Training Course on Geothermal Electricity

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Manual

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The GEOELEC project is a pan-European project on geothermal electricity, supported by the *Intelligent Energy Europe programme* of the EU. The objective of the GEOELEC project is to convince decision-makers about the potential of geothermal electricity in Europe, to stimulate banks and investors in financing geothermal power installations and finally, to attract key potential investors such as oil and gas companies, and electrical utilities to invest in geothermal power. One key element will be to present them the huge geothermal potential in Europe (http://www.geoelec.eu/).

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Contents

Session I – Market aspects

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Dr. Constantine Karytsas has a PhD degree in Geology-Energy from Pennsylvania State University (PSU) USA -1992, and a MSc degree in Environmental Geochemistry from the University of Newcastle Upon Tyne (UK) (1984) with over 20 years professional experience in geothermal applications. Recent work amongst others includes the fields of Seawater Desalination, ORC Binary Cycle Power Production, Geothermal Direct Heat Applications, Geothermal Heat Pump Research and Demonstration, and innovative COMBI system Solar Energy Applications. Participation in 80 research and application/demonstration projects (coordinator in 20 of them) funded by the EU, the European Industry, the Greek State and the Government of the United States (Departments of Energy and Environment). Dr. C. Karytsas is the author or co-author of more than 18 peer reviewed journal articles and 60 announcements in the proceedings of international conferences.
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Dimitrios Mendrinos is a geothermal engineer with masters degree in geothermal energy from the University of Auckland, New Zealand, MBA from the University of Surrey, UK, and more than 20 years professional experience in geothermal energy matters. His recent work includes R&D and market development projects on geothermal heat and power (planning, design and management of geothermal field exploration, exploitation, production monitoring, reservoir engineering and power generation) and ground source heat pumps. He has been the coordinator of the GROUND-REACH and GROUND-MED European projects, and Technical Manager of the GROUNDHIT and LOW-BIN European projects. In addition, he has more than 15 publications in international journals plus 35 announcements in international conferences related to geothermal energy.
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Abstract
Geothermal resources of Europe can contribute to the EU targets of 20% less greenhouse gas emissions, 20% RES share and 20% more energy efficiency by 2020. The session provides an overview of the present status and future prospects of global geothermal electricity market niche, including market size (turnover, capacities, energy yields), near term growth, quality of resources, technologies employed, key players, investment and electricity generation costs, market barriers and incentives.

Keywords: geothermal, power plants, resources, market, development, costs

International Geothermal Market overview
Geothermal energy is the heat of the earth. Depending on the geological environment they are encountered in, geothermal resources are characterized as magmatic/volcanic systems, thermal aquifers, geopressured basins and crustal heat. A global geothermal resource estimate of above categories, in comparison to fossil fuel reserves, is presented in Table 1.

Table 1. World geothermal resources compared to global fossil fuel reserves

Geothermal resources	billion TOE	Fossil fuel reserves (end 2011)	billion TOE
Crustal heat	10.775.600	Coal	422
Magmatic/Volcanic	327.360	Oil	234
Geopressured	55.924	Natural gas	188
Aquifers, thermal	18		

Geothermal exploitation technology requires drilling one or more production wells delivering subsurface hot fluids to the surface, which after feeding a geothermal power plant, are injected back to their origin formations through reinjection wells. In that case, e.g. when deep hot fluids are available, the geothermal resource is termed as a hydrothermal system. Almost all geothermal power plants today are located in such hydrothermal systems, which are encountered mainly at the boundaries of tectonic plates and at geological hot spots, where hot magma is rising towards a thin earth crust. Location of geothermal power plants is shown in Figure 1.

The geothermal plant at Soultz, proved that the exploitation of other parts of the earth crust, where deep hot formations do not naturally deliver the necessary amounts of fluids, is also technically feasible. In these geologic conditions, the hot rocks are artificially fractured by hydraulic fracturing, acidizing, propellants, etc., in order to engineer a man made reservoir, through which surface water is circulated serving as the heat transfer media. These are termed as enhanced geothermal systems (EGS). At present only a few EGS plants are in operation or under development around the globe, but future large scale exploitation of geothermal energy lies in this technology.

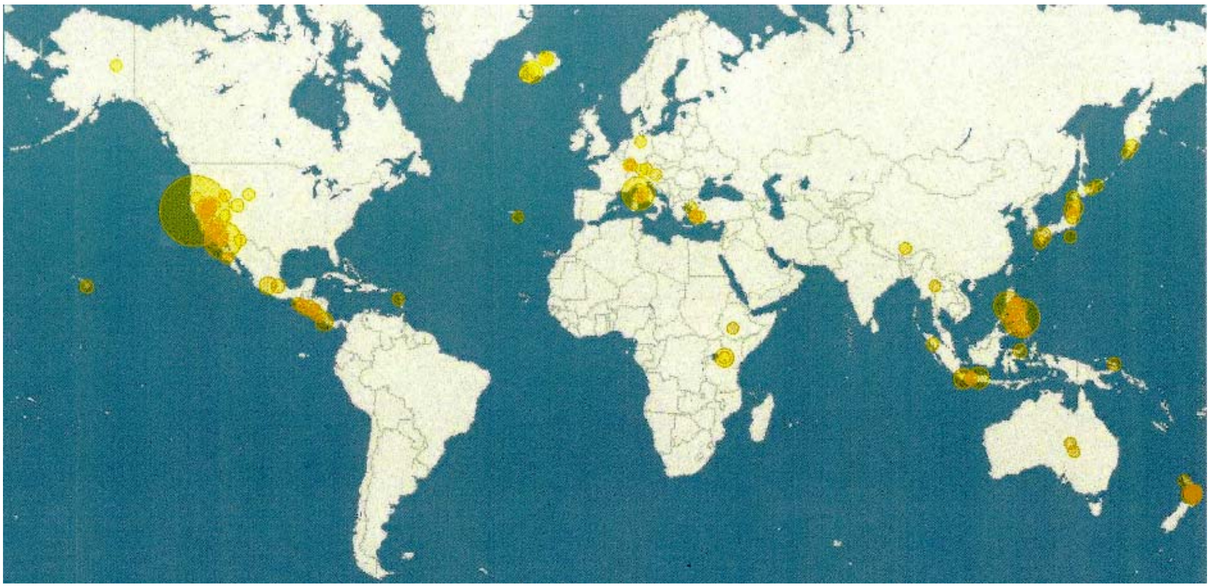

Figure 1. Power plants around the globe (yellow); the larger the cycle, the higher the installed plant capacity.

Depending on the temperature and permeability of the geothermal resource, production wells can deliver to the surface, either dry steam, or two phase mixture of steam and liquid water, or only liquid water.

Only a handful of dry steam resources are encountered around the globe. The most important are the geothermal fields of Larderello, Italy, Geysers, California, and Kamojang, Indonesia. In such fields, the steam from the production wells is directly conveyed to a steam turbine in order to generate electricity. This is termed as a dry steam plant.

In most cases, production wells deliver a mixture of steam and liquid water, which is flashed in order to separate the steam and the liquid (flash plant); the steam is conveyed to a turbine to generate electricity and the separated liquid can be further utilized for power generation or for its heat (cogeneration plant) and then reinjected to its origin reservoir. A flash plant is economically feasible if the production wells deliver more than 150°C.

In cases where resource temperature is lower than 150°C, production wells deliver liquid water with the aid of a submersible or line shaft pump, which feeds a binary power plant. In such a plant, the hot water delivers its heat to a closed loop of secondary fluid, which vaporizes, drives a turbine and condenses in a closed cycle (organic Rankine or Kalina).

In general, exploitation of hydrothermal resources down to 3-4 km depth is a mature commercial technology done by:

- Binary plants for T=100-180°C
- Flash plants for T>180°C
- Dry steam at favourable locations

EGS from 3-6 km depth is a new technology, while supercritical plants (T>350°C) from 5-10 km depth will be a future technology.

The geothermal power market in terms of historical evolution, present status and future projection of installed plants is summarized in Table 2 (world) and Table 3 (EU). Prediction of future installations was based on projects which are at present under development (2015) or announced (2020). The market is dominated by mostly dedicated geothermal field operators and lesser by diversified power utilities, with presence of oil and gas companies, mainly in Indonesia. The six major geothermal field owners and plant operators control >6,5 GWe or 60% of installed capacity.

At global level, market growth which was 3% during the past 20 years, is expected to exceed 10% in the next years, resulting in more than double installed geothermal capacity from 11,5 GW today to 24 GW by 2020. At EU level, market growth patterns are expected to increase from 2% today to 6% during the next years, due to wider geothermal development, as EU member states try to reach their 2020 targets for 20% less greenhouse gas emissions, 20% renewable energy share and 20% more energy efficiency, resulting in installed capacity to increase from less than 1 GW today to 1,5 GW in 2020.

Table 2. World geothermal power plant capacity

MWe	historical evolution					present	forecast	
Country	1990	1995	2000	2005	2010	2012	2015	2020
USA	2.775	2.817	2.228	2.544	3.093	3.187	4.136	5.442
Philippines	891	1.227	1.909	1.931	1.904	1.972	2.112	3.447
Indonesia	145	310	590	797	1.197	1.335	2.325	3.453
Mexico	700	753	755	953	958	990	1.208	1.208
EU	552	641	805	822	896	941	1.113	1.499
New Zealand	283	286	437	435	628	750	1.350	1.599
Iceland	45	50	170	322	575	675	890	1.285
Japan	215	414	547	535	536	537	568	1.807
Kenya	45	45	45	127	167	205	402	560
El Salvador	95	105	161	151	204	204	287	290
Costa Rica	0	55	143	163	166	201	201	201
Nicaragua	35	70	70	77	88	124	209	240
Turkey	21	20	20	20	82	115	206	1.232
Russia	11	11	23	79	82	82	190	194
Papua NG	0	0	0	39	56	56	75	75
Guatemala	0	33	33	33	52	52	120	141
China	19	29	29	28	24	24	60	84
Ethiopia	0	0	9	7	7	7	45	70
Australia	0	0	0	0	1	1	43	70
Chilli	0	0	0	0	0	0	40	160
Honduras	0	0	0	0	0	0	35	35
Nevis	0	0	0	0	0	0	35	35
Argentina	1	1	0	0	0	0	30	300
Canada	0	0	0	0	0	0	20	493
Thailand	0	0	0	0	0	0	1	1
Bolivia	0	0	0	0	0	0	0	100
Iran	0	0	0	0	0	0	0	50
Peru	0	0	0	0	0	0	0	40
Armenia	0	0	0	0	0	0	0	25
Tanzania	0	0	0	0	0	0	0	20
Norway	0	0	0	0	0	0	0	5
Switzerland	0	0	0	0	0	0	0	3
	5.832	**6.867**	**7.974**	**9.064**	**10.717**	**11.456**	**15.701**	**24.162**

Table 3. Geothermal power plant capacity in EU member states

MWe	historical evolution					present	forecast	
Country	**1990**	**1995**	**2000**	**2005**	**2010**	**2012**	**2015**	**2020**
Italy	545	632	785	790	843	883	923	1.019
Portugal	3	5	16	16	29	29	39	60
France	4	4	4	15	16	16	41	42
Germany	0	0	0	0	7	12	92	184
other	0	0	0	1	1	1	18	194
	552	**641**	**805**	**822**	**896**	**941**	**1.113**	**1.499**

The different types of installed geothermal power plants today are presented in Table 4, while the corresponding manufacturers and their market position in Table 5. Average plant sizes are 5 MWe binary, 30 MWe flash and 45 MWe dry steam, with maximum at around 100-130 MWe. Six major turbine manufacturers account for 95% of total installed capacity.

Table 4. Types of geothermal power plants installed today

Geothermal plant type	installed MWe
Flash, condensing	6.904,3
Dry steam	2.862,0
Binary	1.303,0
Flash, back Pressure	146,6

Table 5. Geothermal power plant manufacturers with their corresponding installed capacity

Manufacturer	Steam MWe	Binary MWe	total MWe
Mitsubishi	2.729		2.882
Toshiba	2.721	25	2.746
Fuji	2.315		2.423
Ormat		1.234	1.234
Ansaldo	1.556		1.556
General Electric	532		532
Alstom	155		155
Assoc. Elec. Ind.	90		90
Kaluga	72	10	82
British Thomson Houston	82		82
Mafi Trench		72	72
Qingdao Jieneng	62		62
UTC Turboden (MHI)		19	19
Kawasaki	15		15
Westinghouse	14		14
Elliot	12		12
Harbin	11		11
Enex		11	11
Turbine air system		8	8
Parsons	5		5
Makrotek	5		5
Siemens		4	4
misc.		3	3

The investment costs of geothermal power plants depend on the depth, temperature and chemistry of the resource, as well as the delivery flow rates of the wells. The dry steam, flash and binary plants in operation today exploit the most favourable resources usually from 2-3 km depth, going down to 4-5 km for EGS plants. Investment and levelized electricity generation costs in recent projects are shown in Table 6. Investment costs include exploration, field development and power plant.

In order to estimate the electricity generation costs presented in Table 6, typical operation costs of 0,011-0,020 €/kWh were assumed, an investment discount factor of 8% for 20 years, as well load factors relevant to the installed country: 90% for USA, Portugal and Germany, 80% for Iceland and world average and 70% for Italy, Turkey and EU average.

The main aspects of global and EU geothermal power markets are summarized in Table 7.

Main market barriers hindering geothermal deployment are lengthy permitting procedures, lack of regulations, high risk in finding & identifying geothermal resources and associated finance availability, as well as know how and competent personnel to few companies only.

In USA, geothermal development is driven by federal and state incentives available to energy producers, manufacturers and utilities, which are summarized in Table 8. They include renewable portfolio standards, tax exemptions, investment subsidies and access to grid.

In EU, geothermal development is supported by feed in tariffs, with the tendency to be replaced by feed in premiums. Following the successful example of Germany, Japan, Indonesia and Turkey have recently introduced aggressive feed in tariff schemes, in order to stimulate large scale geothermal power development in their territory. A list of available feed in tariffs is presented in Table 9.

Table 6. Economic aspects of geothermal power generation

recent projects	Investment, €/MWe			Energy production costs, €/kWh		
	Flash	**Binary**	**EGS**	**Flash**	**Binary**	**EGS**
USA	2.700.000	3.100.000	6.200.000	0,055	0,060	0,100
Indonesia, New Zealand, Philippines	2.300.000			0,044		
EU		4.500.000	11.600.000		0,095	0,213
- Germany		6.500.000			0,104	
Chile	3.600.000			0,072		
Turkey	2.750.000			0,066		

Table 7. Global and EU market size and growth

	2012			2012-2020	
	installed	annual sales		annual growth	
	capacity	electricity	value	capacity	investments
	MWe	GWh	billion €	MWe	billion €
World	11.456	71.887	7,2	1.588	4,4
EU	941	5.982	0,9	70	0,5

Table 8. Incentives to geothermal electricity development in USA

Jurisdiction	Statute	Incentive Title	Tax	Type	Taxpayer	yrs	Amount	Max	Expire
Federal	§45	Renewable Electricity Production	Income	Credit	Producer	10	$0.022/Kwh	-	2013
	§48	Investment In Energy Property	Income	Credit	Owner	5	10%	-	2016
	§168(e)(3)	Certain Energy Property	Income	Deduction	Owner	5	200% DB	-	2016
Alabama	§40-18-190	Alternat. Energy Electricity Prod. Facilities	Income	Credit	Utility	20	5%	-	2015
	§40-9B-4	Alternative Energy Production Facilities	Property	Abatement	Utility	-	100%	-	2018
Florida	§196.175	Renewable Energy Source Devices	Property	Exemption	Owner	10	100%	-	-
	§220.193	Renewable Energy Production	Income	Credit	Producer	-	$0.01/kWh	$1 million	2016
Illinois	35 §10/5	Ren. Energy & Conservation Job Creation	Income	Credit	Employer	10/15	Varies	-	-
Indiana	§6-1.1-12-26	Renewable Energy Property	Property	Exemption	Owner	-	100%	-	-
Kentucky	§154.27-010	Renewable Energy Facilities	Income	Credit	Producer	-	50%	-	-
	§154.27-010	Renewable Energy Facilities	Sales	Exemption	Purchaser	25	100%	-	-
Maryland	§10-720	Renewable Energy Production	Income	Credit	Producer	5	$0.0085/kWh	$2.5 million	2015
	§9-203	Solar, Geothermal & Conservation Devel.	Property	Credit	Owner	-	100%	-	-
	§7-242	Renewable Energy Systems	Property	Exemption	Owner	-	100%	-	-
Massachusetts	62§ 2a(2)(G)	Conservation / Alternative Energy Patents	Income	Deduction	Owner	5	100%	-	-
Michigan	§125.2681	Renewable Energy Renaissance Zones	Varies	Abatement	Owner	15	100%	-	-
Mississippi	§27-7-22.29	Alternative Energy Job Creation	Income	Credit	Employer	20	$1,000/emp	100%	liab
	HB1701 2010	Clean Energy Manufacturing Facilities	Income	Exemption	Manufacturer	10	100%	-	-
	HB1701 2010	Clean Energy Manufacturing Facilities	Franchise	Exemption	Manufacturer	10	100%	-	-
	HB1701 2010	Clean Energy Manufacturing Facilities	Sales	Exemption	Manufacturer	10	100%	-	-
New Hampshire	72 §73	Renewable Generation Facilities	Property	Abatement	Owner	5	Varies	-	-
New Jersey	§54:10A	Alternative Energy Technology Company	Income	Credit	Investor	3	30%	$500,000	-
	§54:4-3.113	Renewable Energy Systems	Property	Exemption	Owner	-	100%	-	-
North Carolina	§105-130.28	Renewable En. Property Manufacturing Fac.	Income	Credit	Manufacturer	5	25%	-	2013
Ohio	§3706	Air Quality Renewable/Energy Efficiency/Con	Property	Exemption	Owner -	-	100%	-	-
Pennsylvania	73 §1649.701	Alternative Energy Production	Income	Credit	Producer	-	15%	$1 million	2016
Rhode island	§44-18-30(57	Renewable Energy Systems & Equipment	Sales	Exemption	Purchaser	-	100%	-	-
	§44-3-21	Renewable-Energy Systems	Property	Exemption	Owner	-	100%	-	-
South Carolina	§12-6-3588	Renewable En. Manufacturing Plant/Equip	Income	Credit	Owner	15	10%	$5 million	2015
Tennessee	§67-6-232	Manufacturers Of Clean Energy Tech.	Sales	Credit	Manufacturer	8	99.50%	-	-
	§67-4-2109(n	Green Energy Supply Chain Manufacturers	Income	Credit	Manufacturer	-	100%	-	2028
Vermont	HB446 2009	Clean Energy Assessment Districts	Property	Financing	Owner	-	Varies	-	-
	32 §9741(46)	Renewable-Energy Systems	Sales	Exemption	Purchaser	-	100%	-	-
Virginia	§15.2-958.3	Clean Energy Assessment Districts	Property	Financing	Owner	-	Varies	-	-
	§58.1-3221.4	Renewable Energy Manufacturing	Property	Assessment	Manufacturer	-	Varies	-	-
	§58.1-439.12:03	Green Job Creation	Income	Credit	Employer	5	$500/job	$175,000	2014
Wisconsin	§66.0627 (8)	Renewable En. & Energy-Efficiency Project	Property	Financing	Owner	-	Varies	-	-

Table 9. Feed in tariffs (in black) and premiums (in red)

country	€/kWh	country	€/kWh	country	€/kWh
Japan <15MW >15MW	 0,4077 0,2692	Italy - feed-in premium	0,1300 0,0800	Turkey - max - min	 0,10 0,08
Switzerland <5 MW >20MW	 0,3330 0,1890	Slovenia - feed-in tariff - feed-in premium	 0,1524 0,1036	Belgium green certificates (min)	 0,0900
Germany - EGS - other	 0,3000 0,2500	UK - feed-in tariff equiv. 2 ROCs per MWh	 0,1422	Portugal Azores only	0,0884
France continental - max - min	 0,2800 0,2000	Indonesia - max - min	 0,1308 0,0833	Austria	0,0750
France overseas - max - min	 0,1600 0,1300	Greece	0,1220	Estonia - feed-in premium	 0,0537
Slovakia	0,1905	Romania max-min - feed-in tariff equiv. 2 green cert. per MWh	0,1100 0,0540		
Czech Republic - feed-in tariff - feed-in premium	 0,1810 0,1420	Hungary - max - min	 0,1070 0,0390		

Table 10. Developers of new geothermal power projects

Company	Location	Core Business	operating, MWe	new projects, MWe
Gradient resources	USA	Geothermal	0	1025
Pertamina	Indonesia	Oil & gas	642	875
Oski Energy	USA	Geothermal	0,8	655
Ram Power	USA, global	Geothermal	40	610
Enel	Italy, global	Power utility	955	505
Contact Energy	New Zealand	Power utility	336	490
Landvirksjun	Iceland	Geothermal	63	480
CallEnergy	USA	Power utility	329	470
Calpine	USA	Power producer	1309	420
Idatherm	USA	Geothermal	0	400
Ormat	USA, global	Geothermal	777	350
US Geothermal	USA	Geothermal	54	350
Itochu	Japan, Indonesia	Trade & investments	0	330
EDC	Philippines	Geothermal	756	305
KenGen	Kenya	Power producer	150	280
Altera	USA, global	Power producer	198	280
Zorlu	Turkey	Power producer	15	185
Terra-Gen	USA	Power utility	392	180
			total:	8190

In developing countries support sources to geothermal projects are carbon credits and loans from World Bank ($336 million in 2012, $1710 million overall), Japan International Co-operation Agency, French Development Agency, European Investment Bank ($256 million), German development bank KfW, African Development Bank ($129 million), Asian development bank ($557 million), Interamerican development bank ($416 million) as well as national development banks .

Global geothermal market development is done by ambitious new-coming companies, the most important of which correspond to ~65% of total power plant capacity under development worldwide and are presented in Table 10.

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Session II – Legal, environmental and financial aspects

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Curriculum vitae

Dr. Florence Jaudin, active since 1985, in BRGM, in managing, analysing and diffusion of technical and scientific data on geothermal energy at national level. She also contributed in promoting geothermal energy trough several national and international associations, and has also been involved in several training operations supported by French institutions and European Community. From 2004, she coordinates the BRGM contribution on several European projects on geothermal energy (GEOFAR, GEOTRAINET, GTR-H, GROUND-REACH, LOW-BIN, etc.) she is also involved in several French geothermal training programs.

Dr. Thomas Reif, GGSC Treuhand is working closely together with the law firm Gaßner Groth Siederer & Colleagues, Berlin and Augsburg. The Augsburg Branch is dealing for over eight years in that business offering Due Diligences (financial, legal, tax and environmental), feasibility studies on financial issues and consulting in company law in the Bavarian region of the Molasse Becken. GGSC belongs to a network of professionals of the Geothermal Business covering the geological, drilling and technical aspects. The broaden knowledge enables GGSC profound studies in a standard setting art. The upcoming Geothermal Business in the northern part of Germany (Norddeutsches Becken), which differs geologically from the south and south western parts of Germany, is a challenge not only for the geologists but also for true economical statements in financial feasibility studies evaluating the bunch of risks in a fair manner. Beside the national sector GGSC is focusing in the domains of geothermal energy comprising high enthalpy systems.

Risk insurance for geothermal projects

Abstract

Any industrial project is exposed to risks, even if these risks do not ultimately materialize.

Nevertheless, unlike any common project, a geothermal one undergoes an additional particular risk that lies in the geological characteristic of the geothermal resource. This risk, known as the geological risk, is an inherent part of any geothermal project.

The geological risk covers:

- *The short-term risk of not finding a sufficient geothermal resource (temperature and flow rate) during the drilling phase for an economically sustainable project to take place;*
- *The long-term risk of the geothermal resource depleting over time rendering the whole project economically unprofitable once operation of the geothermal plant has taken place;*

Regardless of the thoroughness of the exploration phase that takes place upstream the drilling phase, the geological risk can only be fully purged when drilling confirms the expected temperature and flow rate. Likewise, in spite of the geothermal plant being operated, there is no guarantee that the original conditions remain over time and that the original temperature and flow rate will not decline.

When considering the geological risk, it is therefore the whole financing of the geothermal electricity project which is at stake. Geothermal projects require high upfront investments that will never be unleashed unless the geological risk is adequately handled. Yet, this can only be achieved by obtaining an insurance policy for the geological risk.

There are different insurance designs existing in Europe to cover the geological risk. Apart from Germany where the private insurance sector engaged in providing market-based insurance policies for geothermal projects, insurance is usually made available from national insurance funds that have been set up on the initiative of governments willing to support geothermal development.

In this respect, national funds may either offer a post-damage guarantee for the geological risk (e.g. France, The Netherlands, Switzerland) or a guaranteed loan, which is forgiven in case the risk materializes (e.g. Germany, Iceland). Both insurance concepts offer pros and cons. However, they undoubtedly contribute to the strengthening of confidence into the geothermal sector.

In this context, insurance is of such significant importance for geothermal electricity development that it is the interest of all European policy makers and investors to give some consideration to the establishment of a European insurance fund to cover the geological risk at European stage.

This contribution to the training course deals with the notion of geological risk and provides an insight into the different existing insurance concepts that cover such a risk in Europe. Last but not least, an overview of a proposed European Geothermal Risk Insurance Fund (EGRIF) covering the geological risk in Europe is also discussed.

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Regulatory barriers

Financing costs of geothermal power projects

Session III – Geothermal exploration and resource assessment

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Curriculum vitae

Adele Manzella, Senior Research Scientist, worked in seismology, numerical modeling for seismic and electromagnetism. Working since 1990 as a geophysicist in geothermal exploration to conduct field and theoretical investigations of geothermal systems in Italy and abroad, in particular using the magnetotelluric method. On 2006 obtained the G.W. Hohmann Award for Teaching and Research in Applied Electrical Geophysics, SEG Foundation, for “outstanding application of electrical and electromagnetic methods to the study of geothermal resources”. Responsible for over 20 projects related to geothermal, crustal and volcanology exploration using geophysical methods, lectured at the annual International School of Geothermics of Pisa and at short courses on geothermal exploration in Chile, North Korea, Ecuador, Ethiopia, Uruguay and Italy, authored about 40 articles in peer-reviewed journals with geothermal-related subjects, and over 100 presentations at international symposia and congresses. She is the scientific coordinator of the two main CNR projects (VIGOR and ATLAS) of geothermal assessment of southern Italy.

Pierre Durst is a Research Scientist, who did his PhD on geochemical modelling on the Soultz-sous-Forêts geothermal project. He worked five years on geochemical and reservoir modelling related to CO_2 storage, then four years on hydrogeological modelling related to water resources management and geothermal resources assessment. Currently he is working on geothermal resources assessment as well as on potential risks and impacts related to geothermal exploitation.

Overview of geothermal energy resources and exploitation: Origin and relation with Earth dynamic

Abstract
This chapter is dedicated to give an overview of geothermal energy from a geological point of view. We will develop the mechanisms and processes involved in order to provide basic comprehension of how the potential exploitation relates to Earth structure and dynamic, as following:

- *Thermal process and Earth internal structures: Where does that heat come from? How is it distributed and transported within the Earth?*
- *Heat flow and geothermal gradient: This chapter will focuses on the repartition of temperature in the first kilometres of the Earth crust, where the heat can potentially be exploited.*
- *Plate tectonic and geothermal resources: Where are located the potential exploitation area in regards to Earth dynamic?*
- *Different types of geothermal energy: A brief description of the potential use of geothermal energy, depending of the available resources and the expected use.*

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Resource assessment: targets and tools

Abstract

Geothermal exploration is aimed at detecting the geothermal resource at depth, defining its physical and chemical features. Geothermal resources can be analysed on different scales and for various purposes, following a step-by-step procedure and zooming from regional, local and reservoir scales. Following the general overview of the previous session, Session IV will analyze in detail how to locate a potential geothermal reservoir, defining its geometry, size and the heat content, and then retrieve information regarding productive zones or areas where stress condition are suitable for EGS development by enhancement of natural permeability. Different tools and approaches can be used to investigate geothermal resources, which depend on the geological context of the site, from sedimentary to volcanic to crystalline reservoirs, and on the nature of the resource, both for natural system and EGS perspectives. The course will provide an overview of the most common geological, geophysical, geochemical methodologies and the collected information, and will explain how to integrate the different data and provide the conceptual model of the resource to be used for locating the exploratory drilling.

With the help of case studies, the presenter will exemplify the exploration procedure and will show what are the main parameters of a conceptual geothermal model, how to compile a body of basic data against which the results of future monitoring can be viewed, and to determine pre-exploitation values of environmentally sensitive parameters.

Keywords: Geothermal assessment, exploration methods, geology, geophysics, geochemistry, monitoring parameters, environment

Geothermal assessment and exploration: an overview

The objectives of geothermal exploration are:

- To identify geothermal phenomena.
- To ascertain that a useful geothermal production field exists.
- To estimate the size of the resource.
- To determine the type of geothermal field.
- To locate productive zones.
- To determine the heat content of the fluids that will be discharged by the wells in the geothermal field.
- To compile a body of basic data against which the results of future monitoring can be viewed.
- To determine the pre-exploitation values of environmentally sensitive parameters.
- To acquire knowledge of any characteristics that might cause problems during field development.

The relative importance of each objective depends on a number of factors, most of which are tied to the resource itself. These include anticipated utilization, technology available, economics, as well as situation, location and time, all of which affect the exploration programme.

Before attempting an exploration program, it is important to define the main features of a geothermal system and therefore the exploration targets.

A conventional geothermal system is made up of four main elements: a heat source, a reservoir, a fluid, which is the carrier that transfers the heat, and a recharge area. The heat source is generally a shallow magmatic body, usually cooling and often still partially molten. The volume of rocks from which heat can be extracted is called the geothermal reservoir, which contains hot fluids, a summary term describing hot water, vapour and gases. A geothermal reservoir is usually surrounded by colder rocks that are hydraulically connected with the reservoir. Hence water may move from colder rocks outside the reservoir (recharge) towards the reservoir, where hot fluids move under the influence of buoyancy forces towards a discharge area.

The mechanism underlying geothermal systems is by and large governed by fluid convection. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat, which is supplied at the base of the circulation system, is the energy that drives the system. Heated fluid of lower density tends to rise and to be replaced by colder fluid of high density, coming from the margins of the system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease.

One aspect of a conventional geothermal system is that it must contain great volumes of fluid at high temperatures or a reservoir that can be recharged with fluids that are heated by contact with the rock. A geothermal reservoir should lie at depths that can be reached by drilling. It is unreasonable to expect to find a hidden hydrothermal system at depths of less than 1 km; at the present time it is not economic to search for geothermal reservoirs that lie at depths of more than 5 km, although actual technology allows reaching depth up to 10 km. In order to be productive, a well must penetrate permeable zones, usually fractures, which can support a high rate of flow. When this requirement is no met, actual technological development is attempting to enhance the natural permeability (EGS). Enhancing a geothermal system generally involves drilling along deviated well paths and with large diameters, drilling with formation damage mitigating technologies, stimulating the reservoir by hydraulic fracturing, and/or targeting fault zones that will produce with high flow rates, which are usually higher than those in hydrocarbon production. Thus, one of the key geological issues, especially critical for EGS development, is knowledge of the stress field and an understanding of geomechanics in the subsurface. The geological characterization must therefore also include various methods that constrain the stress field of a reservoir and elucidate the stress states along faults slated for stimulation. Specific stress conditions are then required, and they should be defined during exploration.

The geological setting in which a geothermal reservoir is to be found can vary widely. The largest geothermal fields currently under exploitation occur in rocks that range from limestone to shale, volcanic rock and granite. Volcanic rocks are probably the most common single rock type in which reservoirs occur. Rather than being identified with a specific lithology, geothermal reservoirs are more closely associated with heat flow systems. As far as geology is concerned, therefore, the important factors in identifying a geothermal reservoir are not rock units, but rather the existence of tectonic elements such as fracturing, and the presence of high heat flow.

The high heat flow conditions that give rise to geothermal systems commonly occur in rift zones, subduction zones and mantle plumes, where large quantities of heat are transported from the mantle to the crust of the earth. Geothermal energy can, however, also occur in areas where thick blankets of thermally insulating sediment cover basement rock that has a relatively normal heat flow. Geothermal systems based on the thermal blanket model are generally of lower grade than those of volcanic origin.

The different elements of a geothermal system represent targets for the application of geological, geophysical and geochemical prospecting techniques. Because of the high temperatures involved, both in the geothermal reservoir and in the source of the geothermal system, we can expect major changes to have taken place in the physical, chemical and geological characteristics of the rock, all of which can be used in the exploration project.

Heat is not easily confined in small volumes of rock. Rather, heat diffuses readily, and a large volume of a rock around a geothermal system will have its properties altered. The rock volume in which anomalies in properties are to be expected will, therefore, generally be large. Exploration techniques need not offer a high level of resolution. Indeed, in geothermal exploration we prefer an approach that is capable of providing a high level of confidence that geothermal fluids will be recovered on drilling.

A geothermal assessment program is generally combined with comprehensive assessment of the geologic setting, especially of the tectonic and structural framework. Thus, fruitful exploration strategies typically involve the following:

- Assessment of the geologic and geodynamic setting
- Geochemistry including fluid and rock isotope chemistry
- Structural analysis of faults, fractures, and folds
- Determination of the regional stress field
- Potential methods, mainly gravity and magnetic surveys
- Electrical and electromagnetic methods
- Seismic methods, both active and passive

A typical procedure in a geothermal project foresees exploration to follow a down-scale workflow, summarized in Figure 1.

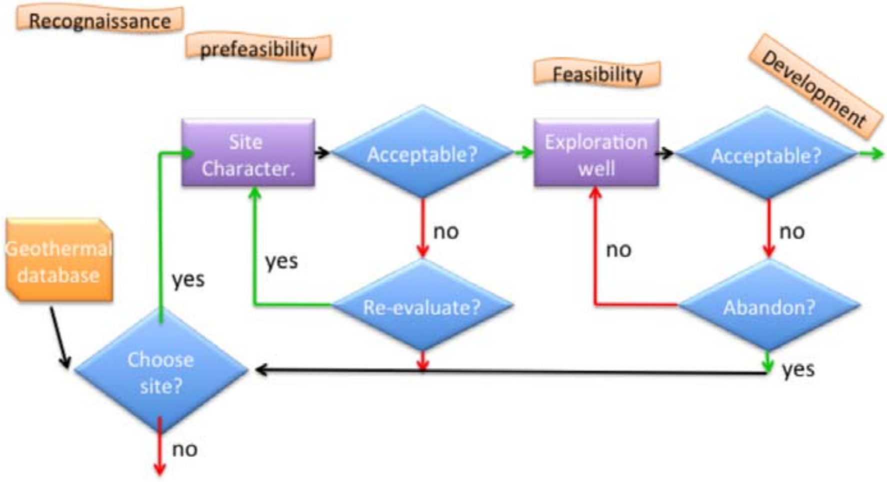

Figure 1. The three phases of a geothermal project development that incorporate exploration.

The assessment programme on a regional basis will begin with a review and coordination of the existing data (reconnaissance phase). All heat flow data acquired previously will have to be re-evaluated, re-gridded, smoothed, averaged and plotted out in a variety of forms in an attempt to identify areas with higher than normal average heat flow. Similarly, the volumes of rocks with ages younger than 106 years should be tabulated in a similar way to provide a longer-range estimate of anomalous heat flow from the crust. Because fracturing is important, levels of seismicity should be analysed, averaged and presented in a uniform format. All information on thermal springs and warm springs should be quantified in some form and plotted in the same format. Comparison of these four sets of data, which relate directly to the characteristics of the basic geothermal model described above, will produce a pattern that will indicate whether the area possesses the conditions favourable for the occurrence of specific geothermal reservoirs. These areas should then be tested further, by applying some or all of the many geophysical, geological and geochemical techniques designed to locate specific reservoirs from which fluids can be produced. Surface manifestation may also be detected by remote sensing techniques, which may be able to map superficial thermal anomalies and topographic changes associated to shallow geothermal anomalies.

The objective of the more detailed studies is to identify the existence of a productive reservoir at attractive temperatures and depths. Detailed geophysical, geological and geochemical studies will be needed in order to identify drilling locations once a prospect area has been defined from reconnaissance.

Geochemical surveys provide the most reliable indications of reservoir temperatures if the thermal fluids emerge at the surface. In any event, all springs and other sources of groundwater should be sampled and various geothermometer calculations carried out. Some prospect areas will probably show much more positive geochemical indicators than others. This could merely reflect the difference in the amount of leakage from subsurface reservoirs, but it does provide a basis for setting priorities for further testing; the geothermal reservoirs that show the most positive indications from geochemical thermometry should be the ones that are investigated first by other geophysical techniques.

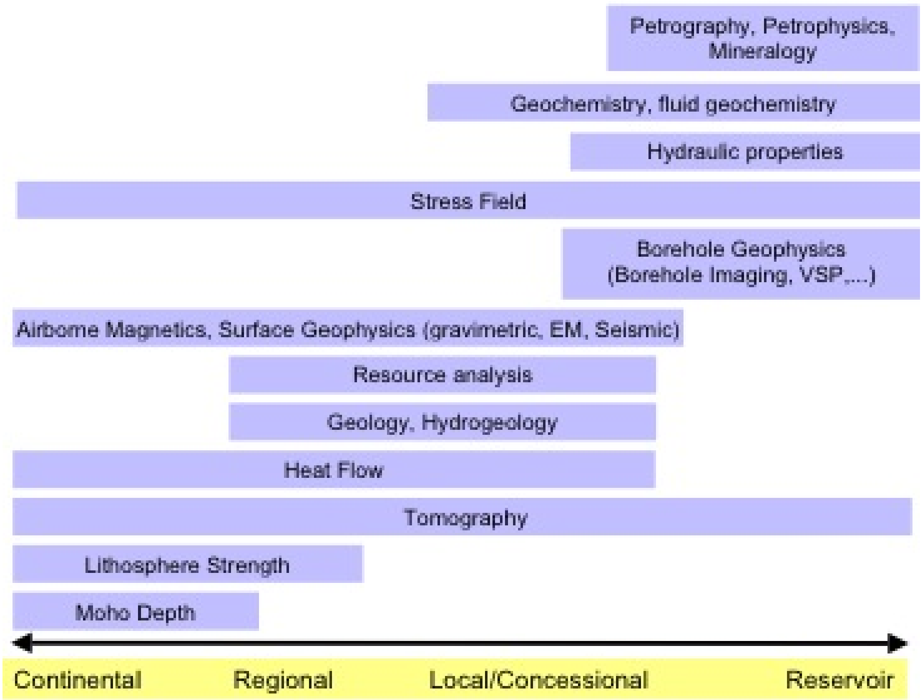

Figure 2. Different information and knowledge available on regional, local/concessional and reservoir scales, to be integrated for site-screening and exploration.

Geophysical methods play a key role in geothermal exploration since many objectives of geothermal exploration can be achieved by these methods. The geophysical surveys are directed at obtaining indirectly, from the surface or from shallow depth, the physical parameters of the geothermal systems. A geothermal system generally causes inhomogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), elastic properties influencing the propagation velocity of elastic waves (seismic survey), density (gravity survey) and magnetic susceptibility (magnetic survey). Most of these methods can provide valuable information on the shape, size, and depth of the deep geological structures constituting a geothermal reservoir, and sometimes of the heat source.
In summary, geothermal exploration for conventional and EGS means, on the one hand, that a reservoir should be understood as a part of a complex geosystem and, on the other hand, it is part of a complex mechanical rock response in the subsurface reacting – either positive or negative – to all manipulations that need to be done from exploration over reservoir access to exploitation. Consequently, geothermal exploration should encompass a broad palette of approaches, which are summarized in Figure 2, from geosystem analysis to reservoir characterization to reservoir geomechanics.

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Session IV – EGS technology

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Presenters

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Curriculum vitae

Prof. Dr. Jan-Diederik van Wees is principal scientist of geothermal research at TNO, and is extra-ordinary professor at Utrecht University on tectonics and geothermal energy. He has published over 60 papers in leading international journals on tectonics, resource assessment, reservoir engineering, and techno-economic models. His current research expertise focuses towards enhanced geothermal systems (EGS) and direct use applications in Europe. Van Wees serves in various co-ordinating roles in major European and national geothermal research projects, including sub-program management (resource assessment) in the Joint Program on Geothermal Energy of the European Energy Research Alliance. Under his leadership, TNO has developed various state-of-the-art geothermal information systems and performance assessment methodologies, including thermoGIS for geothermal aquifers in the Netherlands and a decision support system for the performance assessment of enhanced geothermal systems. Further TNO is active in the EU project GEISER focused towards in depth understanding and mitigation of induced seismicity at geothermal operations.

Prof. Dr. Günter Zimmermann is professor at the Technical University of Berlin since Oct. 1, 2012 and research associate at GFZ Potsdam, at the reservoir technology section since Feb 2002. His education included Diploma in Physics, University Bonn (July 2, 1987), as well as Ph.D. (Dr. rer. nat., Sept. 12, 1991), Habilitation (Lehrbefähigung, Nov. 22, 2006) and Venia Legendi (Lehrbefugnis, Aug. 02, 2007) from the Technical University Berlin. His work experience included postdoctoral research fellow at the Technical Universities of Berlin and Braunschweig (1991-2002) and lecturer (Oct. 1997-Sep.2012) at the Technical University of Berlin. His research interests are in geothermal technology, hydraulic fracturing and fracture mechanics and Coupled thermal-hydraulic reservoir modelling.

Pierre Durst is a Research Scientist, who did his PhD on geochemical modelling on the Soultz-sous-Forêts geothermal project. He worked five years on geochemical and reservoir modelling related to CO_2 storage, then four years on hydrogeological modelling related to water resources management and geothermal resources assessment. Currently he is working on geothermal resources assessment as well as on potential risks and impacts related to geothermal exploitation.

Abstract

This session provides an insight into subsurface technology of Engineered Geothermal Systems (EGS), in particular the process of hydraulic fracturing and induced seismicity in EGS projects. Basic concepts of geomechanics and hydraulic fraccing, results of hydraulic stimulation and induced seismicity in EGS projects will be covered by lessons learned from the GEISER FP7 project.

The setup of this session is as follows

Part 1 theoretical background:

- *Basics of Rock mechanics, tectonic faulting and seismicity*
- *Hydraulic stimulation : best practice from oil and gas, objectives and physical principles*

Part 2: EGS case studies

- *Enhancing flow rates*
- *Induced seismicity*

Part 3: outlook

- *Mitigation strategies*
- *Best practice guidelines*

Keywords: enhanced geothermal systems, hydraulic stimulation, induced seismicity

Introduction

The development of renewable energies is more urgent than ever. Geothermal energy systems have a strong undeveloped potential in continental Europe that is estimated to be between 10,000 and 50,000 MW. But only in the European magmatic areas in Italy, Iceland and Portugal, production of high temperature heat (>200°C) has been harnessed for the generation of electricity (>1,400 MW). Technological development of site-independent technologies to extract high temperatures at very deep levels and independent from natural hot water resources would allow production of geothermal energy in areas which are not marked by magmatism. There, the key is to use open fractures in high-temperature rock so that water and steam circulating into them can rapidly transfer heat to the Earth’s surface. Where fractures are not naturally abundant, one needs to create new fractures or to reactivate existing ones to increase the permeability. This can be carried out by hydraulic stimulation, hydraulic fracturing or acidization, which all consists of injecting fluids at high pressures in the underground. Such so-called enhanced geothermal systems (EGS) hold the key to future growth of geothermal energy but more experience is required to successfully develop these systems.

Theoretical background

Tectonic stress and geomechanical properties of rocks explain jointly the process of natural seismicity as well as the process of breaking rock by fluid injection. Natural fault motions are characterized by shear failure resulting in earthquakes. The spatial distribution and nature of earthquakes is strongly controlled by tectonics, the natural deformation of the earth. Hydraulic fraccing relies on the stress state of the rock and its geomechanical properties. Since decades tensile fraccing, marked by hardly any shear failure, is used routinely in oil and gas to improve the performance of wells. For shale gas and EGS operations hydraulic stimulation often involves the generating of shear fractures in order to connect wells with permeable fractures over large distances.

EGS case studies

Most EGS projects require drilling to several kilometers depth to reach adequate temperatures (about 120°C). In Europe, a few EGS pilots have been performed (Figure 1). These stimulations are often accompanied by vast amounts of induced seismicity, which can be used to characterize the reservoir, but which is also of major concern when it releases sufficient energy to cause possible surface damage or to be felt by the population.

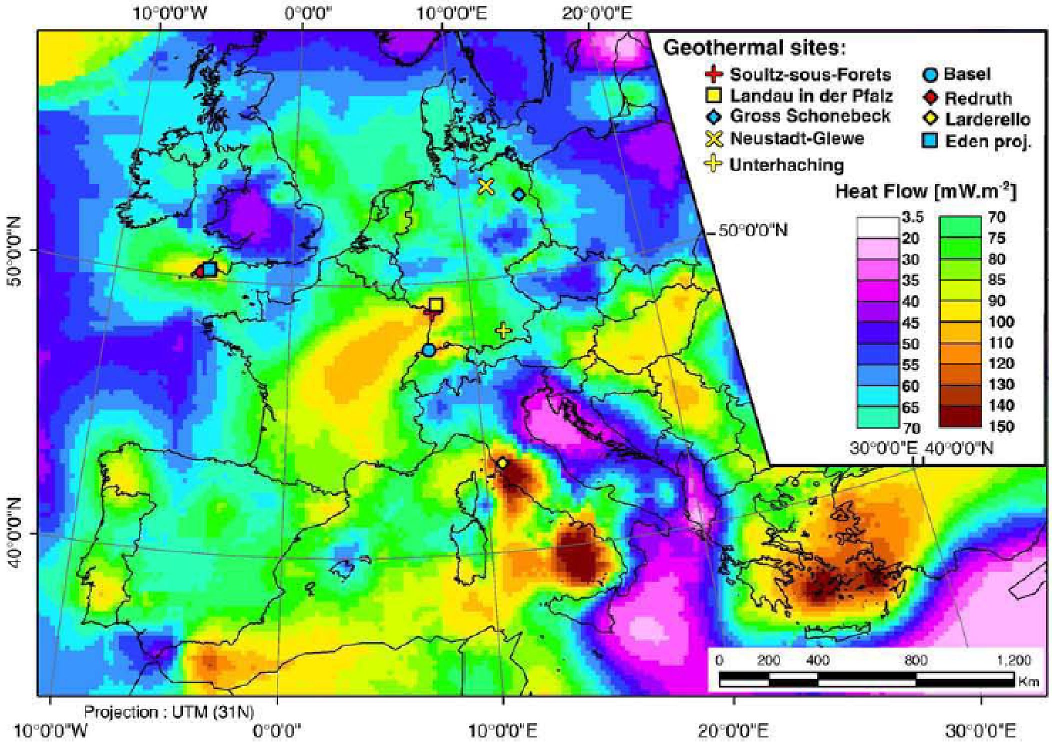

Figure 1. Heat flow map of Europe and geothermal projects.

In this session we present in detail the results from Soultz-sous-Forêts and Groß Schönebeck. Soultz-sous-Forêts was Initiated in 1986, and the project has now a long history which is broadly documented) and benefits from a vast amount of field observations in numerous domains (geology, geochemistry, geophysics, petrophysics, hydrogeology, etc.) gathered during the exploration, drilling, stimulation, circulation, production phases. Today, 1.5 MWe net power can be delivered to the French electrical network.

Over the development of the EGS, four wells have been drilled and stimulated to create the heat exchanger prior to production. The bottoms of the holes are aligned in a N170°E direction consistent with the horizontal principal stress direction.

At the current stage, Soultz is producing from a reservoir at around 5000m depth, at T=190°C, with stimulations after the year 2000 in the wells GPK2, GPK3 and GPK4, circulation tests since 2005 and the longest circulation test in 2010. From logging measurements, it has been noticed that the reservoir consists of strongly altered granite with hydrothermally altered and fractured zones. The hydraulic exchanger of the current Soultz reservoir is dominated by such an altered fracture zone, which extends on large scale as a planer structure linking GPK2 and GPK3 in the deeper reservoir.

Groß Schönebeck is developed from a reopened oil and gas well which was deepened to 4294 m depth to serve as an in-situ geothermal laboratory. Nine months after reopening, the bottom hole temperature was 149 °C at 4285 m depth. The reservoir of interest is composed of sandstones, conglomerates and underlying andesitic volcanic rocks. The sandstones constitute the principal targeted reservoir. They are well-sorted, middle to fine grained, with 8 to 10 % porosity and in-situ permeability of 10 – 100 mD. In contrast to the Dethlingen sandstone formation, the permeability of the volcanic rock is rather high due to connected fractures. Several stimulation operations were carried out in this well at the reservoir level to enhance water productivity and they are discussed in the next section in parallel with the induced seismicity. To complete the doublet system of this EGS site, the production well was drilled in 2007 down to the volcanic rocks. The stress magnitudes in the Dethlingen sandstone at 4.1 km depth were determined to be S_V=78 - 100 MPa from density logs, S_H=98 MPa (at N18E) estimated from transitional form of stress regime from normal faulting to strike slip faulting, and S_h=55 MPa from leak-off tests in both wells. In the volcanic section, mainly the minimal principal horizontal stress is different and is equal to S_h=72 MPa.

During stimulation, the strongest micro-earthquakes (with $M_w \leq -1$) occurred on a pre-existing fault, which theoretically was relatively critically stressed. The strike and dip of this fracture plane are 17°±10° and 52°±10° SE respectively.

In Soultz, Groß Schönebeck, and other pilot sites, the observed induced seismicity, spatially lines up in relatively large and planar fault and fracture zones. Mechanical models for seismic rupture clearly demonstrate that the geometrical and rheological alignment of these fractures, in interaction with the pre-existing and perturbed stress field due to hydraulic stimulation is key to induced seismicity. Connecting to critically stressed crustal scale faults, can -in theory- trigger relatively large events.

Outlook

The predicted contribution of EGS in the worldwide geothermal energy production portfolio is significant for 2050. Widespread growth of EGS is anticipated after 2020 since, at that point, easy accessible hydrothermal systems are becoming scarce. Moreover, research and development will enable EGS to be ready for large scale deployment, both in terms of securing public acceptance and environmental safety with regards to induced seismicity and in terms of reducing levelized (the levelized cost of a given energy is the ratio between the sum of all costs necessary to produce this energy over time and the production duration) costs of energy (IEA, 2011).

In Australia and in the USA, generous funding of EGS projects provides the opportunity for these countries to develop EGS technology. In Europe, to face these challenges, the European Energy Research Alliance (EERA) Joint Program on Geothermal Energy (JPGE) aims at providing an outstanding contribution bringing together 20 leading European geothermal research institutions in a single strategically oriented joint research and development program. The EU funds research activities partly under the umbrella of the JPGE which includes for instance the EU project GEISER (2010-2013) that investigates geothermal engineering integrating mitigation of induced seismicity in geothermal reservoirs.

With an emphasis on expanding the geothermal resource base by including potential sites for enhanced geothermal systems (EGS), engineering concepts need to be developed for a variety of geological settings that are not normally accessed for geothermal electricity production. As the enhancement of a geothermal reservoir involves fracturing of the reservoir rocks, the risks of this process needs to be understood in detail to both increase the probability of creating the enhanced flow paths for fluid circulation to make exploitation of the reservoir economically viable and to reduce the risk of triggering earthquakes that can be felt at the surface, disturb the public and cause damages to buildings.

It is clear that we need a more sound theoretical understanding complemented by hands on experience in pilot projects. For these pilot projects we need guidelines for safe and reliable EGS operations. The EU project GEISER will provide these. Key is a dynamic –forewarning- traffic light system. The reliability of the dynamic model comes from physics and probabilistic based underpinning for seismicity forecasting, calibrated to geological subsurface information and real-time monitoring data. This approach allows adjusting operational conditions to mitigate unsolicited effects and to improve system performance.

Further the guidelines will propose a strategy to enhance public support to EGS projects, based on lessons learned from past projects. A cost-benefit balance for the stakeholders throughout the entire exploration and production workflow is important, capable of identifying and proper addressing different interests and (perceived) risks regarding a specific EGS project. In view of the latter, nuisance and trivial damage should be addressed with care and considered as a significant project risk. For structural damage a procedure is needed to evaluate and compensate the costs involved.

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The Soultz projects: towards the deep geothermal exploitation

Abstract

Following the general EGS technology course, this chapter is dedicated to the Soultz-sous-Forêts project as the example of the deep geothermal exploitation. We will develop the 20 years scientific research to end at the application of non-conventional geothermal exploitation, as following:

- *Concept and history: why develop the deep geothermal energy, how, the main research projects and their contributions.*
- *General presentation of the Soultz project: partners, main steps of the project.*
- *General context: why this location, main characterisation as geology, stress field, fluids,…*
- *Principle of permeability enhancing: how create thermal exchanging surfaces, which mechanisms, result and consequences.*
- *Feasibility of a deep geothermal loop: development of the upper reservoir (3500m) and the first circulation test.*
- *Toward the 200°C, development of the lower reservoir at 5km depth: deep wells, production tests, tracer tests, hydraulic stimulation, induced microseismicity, chemical stimulation, understanding of the hydraulic circulation.*
- *Exploitation of the 200°C: circulation test and tracer test, circulation model, pumps, surface power plant and electrical production.*
- *Issues, potentiality and industrial development.*

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Session V – Drilling

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Curriculum vitae

Wulf Brandt, presently drilling consultant, holds a diploma in drilling engineering and oil production techniques of the Mining Academy of Freiberg/Germany. Since 1983 he dealt with various aspects of utilizing geothermal energy, for example he was responsible for opening the first East German geothermal heating system 1984 in Waren/Mueritz. He finished his career as a scientist with GFZ Potsdam (drilling the second well and completion of the thermal water loop Groß Schönebeck). Currently he represents the operator as senior drilling supervisor for a geothermal doublet in the eastern foreland of the Alps. He authored/co-authored several technical/scientific papers.

Abstract

The contribution is focused on drilling of geothermal wells for tapping hydrogeothermal resources and EGS with low enthalpy. Due to the low energy content of the produced geothermal fluid – more or less mineralized water – the flow rate should be as high as possible in order to make the project an economic success. Thus the borehole design differs considerably from oil and gas production: larger diameters and faster temperature changes over an extended well lifetime require an adapted approach.

Keywords: geothermal, drilling, borehole design

Introduction

In the first training course last year, Ungemach and Antics (2012) gave a broad survey on drilling of geothermal wells both in high enthalpy reservoirs as well as into sediments utilized for district heating systems, the latter with emphasis on well completion. The actual course is focused to geothermal wells for power production in regions with "normal" geothermal gradients such as the Bavarian Molasse basin and the Upper Rhine valley. Here a number of sites with geothermal power production have been developed within the last few years (e.g., Soultz (EGS), Landau, Bruchsal, Unterhaching etc.). Production temperatures in the range from 170 to 110 °C allow power production by means of the Organic Rankine or the Kalina cycles. The naturally low efficiency of those processes requires considerably high flow rates.

Flow rate

The most productive oil well ever, “Cerro Azul No.4” in Mexico, spilled over 150000 t crude over a radius of 3 km within one week in 1916, converting the landscape into an oil lake (Figure 1). /http://www.sjvgeology.org/history/gushers_world.html

Figure 1. Cerro Azul blow out

Such high flow rates (here about 250 l/s) are very rare. During the spectaculous blow out of the Macondo well (Deepwater Horizon rig) in 2010 a maximum flow rate 120 l/s has been observed.

For reasons of comparison:

With the well GPK 2 at Soultz-sous-Forêts a flow rate of 30 l/s with 170 °C, represents a usable thermal power of about 12,5 MW.

The most productive geothermal wells in Bavaria (carstic-fractured dolomites of Jurassic age) yield more than 150 l/s thermal water at a withdrawal of the dynamic water table below the static one of 200…300 m. With well head temperatures of about 120…130 °C the usable thermal power reaches the range of 30 MW_{th}.

A reasonable and economical pipe design is based on flow velocities in the range of 2…3 m/s. Therefore production casings in the range from 13 3/8” to 10 ¾” should be the optimum size for the last cemented casing of such wells.

Drilling costs are in general depending of the rock volume to be destroyed. Thus reasonable compromises will have to be found for the casing schemes of high performance geothermal wells. So short 7 5/8” liners turn out to be the minimum acceptable dimension.

Temperature

The oil and gas industry has developed appropriate concepts to adjust casing design and cementation to high pressure/high temperature (HPHT) borehole conditions using higher wall thicknesses and higher steel grades. In some deep geothermal wells similar conditions were encountered. But here cyclic temperature changes due to short time fluctuations of the flow rate and due to production stops result in stresses on the system casing - cement – rock, which is decisive for the borehole integrity.

While in oil and gas wells the tubing - packer completion as a standard insulates the casing from sudden temperature and pressure changes the tubingless completion of geothermal wells immediately leads to changing stresses. Such stress changes particularly affect the long term borehole integrity, as evidenced by the formation of micro annuli and by the integrity of the cement stone itself.

It can be assumed that a good bond between casing and cement will prevent the casing from moving due to the thermal expansion of steel but if there is no cement bond the free pipe tends to "travel". For the sake of casing integrity "buckling" must strictly be avoided, as the premium connections generally used nowadays will lose their tightness properties. It is common practice to set free (un-cemented parts of) casing under sufficient tension which compensates for the thermal elongation. The following example shows the practical importance:

The un-cemented part of the second casing (Top Of Cement 800 m) should be removed <u>after</u> testing the well in order to create the pump chamber for installing an electrical submersible pump with its large diameter. During the test that casing will expand as it is heated up by the produced thermal water from the state of the geotherm (temperature distribution according to the geothermal condition at depth) to the wellhead temperature while testing (e.g., 120 °C).

Delta l = TOC * Alpha * Delta T

With TOC – Top of cement

Coefficient of thermal expansion - Alpha=12*10^-6/°C

Thus a temperature change of about 100 K will result in an elongation of the casing of 0,96 m. In order to prevent buckling of the casing that elongation can be compensated by pulling the casing in tension. The resulting force amounts to 3370 kN resp. 343 t.

F res = E*A*delta l/TOC*10^-3

with E = 2,1 * 10^5 N/mm²

A = 13398 mm² (13 3/8"casing)

In addition, it is necessary to compensate for the own weight of the un-cemented casing (here about 71 t must be pulled in order to prevent the casing at the top of cement from compression) as to add the minimum landing force of the slips (e.g. 10 t). So considerable forces in the range of 420 t have to be pulled to avoid buckling of the casing.

So the casing concepts have to take into consideration those influences from temperature changes by producing hot and injecting cold water over the lifetime of the wells (test, hydraulic stimulation, production, and injection) either by designing the system casing – cement in such a way that it can withstand the resulting forces or to allow free movement of the un-cemented part of the casing.

Tie back strings are common to connect a liner hanger to the surface, e.g. to protect the upper casings from unduly high internal pressures during stimulation jobs. Here a piston seal is moving within the polished bore receptacle on top of the liner hanger.

For the wells at Soultz-sous-Forêts that principle has been applied to the well head – the free casing (not imposed to buckling by its design) moves in a stuffing box situated within the cellar (see Figure 2).

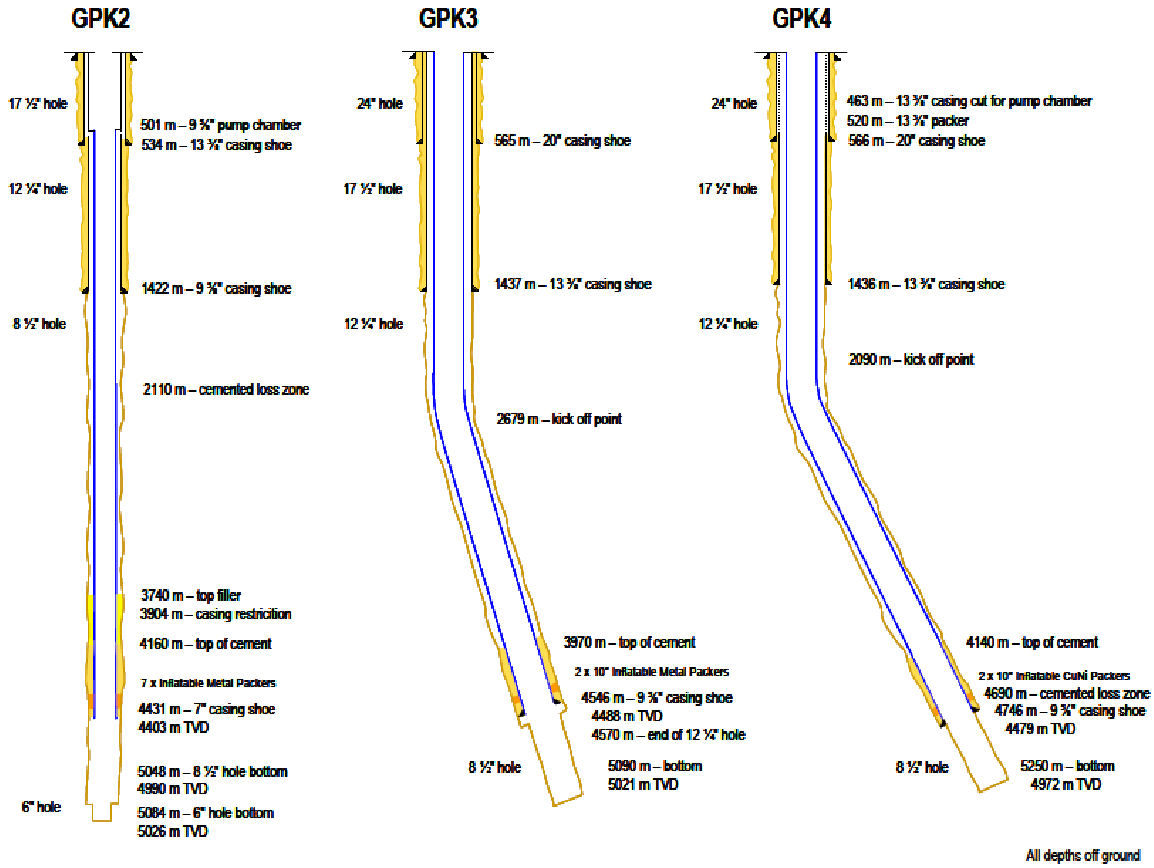

Figure 2. Casing design Soultz-sous-Forêts /Tischner et al., 2006

The un-cemented part of the hole is formed by solid rock belonging to a uniform hydrogeological section.

Heating up of geothermal wells during production does not only affect the casing elongation but it can cause considerable damage by the expansion of water or mud trapped behind the casing if it cannot escape into the surrounding rock.

Often the resulting external pressure exceeds the resistivity of the casing resulting in an unexpected casing collapse.

Casing design and geological conditions

The site related geological knowledge is crucial with regard to cost effective drilling and the prevention of drilling troubles. The following principles are mandatory:

- Define casing setting depths to allow for a maximum stability of the preceding drilling section.

- Eliminate strongly different formation pressure gradients within drilling phases since differential sticking can cause costly fishing operations or even endanger the whole well.
- Some formations require special mud systems such as salt layers, or should be protected for other reasons by setting the casing as soon as possible.
- Separation of formations against circulation or gas migration behind the casing

Casing – bit combinations

The industry offers a broad selection of casing dimensions and of bits as well. But it is worth mentioning that certain combinations of casings have been ruled out as "standards" with short time availability not only for pipes but also concerning float equipment, liner hangers, packers etc. If it is necessary to change to "exotic" dimensions (including features like "special drift" and "special clearance" the designing engineer must check that all necessary equipment will be available in due time. A useful survey on possible casing-bit-combinations is shown in Figure 3.

To overcome those constraints generally ongoing R&D at Baker Hughes INTEC GmbH, for example, is directed to combinations of conventional borehole design with expandable liner techniques or even to the creation of monodiameter boreholes (see Figure 4).

Case histories of drilling 4000…5000 m deep geothermal wells are content of the oral presentation.

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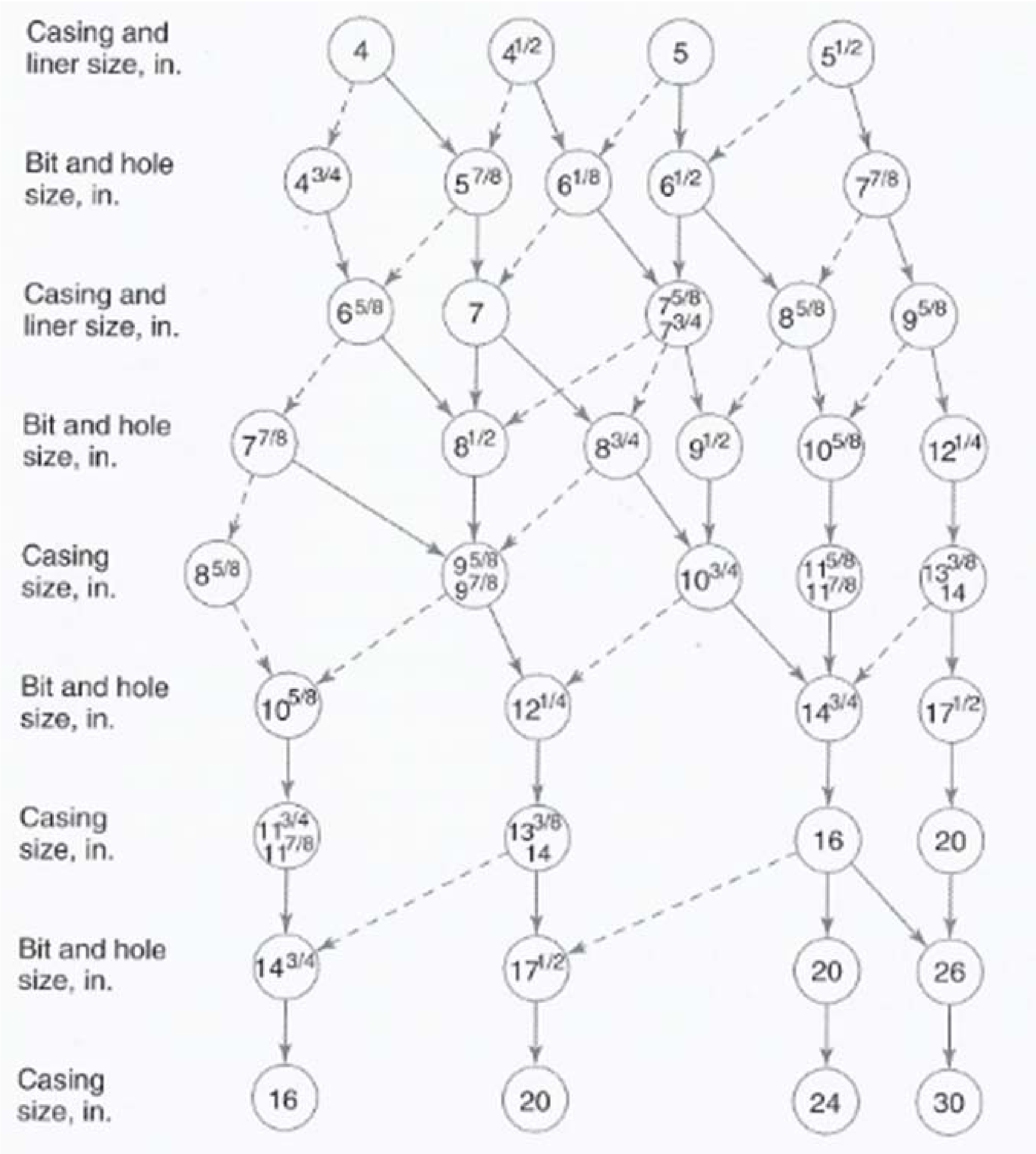

Figure 3. Casing - bit – combinations /Barker, 1998

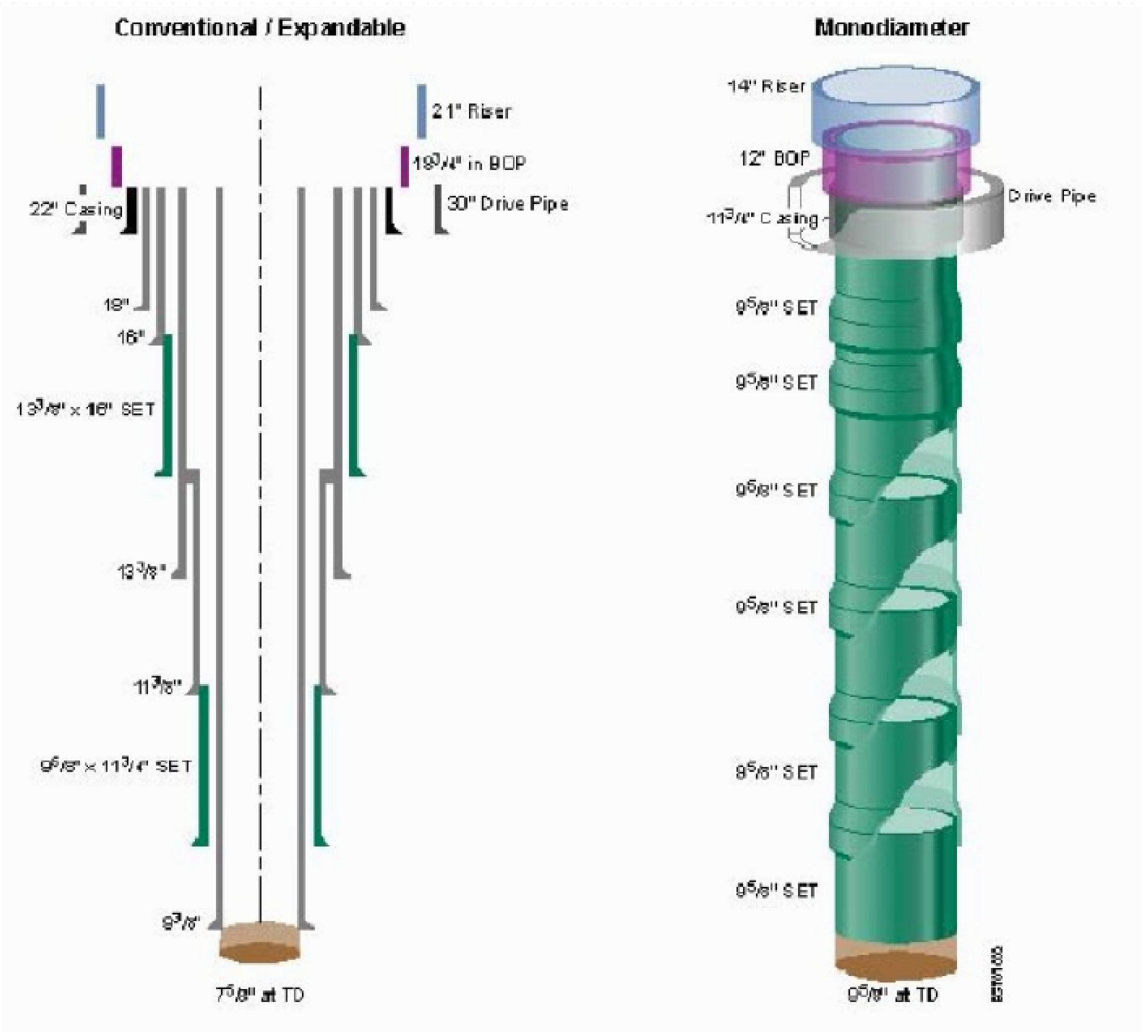

Figure 4. Borehole design with expandables /Oppelt, 2008

Session VI – Flash steam and binary technology

E. Hallgrímsdóttir and P. Bombarda

Presenters


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Curriculum vitae

Mrs. Elín Hallgrímsdóttir is a Mechanical Engineer, MSc, from Danmarks Tekniske Universitet in 1998. Mechanical Engineer, CandSc, from University of Iceland 1996. Mrs Elín Hallgrímsdóttir has experience within thermodynamics and process engineering as well as project management and quality systems. Mrs Hallgrímsdóttir has participated as assistant project manager and senior designer within numerous projects in Mannvit such as in the Nesjavellir and Hellisheidarvirkjun geothermal combined heat and power projects. Mrs Hallgrímsdóttir held the position of Mannvit project manager in a feasibility study for KenGen in Kenya. Mrs Hallgrímsdóttir has further given presentations on geothermal energy for short courses held by Mannvit.

Dr. Paola Bombarda has a PhD in Energetics -1994 and MSc Degree in Mechanical Engineering -1990, both from Politecnico di Milano (I) and is Assistant Professor of “Energy and Environmental Systems” at Politecnico di Milano since 1995. She has a deep knowledge in thermodynamic analysis of energy systems for power generation, cogeneration, trigeneration and plant performance optimization, with specific interest in renewables and above all in geothermal energy. She has gained wide experience in modeling, simulation, thermodynamic analysis and optimization of geothermal power plants (dry steam and flash, binary, hybrid plants) for which she also tackled techno-economic analysis and electric energy cost estimation. Particular expertise is acquired for ORC plants. Research activity is devoted also to the study and analysis of complex energy systems including geothermal heat pumps. Participant to several national and European research projects on geothermal energy and energy systems. Lecturer for the subject “Geothermal energy” in the frame of the master RIDEF at Politecnico di Milano. She contributed with papers and presentations to the main international geothermal Conferences.

Abstract
This is an overview of geothermal power plants with focus on flash and binary thermodynamic cycles, geothermal steam gathering system and mechanical equipment used. Further provided examples highlight special features of utilizing geothermal fluid for power generation. The examples taken are connected to the special conditions encountered in geothermal energy.
Flash steam cycles with single flash and double flash as well as different binary cycles as ORC and Kalina Cycle are introduced and compared. Models for different thermodynamic cycles are used to calculate the same example for visual comparison of the different cycles.
An overview of the design process of a geothermal steam gathering system with emphasis on particularities of the geothermal fluid is presented. The presenter goes through a calculated example to show methods used for basic engineering within steam gathering system design.
A presentation will focus on mechanical equipment used in geothermal power plants. Emphasis will be on different design considerations compared to conventional steam plants. A calculated example will show methods used for basic engineering within mechanical equipment design.
Operation and maintenance of geothermal power plants with emphasis on the geothermal part of the plant is introduced. Photographs of extreme conditions are discussed with solutions.

Keywords: Geothermal energy, electricity generation, process flow, binary technology, steam gathering system, operation and maintenance

Process flow and steam gathering system
Geothermal power plants utilize heat energy from the Earth to generate electricity and can also be designed to generate combined heat and power (CHP). They are cost effective, reliable and environmentally friendly. The specific geothermal power plant configurations must match the heat resource to maximize its potential but should also take into account a variety of other criteria including, local conditions and requirements as well as the needs of the local community. Thermodynamic cycles used in geothermal energy production will be reviewed with examples. Flash steam cycles with single flash and double flash as well as different binary cycles as ORC and Kalina Cycle are introduced and compared through both capacity and cost.
An overview of the design process of a geothermal steam gathering system with emphasis on particularities of the geothermal fluid is presented. Models for different thermodynamic cycles will be used to calculate the same example for visual comparison of the different cycles.

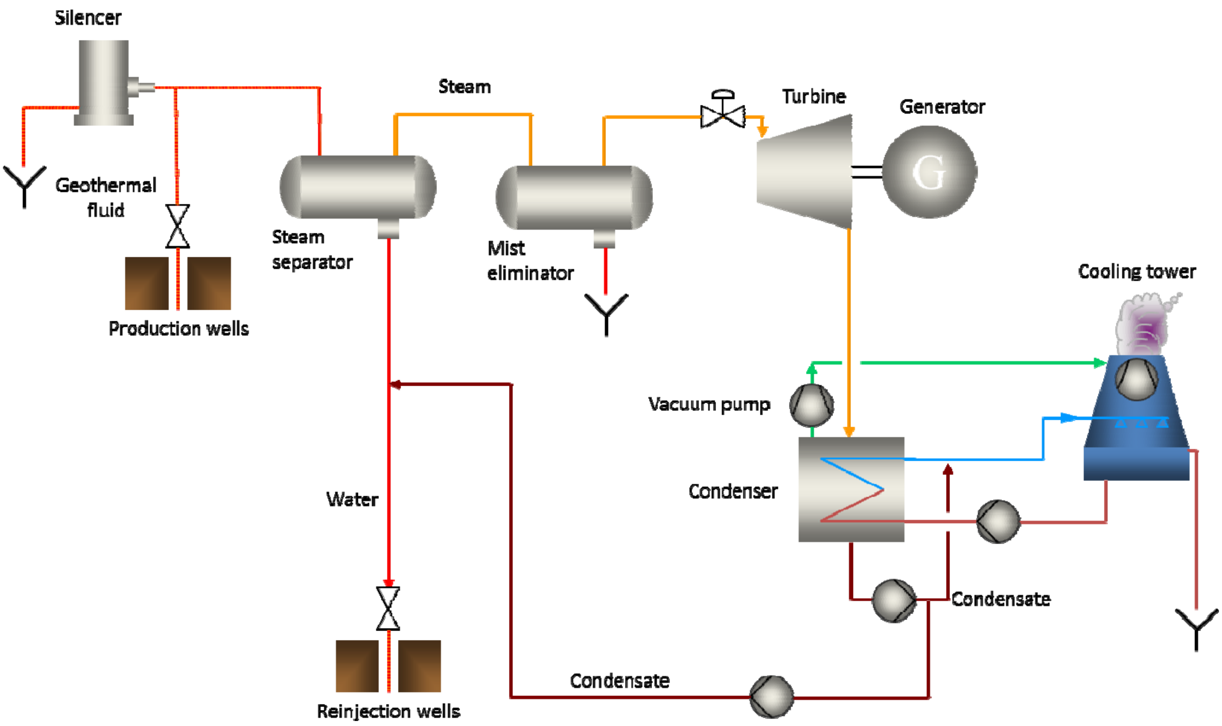

Figure 1. Process Flow Diagram of Steam Power Plant with Condenser

Figure 2. Steam field of Hellisheiði Power Plant

All geothermal fields are unique and the steam gathering system carries the energy from the field to the power plant. To join multiple wells into one steam gathering system requires for example decision of optimum separator pressure. The presenter will go through a calculated example to show methods used for basic engineering within steam gathering system design. The example taken will be connected to the special conditions encountered in geothermal energy.

The steam field design includes situating wells drilled in groups as appropriate. Wells are preferably situated higher in the landscape than the separator station and power station. If possible the power station should be situated a little lower than the separator station. This is preferred to facilitate natural fluid flow. The distance between separation station and mist separators should be selected long enough for the moisture to condensate in the pipeline before entering the mist separators.

When the geothermal fluid is two phase, and steam represents a low fraction of it, or the geothermal fluid is fully constituted by water, typically with medium-low temperature sources, the binary technology is applied, and generally a downhole pump (i.e. a pump installed directly in the well) is required. The geothermal fluid loop is in this case completely separated from the power generation cycle; the adoption of the downhole pump, though requiring a high auxiliary power consumption, can assure a constant discharge flow at a convenient pressure, so as to keep the geothermal fluid in liquid phase, avoiding any flash process. In this way two important results are obtained: all the non-condensable gases (mostly CO2) are maintained in the liquid phase, and, salt precipitation, which could otherwise occur after the flash process, both downhole and on surface, is strongly reduced. Geothermal fluid leakage can be effectively avoided, because the fluid is confined in a limited part of the plant, and total reinjection is then feasible, thus leading to a virtual zero emission plant and sustainable reservoir exploitation.

The power generation cycle is a closed cycle, whose design guidelines relies on fundamental thermodynamic principles, is realized by means of a convenient working fluid. The easiest possible scheme is shown in Figure 3.

The working fluid evaporation occurs in the evaporator, the heat exchanger charged with heat introduction; the vapour so generated enters afterwards the turbine, which is charged with power generation; subsequently the vapour condenses in the condenser, the heat exchanger charged with heat rejection to the ambient, and finally the condensate enters into the pump, which is charged with working fluid pressurization.

The working fluid selection is a crucial choice: being the cycle closed, whatever working fluid can be selected, but this choice has a huge effect on plant performance and component size, and thus cost.

The two different categories of binary cycles commonly available, Organic Rankine Cycles (ORC) and Kalina cycles, differentiate as far as the working fluid is concerned: in ORC a pure working fluid, (or seldom an azeotropic mixture) is utilized, while in Kalina cycle and Kalina derived cycles, a mixture of water and ammonia is selected.

At present, most commonly used working fluids for ORC geothermal applications are some hydrocarbons and refrigerants (several refrigerants are non flammable or flammable only under extreme ignition conditions, and are therefore particularly eligible when non–flammability is desired; other fluids, like siloxanes, may be selected at higher temperatures, as, for example, for biomass applications). As a first, general rule of thumb, the working fluid must be selected according to its critical temperature and the temperature of the geothermal source.

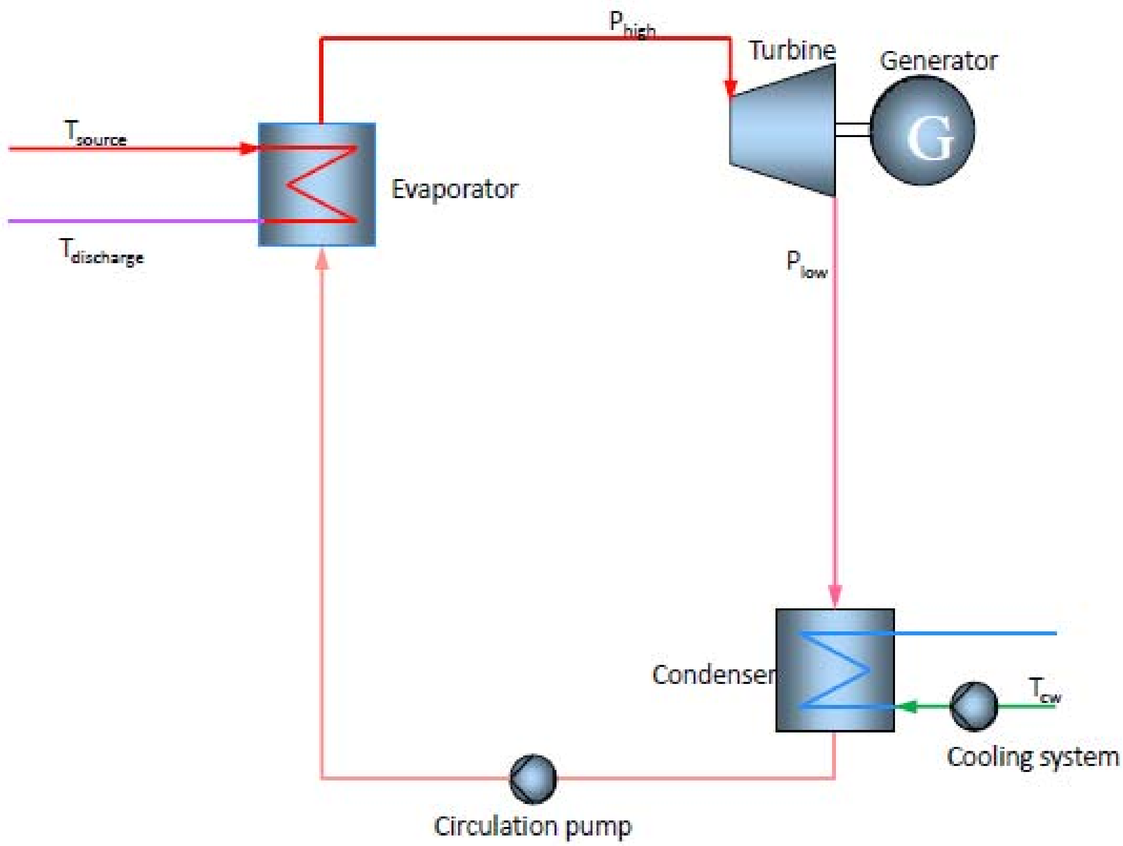

Figure 3. Binary plant scheme

The heat introduction process, which implies the working fluid phase change, has a high influence on the cycle efficiency: with a pure (or azeotropic) fluid the phase change process in subcritical conditions is at constant temperature and pressure (Figure 4, top, left), with a mixture, instead, the phase change process occurs at constant pressure and variable temperature (Figure 4, top, right). If the hot thermal source is a variable temperature heat source, (which is the case for the geothermal source) a phase change process at variable temperature can better match the geothermal source, as shown in Figure 4; it can also be noted from Figure 4 that heat introduction at variable temperature is also obtainable by means of a cycle with pure fluid, multiple pressure evaporation (Figure 4, bottom. left) or supercritical cycle (Figure 4, bottom, right).

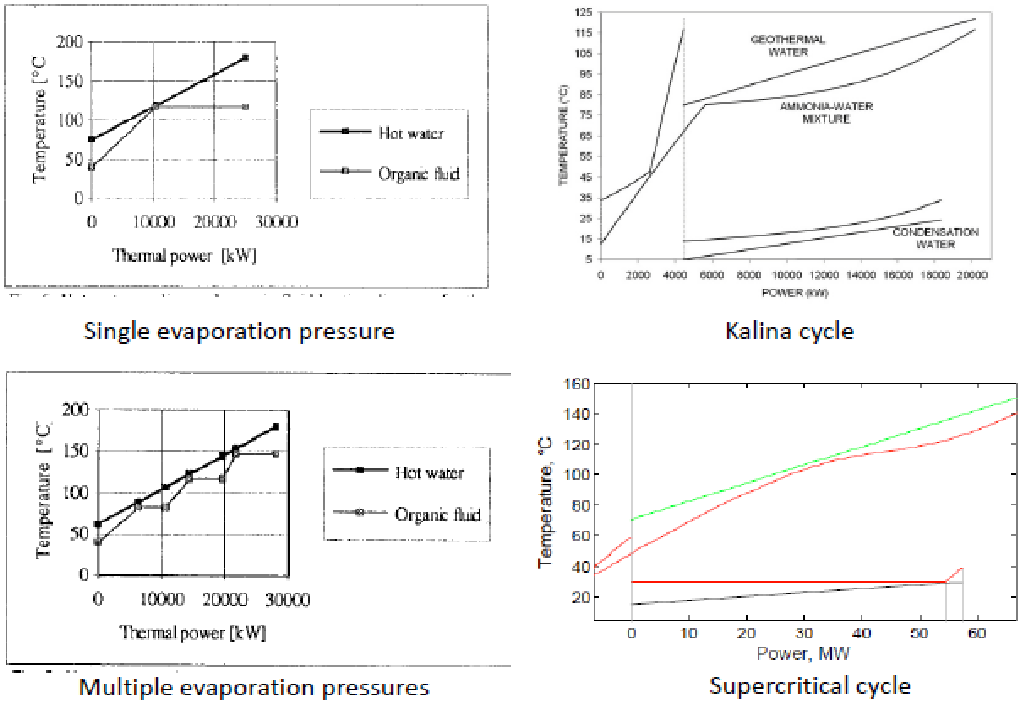

Figure 4. Heat introduction process in case of a) pure fluid b) mixture, c) pure fluid, multiple evaporation pressure, d) pure fluid, supercritical pressure

Most of the existing geothermal binary plants are ORC with single pressure evaporation, but all the technical options shown in Figure 4 are available on the market; high efficiency plant configurations will be of great interest in the future, above all in Europe (techno-economic optimization with high drilling cost leads in fact to high binary plant specific cost, in order to fully exploit the source)

In order to give the best possible performance, the selected thermodynamic cycle need to be optimized, also taking into account scaling hazard, which may limit the cooling of the geothermal fluid. Need for an optimization process can be understood e.g. referring to the single evaporation pressure cycle: a too high evaporation pressure would lead to a high cycle efficiency but also to a poor heat introduction in the cycle, and vice versa for a too low evaporation pressure.

In some cases the cycle efficiency may be improved by means of an internal heat transfer, occurring in a recuperator. (Figure 5); this happens when the working fluid is such that the end point of the expansion process falls into the superheated vapour region, and therefore the vapour can be profitably cooled (thus heating the liquid coming from the pump) prior to enter the condenser.

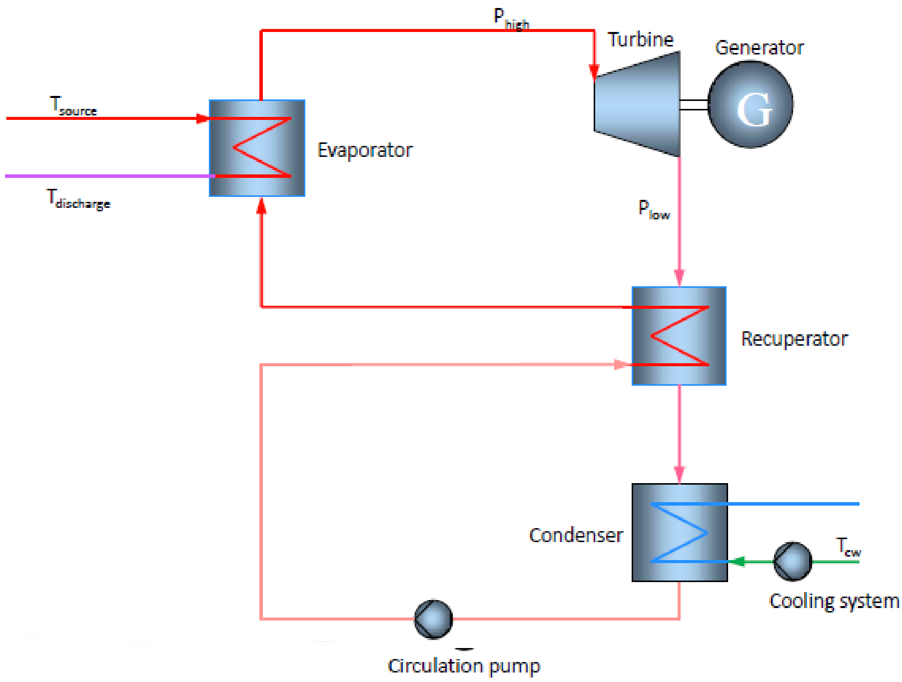

Figure 5. Binary plant with recuperation

When using a mixture as working fluid, i.e. with Kalina cycles, the composition may be changed throughout the plant with the aid of separators and mixers (Figure 6); several recuperators (heat exchangers charged with internal heat transfer) could also be appropriate; as a result, different plant scheme exist and some of them are quite complicated.

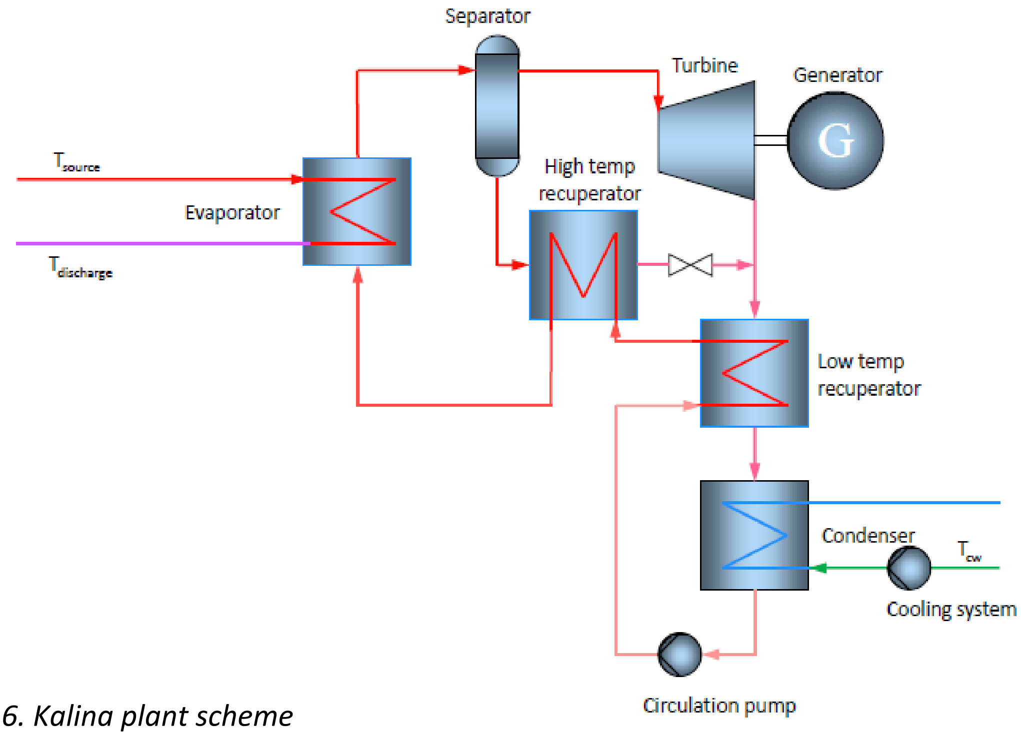

Figure 6. Kalina plant scheme

The cycle efficiency depends on (i) geothermal source and ambient conditions and (ii) cycle design features: the influence of the geothermal source and ambient conditions can be understood recalling that for the reference ideal cycle holds

$$\eta = 1 - \frac{T_{amb}}{\dfrac{(T_{geoth,source} - T_{reinjection})}{\ln\left(\dfrac{T_{geoth,source}}{T_{reinjection}}\right)}}$$

The ambient temperature is variable according to the site, but in a rather limited range, while the geothermal source temperature may have a larger variation: as a matter of facts (Figure 7), existing binary plant efficiencies are comprised between 0.05 and 0.15; higher efficiencies are expected for plants fed by higher temperature geothermal sources.

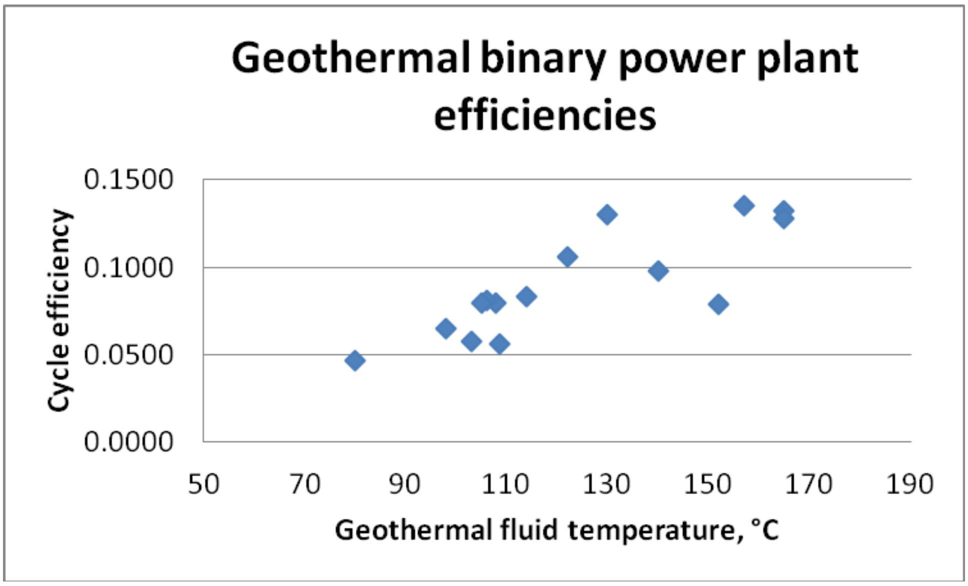

Figure 7. Binary plant efficiencies

Plant balance must be finally considered, detracting auxiliary consumption (mainly downhole pump and cooling auxiliaries) from the calculated net cycle power.

Finally, in case the geothermal source is two phase, plants which comprise a steam section and one or more binary section can also be realized: this kind of plant allows the highest geothermal source exploitation.

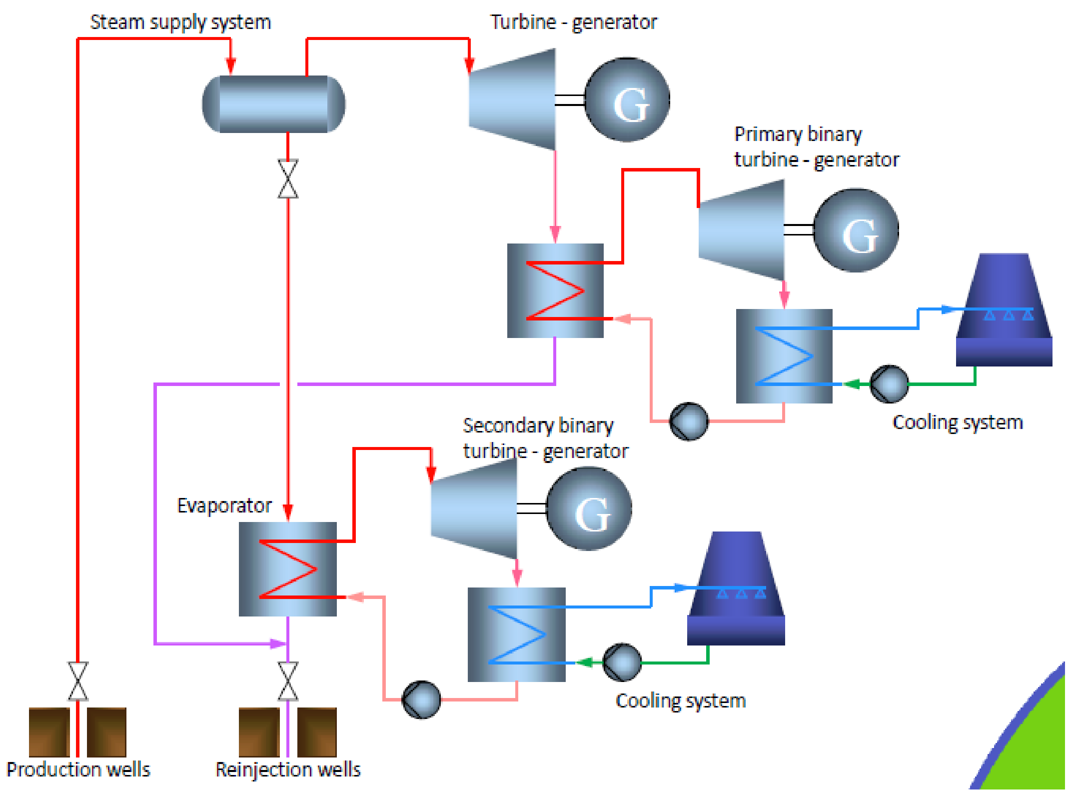

Figure 8. Mixed steam/binary plant

Cascade use / cogeneration schemes are also feasible, as well as hybrid plants using the geothermal source in addition to another thermal source (e.g. solar or biomass or wastes).

Mechanical equipment and operation and maintenance

Mechanical equipment used in geothermal power plants are proven traditional equipment adjusted to the geothermal fluids. Emphasis within the course will be on different design considerations compared to conventional steam plants such as geothermal turbine sizes and control solutions at turbine inlet connected to operation of the geothermal steam field. Choice of material for geothermal turbines has to be adjusted to the available steam and is therefore different from material in traditional steam turbines. Non-condensable gases must be considered and removed from the condenser by means of a proper system since they would otherwise accumulate in the condenser. The steam entering the turbine is saturated and therefore, the steam starts to condense in the turbine. As a result droplets form in the flow and the droplets wear down the turbine blades. To decrease the amount of droplets in the flow, it is important to carefully design lead ways for the condensate in the turbine. Scaling may also occur especially at the first-stage nozzle nearest the turbine inlet leading to reduced generator output. Scaling can impact the effectiveness of the guide vanes. Scaling is removed during regular turbine maintenance.

The presenter will go through a calculated example to show methods used for basic engineering within mechanical equipment design. The example taken will be connected to the special conditions encountered in geothermal energy.

In this session operation and maintenance of geothermal power plants with emphasis on the geothermal part of the plant is introduced. Photographs of extreme conditions will be shown and discussed with solutions.

Figure 9. Machine hall of Hellisheiði Power Plant

Figure 10. Scaling and corrosion in turbine casing

A binary plant consists of several heat exchangers, a multistage centrifugal pump and a turbine.
Different kind of heat exchangers (e.g. shell & tubes, plates) are eligible. Depending on the flow specific conditions: possible corrosion on the side of the geothermal fluid oblige to adopt special and costly materials for the heat exchangers, with a great influence on the cost of the unit, and possible scaling and fouling require removable covers and straight cleanable tubes.
The pump is usually operated at variable speed, so that greater flexibility and efficiency are achieved. Axial flow turbines are most widely used in ORC plants: organic fluids exhibit usually low enthalpy drop during expansion, and a small single stage turbine, (or, if needed, a few stages turbine) is commonly appropriate. In most of the existing plants the turbine rotates at 3000 rpm, though recently faster (coupled to a variable speed electric generator) and smaller turbines have also been employed. The adoption of radial turbines has also been proposed: it must be pointed out that both radial inflow and radial outflow turbines have been considered. The radial inflow scheme allows larger work per stage and moreover, partial admission vanes can be easily accommodated; radial outflow scheme consents a small work per stage (several stages are then needed) but tolerates high variations of the volumetric flow between the inlet and outlet of the turbine.
Most of the problems encountered with steam turbine are not present with binary turbines: in ORC plants, the selected working fluid is not chemically aggressive, and it is usually such that the expansion ends in the superheated vapor region, thus preventing the turbine blades from droplets erosion; moreover the turbine is subjected to low mechanical stress due to the low peripheral speed. In Kalina cycle based plants, the working fluid is toxic and corrosive, and particular attention is to be paid for possible leakages. As a whole, limited O&M requirements and long life are typical for binary plants.

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Session VII – Plant operation, energy supply and grid integration

F. Heilemann and S. Reith

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Curriculum vitae

Dr.-Ing. Franz Heilemann is experienced in planning, construction and operation of electricity grids on all voltage levels. The development of interdisciplinary smart grid strategies with integration of renewables and customers as well as economic analyses, efficiency benchmarks and regulatory management are part of his work at the network operator EnBW Regional AG. His dissertation at the University of Stuttgart was focused on stability problems of large interconnected power systems and their improvement.

Sören Reith did his Bachelor at the Baden-Wuerttemberg Cooperative State University Karlsruhe (DHBW), followed by his Master at the Karlsruhe Institute of Technology (KIT), which he finished in 2011. Parallel to his studies he was working in different departments of EnBW. Since 2009 he gathered experience in the research and development department of EnBW. Currently he is working on his doctoral thesis in the field of deep geothermal energy production in cooperation with the University of Stuttgart.

Abstract

The integration of electricity from geothermal power plants into the electricity grid has to be seen from different perspectives. In the following the legal aspects and the function of the regulated energy market are explained as well as demand for geothermal power and the process, the costs and the legal background of grid integration. This gives the reader a broad understanding of the main foundations for grid integration of geothermal electricity. Based on regulated energy markets different legal systems in Europe support the integration of renewable power into the market, which is met by a growing demand for renewable power in general and geothermal power in particular. The growing share of renewable power causes problems in grid stability. That's why besides legal also technical requirements determine the process of grid integration. The costs for grid integration are very site specific and are determined by the network connection point and the installed capacity of the power plant.

Keywords: grid integration; costs of grid integration; energy market; electricity grid

Regulation and energy trade

Electricity supply has developed since its beginnings in the late 19th century in monopolistic structures. Because of expensive infrastructure and its associated economic advantages of a monopole, vertically integrated energy suppliers got the task of supplying the public and the industry with electricity.

With the electricity market directive 96/92/EG the European Union has changed this monopolistic market structure. The goal of this directive was free trade and competition on the electricity market (Konstantin, 2007, S. 37). Since then several other EU directives and decisions have brought European wide energy trade and the possibility for every customer to choose its electricity supplier. Part of this is the free access to the electricity grid. Several European and national political requirements like for example the so called unbundling, which means the legal separation of production, transport and distribution, shall give every user a fair, transparent and equal access to the electricity network (European Parliament and the Council, 2003, Art. 7-9).

In the liberalised energy markets, electricity became a trade product which is similar to shares or other commodities traded over a stock exchange or in bilateral contracts. Bilateral or the so called over-the-counter trade is a classical contract between two parties, which negotiate price, amount and time of delivered electricity. However, trading over the stock exchange works with standardized products. The products are characterized by the period of supply (hours or time periods) and are offered in €/MWh. As a reference for energy prices the spot-market is used. Here suppliers and buyers of electricity can put their offer and demand requests in an anonymous order book. At 12 o'clock the order book is closed for the following day. Demand and offers are merged in a merit order, where the most expensive power plant which is needed to satisfy the demand sets the price.

Besides the free electricity trade, renewable electricity is in many countries supported by different federal programmes. With the Electricity Feed-in Act (StrEG) Germany started 1991 to support renewable energies with feed-in-tariffs and the legal obligation for grid operators to connect renewable capacity to the electricity grid (BRD, 1990). 2000 the "Renewable Energy Act (EEG)" has replaced this act and has introduced geothermal energy into the federal support mechanism. Similar regulations also exist in other European countries for example France. Since 2000 the "Loi n°2000-108" supports renewable energy sources (RES) with feed-in-tariffs, an obligation for the grid connection and special tenders for renewable energies (BMU, 2011).

Electricity Grid

The natural monopole of the electricity grid is strongly regulated. National regulation authorities monitor the discrimination free access and the cost efficient operation of the networks. The operators are paid for their effort by network-use fees. These fees at least have to be made public. In Germany the authority in charge approves them with a benchmark system, which takes among others the geographical differences into account (Konstantin, 2007).

The integrated European electricity grid enables a secure electricity supply in Europe by connecting numerous power plants. This redundancy leads on the one hand to a secure and efficient power supply; on the other hand long distances have to be bridged. The transported power is the key parameter for the network design. The power can be calculated with $P = U * I * \sqrt{3}$. As the current is limited by the heat resistance of the wire, the voltage is the only parameter, which can be adapted to the power demand. This fundamental law of electricity transport leads to the insight, that different network levels are necessary for different transport tasks.

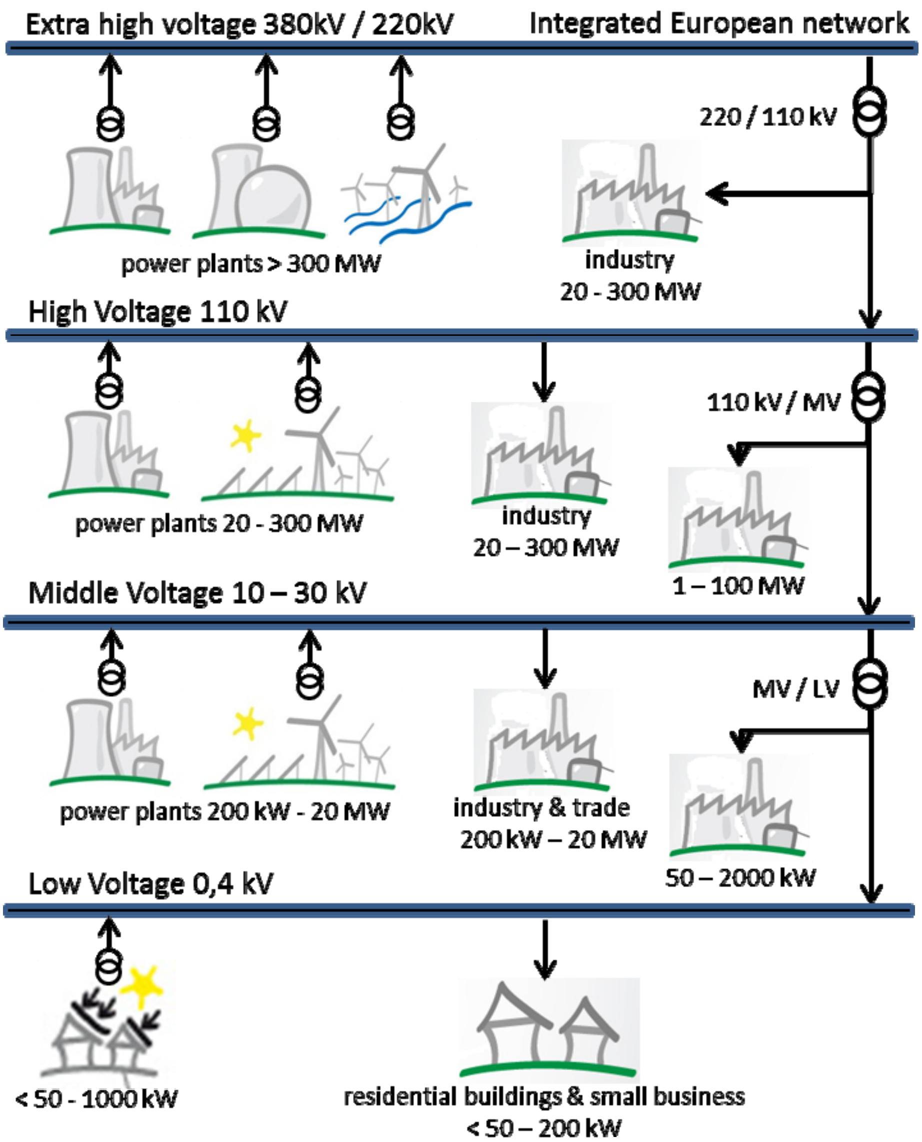

Figure 1. Schematic diagram integrated network (own illustration based on Konstantin, 2007, S. 330)

Figure 1 gives an overview of the different network levels. The electricity of big power plants (>300 MW) is feed into the extra high voltage grid. This grid level transports the electricity over long distances to consumption centres. The long distances make an extra high voltage of up to 380 kV necessary. Transformer stations transform the electricity to 110 kV (High Voltage). This level is used to distribute electricity to regional consumption centres or large industrial companies. The next step is to transform the electricity to the middle voltage level (10 – 30 kV), which supplies districts, bigger cities and industrial sites. Residential buildings and small businesses are finally connected to the grid by the low voltage level with 400V (Konstantin, 2007, S. 331).
Geothermal power plants (single power plants in a complex) in high enthalpy regions like Italy or Iceland deliver up to 750 MW or more. These power plants usually feed their electricity direct into the high or extra high voltage level. In low enthalpy areas like Germany typical geothermal power plants have an installed capacity of 1 - 5 MW, which means that they are connected to the medium voltage grid.

Demand for geothermal power

The European Union has set itself ambitious goals for becoming a high-efficiency, low carbon economy. Until 2020 20% of the energy consumption shall be met with renewable energy. Additionally CO_2-emissions shall be cut by 20 % and the energy efficiency shall be increased by 20 % (European Commission, 2012). Geothermal energy is defined under German law as a renewable energy source and is needed to achieve these goals (BRD, 2012, § 3; 3). Geothermal electricity in Germany has a technical potential of nearly 300 TWh/a and can so contribute to renewable energy generation (Paschen, Oertel, & Grünwald, 2003). 300 TWh/a would be ~ 60 % of the annual German electricity demand (based on 2010) (BMWi, 2012). Currently there are 10.7 GW_{el} of geothermal capacity installed worldwide. Germany has with 7.3 MW_{el} only a small share in this capacity. Until 2020 the German government predicts an installed capacity of ~ 200 MW_{el} while the German renewable Energy federation expects up to 470 MW_{el} (Geothermie Bundesverband). The high availability of geothermal power plants also contributes to the demand for geothermal energy. Geothermal power plants have one of the highest capacity factors[1] of all electricity production technologies. With ~ 90 % geothermal power plants have a capacity factor which is as high as the capacity factor of nuclear power plants (Tidball, Bluestein, Rodriguez, & Knoke, 2010). This makes geothermal power besides hydropower one of the only renewable power plants which are suitable for base load. Beside the electricity production it is possible to use geothermal power as a heat source for district heating. Geothermal power plants can so be used as combined heat and power source. This improves the efficiency of the power plant as well as the economic situation.

[1] full-load ratio of a power station per annum

Grid integration of an increasing share of renewable power generation – challenges for the network and system operation

The European 20-20-20 energy and climate targets, particularly the enormous increase of renewable generation will have a huge impact on both, the transmission and the distribution network as well. This becomes not only a question of balancing the power according to the equilibrium of generation and consumption and therewith the frequency control from the viewpoint of the Transmission System Operator (TSO), but becomes even more challenging for the Distribution System Operator (DSO). He has to deal with local and regional reverse load flow conditions, voltage problems and the overloading of lines. This can be summarized in the task of managing the system in a secure and cost efficient manner.

How dramatic the future development could be, illustrates the situation in Germany. Currently the system peak load amounts to nearly 80.000 MW. To reach the intended target of a 35% share of renewables in 2020 the capacity of installed renewables alone will be as high as the maximum peak load. In addition the priority feed-in of RES, the volatility and the intermittent generation will cause substantial problems for system stability in the West European Interconnection[2] as well as supply problems in the local areas of the DSO where renewables are connected to the grid. To meet these challenges a massive grid expansion and a frequent use of balancing power are necessary, which is associated with considerable costs.

A paradigm shift in the sense that load follows generation is needed. The incorporation of the customer and the development of smart grids with highly complex, real time communication systems to adapt generation and consumption and to realize an optimal use of network assets in a secure and cost efficient manner will be inevitable. That'll lead to additional and new requirements for decentralized power plants based on renewable feeding. For the medium and high voltage levels it'll be necessary to implement a load and generation management system to be able to operate the system effectively while keeping the quality standards and to optimize the connection capacity for RES in case of given network assets.

Costs of grid integration

To ensure a secure and reliable network operation network operators have specified requirements for the network connections of RES. An additional boundary condition for the grid connection in Germany is the incentive regulation for DSOs, which was introduced by the Federal Network Agency (BNetzA). DSOs are obligated to connect power plants in total (costs for DSO and power plant operator (PPO)) as cost efficient as possible. The most important point in the question of cost allocation is the network connection point (NCP). Objectives and transparent criteria to determine the NCP are given by law and regulations. This point marks the border of property, the responsibility for assets and defines the cost allocation between the PPO and the DSO.

[2] European transmission network

The costs for the grid integration of a power plant depend on the chosen NCP and the integrated power. The NCP is needed to define the length of the wire, the needed assets like transformation stations and other side conditions, while the integrated power defines the voltage level and the needed type of wire. A general forecast for the costs of grid integration is therefore not reliable.

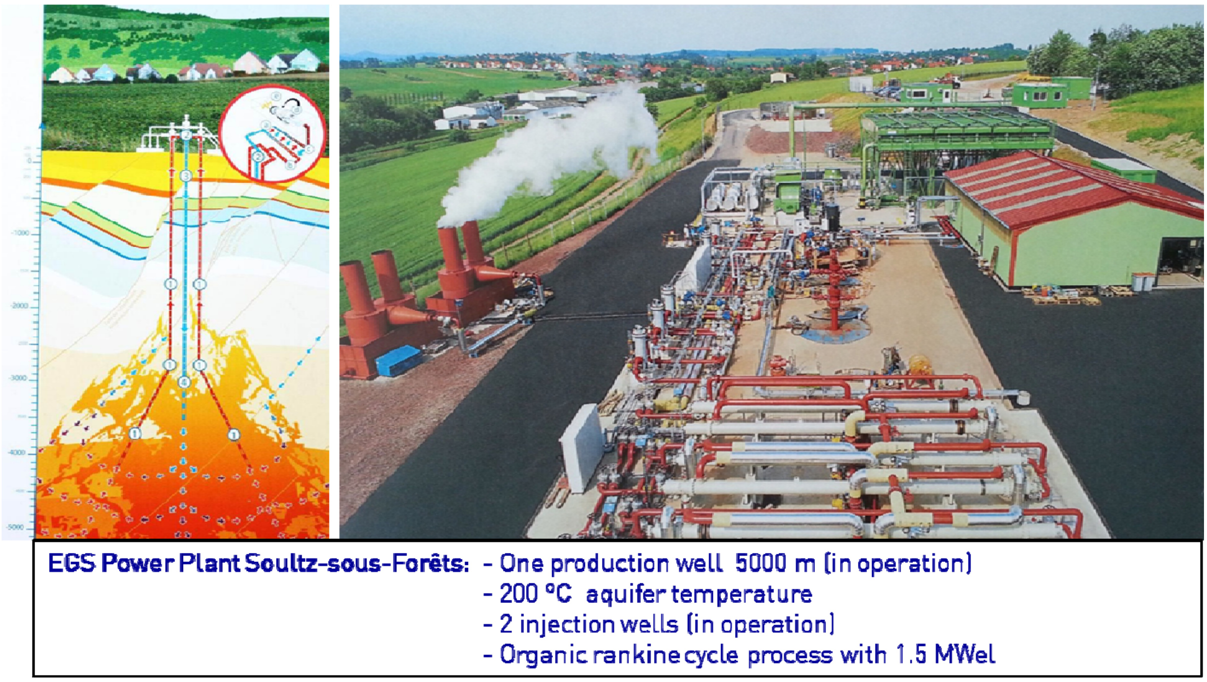

Figure 2. The Soultz Project: Geothermal plant in the Upper Rhine Valley

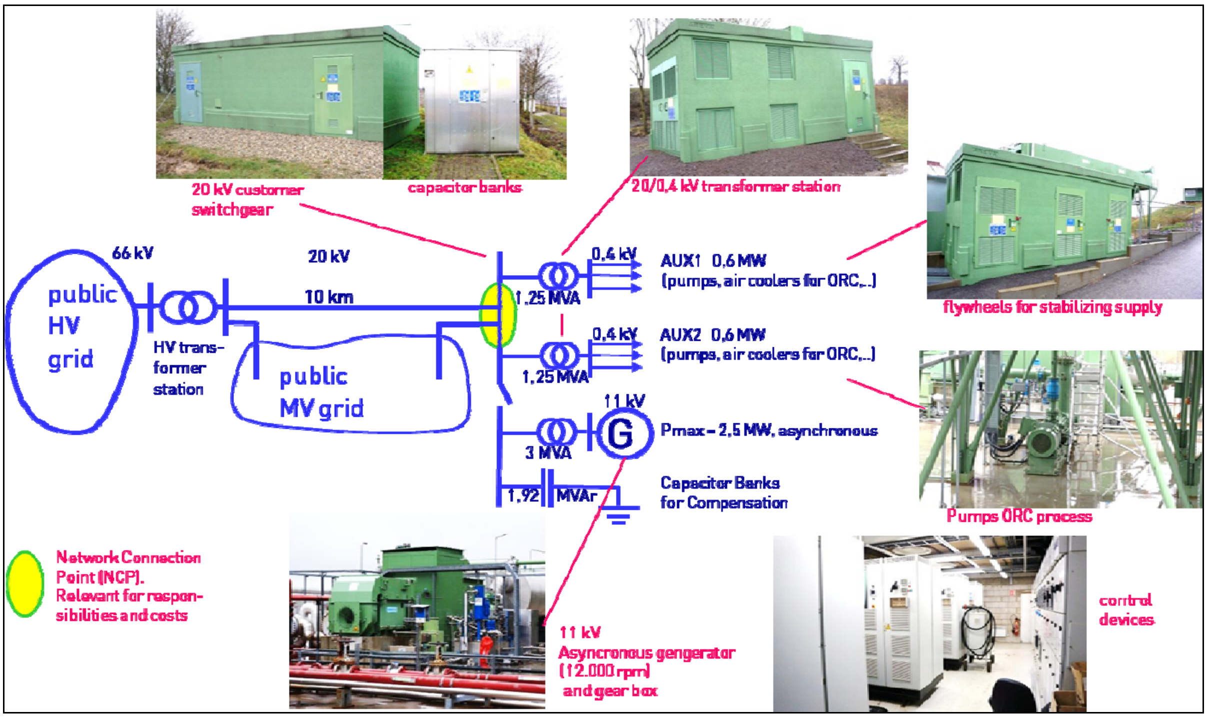

Figure 3. The Soultz Project. Electrical connection scheme and supply devices

The integration of a power plant therefore has to be investigated site specific. As an example Figure 3 shows the connection scheme for the geothermal power plant in Soultz-sous-Forêts (France) (see Figure 2).
The connection to the public grid lies very close to the power plant so that routing costs could be kept to a minimum. The costs for the equipment obviously depend on the requirements of the power plant. For the geothermal power plant in Soultz the costs of main parts of the electrical equipment are given in Table 1.

Table 1. Grid integration costs at the Soultz EGS power plant

Generation	Transformer	46,000 €
	Switchgear	68,000 €
Auxiliaries	Transformer	93,000 €
	Switchgear	112,000 €
Compensation	Capacitor banks	24,000 €
Connection devices (general)	Medium voltage lines/cables	70 – 120 €/m
	Medium/low voltage substation	30,000 € - 50,000 €
	High/medium voltage transformer station	1 – 1.5 Mil. €

Process of grid integration
Basis for the determination of an appropriate NCP for the connection of the power plant is the information provided by the PPO. Criteria are the maximum real power P_{max} and the apparent power S_{max} of the plant as well as its location and the request for connection. This enables the DSO by means of network calculations to determine the appropriate NCP.
Usually the local network operator provides checklists, requirements, technical regulation and conditions for the connection and commissioning of the decentralized generation units. In this process the metering concept and the telecommunication devices also need to be specified. Construction and commissioning are rounding up the implementation. The PPO has to provide the conformity declaration to all these specifications. Figure 4 shows the process of grid integration in a flow diagram (BDEW, 2008; VDN, 2004).
In the process of grid connection, the PPO has to choose a model of remuneration. According to the law and regulations in Germany, PPOs can choose between three main models within the Renewable Energy Act (EEG).

1. "Normal" EEG remuneration (currently 25 Ct/kWh for geothermal power, according to §28 EEG).
2. Remuneration according to "Direct Marketing + Market Premium"
3. "Direct Marketing + Avoided Network Charges" model.

For the PPO the different models lead on the one hand to different income possibilities, which have to be calculated for every power plant individually. On the other hand the model selection leads to different contract partners. While in model one the remuneration is completely paid by the DSO, in model two and three the PPO sells its electricity on the free market (direct marketing) and gets an addition from the DSO. The DSO itself finances this support for renewable energy by a levy for the electricity customer. The system is flexible and can be freely selected by the PPO each month if required (BRD, 2012).
In case of the limitation of the production due to the network operator's constraints and system stability requirements, the plant operator is compensated by the DSO for the remuneration losses (BDEW, 2012; BNetzA, 2011).

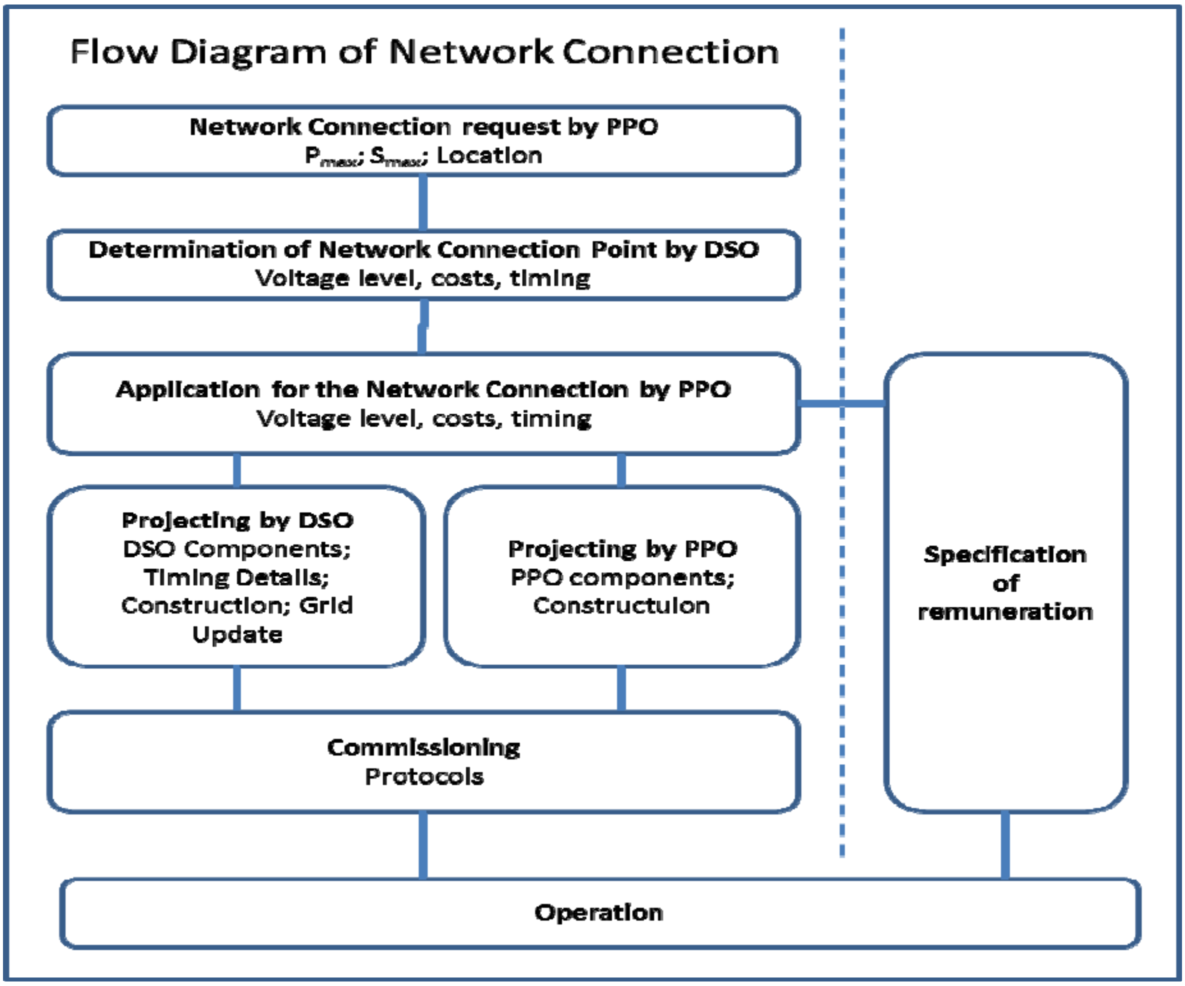

Figure 4. Flow diagram of grid integration (own illustration)

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