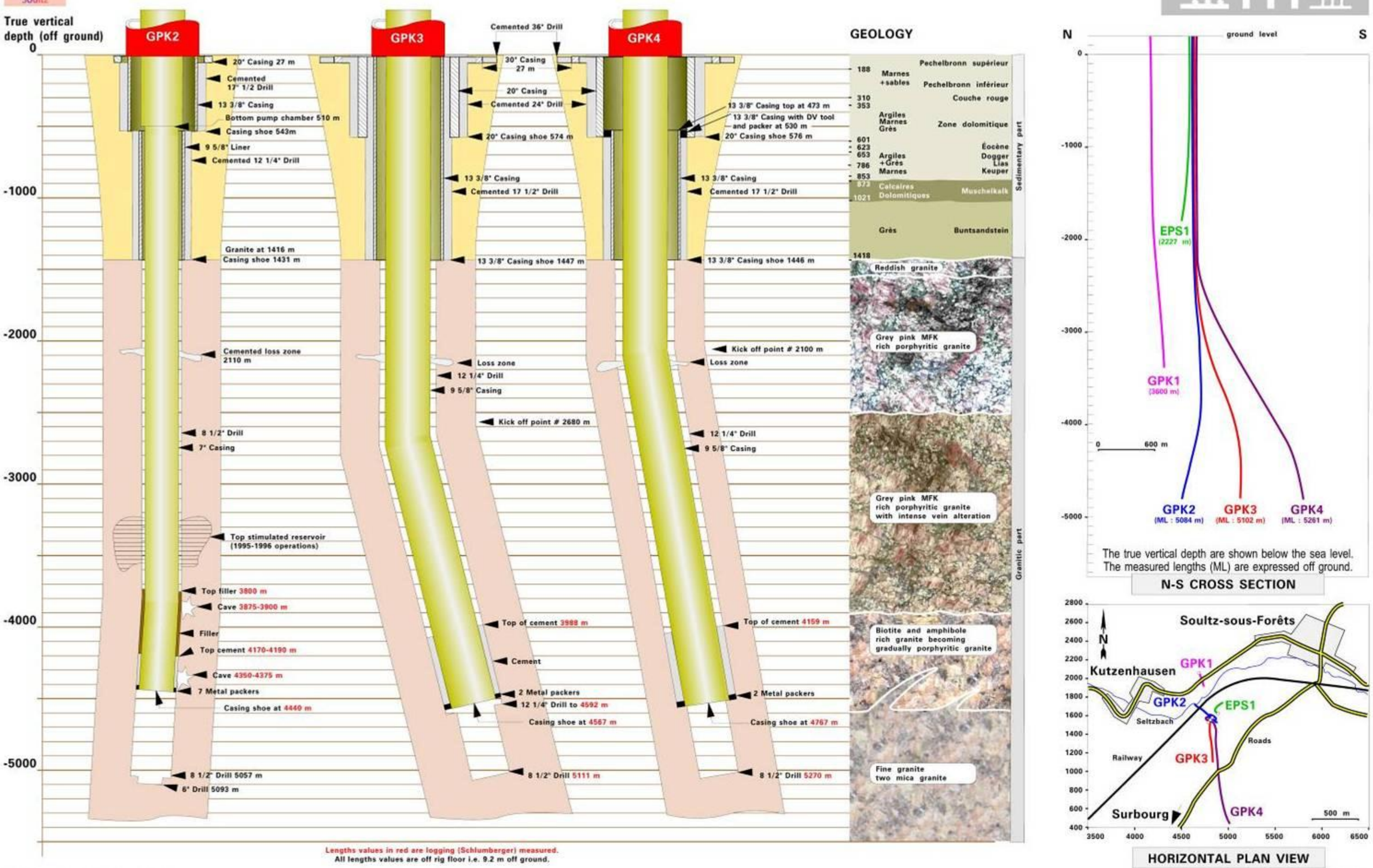
- Vertiefung GPK2 bis 5080 m Tiefe und Stimulation
- Bohren GPK3 bis 5100 m Tiefe und hydraulische Stimulation
- Bohren GPK4 bis 5270 m und hydraulische Stimulation
- Zirkulation zwischen GPK3 (Injektion), GPK2 und GPK4 (Produktion)
- Chemische Stimulation
- VSP-Kampagne zur Charakterisierung des Kluftnetzwerkes



Beobachtungen:
- bis zu 20-fache Erhöhung der Produktivität
- hauptsächlich Scherung auf Kluftflächen
- stimuliertes Volumen ca. 3 km³

Technische Entwicklungen:
- Bohrmeißel mit längeren Standzeiten
- Entwicklung von HT-Dichtungen
- ‚freie‘ Casings für extreme Temperatur-schwankungen
- Packer für Stressmessungen
- Prototypen von HT-Tools für bildgebende Logs

3 DEEP WELLS AT SOULTZ
SCHEMATIC VIEW

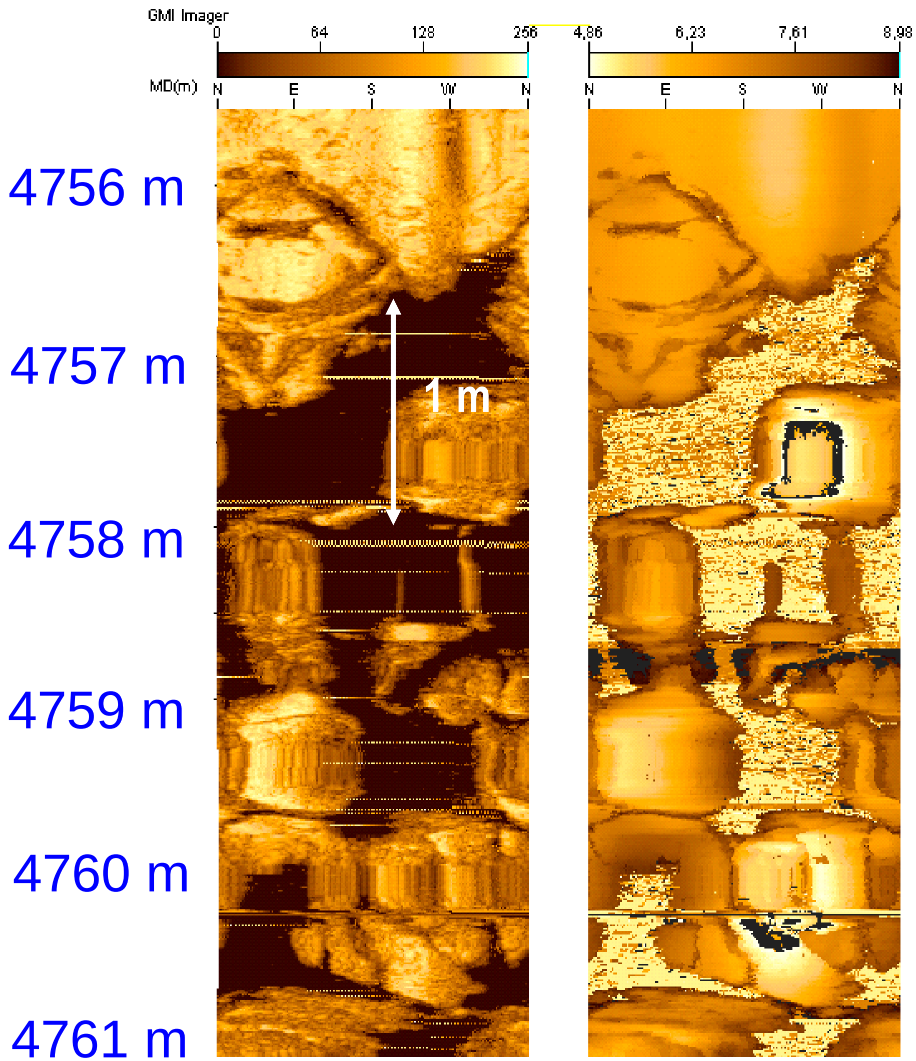


Réf. GJJ/AF - Réf. document : Mer0516.dsf - Mise à jour 14/12/2005

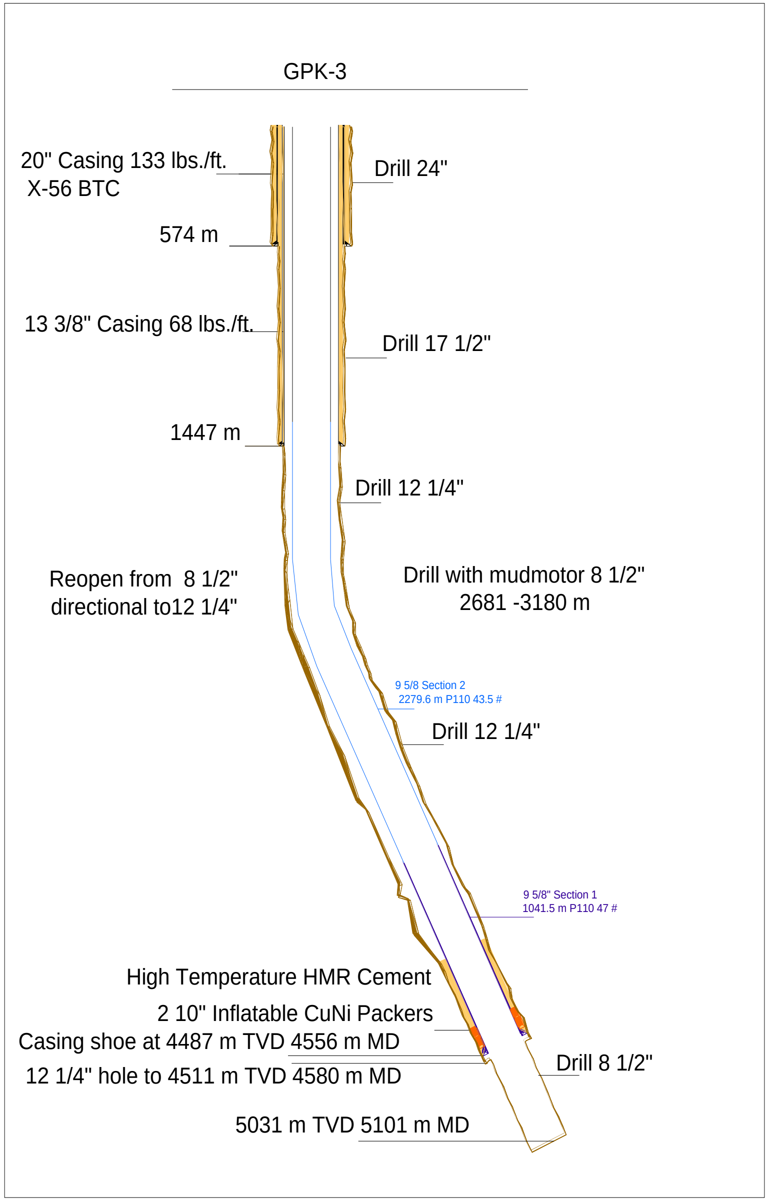
Beispiel für natürliche Störungen in 4700 m Tiefe

UBI-Log (accoustic borehole televiewer)

in GPK3:



Abteufen der zentralen Injektionsbohrung GPK3



24” Drilling, 20” Surface Casing, Cement

17 ½” Drilling, 13 3/8” Intermediate Casing, Cement

12 ¼” Drilling

Kick Off with 8 ½” DHM

Reopening from 8 ½” to 12 ¼”

12 ¼” Drilling

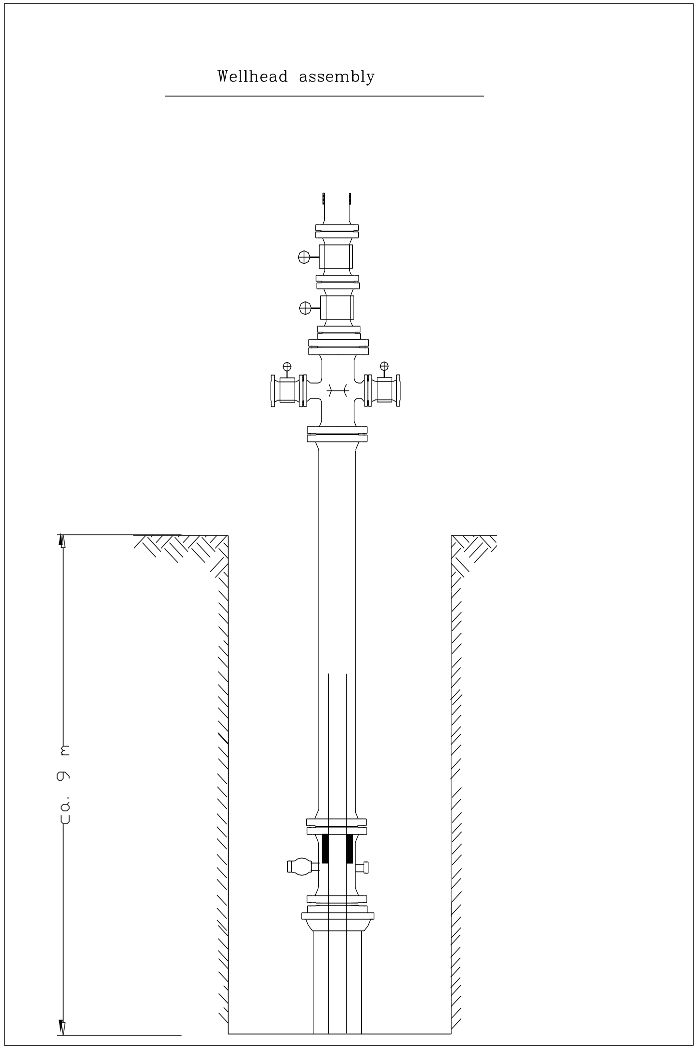
8 ½” Drilling, Sand

Set the ‘free’ 9 5/8” Casing, HMR-Cementation, Set CuNi Packers

Clean The Open Hole

Géothermie Soultz

Abdichtung des freien Casings am Wellhead



Valves

Riser

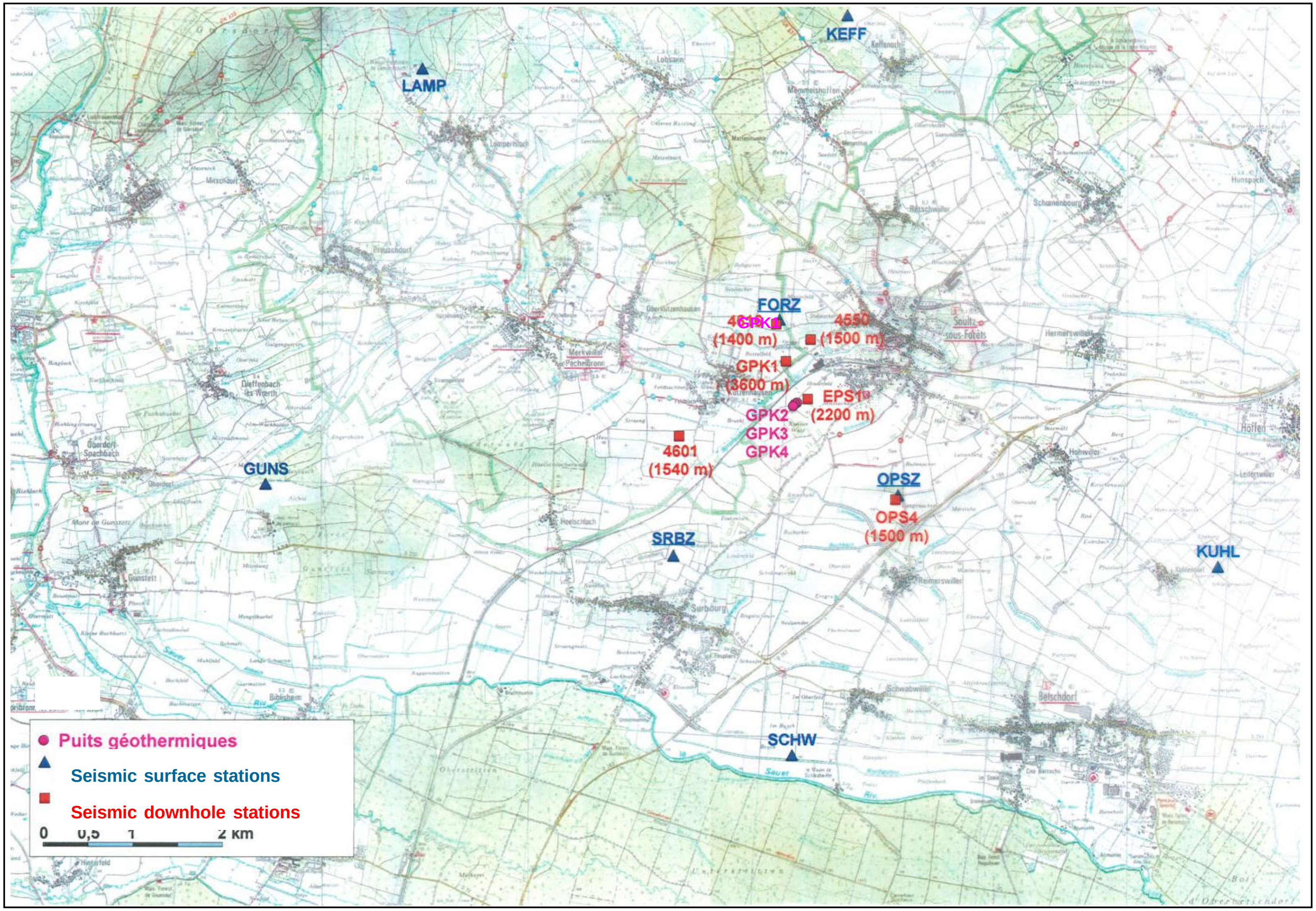
'Free' 9 5/8" Casing

Pack Off

200º C & 200 bar

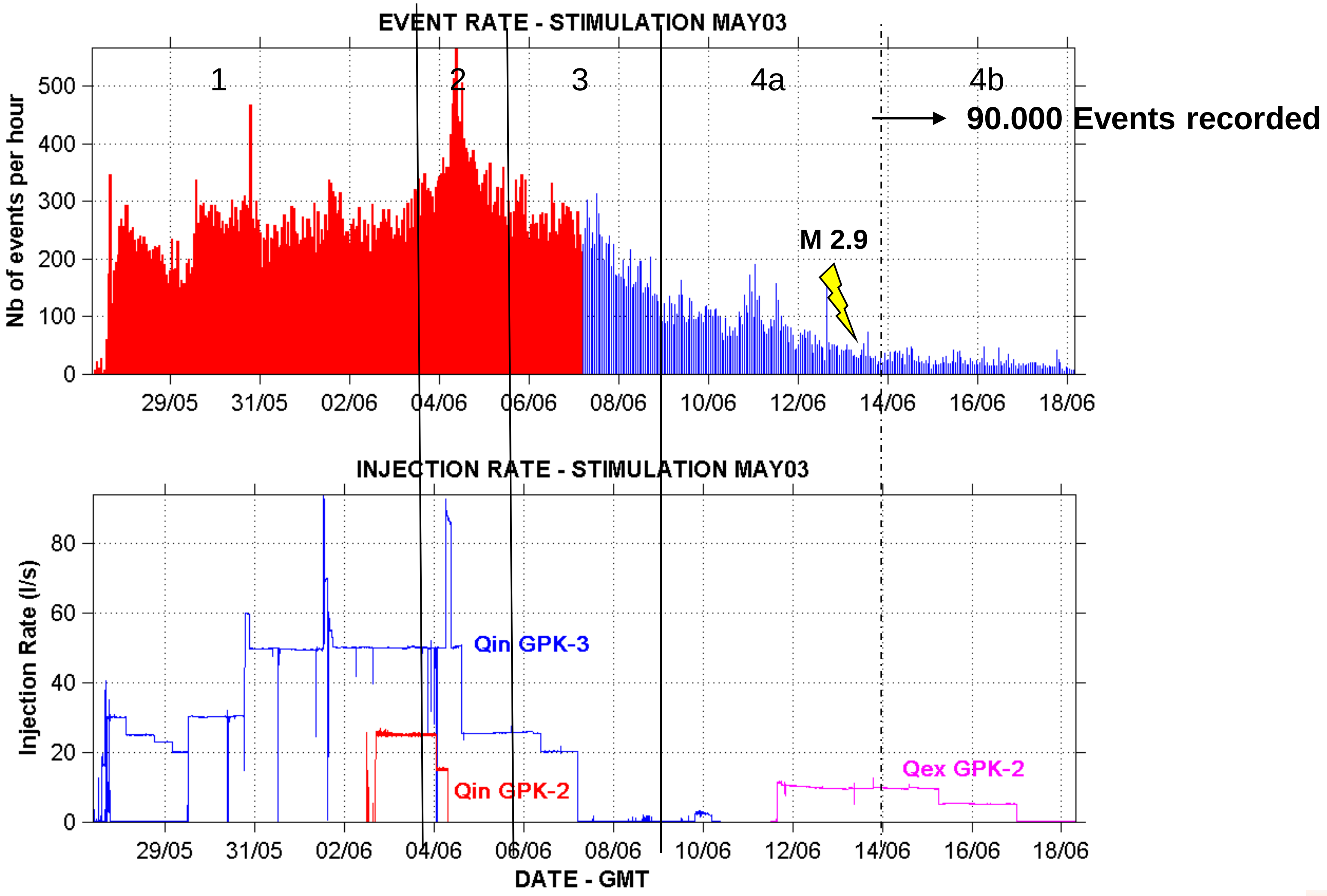
Cellar

Seismic network:



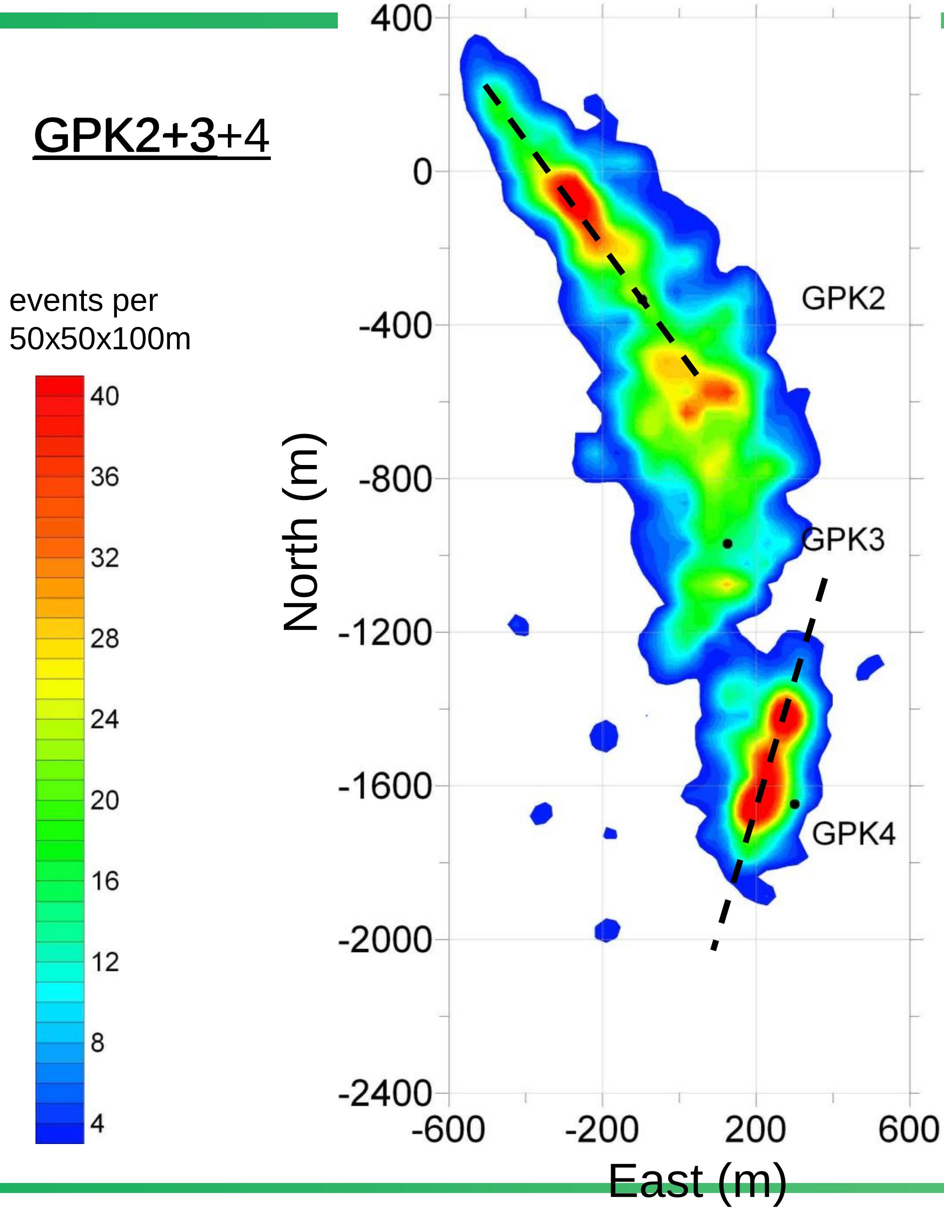
Géothermie Soultz

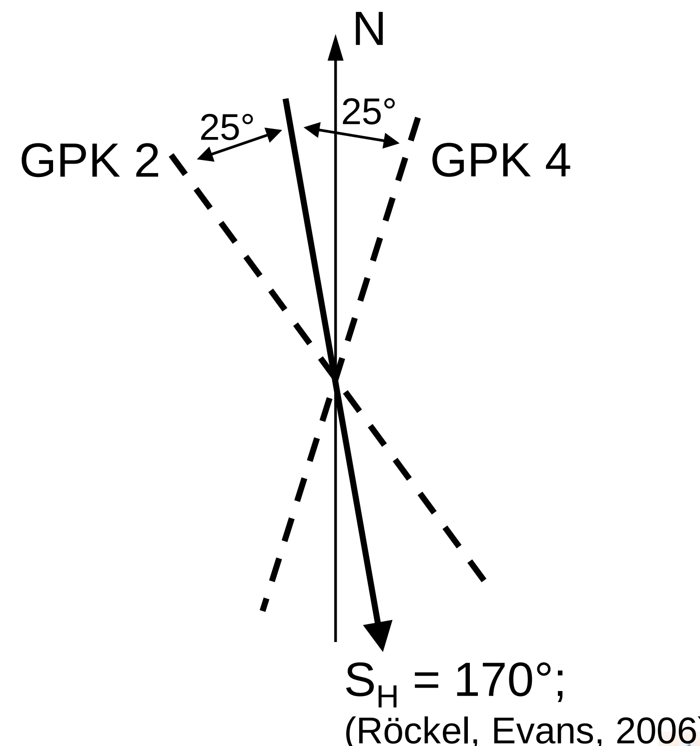
Hydraulische Stimulation GPK3



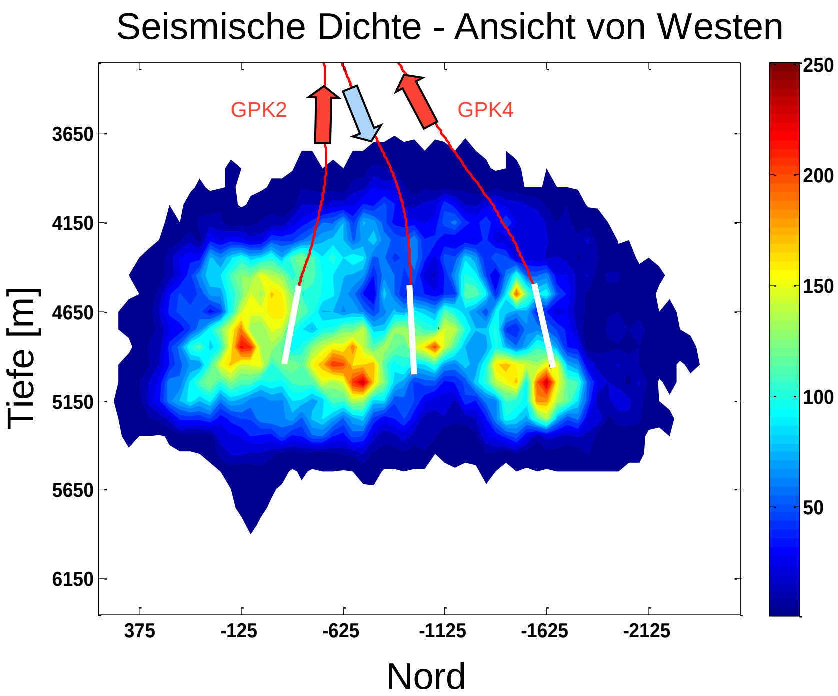
Seismic events (4900-5000m)

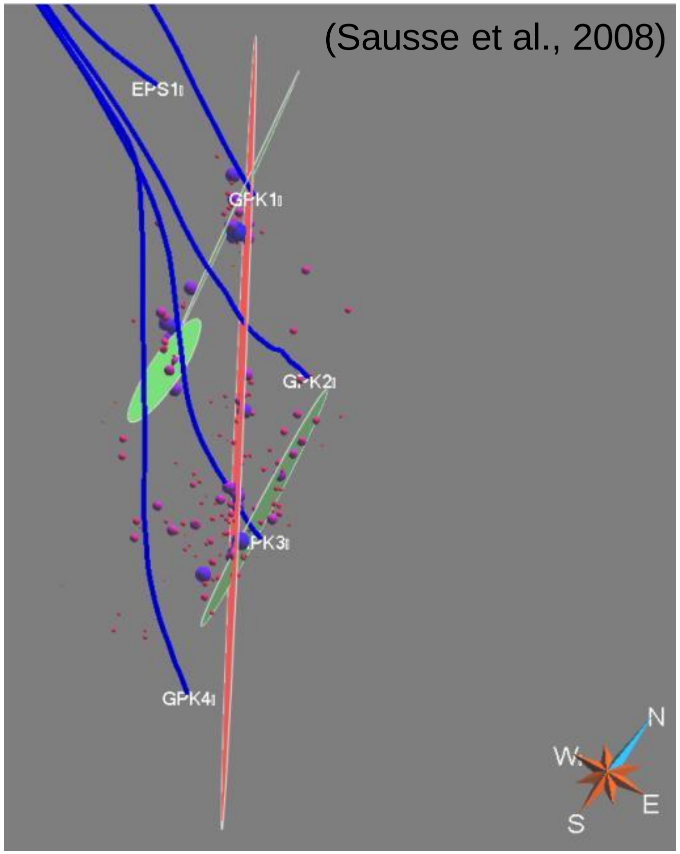
GPK2+3+4





Hydraulik und 3D-Strukturen





Zirkulation über 5 Monate ohne Produktionspumpen:

15 l/s, max. 160 °C

→ 6 MW_{th}

→ Thermalwasseranteil ca. 70 - 80 %

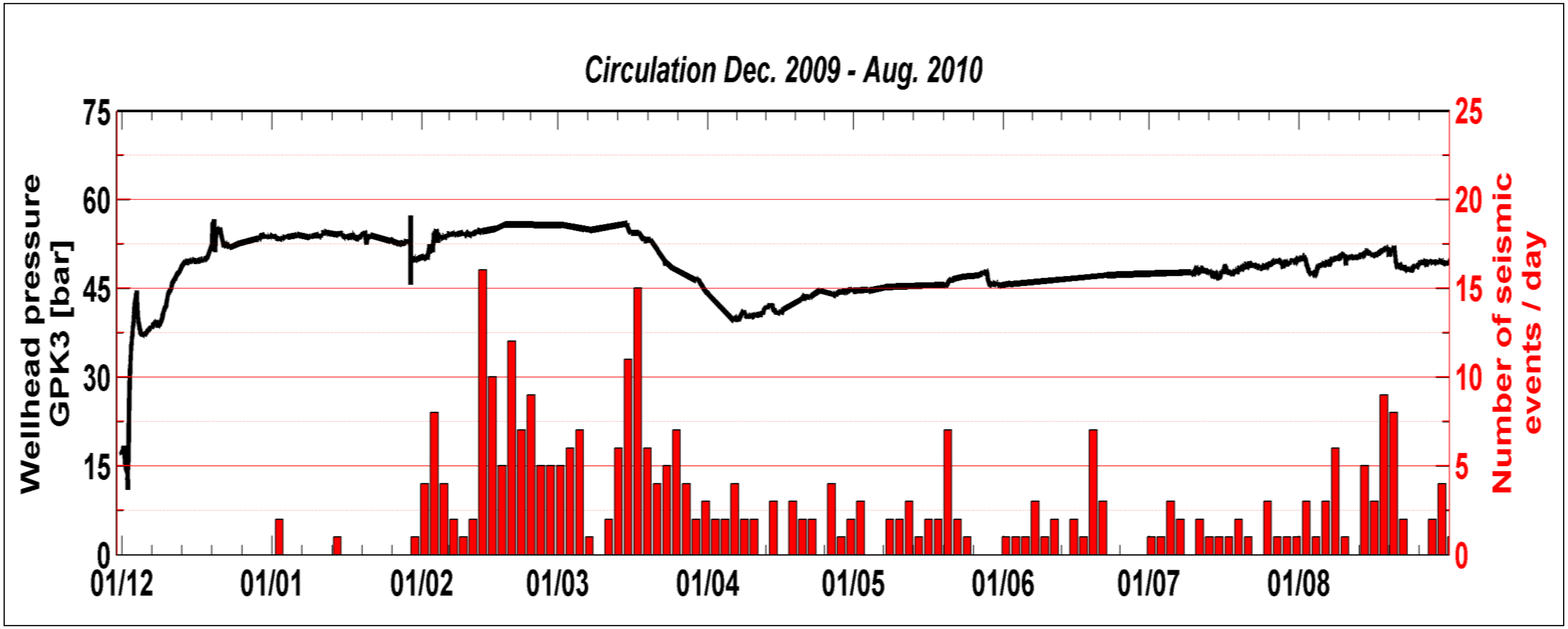
→ Hydraulisches Ungleichgewicht GPK2 <-> GPK4

3D-Modell der Störungen im Reservoir, basierend auf Bohrlochmessungen und VSP:

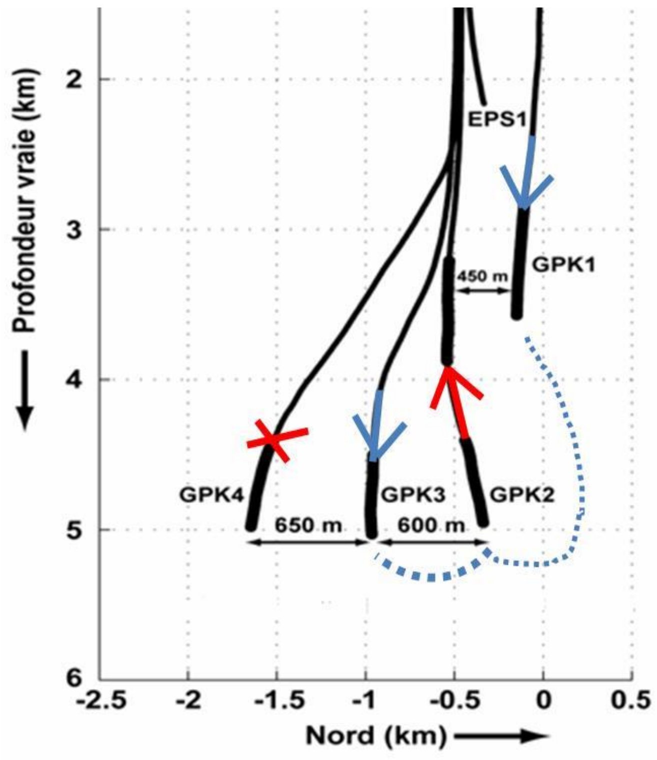
-> Hauptstörung verbindet GPK2 und GPK3

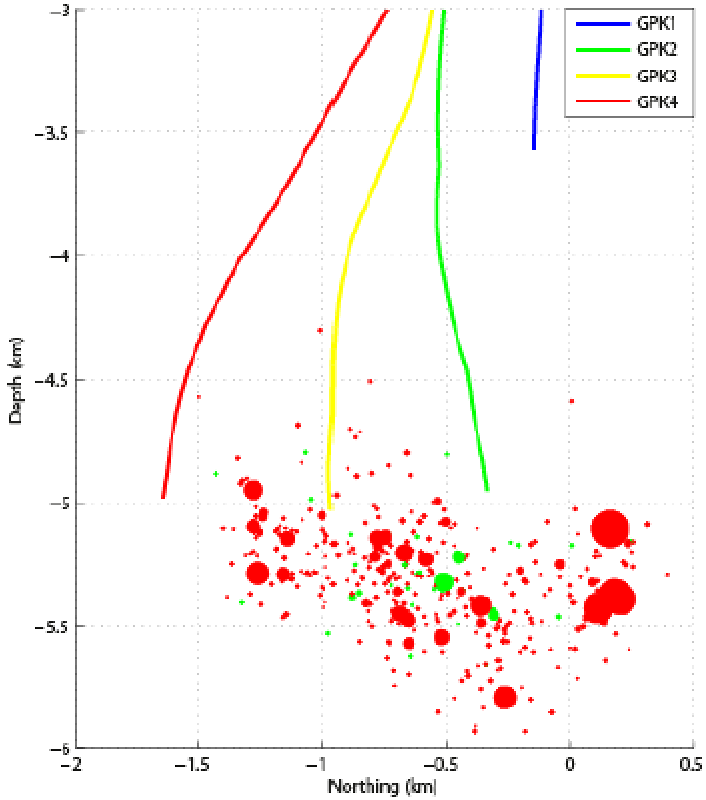
Reservoir: hydraulisches Monitoring

e. g. induced micro-seismicity activity at depth,
December 2009 – August 2010:



Reservoir: induced micro-seismicity activity at depth

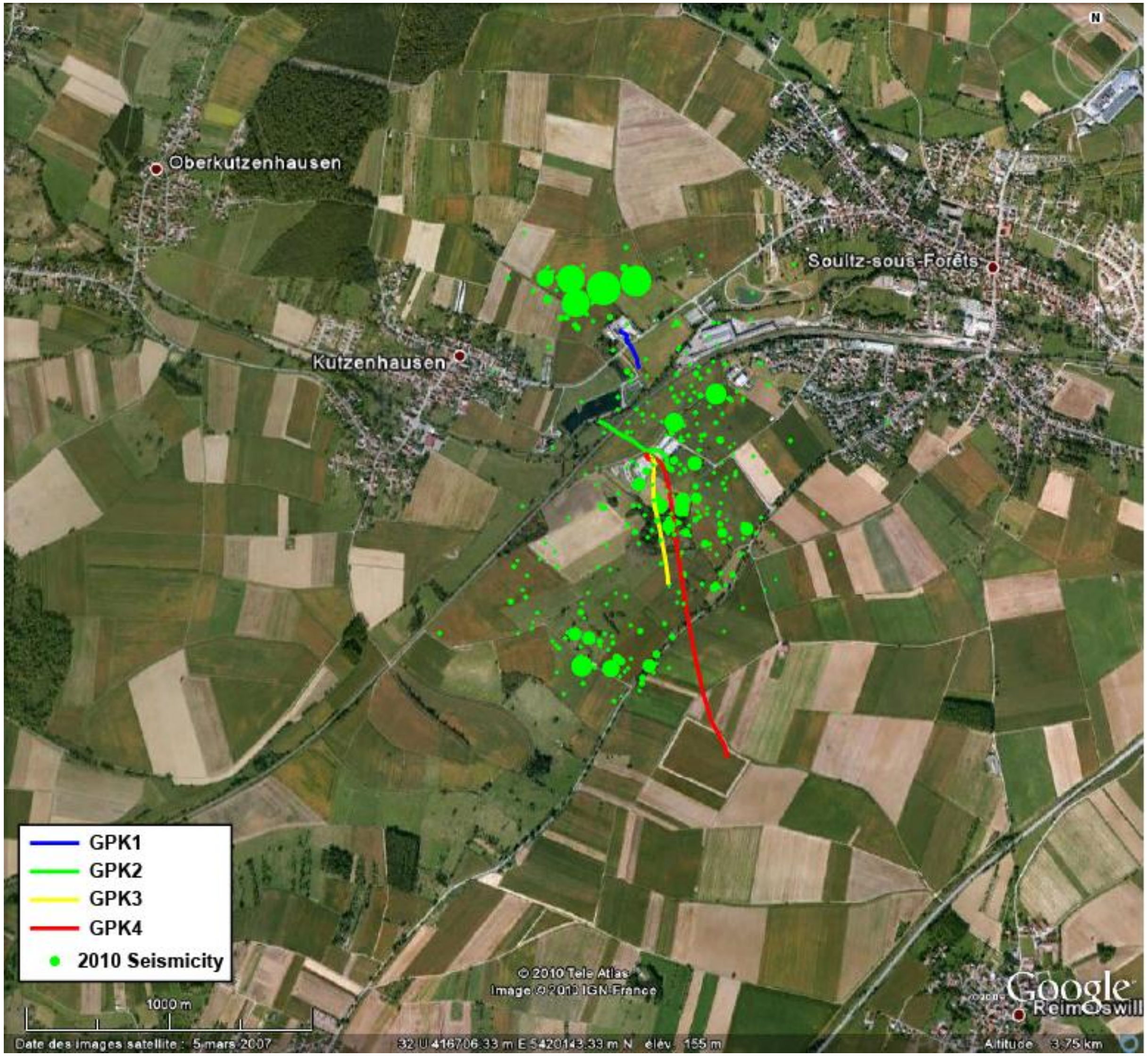




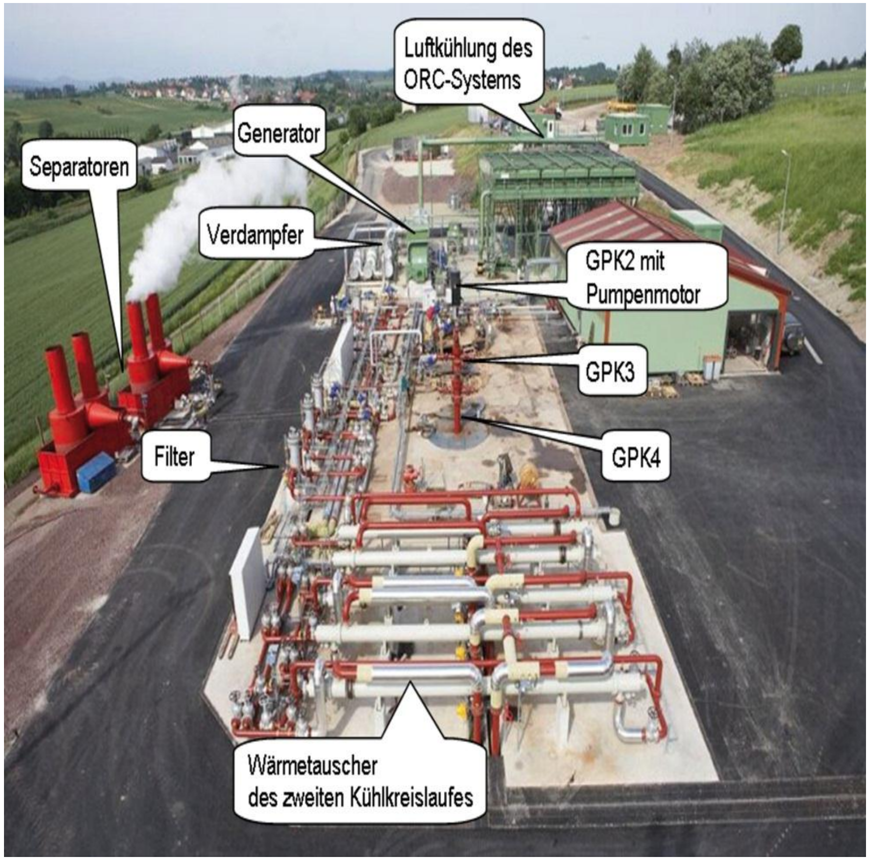
In green, October events

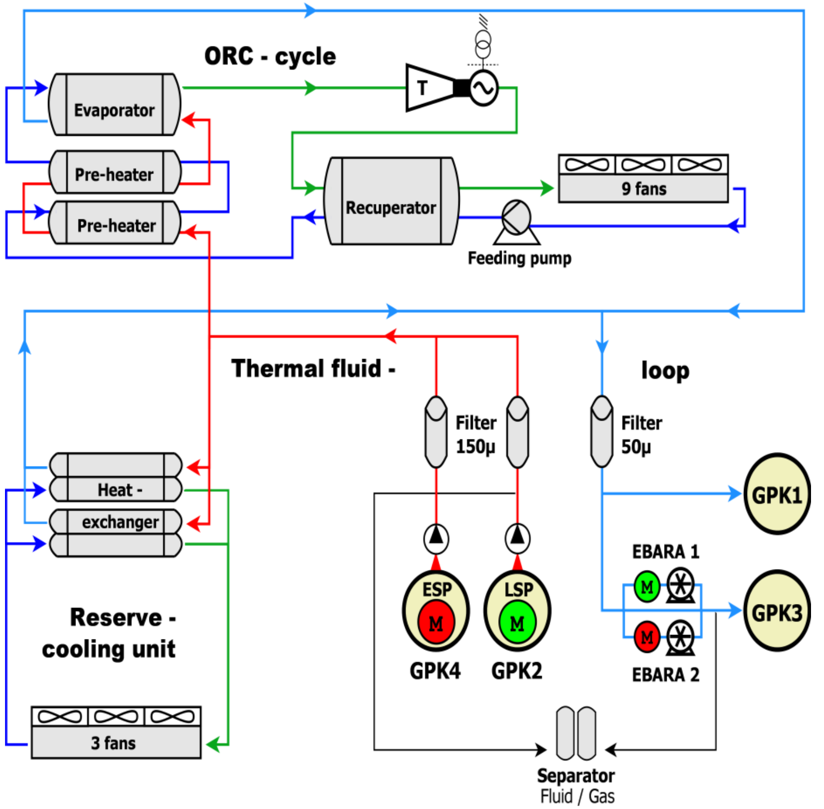
During recent circulation tests, micro-seismicity developed always in the same areas

Lokation der seismischen events in 2010:

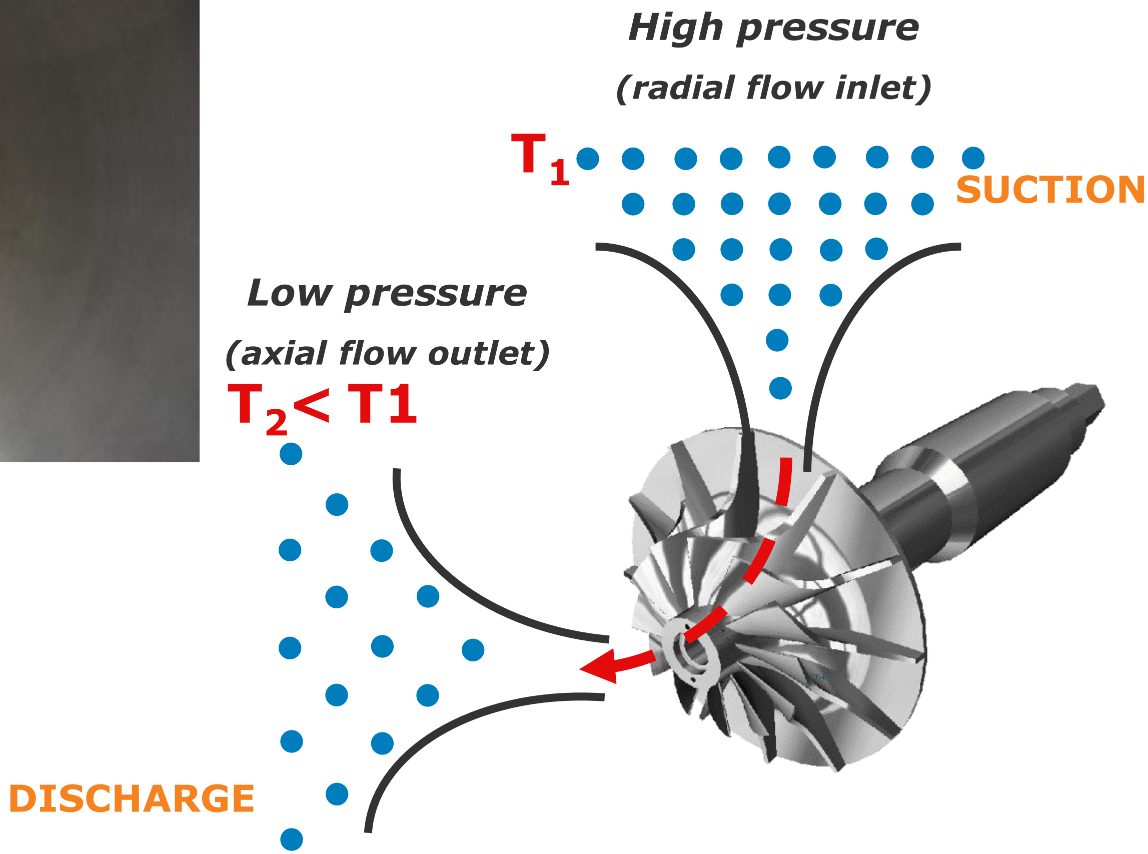


Die Kraftwerks - Anlage

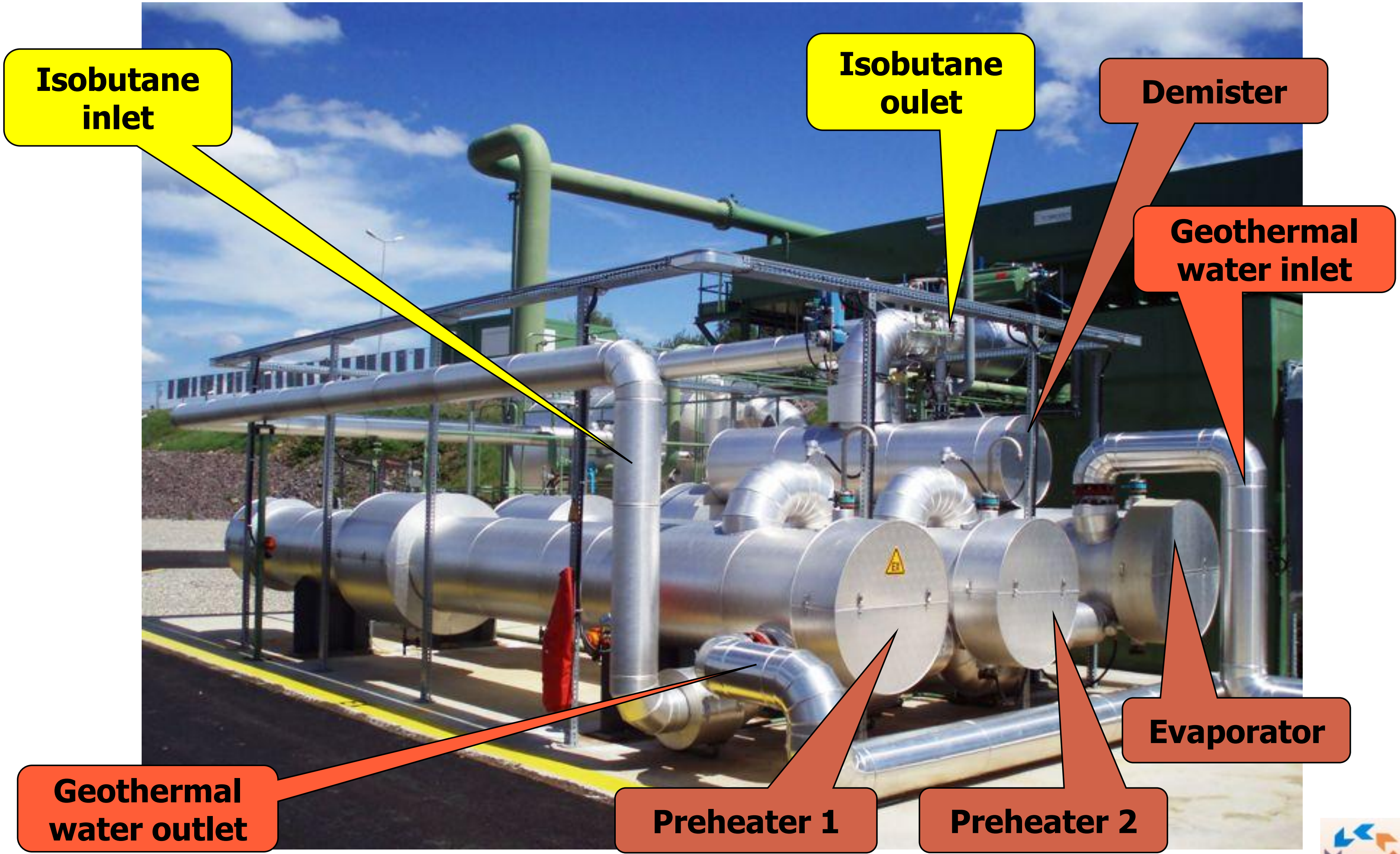




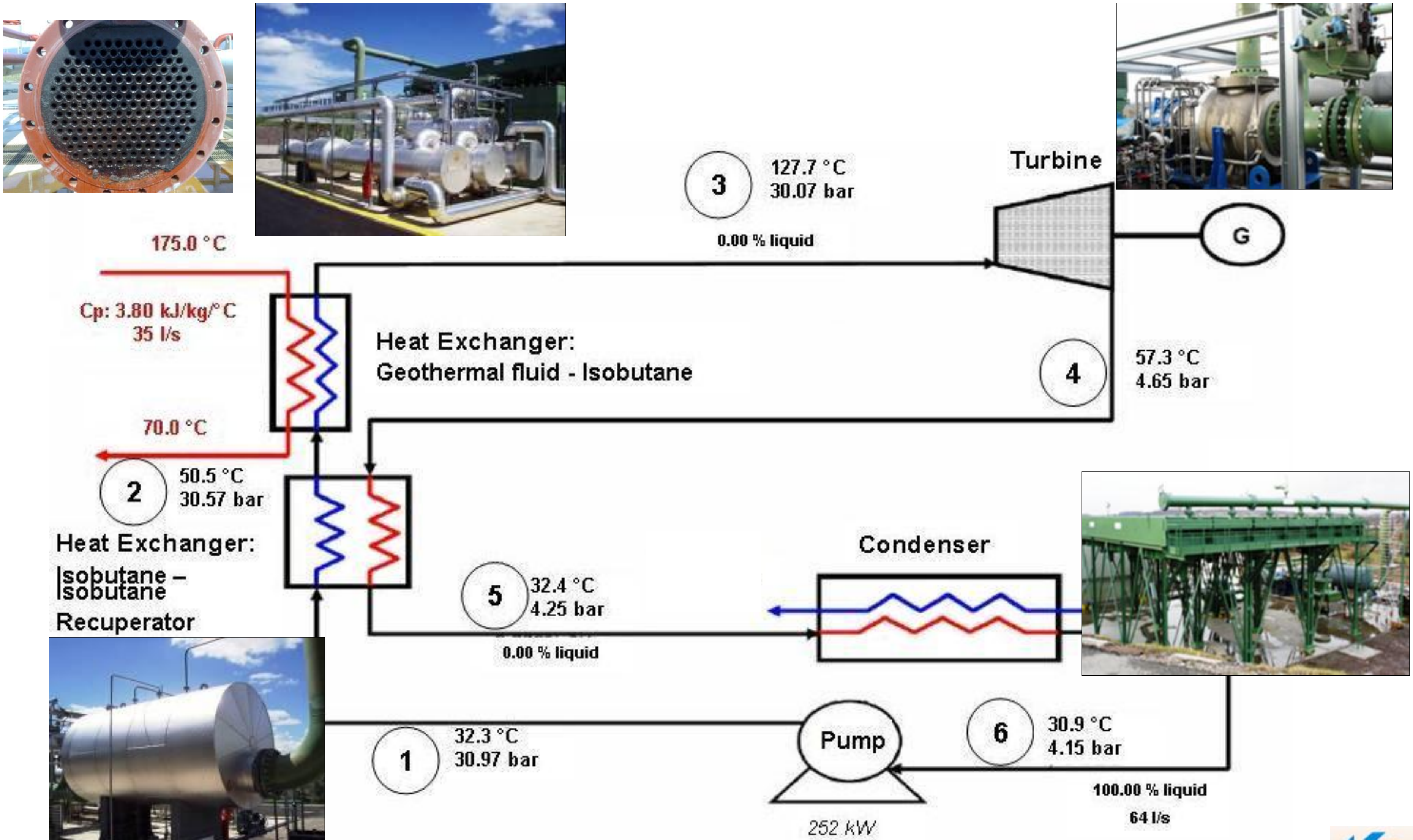
RADIAL - TURBINE (CRYOSTAR)



HEAT EXCHANGERS



Kraftwerksdesign - Schema



Gestängepumpe in GPK2

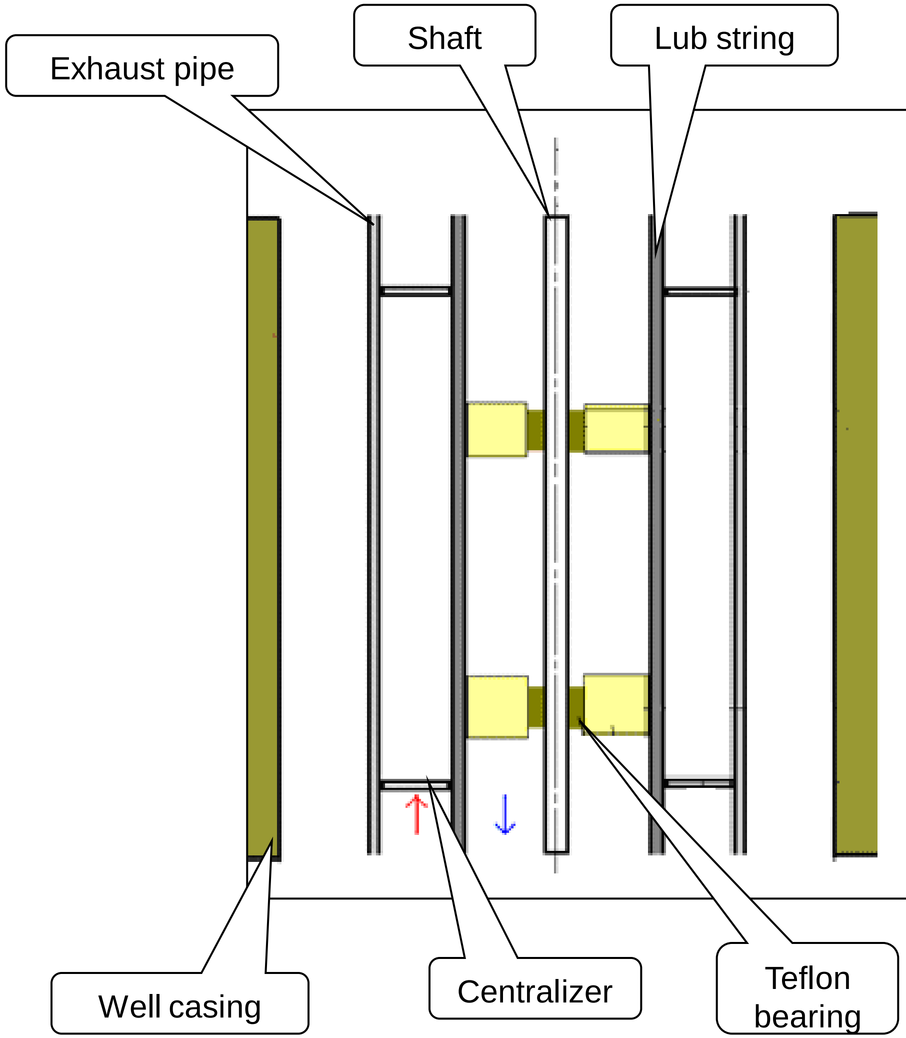




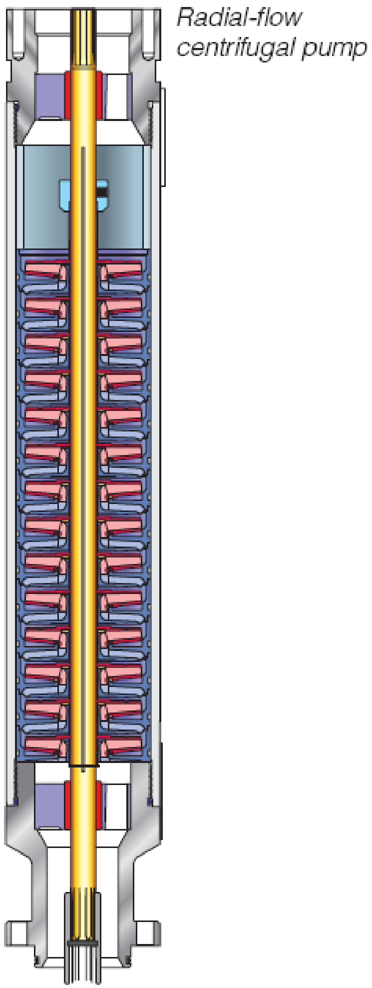


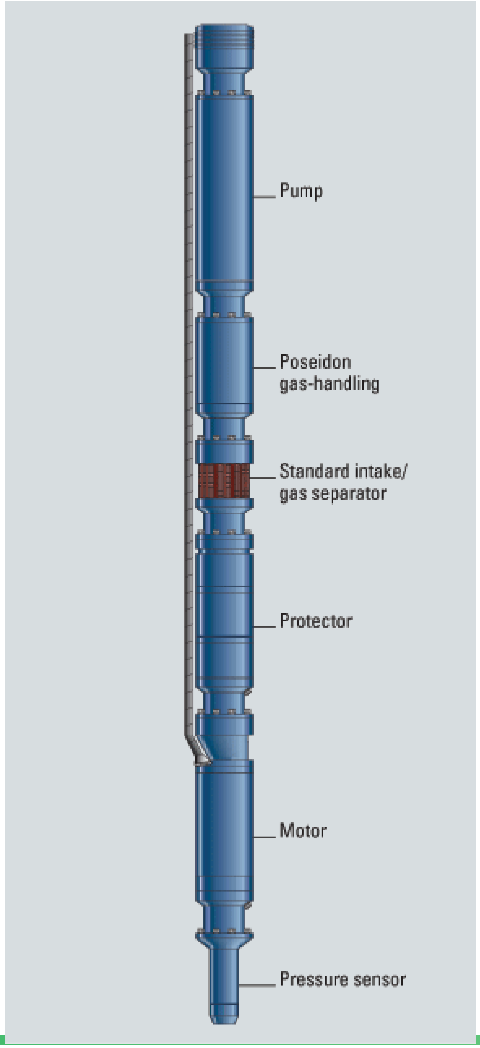
- Einbautiefe 350 m
- max. Leistung ~ 300 kW

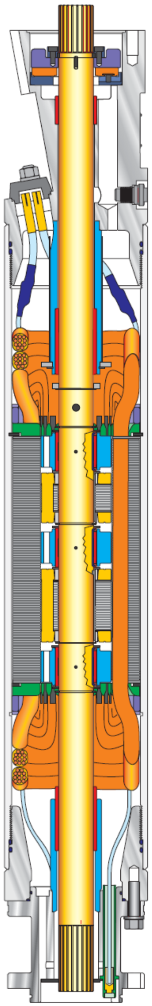
LSP in Soultz (GPK2 well)



Electro Submersible Pump (ESP)







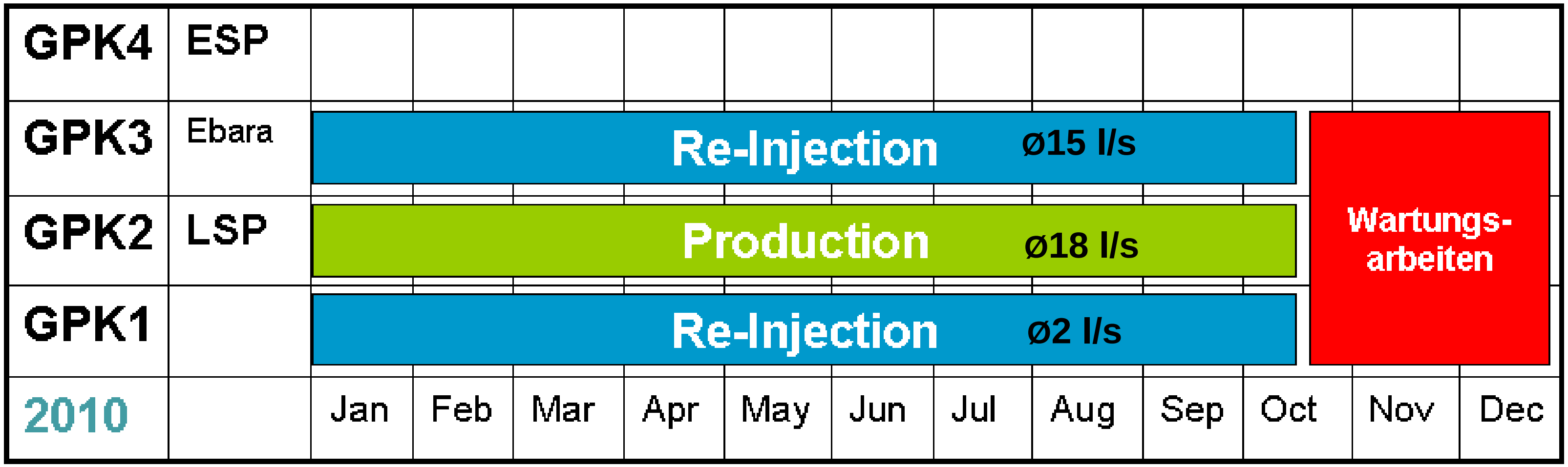
Unterwassermotorpumpe in GPK4

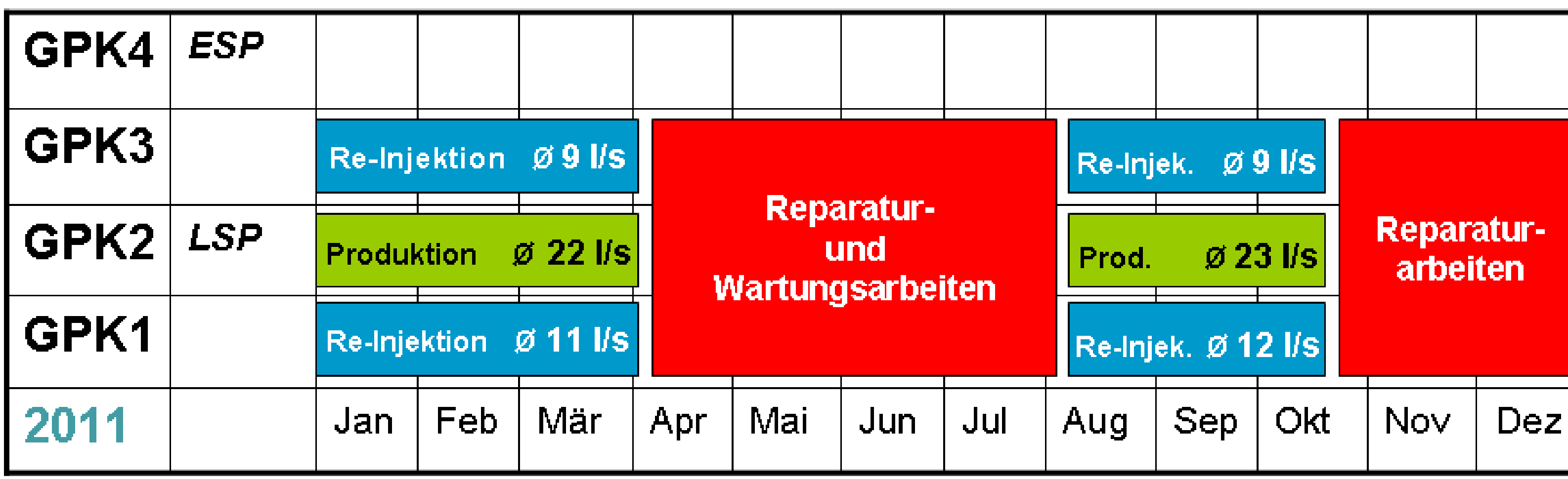
Einbautiefe 500 m

Pumpleistung: ~ 300 kW

Géothermie Soultz

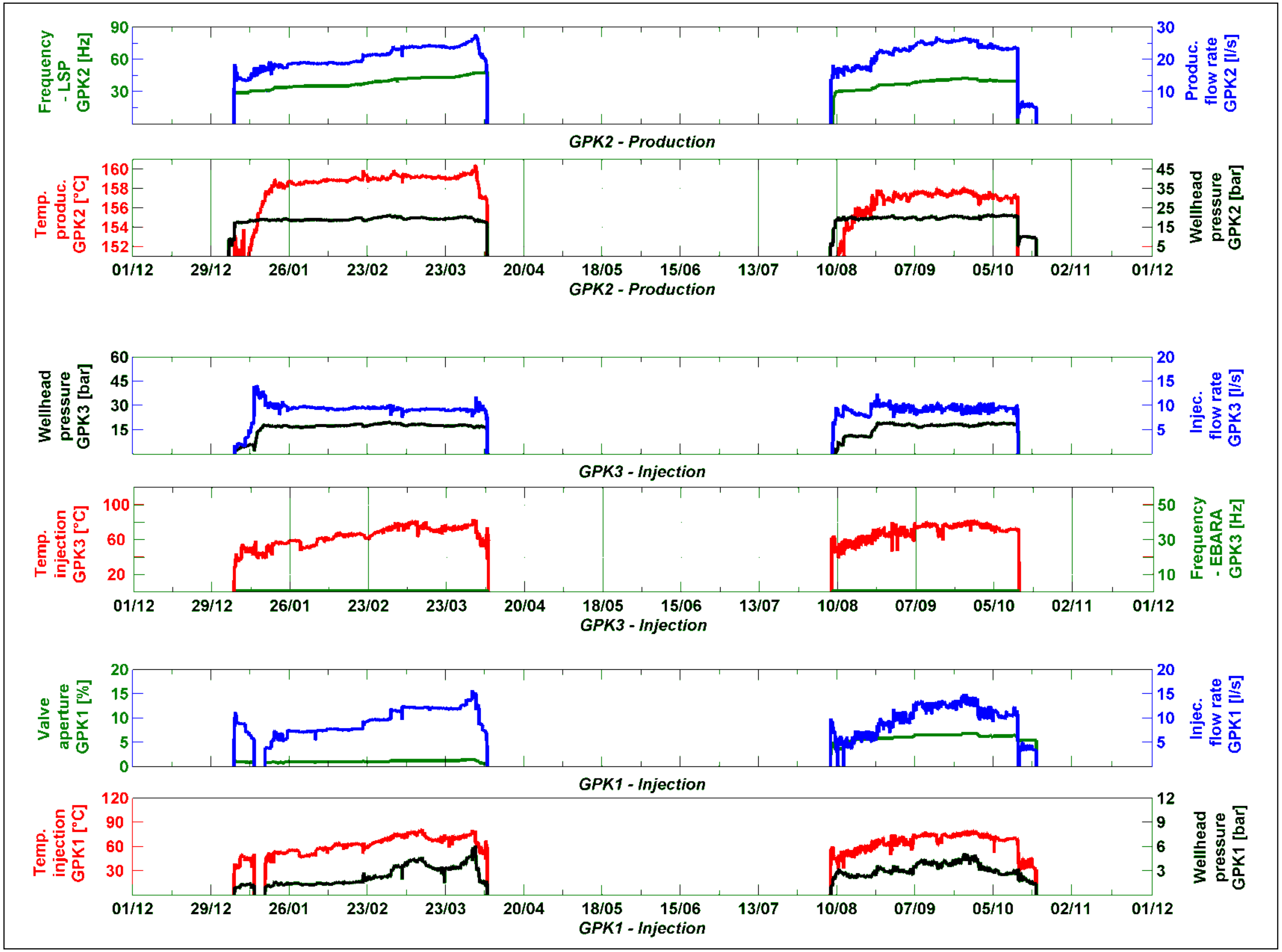
Zirkulations - Schema 2010 / 2011



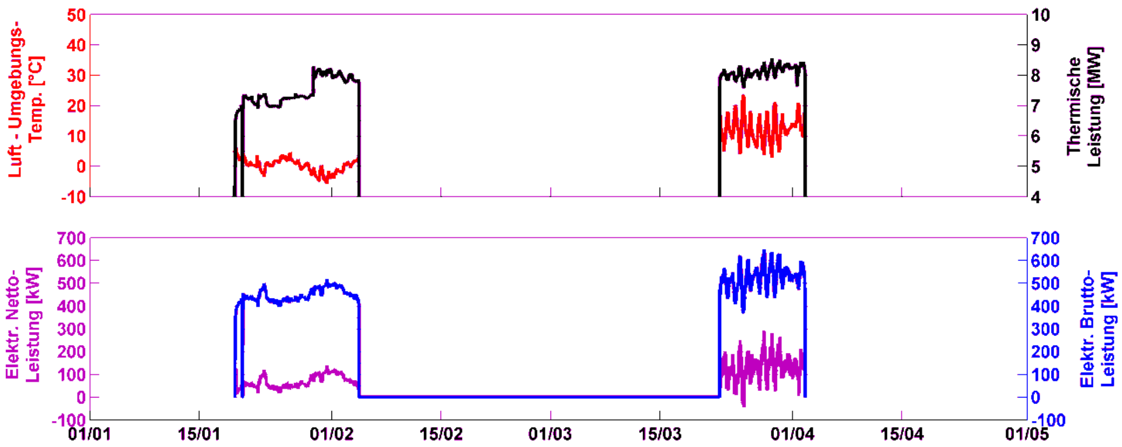


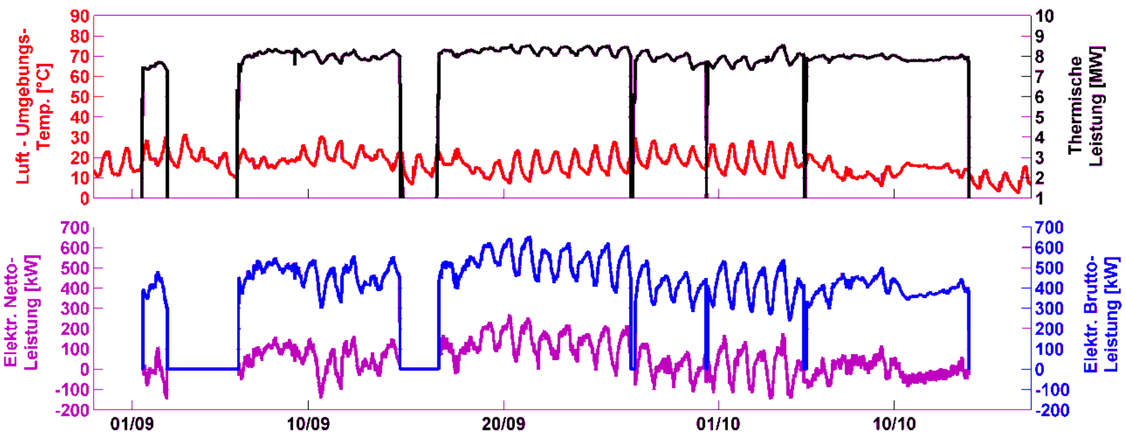
Géothermie Soultz

Hydraulische Parameter 2011



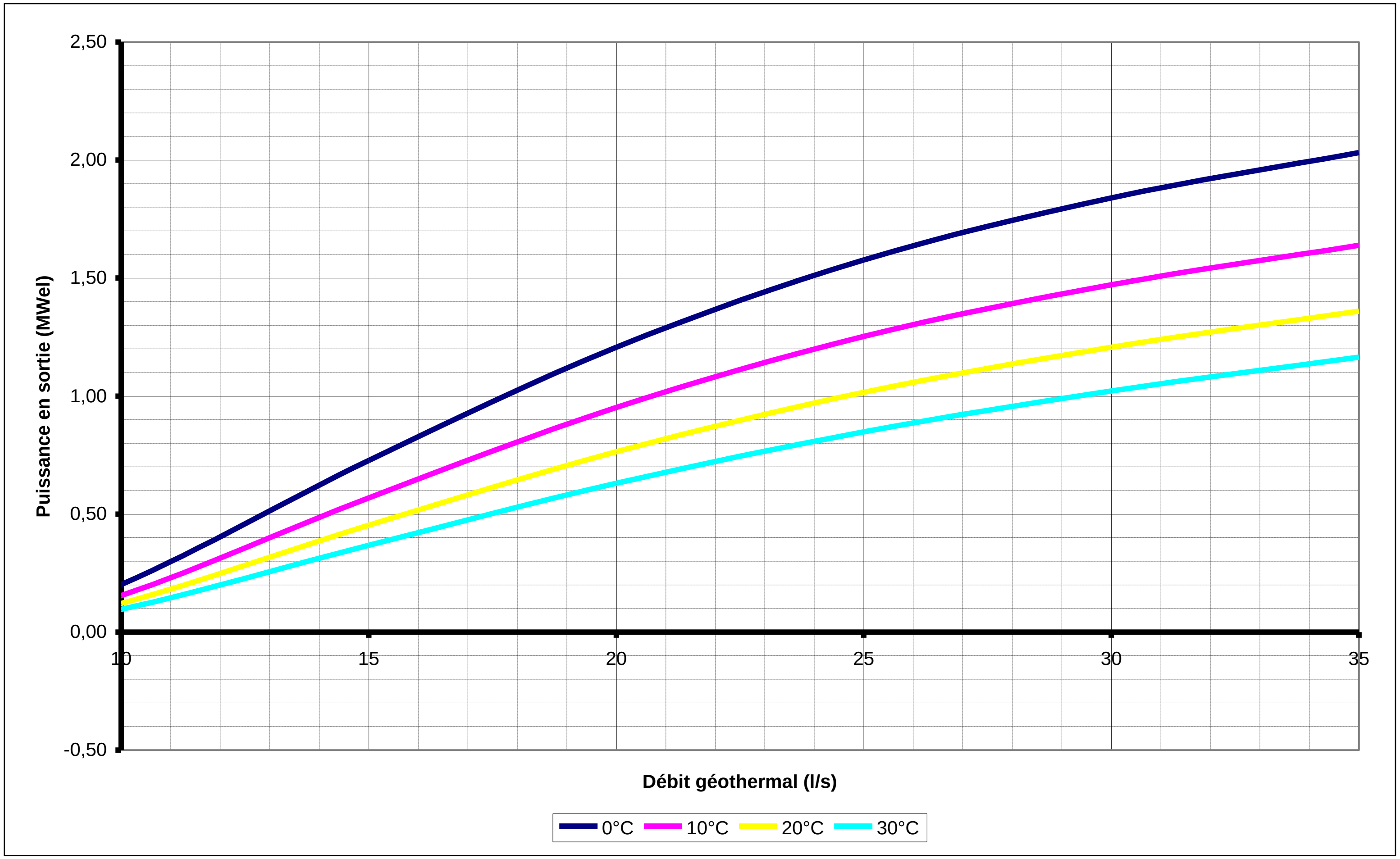
Strom – Produktion 2011





Géothermie Soultz

Strom – Produktion

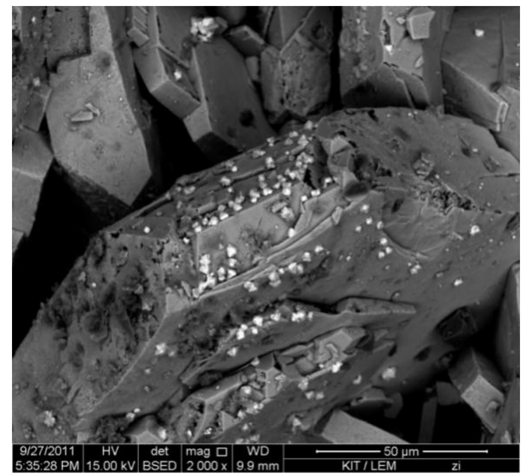


Géothermie Soultz

SCALING STUDY: MINERALOGICAL RESULTS

- Scaling characterization
  - Mineralogical and geochemical studies with KIT/EnBW
- Main minerals: Barite-Celestine (Ba, Sr) SO_4 & Galena (PbS) and trace minerals (other sulfides)

Scaling sample from GPK4 pipe



SEM - Microscopy
Barite-Celestite dominated.
Only traces of sulfides

Geochemical characterization: Trace elements (metals)
What are the mineral formation conditions (sulfides) ?

ENVIRONMENT: NATURAL RADIOACTIVITY

- Radioprotection for workers (blue line, dosimeter)
- Maximum legal annual authorized level: 1 mSv permanently
- Regular monitoring on GPK1/GPK2 plate-forms: 350 measurements
- ASN (Autorité de Sûreté Nucléaire) de Strasbourg
- Max value is 10µSv/h
- Reinjection part (low Temp, 70° C) of the geothermal power point shows higher radiation dose values than the production part (high Temp, 160° C)

Research study on anti-scalant products
Test in real conditions

DOWN-HOLE PUMP: LSP FAILURE APRIL 2011

Hydraulic part of the LSP

Damaged impellers

cutting samples

Materialforschung

-> Wellenbruch durch Friktion und anschließende Überhitzung

-> Erosion an Impellern

-> in-situ-Korrosionsproben, Test von Inhibitoren, Wasserchemie, Online-Messung von pH, T, Redoxpotential, el. Leitfähigkeit

Zusammenfassung und Ausblick

Aktueller Stand:

-> Zirkulation des Reservoirs mit Tauchpumpen mehrfach erfolgreich demonstriert
-> ausführliche Tests der Komponenten
-> Anlage ist bereit für die Wiederaufnahme des Testbetriebes und Abnahme
-> Möglichkeit, in GPK1 zu verpressen

Projektphase 2009 – 2011:

-> Langzeitbegleitung des Kraftwerksbetriebes
-> Optimierung der ober- und untertägigen Materialauswahl
-> Reservoirmonitoring und Reservoirmodelling – hydraulisch, thermisch, mechanisch, geologisch, chemisch und in Bezug auf Mikroseismik
-> Optimierung der Energieausbeute durch Anpassen des Zirkulationsregimes
-> Wissenstransfer - Soultz als Trainingszentrum für Geothermie

Géothermie Soultz

Einspeisevergütung

Einspeisetarife in Frankreich:

Bis Mitte 2010: 12 ct/kWh auf die Nettoleistung

Erhöhung auf 20 ct/kWh auf die Nettoleistung fand im dritten Quartal 2010 statt!

Géothermie Soultz

Danke für Ihre Aufmerksamkeit!

Dankeschön an alle wissenschaftlichen und technischen Partner
im Soultz-Projekt und an die
Fördereinrichtungen BMU, ADEME und EU sowie an die EWIV ‘Wärmebergbau’.

ADEME
Agence de l'Environnement et de la Maîtrise de l'Energie

PtJ Projektträger Jülich Forschungszentrum Jülich

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

BESTEC GmbH best technology for nature

eDF

és électricité de strasbourg

PFALZWERKE

EnBW

EVONIK INDUSTRIES

Géosciences pour une Terre durable brgm

BGR

INSU

Nancy-Université

MeSy GEO-Meß-Systeme GmbH

EOST Ecole et Observatoire des Sciences de la Terre

GGA INSTITUT

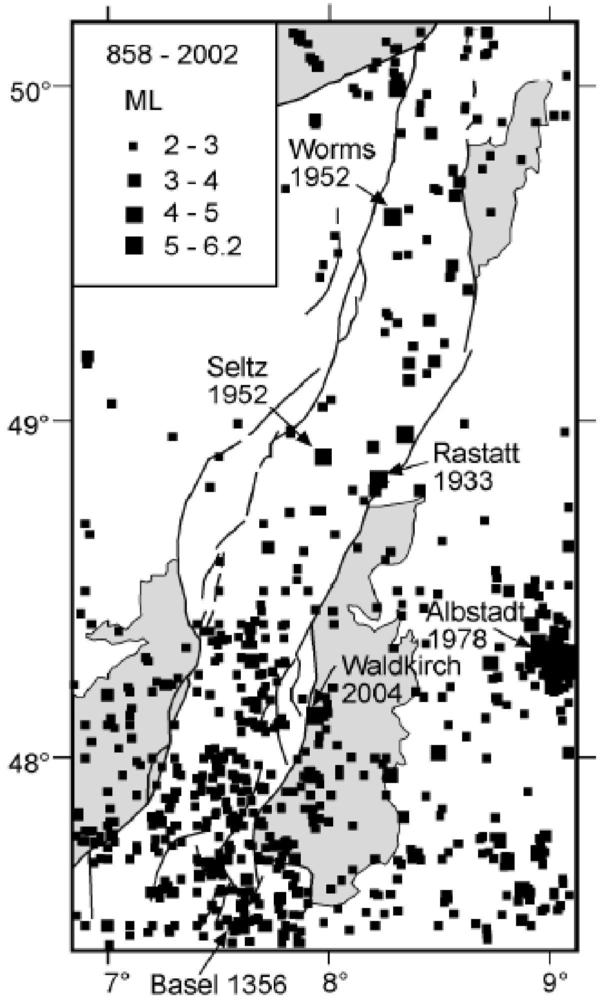
G · T · C

IFE Institute for Energy Technology

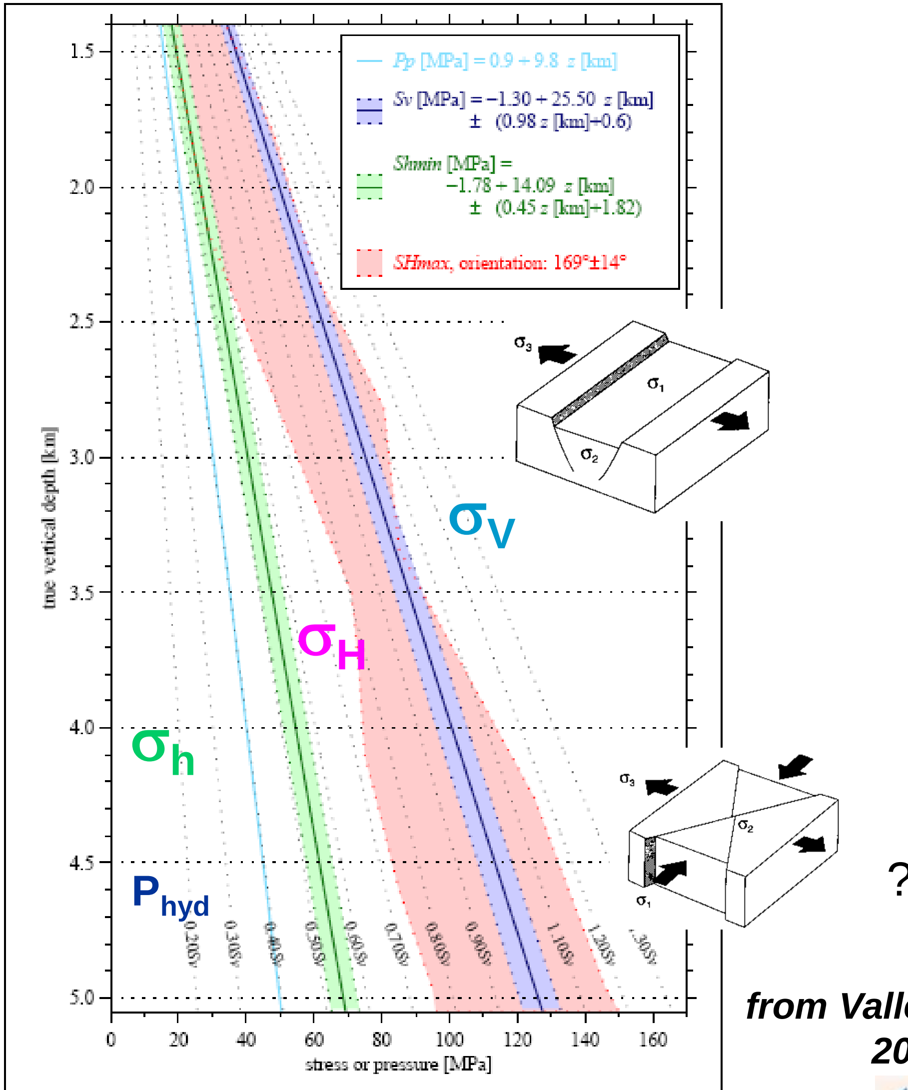
DHM

Géothermie Soultz

Natural seismicity & stress field

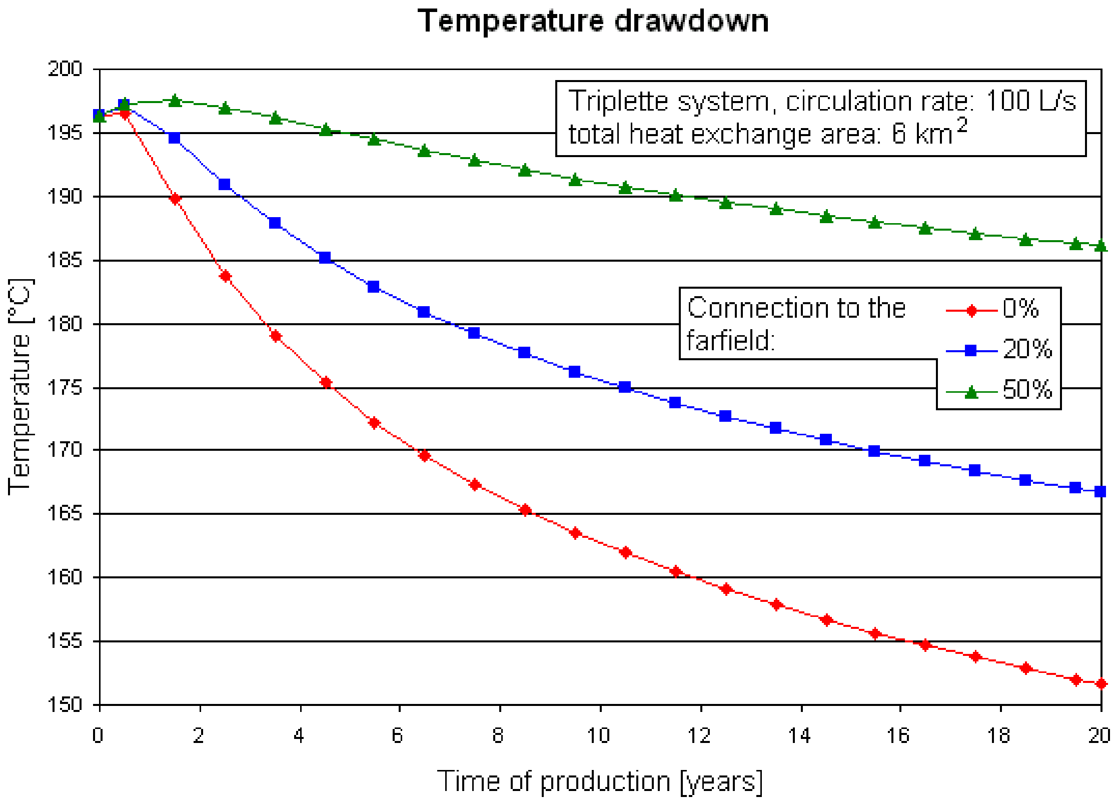


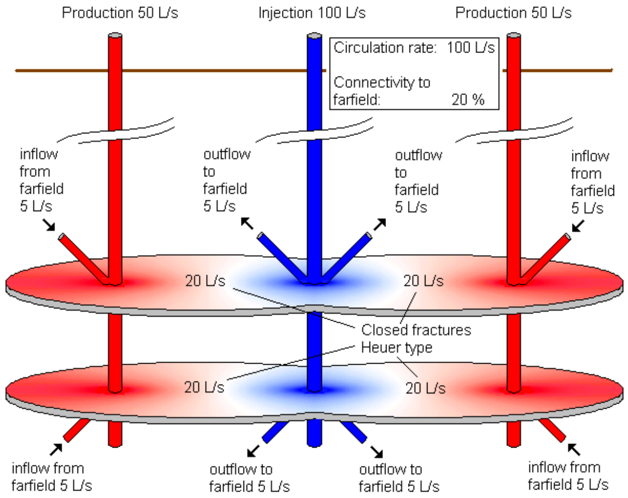
in Peters, 2007



from Valley, 2007

HDR to EGS, the change in the understanding of a “closed” HDR system to a partly “open” EGS

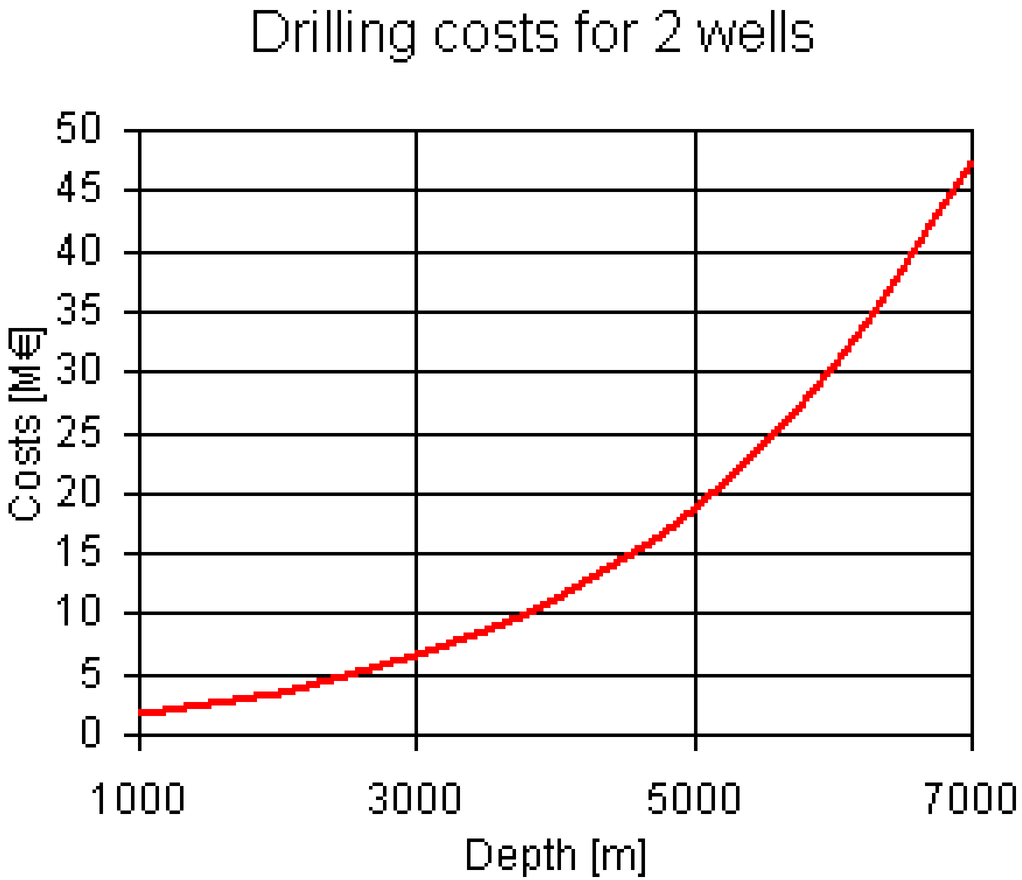




Connectivity to farfield: 50%

from Heidinger, 2008

EGS Structure - Drilling costs



Wellheads at Soultz-sous-Forêts

from Heidinger, 2008

Total costs for two boreholes depending on depth: Exponential behaviour
Frorm Garnish J.D., 1987; Legarth B.A.& Wohlgemuth L., 2003

Géothermie Soultz

Chemische Stimulationen

Chemische Stimulationen zur

- Lösung von Kluftfüllungen wie Calcit (HCl)

- Lösung von hydrothermal alterierten Mineralen wie Illit (RMA: HCl und HF)

- Anwendung in Hochtemperatur-Sandsteinen (OCA: Zitronensäure, HF, HBF, …)

- Komplexbildung mit Elementen wie Ca, Mg, Fe (NTA: Nitrilotriacetic acid)

-> Wirkung auf näheres Bohrlochumfeld beschränkt!

Stockage d‘acide: ~ 200 m³

Pompe haute performance (plusieurs kW)

More about chemical stimulations….

OCA stimulation for GPK3 – for high temperature sandstone formations or formations with more than 5 % zeolite or chlorite. Was tested on GPK3 cutting samples.

Preflush ~ 1200 m³ of fresh water at 35 l/s (GPK4 30 l/s)

Main flush of 250 m³ OCA: 5 – 10 % citric acid $C_6H_8O_7$, 0.1 – 1 % HF, 0.5 – 1.5 % HBF_4, 1 – 5 % NH_4Cl at 55 l/s (in weight: 10 – 20 t citric acid, 0.2 – 2 t HF, 1-3 t HBF_4, 2 – 10 t NH_4Cl)

Postflush ~ 1300 m³ of fresh water with flow rates of 45 and 30 l/s (GPK4 40 and 35 l/s)

RMA stimulation for GPK4 – hydrothermal deposits like carbonates and clay

Preflush of 2000 m³ fresh water at steps of 18, 22 and 28 l/s

Preflush of HCl, 25 m³ at concentration of 15 % (deox.) at 22 l/s (3 t)

Main flush of 200 m³ RMA, 12 % HCl and 3 % HF plus inhibitor at 22 l/s (24 t HCl & 6 t HF)

Postflush of 2000 m³ fresh water at 22 and 28 l/s

NTA stimulation for GPK4 – strong chelating capacity with respect elements like Ca, Mg, Fe and other metals

Chelatants form complexes with cations like Fe, Ca, Mg, and Al and dissolve calcite etc…
$C_6H_9NO_6$ -- Nitrilotriacetic acid.

Preflush (to pressurize reservoir??) of 4500 m³ at 24 l/s

Main flush of 200 m³ of caustic soda and 19 % diluted Na_3NTA at 35 l/s (38 t)

Postflush of 400 m³ fresh water at 40 l/s

SITE INSPECTION REPORT

Sites visited
Geothermal Power plant Soultz-sous-Forêts / France
Route de Soultz – BP 40038
67250 Kutzenhausen / France
www.geothermie-soultz.fr
contact person: Bernd Melchert, Geologist
Tel.: +33 3 88805363
Fax: +33 3 88805351
e-mail: melchert@soultz.net

Geothermal Power plant Insheim / Germany
76865 Insheim / Germany
http://www.pfalzwerke-geofuture.de/6240.php
contact person: Jörg Baumgärtner / BESTEC GmbH
Oskar-von-Miller Str. 2
76829 Landau / Germany
Tel.: +49 6341 973420
Fax: +49 6341 973411
Cell: +49 172 7116787
e-mail: baumgaertner@bestec-for-nature.com

Geothermal Power plant Landau / Germany
Eutzinger Straße 42
76829 Landau in der Pfalz / Germany
http://www.geox-gmbh.de/default.htm
contact person: Jörg Baumgärtner / BESTEC GmbH
contact details see above

Participants Site Inspection
Richard Artley / GP International S.A.
Michael Graf / OMV
Wolfgang Jauk / OMV
Peter Trupp / TU Vienna

Date visit: 27th of April, 2012

Report prepared by: Michael Graf and Peter Trupp

Power plant Soultz-sous-Forêts

Bernd Melchert gave a presentation of the project itself incl. base information on geothermal energy and power plants, HDR and EGS, the conditions and the history of the project in Soultz as well as the lessons learned during the various project phases – for details please refer to attached presentation “Soultz_Geothermie_Melchert_April_2012_OMV”.

After the presentation, the power plant itself was inspected.

Please refer also to the pictures taken attached.

Following some additional information given during the presentation and the site inspection are listed, that cannot be found in the presentation.

Geology at Geothermal power plant projects in Germany:
While in the area of the Rheingraben the base rock consists of Granit with very little permeability, the formations hosting geothermal reservoirs in the Bavarian area close to Munich are originated in the Jurassic and have much better permeability even before stimulation.

Differentiation EGS, HDR, HWR, HFR:

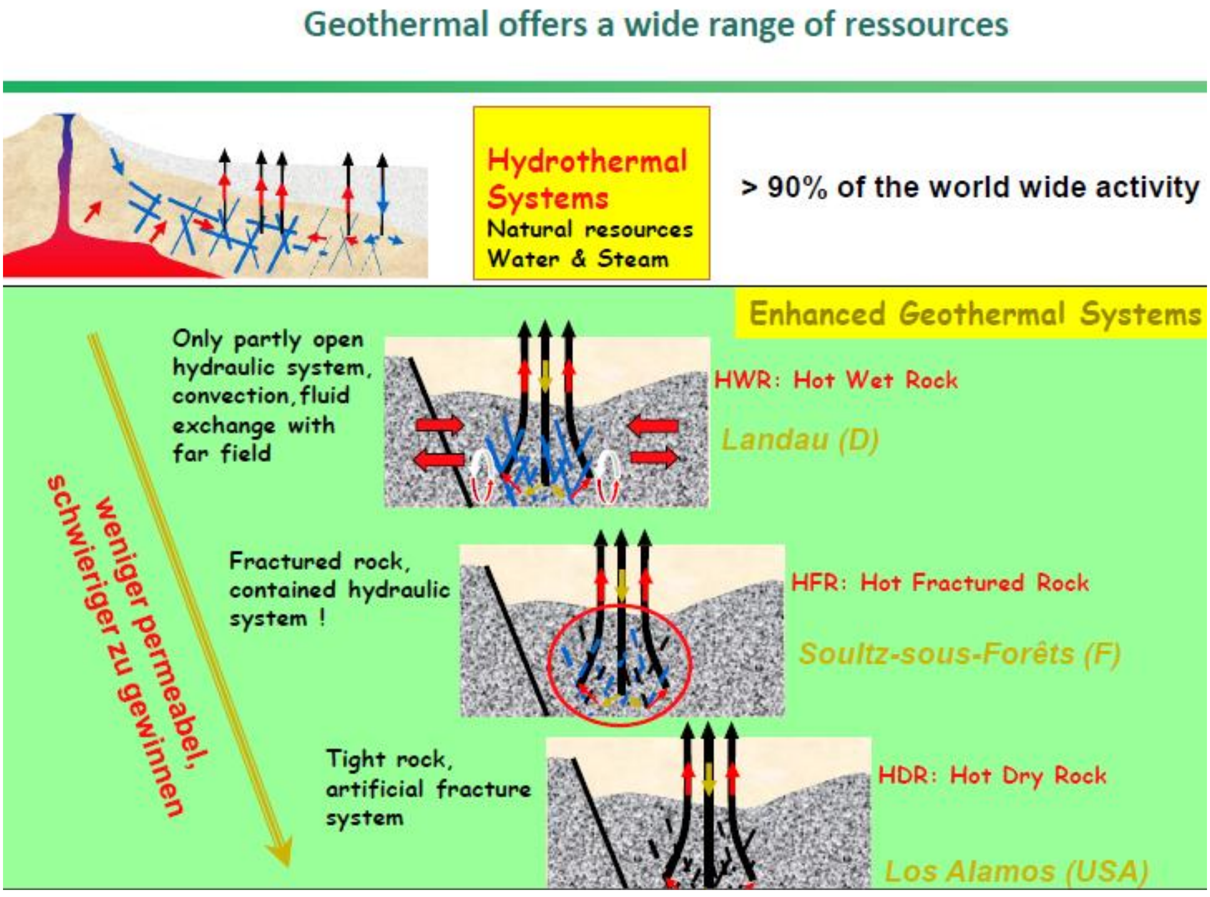


Figure 1: Differences between HDR, HFR, HWR, EGS and hydrothermal reservoirs

It was explained that the all the designated reservoirs that need enhancement are EGS (Enhanced Geothermal Systems), depending on the extent of preexisting fractures and naturally existing geothermal fluids a formation can be categorized into HDR, HFR or HWR.

Fracturing in Soultz:
The fractures in Soultz after stimulation vary in size from a few mm to some cm and even in the area of dm and partially m. There are even some tremendous large fracture apertures partially, which are based on naturally occurring disturbances, as can be seen in the UBI-Log (acoustic borehole televiewer) below.

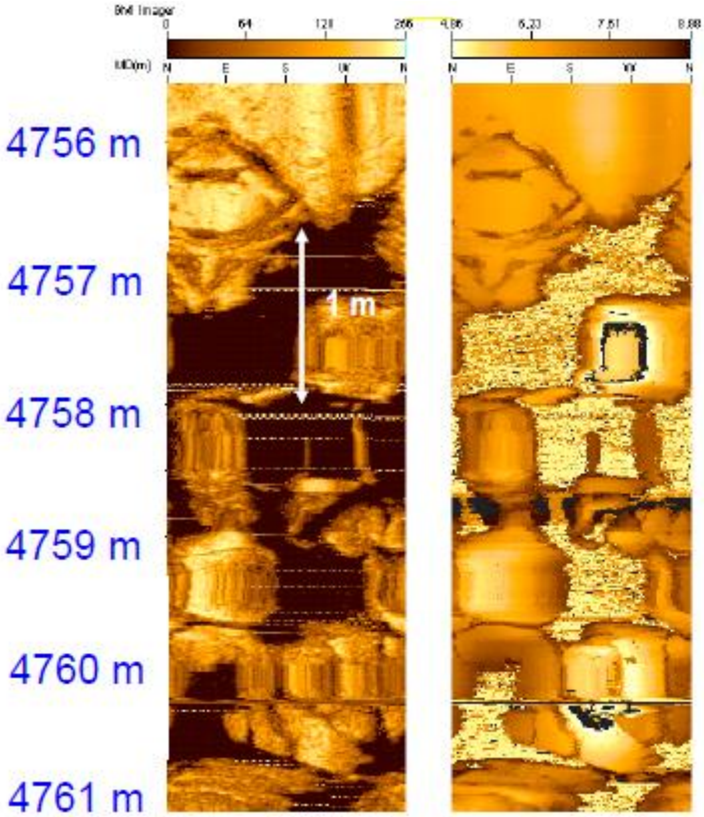


Figure 2: Image of a bore hole section taken with acoustic borehole televiewer

The fracturing in Soultz was performed with stepped increasing water flow for 1 week (50 to 80 l/s) with pressures below 200 bar. During the stimulation a total of 25.000 m³ where injected.

During stimulation, a liquid flow is adjusted and the pressure is rising in the formation and creates seismic events thereof. After a while of liquid injection, the pressure remains constant as new fractures where established and the water found its way. When the liquid injection is shut off suddenly, this can lead to earthquakes due to the instant pressure change. Consequentially, even in case stimulation has to be stopped due to seismic events with big magnitude, the stop should be smooth with constantly reduced volume flows and pressures and not instantly. Also in case of a working power plant producing a formation has to be shut down in case of maintenance, the flow should not be stopped abrupt.

The pressure that will be applied on a formation for stimulation is fixed after several tests and investigations during exploration drillings and is related to the pore pressure of the rock.

When once the rock is stimulated (main reason is shear failure) the new rock arrangement remains as it is and will not snap back to its previous arrangement.

The borehole in HDR and other EGS reservoirs typically is completed with casing strings down to a depth where solid basement rock is reached and the rest below in the pay zone is an open hole completion. While stimulation the pay zone is isolated from the cased zone with packers and the pressure then is only applied to the open hole completion during fracturing.

With 3D seismic already before stimulation, a pretty good image of preexisting fracture networks can be generated.

Temperature Gradient in Soultz:
As recording of the temperature gradient in Soultz has shown poor values between depths of

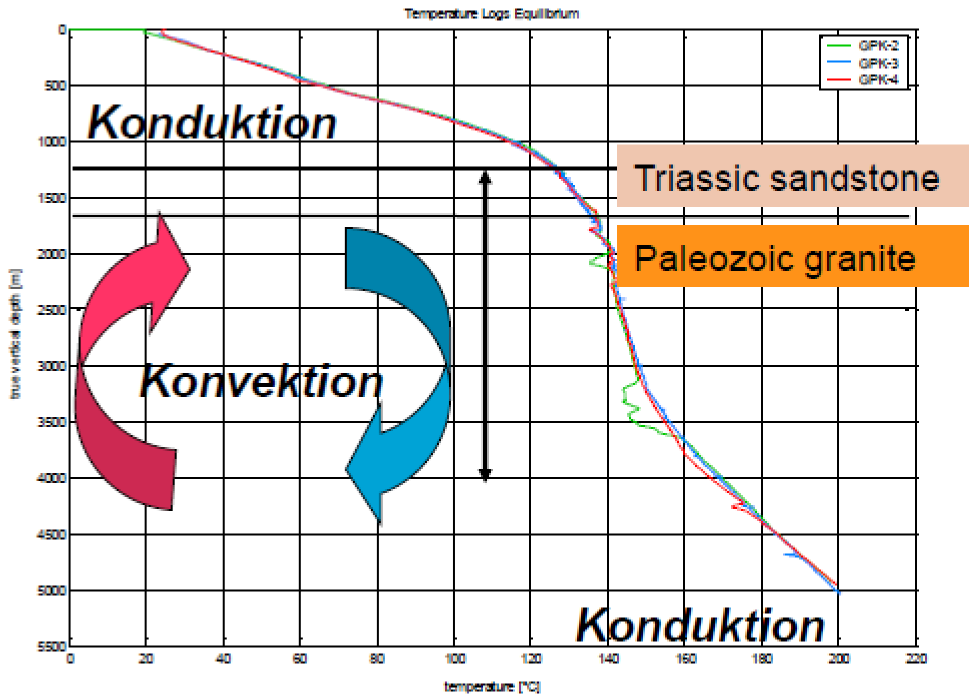


Figure 3: Temperature Gradient at Soultz

1.200m and 3.200m it was concluded that in this depths there is convection due to naturally existing liquids circulating and as a consequence the formation hosting the reservoir in Soultz is not a confined HDR system as originally expected, but is an open system.

Design of the Reservoir:
Originally the design of the system was with the following parameters:
Formation temperature 200°C in 5000m depth
Production water temperature 180°C, injection water temperature 60 to 70°C
Produced water volume flow 60l/s (2 times 30l/s)
Capacity power plant 1,5MW_{el}
The Soultz site was expected to be HDR. However, water and natural fractures were found during erection.
In reality today the injection pump is injecting 20 l/s at a pressure of 50bar
At this pressure no substantial growth of the reservoir is observed.

It has shown that it is important to keep the pressure in the circuit above 18bar where the pressure is lowest (suction side of the injection pump) to prevent the plant from excessive scaling. Currently the pressure is maintained at 20bar.

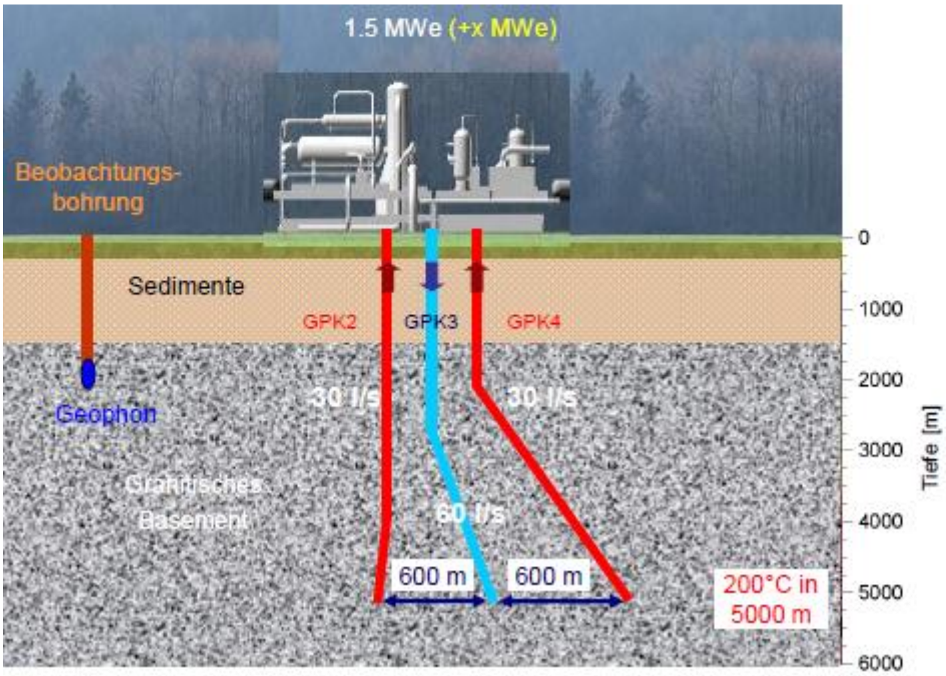


Figure 4: Design conditions at Soultz

The problem with scale is not only that the system has to be cleaned frequently, but also that the scale contains radioactive material as the system in Soultz is an open system where a reasonable amount of fluid reaching surface is naturally occurring geothermal fluids which includes radioactive isotopes. The precipitated scale has to be treated as hazardous waste which is expensive. In Soultz the disposal of about 20 to 30kg of radioactive waste costs about 20.000,- €.

Figure 5: Sample of scale that forms in the Soultz installation

Seismic survey:
3D Seismic which is state of the art today even can show fractures of only a few mm. The seismic surveys generally can illustrate fractures and fissures. 3D seismic survey costs in the range of 100 k€ depending on site size.

Complementary Magneto telluric survey can be beneficial to show possible areas with liquids contained in the rock.

Types of Rock at the Soultz installation:

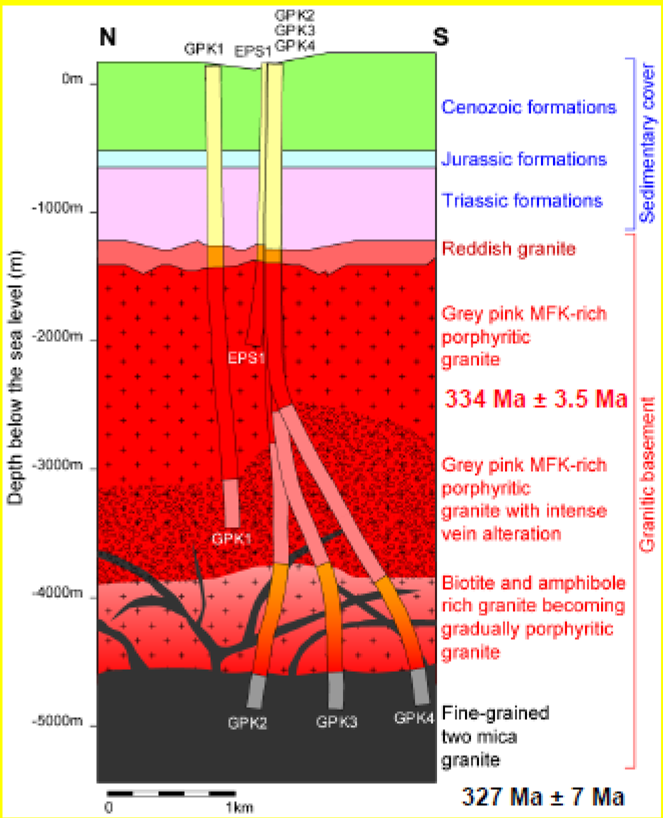


Figure 6: Cross section of the formation at Soultz

Figure 7: fractured Granite (top) and Quartz (bottom)

The fractured Granite shown in Figure 7 exists in the area between 3000m and 4000m depth in Soultz and contains fractures already before stimulation (see red circle). Some of the fractures later filled up with Quartz, as also shown in Figure 7.

Figure 8: aged Granite

The sample as shown in Figure 8 also is from depths of 3000m to 4000m and it shows that naturally existing geofluids already where passing this layer aging the rock.

Figure 9: Fresh Granite

The sample in Figure 9 shows fresh granite as it is in depths of 2 to 3 km in Soultz.

One of the Lessons Learned in Soultz was that it would have been better to stay at shallower depths of about 3 to 4 km where there is already a preexisting fracture network and naturally circulating geofluids are present, even when temperature is lower in this area, than drilling deeper into hotter rock with lower permeability.

Seismic Events during stimulation:
During Soultz formation was stimulated about 20.000 seismic events occurred, with almost all of them with a magnitude of below 1 acc. Richter. Only 2 earthquakes that where felt at surface where registered, 1 at a magnitude of 2,9 and 1 at 2,7.

As a comparison at the Basel project water at pressures of up to 300bar was injected and stronger earthquakes occurred. At the geothermal project in Hanover even up to 700bar where applied without any felt earthquake at surface due to different geology.

If a stronger earthquake occurs due to stimulation, then the stimulation typically was only the trigger to unload already existing stress in the rock, as the energy released in an earthquake is much bigger than the energy implied to the formation due to stimulation.

Chemical stimulation:
In Soultz also chemical stimulation was applied to dissolve Quartz with acids.

Cementing the casing:
In Soultz the casing string is not completely cemented as in the case of Soultz the length of the casing would vary more than 10m due to temperature and if cemented all the way would be destroyed.

Production Pumps:
The production pumps in Soultz are LSP´s (line shaft pumps) installed at a depth of 240m. Without pumps in operation, tests show that there is an artesian flow of 10l/s.

Drilling at Soultz:
All boreholes were drilled with mud.

Tracer Testing:
Tracer tests have shown that only about 30% of the tracers return to surface from what was injected. This is also a confirmation of the reservoir being not confined but open. Tracers injected in one well that has good connectivity to the production well return after about 1 to 2 days, while injected in the well GPK 4 which has bad connection through the fracture network return only after 2 to 3 weeks.

As a consequence of the bad connection of GPK 4, the well was shut in and is not used today.

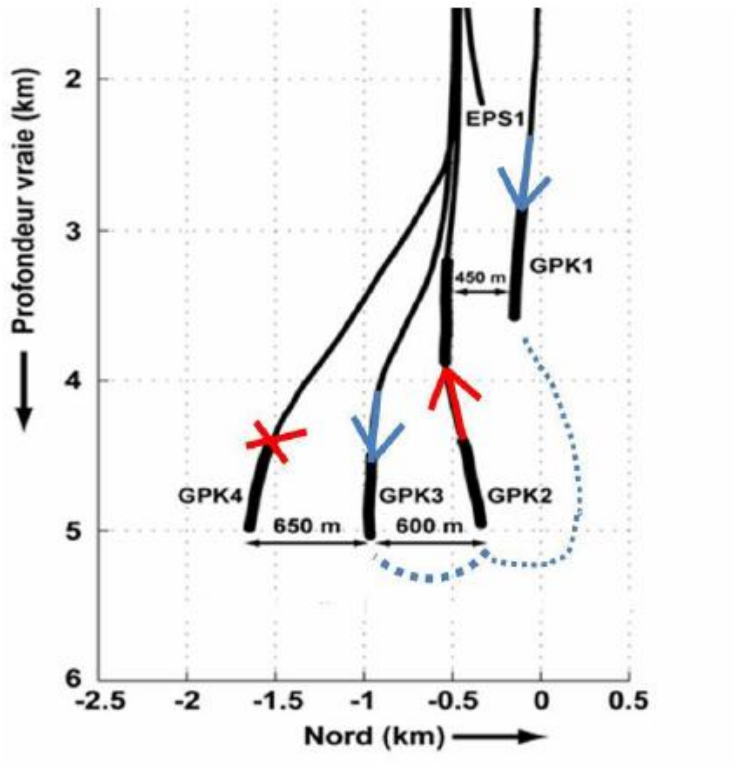


Figure 10: current production scheme at Soultz

A 3D Model shows, that if well GPK4 would be about 500m deeper, there would be good connection to the producing well.

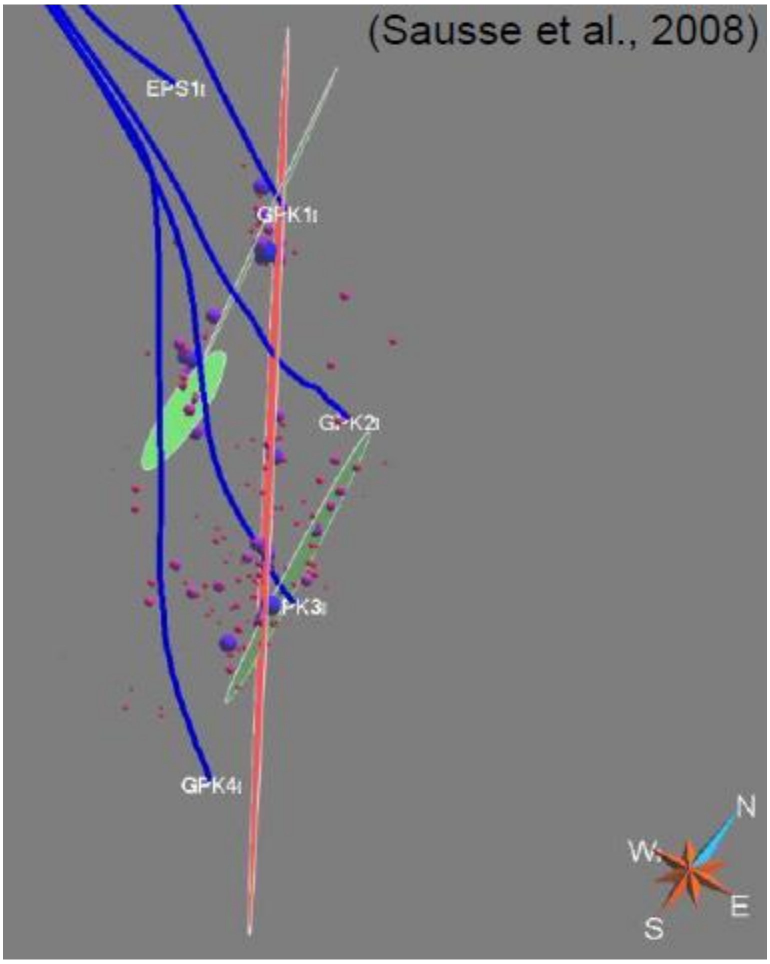


Figure 11: 3D Model of the Soultz formation where main fractures are shown

Tests with ESP Pumps:
Currently there is also another type of pump, other than the LSP, tested. This other pump is an electric submersible pump (ESP) as it is used also in oil production, but modified to the high temperatures. There is no long time experience available yet.

Feed in tariff:
There is different support schemes in France and Germany for Electricity produced by Geothermal power plants. While in France only net produced electricity (parasitic power already deducted) brings revenues with the kWh fed in at 0,12 €, in Germany the gross produced electricity can be fed into the grid with 0,25 to 0,27 € per kWh (power consumption can be bought at standard supply costs).

Killing a well for pump maintenance:
As there is artesian flow, the well needs to be killed before getting access to the production pumps. To do so, a heavy brine is mixed and injected into the production well to stop the artesian flow. If the flow is wanted to be restarted after maintenance, fresh water is injected to decrease density.

Power plant Insheim

Jörg Baumgärtner showed us the construction site and gave us some information about the power plant.

There are 2 wells, 1 production well and 1 injection well, both deviated, with a distance of about 1,5km between the wells at the bottom at a depth of 3.500m. The expected volume flow will be 80 to 85 /s, where the liquid will be injected at 30bar. The produced fluid will have a temperature of about 160°C and the temperature of the injected fluid will be about 60 to 70°C.

The power plant is an ORC type plant with pentane as working fluid and has a capacity of 5 MW_{peak}, although the expected generation will be about 1,4 MW_{el} in average. Heat will be sold on top of the electrical power generated. The expected efficiency of the ORC cycle is 17%.

The investment costs for the power plant are about 12 M€ and the costs for the wells are about 10 M€ per well.

Out of all the electric power consumed of the installation, the pentane pump will consume about 50%.

From project start until start up a period of about 4 years is expected, where the first well was drilled in 2008, the next well was drilled in 2009. Installation of the surface equipment started in early 2012 and the commissioning is scheduled for August 2012. Startup is planned for September 2012.

Before the start of the project the geology was already well understood as in the area there are oilfields produced by Wintershall and GdF.

Power plant Landau

Jörg Baumgärtner showed us the power plant and gave us some basic technical information.

The plant has a capacity of 3 MW_{el} and is based on an ORC cycle, using Isopentane as working fluid. The produced water has a temperature of about 195°C and is reinjected with about 60 to 70°C. The flow is about 50 to 70 /s. The bottom hole distance between the 2 wells is about 1.200m at a depth of 3.300m. The production pump is installed at about 400m.

It is currently discussed that another well is drilled to reduce the risk of major seismic events that can be felt at the surface.

Maintenance costs are about 400 to 500 k€ per year.