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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Bundesamt für Energie BFE

Schlussbericht 15. Dezember 2006

ARBEITEN FÜR DAS IEA GEOTHERMAL IMPLEMENTING AGREEMENT (GIA) 2006

Jahresbericht 2006

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BFE-Vertrags- und Projektnummer: 151‘661 / 41‘661

Für den Inhalt und die Schlussfolgerungen sind ausschliesslich die Autoren dieses Berichts verantwortlich.

Inhaltsverzeichnis

Zusammenfassung

Die Arbeiten für das IEA Geothermal Implementing Agreement werden durch Prof. L. Rybach ausgeführt. Er ist Vice Chairman des Executive Committee; somit ist die Mitwirkung der Schweiz an allen Entscheidungen garantiert. Die Arbeiten laufen programmgemäss, die Resultate sind auf der IEA GIA Homepage ersichtlich und werden zudem durch drei Anhänge dokumentiert.

Abstract

The Swiss activities for the IEA Geothermal Implementing Agreement are performed by Prof. L. Rybach. He is Vice Chairman of the Executive Committee, which guarantees the direct involvement of Switzerland in all decision making. The activities proceed as planned, the results are to be seen on the IEA GIA website and are further documented in three Appendices.

1. Ausgangslage

Die Schweiz ist Teilnehmer des IEA GIA seit Anbeginn (März 1997). Die Teilnahme wird durch das BFE finanziert. Grundlage der Arbeiten in 2006 ist Vertrag Nr . 151'939, Projekt Nr. 41'661.

2. Ziel der Arbeit

Durch die Teilnahme der Schweiz am GIA wird im F&E Bereich ein regelmässiger Erfahrungsaustausch mit Ländern, die in der Geothermie führend sind, auf hohem Niveau ermöglicht. Hier sind insbesondere Informationen bezüglich Neuentwicklungen (z.B. EGS, *Enhanced Geothermal Systems*) zu erwähnen. Anderseits kann das spezifische know-how und die Errungenschaften der Schweiz im internationalen Rahmen eingebracht werden und somit Anerkennung erfahren und Verbreitung finden. Es sind weiterhin interessante und wertvolle Informationen und Kontakte zu erwarten.

Besonders zu erwähnen ist hier die führende Rolle der Schweiz im GIA ExCo: Prof. L. Rybach amtete 1997 – 2001 als Chairman, seit 2002 ist er Vice Chairman und damit auch GIA Officer. Dadurch ist die Schweiz an allen Entescheidungsprozessen direkt beteiligt.

3. Lösungsweg

Die Präsenz der Schweiz wird einerseits an den ExCo Meetings, an ausgewählten Annex Meetings, sowie an besonderen IEA Veranstaltungen (Workshops, Seminare) wahrgenommen, anderseits durch umfangreichen Schriftverkehr zwischen den Officers (Präsident, zwei Vizepräsidenten, GIA Sekretär) sichergestellt. Die Schweiz ist auch an diversen Annexes beteiligt.

4. Ergebnisse

4.1. Arbeiten im ExCo

4.1.1 ExCo Sitzungen

Die 15. Sitzung des IEA GIA ExCo fand am 16. und 17. März 2006 am Hauptsitz der IEA in Paris statt. Die notwendigen Vorbereitungsarbeiten (u.a. Mitwirkung an den Arbeiten für die zu behandelnden Geschäfte) begannen schon im Januar 2006.

Prof. L. Rybach obliegt im ExCo die Koordination der Arbeiten für neue *GIA Participating Countries*. Anlässlich der 15. ExCo-Sitzung wurde der Stand der Bestrebungen präsentiert, für die GIA weitere Teilnehmer (insbesondere Frankreich, Polen, Türkei) zu gewinnen. Frankreich hat den beitritt beschlossen; die Unterzeichnung des GIA durch die Regierung steht unmittelbar bevor.

Ferner konnten in 2006 drei *Sponsoren* aus der Wirtschaft (ORMAT/USA, Geodynamics und Green Rock Energy/Australien) in die GIA aufgenommen werden.

Ebenfalls an der 15. ExCo-Sitzung wurde von L. Rybach der *Swiss Country Report 2005* präsentiert. Der umformatierte, ergänzte Bericht ist Bestandteil des *GIA Annual Report 2005* (s. unten).

Die 16. Sitzung des IEA GIA ExCo fand am 8. und 6. September in San Diego/USA statt. Dabei wurde ein Swiss Country Update präsentiert **(Anhang I)**.

4.1.2 Weitere Arbeiten für die IEA GIA

- Der umfangreiche und aufschlussreiche GIA Annual Report 2005 wurde nach diversen Vorläuferversionen, an denen der Unterzeichnete massgebend beteiligt war, wurde fertiggestellt (aufgeschaltet auf http://www.iea-gia.org/publications.asp).

- Am 5. April 2006 fand bei der IEA in Paris ein REWP Technology and Policy Seminar "Renewable heating and cooling – from RD&D to deployment" statt. Gemäss ExCo-Beschluss vom 17.3.2006 hat Prof. L. Rybach die GIA in seiner Eigenschaft als ExCo Vice Chairman vertreten. Die GIA Präsentation des Unterzeichneten kann von der GIA Homepage http://www.iea-gia.org/ abgeladen werden. Ferner vertrat er die GIA am 49th REWP Meeting am 6. April 2006.

- Ein weiterer Schwerpunkt der Tätigkeit von Prof. L. Rybach lag im Bereich „Geothermal Sustainability". Gemäss ExCo-Beschluss vom 17.3.2006 hat er mit GIA-Sekretär Dr. Mike Mongillo ein GIA-Grundlagenpapier erarbeitet, welches am GRC Annual Meeting 2006 (11.-13. September, San Diego/USA) präsentiert wurde. Drain wird festgestellt, dass Geothermie nur unter bestimmten natürlichen und technisch-ökonomischen Bedingungen als erneuerbare Energie angesehen werden kann. Die Nachhaltigkeit der geothermie ist von der Art und Intensität der Nutzung abhängig. **(Anhang II)**. Die vielbeachtete Präsentation und Publikation erhielt ein Best Paper Award.

- L. Rybach ist Executive Group Member des EU Projektes ENGINE (ENhanced Geothermal Innovative Network for Europe). In dieser Eigenschaft hat er eine enge Zusammenarbeit zwischen IEA GIA und ENGINE in die Wege geleitet. Die Schweiz ist am ENGINE-Projekt durch drei Kooperationspartner beteiligt: Deep Heat Mining Association, CREG Neuchâtel und Geowatt AG Zürich.

- Für IEA GIA Annex VIII (Direct Use of Energy) hat L. Rybach (zusammen mit Dr. Yonhoo Song, KIGAM/S.Korea) ein Questionnaire ausgearbeitet. Die Auswertung der eingegangenen Antworten ist im Gange.

- Im Rahmen von IEA GIA Annex I (Environmental Impacts of Geothermal Energy Development) untersucht Subtask D (Seismic Risk From Fluid Injection Into Enhanced Geothermal Systems) die bei EGS-Systemen möglicherweise auftretende, künstliche Seismizität. Zwei wichtige Dokumente wurden dem IEA GIA ExCo zur Vernehmlassung unterbreitet: 1) „White Paper" Induced Seismicity Associated with Enhanced Geothermal Systems; 2) Protocol for Induced Seismicity Associated with Enhanced Geothermal Systems. L. Rybach hat hierzu als ExCop Mitglied Stellung genommen, worin auf die noch bestehende grosse Kenntnislücken hingewiesen wird (**Anhang III**). Die vorgeschlagenen Forschungsarbeiten erhalten durch das Basler Erdbeben vom 8.12.2006 unerwartet hohe Aktualität.

- Schliesslich hat L. Rybach massgeblich an der Erstellung des IEA GIA End of Term Report 2002-2007 sowie am IEA GIA Strategic Plan 2007-2012 mitgearbeitet. Auch diese unfangreichen Dokumente sind auf der IEA GIA website zu finden (http://www.iea-gia.org/).

4.1.3 Laufende Administration

Prof. L. Rybach wirkt als GIA ExCo Vice Chairman und Officer an allen Vernehmlassungen und Entscheidungen mit. Die weiteren Officers sind Dr. David Nieva/Mexico (ExCo Chairman), Dr. Allan Jelacic/USA (ExCo Vice Chairman), Dr. Mike Mongillo/New Zealand (GIA Secretary). Die Arbeiten werden weitgehend per e-mail abgewickelt. Im Durchschnitt erfolgt täglich mindestens ein e-mail- Wechsel(!). Diese Arbeiten nehmen entsprechend viel Zeit in Anspruch.

5. Diskussion

Konkrete, sichtbare Erzeugnisse sind wie erwähnt auf der IEA GIA Homepage sowie aus den **ANHÄNGE I - III** ersichtlich. Auch kann vermeldet werden, dass der im Rahmen von GIA Annex III/Subtask C von der Schweiz (insbesondere Dr. Thomas Mégel, Geowatt AG Zürich) erstellte *Enhanced Geothermal System Project Management Decision Assistant* nun erhältlich ist. Exemplare davon wurden in 2006 bereits nach Australien, Belgien, Deutschland und Frankreich geliefert. Eine Überarbeitung des PMDA ist für 2007 vorgesehen. Weitere Details sind ebenfalls unter **http://www.iea-gia.org/** zu finden.

6. Schlussfolgerungen, Ausblick

Es kann vorbehaltlos festgehalten werden, dass die Beteiligung der Schweiz am IEA GIA weiterhin erfolgreich verläuft und die erwarteten Benefits erbringt. Die Schweizer Beteiligung nimmt noch zu; neuerdings hat sich das Basler Deep Heat Mining Projekt am Annex I Subtask D „*Seismic Risk From Fluid Injection Into Enhanced Geothermal Systems*" beteiligt. Aus diesem Annex/Subtask sind weiterhin interessante und wertvolle Informationen und Kontakte zu erwarten; die Schweiz sollte sich am Annex I offiziell beteiligen.

Die ExCo hat am 16. März 2006 die Weiterführung des GIA beschlossen. Für den Verlängerungsantrag an die IEA wurde das IEA GIA End of Term Report sowie der IEA GIA Strategic Plan 2007-2012 eingereicht, welche unter Mitwirkung von Prof. L. Rybach verfasst wurden.

Symbolverzeichnis

IEA	International Energy Agency
GIA	Geothermal Implementing Agreement
ExCo	Executive Committee
REWP	Renewable Energy Working Party
GRC	Geothermal Resources Council

Referenzen

Rybach, L., Mongillo, M. (2006): Geothermal Sustainability – A Review with Identified Research Needs. Geothermal Resources Council Transactions Vol. 30, p. 1083-1090

ANHÄNGE:

ANHANG I	Swiss Country Report to 16th IEA GIA ExCo meeting
ANHANG II	Grundlagenpapier “Geothermal Sustainability – A Review with Identified Research Needs”
ANHANG III	Stellungnahme von L. Rybach zu „White paper“ und „Draft Protocol“, IEA GIA Annex I (Environmental Impacts of Geothermal Energy Development), Subtask D (Seismic Risk From Fluid Injection Into Enhanced Geothermal Systems)

A ANHANG I

Swiss Country Report to 16th IEA GIA ExCo meeting

Swiss Country Report to 16th GIA ExCo

L. Rybach[1,2]
1) Institute of Geophysics, ETH Zurich, Switzerland;
2) GEOWATT AG, Zurich, Switzerland (rybach@geowatt.ch)

- Swiss country reports have been presented at the 14th and 15th ExCo. Therefore mainly development highlights will be given this time.
- The report covers the
  - Institutional framework
  - The current geothermal scene (incl. energy use)
  - Publications/meetings, education, websites
  - International activities
  - Market development
- A comprehensive Country Report 2006 will be provided, in the requested format, for the GIA Annual Report 2006.

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THE INSTITUTIONAL FRAMEWORK

On the political scene the main change is that a CO_2 tax has been introduced.

The Energy Law already passed the *Nationalrat* (~House of Represenatives); in September it comes to the *Ständerat* (~Senat); it shall include a Risk Guarantee for deep geothermal drilling (mainly for EGS).

The governmental energy program *SwissEnergy*, which supports renewable energies, provides the general supportive framework for geothermal R&D. A new phase for the years 2006-2010 is now implemented.

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For geothermal, the Swiss Federal Office of Energy (OFEN) provides financing in 2006 for

- Research and Development (0.60 MCHF)
- Pilot and Demonstration (0.14 MCHF; unfortunately terminates in 2006)
- Activities of the Swiss Geothermal Competence Center (the **Swiss Geothermal Association SVG**; 0.5 MCHF)
- The represetation of Switzerland in the IEA GIA (by GEOWATT AG Zurich)

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The major reorganisation and restructuring of the SVG (Affiliated Member of IGA) has been completed.

The SVG acts now as the Swiss Geothermal Competence Center, in the form of the Umbrella Organisation GEOTHERMIE CH.

Its bi-lingual (G/F) Newsletter also carries the name

GEOTHERMIE.CH

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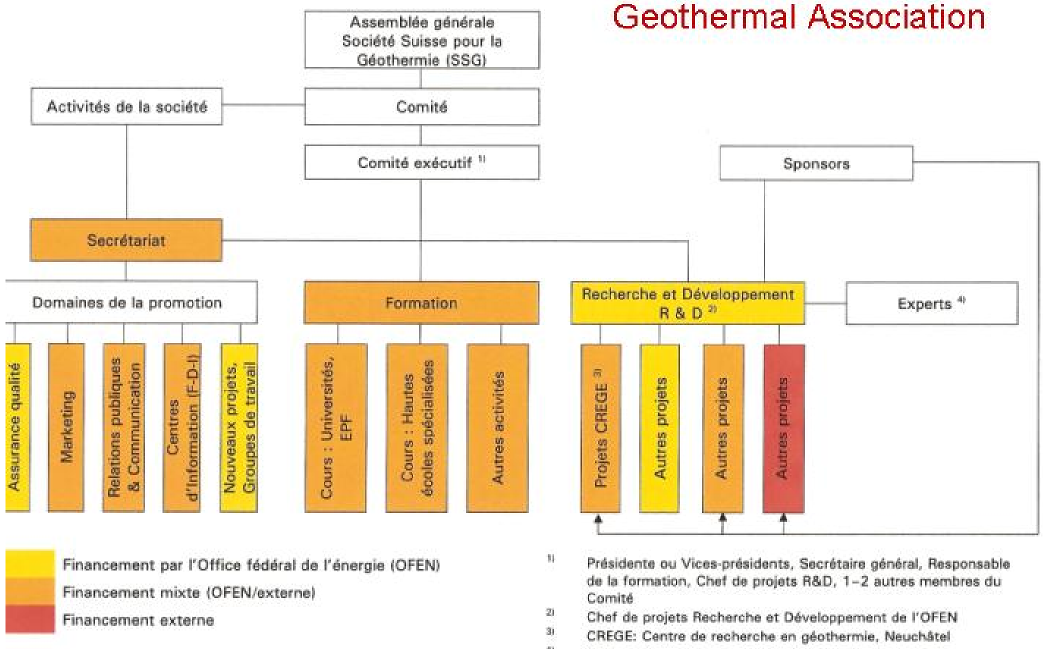
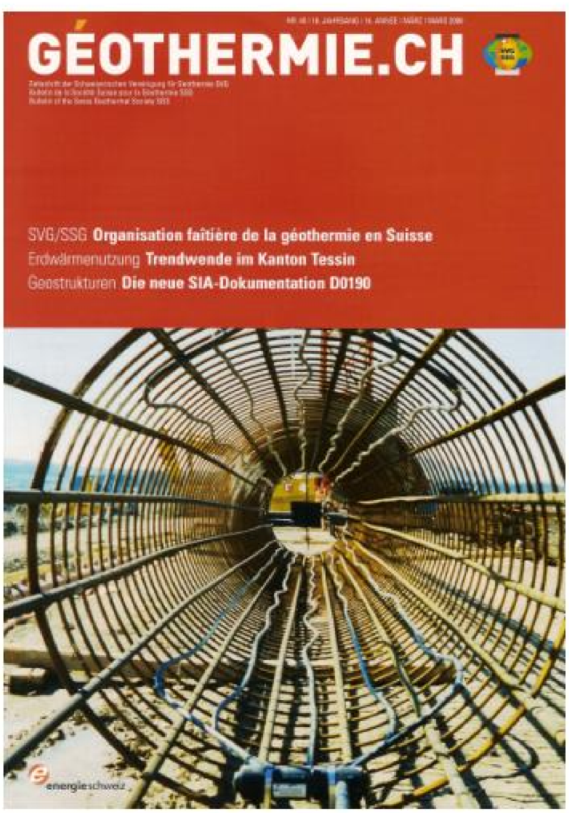
Organigramme de l'Organisation faîtière: Géothermie.ch

Organigramme, Swiss Geothermal Association



1) Présidente ou Vices-présidents, Secrétaire général, Responsable de la formation, Chef de projets R&D, 1–2 autres membres du Comité
2) Chef de projets Recherche et Développement de l'OFEN
3) CREGE: Centre de recherche en géothermie, Neuchâtel
4) Groupe d'experts, en coordination avec l'organisme de



Regular Newsletter of the Swiss Geothermal Association
Title page, no. 40 (16 p.)
Appears twice a year (since 1990)

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THE CURRENT GEOTHERMAL SCENE

- is dominated by the Deep Heat Mining project Basel;
  (created great expectations for geothermal....);

- *courant normal* in other sectors;

- preparation of geothermal engineering norms (SIA: Swiss Association of Engineers and Architects) started.

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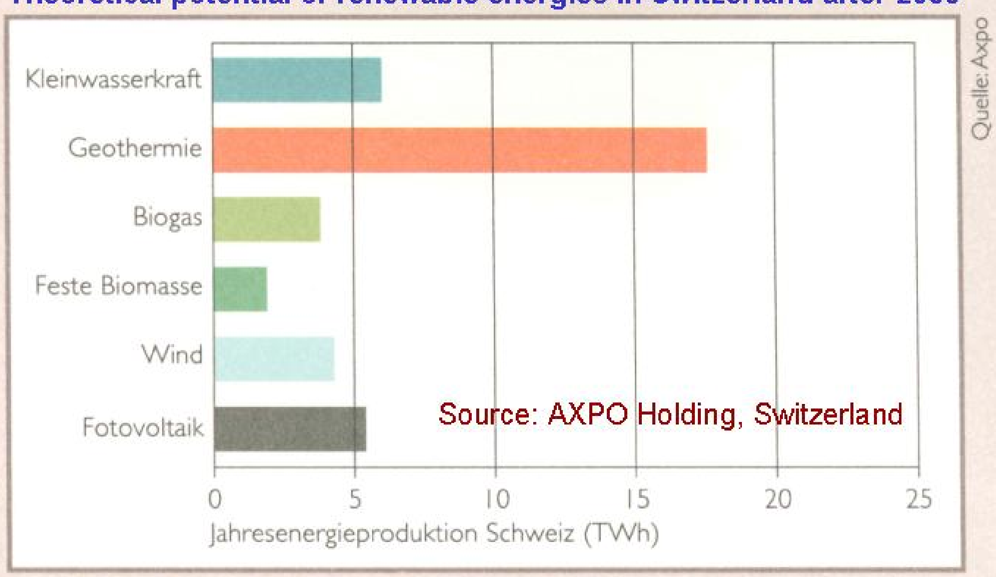
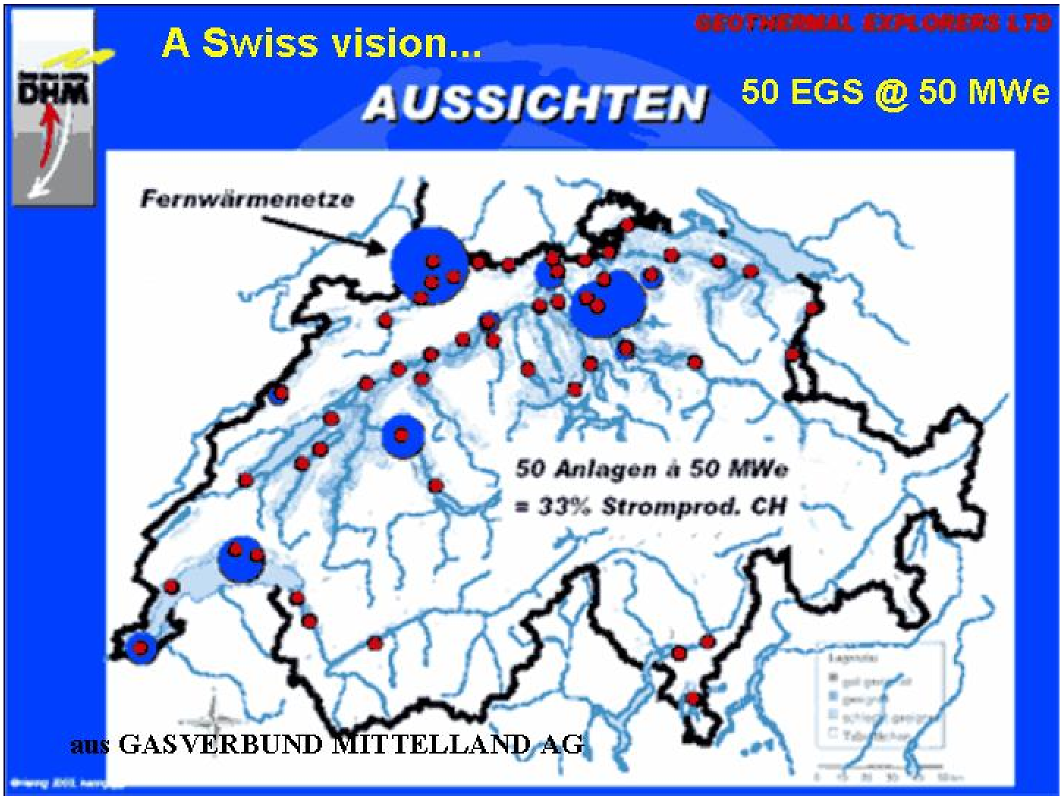
Theoretisches Potenzial von erneuerbaren Energien in der Schweiz nach 2050

Theoretical potential of renewable energies in Switzerland after 2050





Drilling rig (KCA DEUTAG T-45)
DHM Projekt Basel

1st well started spudding on 15 May 2006

Target depth: 5‘000 m

3 wells foreseen.

Photo: Geopower AG Basel

Partners of Geopower AG Basel

Conceivable measures in case of seismic events DEEP HEAT MINING PROJECT Basel

GEOTHERMAL EXPLORERS LTD

Procedures in case of perceived seismicity

PRELIMINARY WORKING PAPER

Stage		Event (A phase is defined when at least one of the three criteria applies)			Measures						Communication		
		Magnitude M_L	Peak ground velocity cm/s	Public perception	Permanent measures	Interruption	Pumping regime	Pressure regime	Monitoring system	Resume operations	Project team	Authorities / institutions	Public
1	"green"	< 2.0	< 2	none		none	regular operation	regular operation	regular operation	-	standard reporting	standard reporting	-
2	"yellow"	> 2.0	2 - 3.4	few calls	permanent recording of injection pressure, draw down, pump rates, volumes, temperatures, regional seismicity, local microseismicity, surface vibrations near borehole	none	reduction of the pump rate	pressure reduction	additional check of full operation of monitoring system	Resumption of operation after minimal 12 hour shut down period	report to PL, PE, GF	adhoc operations meeting	Communiqué on website
3	"yellow"	> 2.5	2 - 3.4	some calls		m	stop pumping	bleed off excess pressure	check data recording, inform SES	Integrated seismic and hydraulic data interpretation; adjust operation parameters	alarm PL, PE, GF	operations meeting with SES and Kantonsgeologe	Communiqué on website
4	"yellow"	> 3.0	2 - 3.4	many calls		until cleared	stop pumping	bleed off excess pressure	check data recording, alarm SES	Integrated seismic and hydraulic data interpretation; reduce operation parameters; evaluate alternative frac-methods (eg acid frac)	alarm PL, PE, GF; inform board	operations meeting with SES and Kantonsgeologe	press release to media
5	"red"	> 3.5	> 3.4	generally felt		until cleared	stop pumping	bleed off excess pressure	check data recording, alarm SES	Following review, board decision, permission by authorities	alarm PL, PE, GF; inform board	operations meeting with SES and Kantonsgeologe, Sicherheits-inspektorat	press conference and pressrelease to media

Haering (2006), 3rd IEA GIA Annex I Subtask D Workshop

GEOTHERMAL RESEARCH IN 2005

Government-funded research is conducted with a **total of 600 kCHF expenditure** in

• Shallow resources (GHP; 240 kCHF)
• Deep resources (aquifers, tunnel waters; 102 kCHF)
• EGS (incl. Soultz participation, 114 kCHF)
• Energy conversion (incl. applications, 42 kCHF)
• Miscellaneous (incl. Program management; 102 kCHF)

In addition: substantial research work is being performed in international frameworks (see later)

Geothermal direct use, fossil energy savings, CO_2 emission reduction in 2006

The customary statistical survey of these issues is underway.

It can be anticipated that the energy use (and with it the other parameters) will increase, relative to the values in 2005, again by 10 %

The numbers so calculated are given below.

Total installed capacity in 2006: 670 MW_t

Total energy produced in 2006: 5250 TJ

Saving of fossil fuels: 125'000 toe

Avoids emission of 385'000 t CO_2

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Publications, meetings

The regular SVG publications:

- Newsletter GEOTHERMIE.CH
- Info sheets
- Technical brochures

Regular technical meetings (one per year)

Next year the European Geothermal Conference EGC 2007 will take place in Unterhaching, Germany, 30 May – 1 June 2007. The SVG is Co-Organizer.

Educational activities

- Regular geothermal courses at ETH Zurich, ETH Lausanne, Neuchâtel University
- Special training courses for professionals (2006: 13 until Sept.)
- Technical visits (2006: 7 until Sept.)

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Swiss geothermal websites

SVG/geothermie.ch	www.geothermal-energy.ch
BFE	www.bfe.admin.ch
CREGE	www.crege.ch
Swiss Deep Heat Mining Project	www.dhm.ch
GEOPOWER AG	www.geopower-basel.ch
Geothermal Explorers Ltd.	www.geothermal.ch
GEOWATT AG	www.geowatt.ch

International R&D activities

in IEA GIA:

- Annex I: participation of Deep Heat Mining project Basel in Subtask D activities;
- Annex III: distributing EGS PDMA;
- Annex VIII: design and evaluation of Questionnaire (with Y. Song);
- Draft Sustainability paper (Rybach & Mongillo).

in numerous EU research projects:

- European HDR Soultz
- ENGINE
- I-GET
- GROUNDHIT

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Table 1. Cost comparison of heating systems in Switzerland (reference system capacity 10 kW), from Hubacher/FWS 2005.

Heating system	Efficiency (η/SPF*)	Investment (CHF)	Capital cost (Annuity, CHF)	Operating cost (CHF)	Total annual cost (CHF)
Oil boiler	0.85	18'000	1'741	1'483	3'224
Gas boiler	0.95	14'500	989	1'882	2'871
Biomass (pellets)	0.90	33'500	2'692	1'814	4'506
Geothermal heat pump (with BHE)	3.4	30'500	2'055	872	2'929
Air-source heat pump	2.6	25'500	1'876	1'110	2'986

*) Seasonal performance factor

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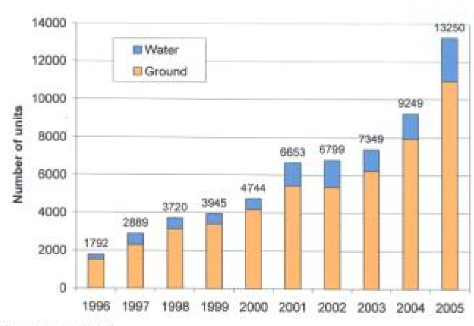
The market plays already...

GHP sales in Germany

(B. Sanner, EGEC communication, 9 March 2006)

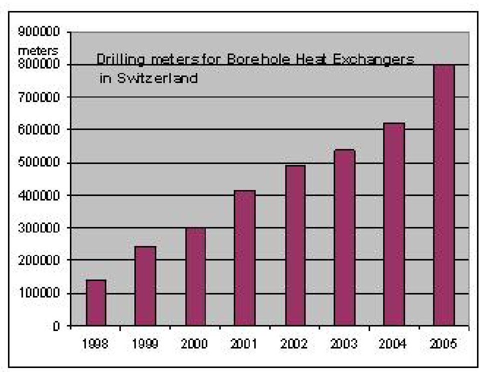


(after data from BWP)

There was a strong increase of heat pump sales in Germany in 2005, with a total of more than 13'000 ground source heat pumps.

The share of ground source heat pumps in the total heat pump sales was above 80 % until 2002, and decreased to only 72.7 % in 2005.

SWITZERLAND



Increase of BHE drilling activities

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In summary:

- Significantly increasing awareness of the general public and of decision makers about geothermal energy
- EGS projects and especially the Deep Heat Mining Project Basel raises great interest but also expectations
- Switzerland continues to be a leading country world-wide in geothermal heat pumps. In 2005, > 800 km boreholes have been drilled for BHEs, which needs 10 MWe new generating capacity
- Switzerland is active in national and international R&D, the latter especially in GIA and new EU projects (ENGINE, I-GET; GROUNDHIT)
- The Swiss Geothermal Association has been reorganized to act as the Swiss Geothermal Competence Center; unified appearance as **geothermie.ch**

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B ANHANG II

Grundlagenpapier “Geothermal Sustainability – A Review with Identified Research Needs”

Geothermal Sustainability—
A Review with Identified Research Needs

L. Rybach[1] and M. Mongillo[2]

[1]Vice Chairman IEA GIA and GEOWATT AG, Zurich, Switzerland
[2]Secretary, IEA-GIA and GNS Science, Wairakei, New Zealand

Keywords

Sustainability, renewability, power generation, sustainable development, renewable resources

ABSTRACT

The immense store of heat in the earth (~10^{13} EJ), provided mainly by decay of natural radioisotopes, is the ultimate source for geothermal resources. It results in a global terrestrial heat flow of 40 million MW_t, which alone would take over 10^9 years to exhaust the earth's heat. So, the geothermal resource base is extremely large and ubiquitous.

Geothermal energy is classified as a renewable resource, where "renewable" describes a characteristic of the resource: *the energy removed from the resource is continuously replaced by more energy on time scales similar to those required for energy removal and those typical of technological/societal systems*. Consequently, geothermal exploitation is not a "mining" process.

Geothermal energy can be used in a "sustainable" manner, which means that *the production system applied is able to sustain the production level over long times*. However, excessive production is often pursued, mainly for economic reasons, such as to obtain quick payback of investments, with reservoir depletion the result (e.g. The Geysers). An enhanced geothermal system (EGS) study showed that sustainable production can be achieved with lower production rates and can provide similar total energy yields as those achieved with high extraction rates.

Regeneration of geothermal resources following exploitation is a process that occurs over various time scales, depending on the type and size of production system, the rate of production and the characteristics of the resource. It depends directly on the rate of fluid/heat re-supply. Time scales for re-establishing the pre-production state following the cessation of production are examined using numerical model simulations for: 1) heat extraction by geothermal heat pumps, 2) the use of a doublet system on a hydrothermal aquifer for space heating, 3) conventional use of low-enthalpy resources, 4) the generation of electricity on a high enthalpy, two-phase reservoir and 5) an EGS. The results show that after production stops, recovery driven by natural forces like pressure and temperature gradients begins. The recovery typically shows asymptotic behaviour, being strong at the start, and then slowing down subsequently, and theoretically taking an infinite amount of time to reach its original state. However, practical replenishment (e.g. 95%) will occur much earlier, generally on time scales of the same order as the lifetime of the geothermal production systems.

It is concluded that: 1) "balanced" fluid/heat production that does not exceed the recharge can be considered fully sustainable, 2) production rates that persistently exceed the rate of recharge (natural or induced) will eventually lead to reservoir depletion, thus stopping economic production, 3) following termination of production, geothermal resources will undergo recovery towards their pre-production pressure and temperature states, 4) the post exploitation recovery typically exhibits an asymptotic behaviour, being strong at the start and slowing subsequently, and reaching a "practical" replenishment (~95% recovery) on time scales of the same order as the lifetime of the geothermal production system, 5) geothermal resources are renewable on timescales of technological/societal systems (~30-300 years), 6) sustainable production secures the longevity of the resource at lower production levels, 7) the level of sustainable production depends on the utilization technology as well as on the geothermal resource characteristics and 8) long-term production from geothermal resources should be limited to sustainable levels.

There is a currently clear need for more research into geothermal production sustainability, with the following investigations identified: 1) determination of "true" sustainable production levels for various geothermal resources and the techniques for defining them at the earliest possible stages of development, 2) compilation and analysis of the cases where stable reservoir performance has been successfully obtained during production, 3) synoptic treatment of numerically modelled production technologies by re-examining the regeneration time scales, 4) numerical modelling of EGS considering long-term strategies and various production scenarios and

5) deriving dynamic recovery factors that account for enhanced regeneration.

One of the aims of this paper is to stimulate discussion of sustainable geothermal energy utilization amongst the geothermal community and the authors encourage and invite comments (send to: mongillom@reap.org.nz before 30 November 2006).

Introduction

Renewability and sustainability are terms often used and discussed. The relevance of these ideas to geothermal energy utilization is described below.

The ultimate source of geothermal energy is the immense heat stored within the earth: 99% of the earth's volume has temperatures >1000°C, with only 0.1% at temperatures <100°C. The total heat content of the earth is estimated to be about 10^{13} EJ and it would take over 10^9 years to exhaust it through today's global terrestrial heat flow of 40 million MW_t. The internal heat of the earth is mainly provided by the decay of naturally radioactive isotopes, at the rate of 860 EJ/yr – about twice the world's primary energy consumption (443 EJ in 2003). Thus, the geothermal resource base is sufficiently large and basically ubiquitous.

Without utilization, the terrestrial heat flow is lost to the atmosphere. In this case, the isotherms run parallel to the earth's surface (i.e. horizontal in flat terrain) and the perpendicular heat flow lines point towards it. If, instead, the isotherms are deformed and the heat flow lines diverted towards heat sinks, the heat flow can be captured (Figure 1). Production of heat/fluid from geothermal reservoirs leads to the formation of such heat sinks and/or hydraulic pressure depressions. Their effects will be treated in more detail below.

Heat/fluid (along with its heat content) can be produced from a geothermal resource at different extraction rates. Excessive production could bring economic benefits, like earlier return of investment, but could also lead to resource depletion or even deterioration. However, by using moderate production rates, which take into account the local resource characteristics (field size, natural recharge rate, etc.), the longevity of production can be secured and sustainable production achieved.

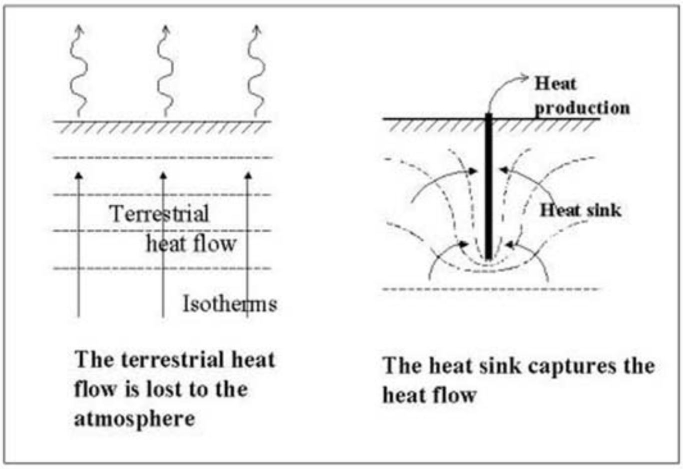

Figure 1. Principle of geothermal heat extraction and production.

Renewability and Sustainability

In general, geothermal energy is classified as a renewable energy resource, hence is included together with solar, wind and biomass alternative energy options in government R&D programs, and is identified as renewable in materials promoting geothermal energy. Renewable describes a attribute of the energy resource, i.e. *the energy removed from a resource is continuously replaced by more energy on time scales similar to those required for energy removal and those typical of technological/societal systems (30-300 years)*, rather than geological times (Axelsson, et al., 2005; O'Sullivan and Mannington, 2005; Rybach, et al., 1999; Stefansson, 2000).

The original definition of sustainable development goes back to the Brundtland Commission Report (1987; reinforced at the Rio 1991 and Kyoto 1997 Summits), where it was defined as:

> *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*

In relation to geothermal resources and, especially, to their exploitation, sustainability means the ability of the production system applied to sustain the production level over long times. Sustainable production of geothermal energy therefore secures the longevity of the resource, at an appropriate production level. A definition of sustainable production from a geothermal system has been suggested recently (Axelsson, et al., 2001):

> *"For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, below which it will be possible to maintain constant energy production from the system for a very long time (100 – 300 years)."*

This definition applies to the total extractable energy (the heat in the fluid plus that in the rock), and depends on the nature of the system, but not on load factors or utilization efficiency. The definition does not consider economic aspects, environmental issues or technological advances, all of which may be expected to change with time.

The terms renewable and sustainable are often confused, and it is important to stress that the former concerns the nature of a resource and the latter applies to how a resource is utilized (Axelsson, et al., 2002).

Effects of Heat/Fluid Production from a Geothermal Reservoir

Geothermal resources are commonly used by withdrawing fluid and extracting its heat content. There are prominent examples that this can happen in a fully sustainable fashion: thermal springs in many parts of the world have been conveying impressive amounts of heat (and fluid) to the surface for centuries, without showing any signs of a decline. In such situations, obviously a balance exists between surface discharge and fluid/heat recharge at depth, i.e. renewability. Any "balanced" fluid/heat production by a geothermal utilization scheme, i.e. which does not produce more than the natural recharge re-supplies, can be considered as "fully" sustainable. Such production rates are, however, limited and in many cases not economical for utilization.

High production rates can exceed the long-term rate of recharge and can lead, with increasing production duration, to depletion, especially of the fluid content. Most of the heat stored in the matrix however, remains in place. Many utilization schemes (high enthalpy steam and/or water dominated reservoirs, doublets in hydrothermal aquifers), therefore apply reinjection, which at least replenishes the fluid content and helps to sustain or restore reservoir pressure. On the other hand, cold reinjected fluid can create thermal depletion in an increasing volume of the reservoir.

Geothermal resources are often taken into excessive production (of the reservoir fluid as the heat carrier), mainly to meet economic goals like quick payback of investments for exploration and equipment, with reservoir depletion the result. There are numerous examples for this approach worldwide, the most prominent is the vapour-dominated field of The Geysers, California, USA. Figure 2 shows the change of production with time, and the effect of reinjection starting in January 1998. Reinjection halted the production decline only temporarily.

"Mining" Geothermal Resources?

Geothermal heat and/or fluid extraction is frequently described as "mining", however, this analogy is absolutely wrong. When a mineral deposit is mined and the ore removed, it will be gone forever. Not so for geothermal; being renewable, the replenishment of geothermal resources (heat and fluid) will always take place, albeit sometimes at slow rates. This incorrect analogy also leads to legal problems and obstacles, and in reality, geothermal energy cannot be defined in physical terms as a mineral resource.

The regeneration of geothermal resources is a process that occurs over various time scales, depending on the type and size of the production system, the rate of extraction, and the attributes of the resource. After production stops, the resources recover by natural processes. The production of geothermal fluid/heat continuously creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn– both during production and after its cessation– generate fluid/heat inflows towards re-establishing the pre-production state (Rybach, et al., 2000). The question of regeneration boils down to the rate of fluid/heat re-supply. The time scales for re-establishing pre-production states are examined below for five resource types and utilization schemes: 1) heat extraction by geothermal heat pumps; 2) hydrothermal aquifer, used by a doublet system for space heating; 3) conventional use of low-enthalpy resources without reinjection; 4) high enthalpy, two-phase reservoir, tapped to generate electricity; 5) enhanced geothermal systems (EGS). Numerical model simulations were used.

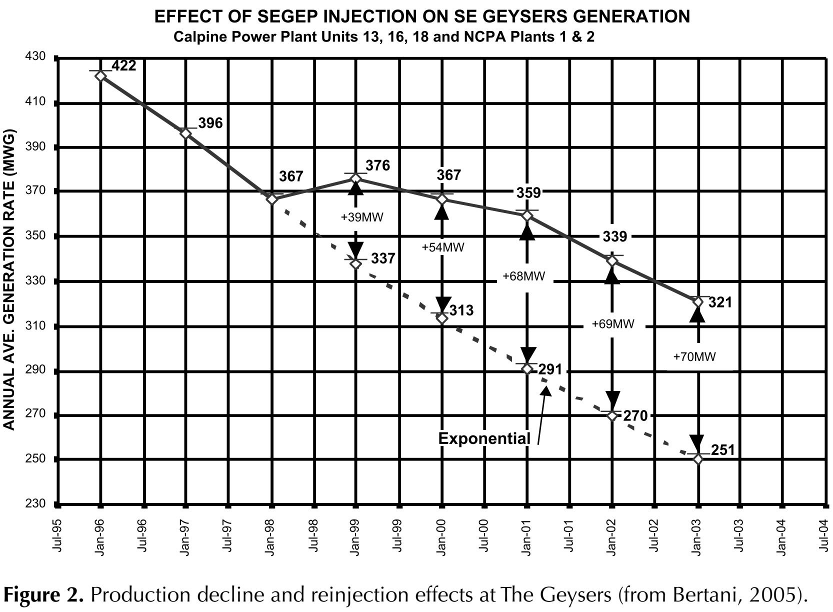

Figure 2. Production decline and reinjection effects at The Geysers (from Bertani, 2005).

Geothermal Regeneration Time Scales

Geothermal Heat Pumps

Geothermal heat pumps (GHP) are ground-coupled heat pumps; they operate with subsurface heat exchanger pipes (horizontal or vertical), or with groundwater boreholes (for an overview see Lund, et al., 2003). Here the issue of sustainability concerns the various heat sources. In the horizontal systems, the heat exchanger pipes are buried at shallow depth; the longevity of their smooth operation is guaranteed by the constant heat supply from the atmosphere provided by solar radiation. In the case of combined heating/cooling by GHPs, the heat balance (in/out) is given by the system design itself: replacement of heat extracted in winter by heat storage in summer. In the case of groundwater-coupled GHPs, the re-supply of fluid is secured by the hydrologic cycle (infiltration of precipitation) and the heat comes "from above" (atmosphere) and/or "from below" (geothermal heat flow); the relative proportions depending on aquifer depth. This leads to an approximately constant aquifer temperature throughout the year without any significant seasonal variation. Any deficit created by heat/fluid extraction is replenished by the (lateral) groundwater flow.

The question of sustainability of GHPs in general, and of borehole heat exchanger (BHE)-coupled heat pumps boils down to: how long can such systems operate without a significant drawdown in production, i.e. becoming economically unviable. Therefore the long-term production behaviour of BHE-based GHPs needs to be addressed.

After a period of operation, the BHE creates a cylindrically shaped heat sink in the ground with isotherms concentrated near the BHE (for details see Eugster and Rybach, 2000). The pronounced heat sink forms a cigar-shaped iso,therm pattern, with the BHE as its centre (Figure 3). The heat sink creates strong temperature gradients in the BHE vicinity, which in turn lead to heat inflow directed radially towards the BHE, to replenish the deficit

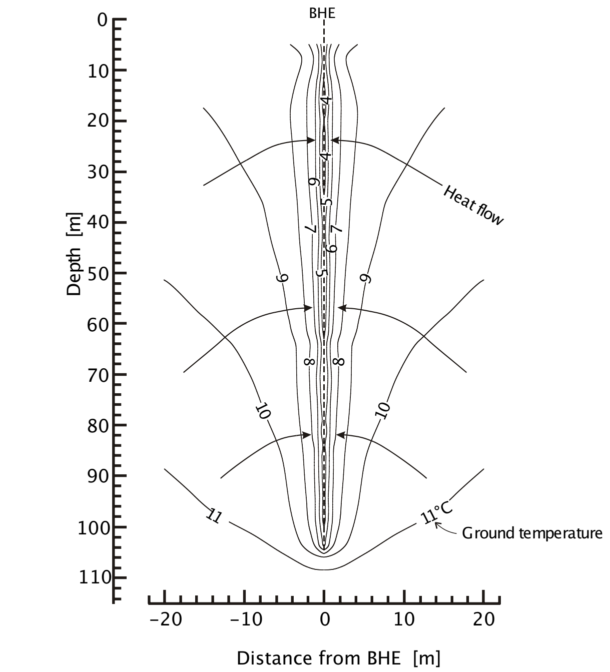

Figure 3. Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg, ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m^2 (from Rybach and Eugster, 2002).

created by the heat extraction. The heat flow density attains rather high values (up to several W/m^2), compared to the terrestrial heat flow (80 – 100 mW/m^2).

During the production period of a BHE (operating in the heating-only mode), the drawdown of the temperature around the BHE is strong during the first few years of operation (Figure 4). Later, the yearly deficit decreases asymptotically. Following heat extraction shutdown, regeneration of the resource begins. During this recovery period (after an assumed 30 years of operation), the ground temperature shows a similar behaviour: during the first years, the temperature increase is rapid, but then

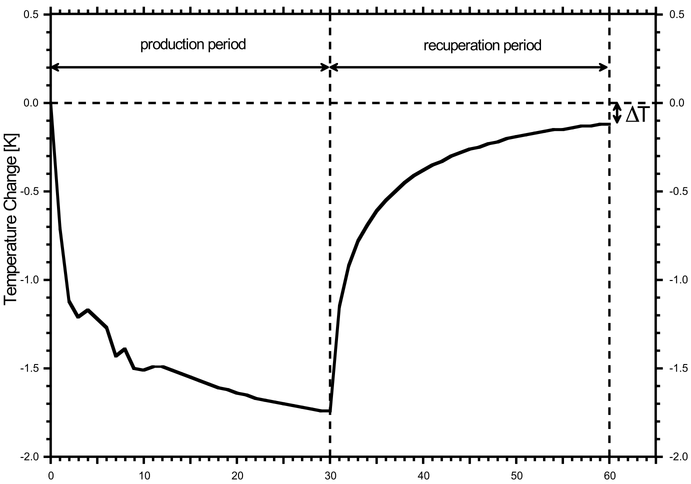

Figure 4. Calculated ground temperature change at a depth of 50 m and at a distance of 1 m from a 105 m long BHE over a production period and a recuperation period of 30 years each (from Eugster and Rybach, 2000).

tends with increasing recovery time asymptotically towards zero (Eugster and Rybach, 2000). The time to reach nearly complete recovery depends on how long the BHE has been operational. Principally, the recovery period equals the operation period.

The results of numerical modelling for a single BHE show that the long-term performance of the BHE/HP system stabilizes at a somewhat lower but quasi-steady level, relative to initial conditions, after the first 10 years. Thus, sustainable operation can be achieved.

The basic studies of long-term performance presented here apply to a single BHE. Similar studies of multiple BHE systems yielded comparable results (Signorelli, et al., 2005).

Doublet System Using a Hydrothermal Aquifer

The heat content of a deep aquifer can be utilised by producing the aquifer's fluid. The fluid's heat is transferred through a heat exchanger to a district-heating network (often via a heat pump), and the cooled water is reinjected into the aquifer by a second borehole at a sufficient distance from the production borehole (doublet operation). Due to this geothermal circuit, the produced hot fluid is continuously replaced by cooled injected water. This leads to an increasing volume of thermal drawdown propagating from the injection to the production well. After the thermal breakthrough time, the temperature of the produced fluid will decrease at a rate depending on the production rate, the distance between the boreholes, as well as on the physical and geometric properties of the reservoir. The increasing thermal gradients in the reservoir cause a corresponding increase in conductive thermal recovery. Hence, a thermal steady state will be reached after a sufficient circulation time, which yields a practically constant production temperature; and production at that rate can be sustained.

The town of Riehen, near Basel, hosts the first and only geothermal based district heating system in Switzerland, with a capacity of 15 MW_t. The use of the doublet system started in 1994. In 1998, an extension of the district heating network into the neighbouring German town of Lörrach was established. For this system, it is essential to secure the production temperature without a considerable drawdown for about 30 years. Numerical simulations performed with the FE-code FRACTure (Kohl, 1992; for details about the modelling and the site see Mégel and Rybach, 2000) demonstrated that the geothermal circuit fulfils this condition.

The steady state production temperature is not reached even after 300 years. The development of the temperature can be characterised by considering the temperature change ĆT over a given time period, e.g. 10 years. This curve indicates the asymptotic behaviour of the production temperature. The maximum value of -0.7°K/10 years is obtained after 20 years production, with the temperature drop decreasing to -0.15°K/10 years after 300 years production. Thus, practically constant heat production can be sustained.

Practical proof of sustainable doublet system operation is provided by the operational experience with the numerous doublet installations in the Paris Basin. Most of these systems have operated since the early 1970s and, so far, no production temperature or water level drawdowns have been observed (Ungemach and Antics, 2006).

Low-Enthalpy Resources

Conventional use of low-enthalpy resources for heat production, without reinjection, is common, especially in Iceland. The Laugarnes Geothermal Field has been used in this manner for over 75 years. Production was increased by a factor of 10 in the mid-1960s, after more than 30 years of low production with negligible pressure change (Axelsson, et al., 2005). Though this increase resulted in a 12 bar pressure drop, a new "semi-equilibrium" level was reached after about 10 years, where it has remained stable for the last 3 decades. This sustainable production, without reinjection, is the result of enhanced recharge amounting to 10 times the natural state value.

The Hamar Geothermal System, Iceland, is another low-enthalpy (65 ºC) example. It has been utilized at 23-42 l/s for the last 33 years, with only a 3 bar pressure decline. A lumped parameter model was used to calculate the effect of 200 years of production at 40 kg/s. The results indicate that >40 kg/s is sustainable with the down-hole pumps located above the current maximum operational depths of 200-300 m. Modelling also shows that, with a conservative system volume of 0.5 km^3, constant production temperature can be maintained for over 200 years. Thus, the sustainable production is >40 kg/s, with a sustainable energy of >11 MW_t (ibid.).

High-Enthalpy Two-Phase Reservoir

Resources of this type are widely used to generate electricity. Some of them show strong signs of pressure depletion. Although this can be beneficial to some reservoirs by locally stimulating increased hot fluid recharge, if a new pressure equilibrium is not established before the pressures drop too far, then well production rates become uneconomic. Reinjection schemes are increasingly being introduced to help sustain pressures and overcome this problem. Reinjection, however, can cause temperature decreases in the resource volume. This problem, together with the high production rates dictated by economic constraints, rather than by balancing the natural re-supply, can limit the productive lifetime of power plants to a couple of decades.

A thorough theoretical study of the electrical production/recovery cycle of a hypothetical reservoir with operational characteristics typical of lower-permeability two-phase reservoirs was conducted by Pritchett (1998) using a maximum permeability (both horizontal and vertical) of 10 md and a relatively high production ratio [(produced energy)/(natural energy recharge)] estimated to be ~6.1 (O'Sullivan and Mannington, 2005). This ratio can vary widely depending on local resource characteristics. The study addressed the change in electricity generating capacity with time for 50 years of continuous two-phase fluid production; then examined the subsequent recovery after shutdown of the power plant operation.

The study showed that pressure recovery occurred much faster than temperature re-establishment. Table 1 shows that the relative recovery increased slowly with time and that it took several times longer than the production duration to reach a reasonable recovery (say 90 %). The recovery rate was strong in the beginning but decreased subsequently, and only after an infinite time was complete recovery reached (asymptotic behaviour). This study contrasts with the two described below in that it used a fixed recharge rate, rather than allowing production enhanced recharge.

Table 1. Relative recovery of a two-phase reservoir after 50 years production (data from Pritchett, 1998).

Reservoir Property	Years After Production Shut-Down		
	50	100	250
Pressure	68 %	88 %	98 %
Temperature	9 %	21 %	77 %

A recent and more realistic study examined the recovery of the Wairakei-Tauhara geothermal system using a well-calibrated computer model based on an extensive database and relatively long production history (>50 years) (O'Sullivan and Mannington, 2005). It assumed a total of 100 years of production at the current rate (~1900 MW_t), and a production ratio (pr) of 4.75 based on a pre-exploitation natural energy flow of 400 MW_t (Allis, 1981). The results showed very rapid recovery of pressure (within ~25 years). The temperature recovery was slower, ranging from 50-120 years for 90%-98% recovery over the "deep recharge zone", to 300 years for 90% recovery further away. Vapour saturation recovery was very slow, taking ~300 years to return to the pre-exploitation state. Hence, this detailed model showed that the Wairakei-Tauhara geothermal system recovered to almost its pre-exploitation state in 300 years, or three times the total production period. This result is in good agreement with a lumped-parameter model estimate (*ibid.*): (recovery time) ≈ (pr-1)* (production time) ~3.75 (production time). A contributing factor to this model showing a more rapid recovery rate than that of Pritchett (1998) is that Wairakei-Tauhara has a much higher permeability (horizontal ~200-800 md; vertical ~5-25 md) (Mannington, et al., 2004) than that used by Pritchett.

Another recent example used a comprehensive numerical model that covers the entire Hengill volcanic system, Iceland. It was used to examine the Nesjavellir Geothermal System during 30 years of intense production (540 kg/s), for both direct use heating (200 MW_t) and electricity generation (120 MW_e), followed by 250 years of recovery (Axelsson, et al., 2005). Preliminary results showed that the pressure recovers on a time scale comparable to that of production. However, the temperature (not well calibrated due to lack of data) recovered much more slowly (>250 years), though the temperature drop at the end of production was only 4-5 ºC (~1.5% of the reservoir temperature). Results also indicated that the effects of this intense (excessive) production should be reversible, with sustainable production at a reduced rate possible after the recovery period.

Enhanced Geothermal System (EGS)

Such a system attempts to extract heat by semi-open circulation through a fractured rock volume, at considerable depth (several kilometers), between injection and production boreholes. The degree of fracturing is enhanced by technical means (man-made fracturing).

The thermal output of an EGS depends on the efficiency of heat exchange in the fractured reservoir. The more heat exchange surface that is encountered by the circulated fluid, the more efficient is the heat extraction. The output temperature (and that of the EGS reservoir) will gradually decrease, though the decrease can be accelerated by effects such as short-circuiting, whereby the circulated fluid follows preferential pathways instead of contacting extended heat exchange surfaces, and additional cooling of the rock mass if significant water losses in the system are replenished by adding cold water to the injection flow at the surface.

On the other hand, special effects like the creation of new heat exchange surfaces by cooling cracks might enhance the heat recovery. More field experience is needed to assess the efficiency and development with time of this effect.

In any case, the issue of EGS sustainability boils down to the question of thermal recovery of the rock mass after production stops. The lifetime of EGS systems is usually considered to be several decades. It can be expected that the recovery duration extends over time periods of similar magnitude, although the time-scale could be beyond economic interest. With favorable conditions like at Soultz-sous-Fôrets (France), hydraulic-convective heat and fluid re-supply from the far field can be effective, thanks to large-scale permeable faults (Kohl, et al., 2000). More detailed theoretical studies using numerical simulation are needed to establish a reliable base for EGS sustainability.

Further studies are also needed to determine, in a general sense, the residual heat, which remains in an EGS reservoir when excessive production rates are applied. Production at lower rates and/or using production enhancement techniques enables the extraction of more heat and thus prolongs the economic life of a given reservoir. In particular, various operational strategies such as load following, variable well flow rates and innovative reservoir/power plant management (e.g. by matching power plant design to reservoir production) should be considered.

Summary

In summary, the following general comments about geothermal regeneration can be made. Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content, but also increases the natural recharge rate into created pressure and temperature sinks (i.e. dynamic recovery). A new and sustainable equilibrium condition can be established. The recovery process begins after production stops, driven by natural forces resulting from pressure and temperature gradients. The recovery typically shows asymptotic behaviour, being strong at the beginning and slowing down subsequently, with the original state being re-established theoretically only after an infinite time. However, practical replenishment (e.g. 95% recovery) will be reached much earlier, generally on time-scales of the same order as the lifetime of the geothermal production systems.

The Key Issue: The Sustainable Production Level

When producing from a geothermal resource the sustainability will depend on the initial heat and fluid content and their regeneration rates (Wright, 1995). In addition, the reaction of the resource to production will largely depend on the rate of heat/fluid extraction. With high extraction rates the energy yield will be correspondingly high at the beginning (and with it the economic reward) but the energy delivery will decrease significantly with time, and can cause the breakdown of a commercially viable operation.

Lower production rates can secure the longevity of production, i.e. relatively constant production rates can be sustained. In addition, sustainable production rates can provide similar total energy yields to those achieved with high extraction rates. To demonstrate this, the results of a study comparing high and low level production from an EGS model are summarized (for details see Sanyal and Butler, 2005). The model reservoir had an area of 3.66 km x 3.66 km, with a vertical extension between 1.22 km and 2.74 km depth. The average initial reservoir temperature was 210°C. A three-dimensional, double-porosity, finite-difference numerical scheme was used to calculate power generation from this hypothetical EGS reservoir. A five-spot borehole array (injector at the model centre and production well at each corner of a square) with high (1800 t/hr) and low (475 t/hr) production rates was considered (injection flow rate = production flow rate).

Production at the high rate yielded higher power generation capacity at the beginning (45 MW_e). A parasitic load of nearly 10 MW_e was needed to pump the high fluid circulation rate through the system. The fluid production temperature decreased with time and reservoir depletion resulted in production stopping after 20 years (Figure 5). The total energy produced amounted to 245 MW_eyear.

At the lower circulation rate, the starting capacity was only 12 MW_e (Figure 6), but the pumping load was nearly negligible. The temperature decline was also much less and the power generation capacity prevailed well beyond 30 years. The total energy produced over 30 years, 250 MW_eyear, was very similar to that from the excessive production.

This example demonstrates that with lower extraction rates longevity of the resource, and thus sustainable production, can be achieved and still generate as much energy as from excessive production. The level of sustainable production depends on the utilization technology as well as on the local geological conditions and resource characteristics. Its determination needs specific studies, especially model simulations of long-term production strategies.

Research Needs

Though numerous basic studies of geothermal production sustainability (Axelsson, et al., 2005; 2001; Lovekin, 2000; O'Sullivan and Mannington, 2005; Rybach, 2003; Sanyal, 2005; Stefansson, 2000; Stefansson and Axelsson, 2003; 2005; 2006; Ungemach, et al., 2005; Wright, 1995) have been conducted, the authors strongly believe that there is still a clear need for significantly more research. In particular, specific, focussed investigations are needed in several areas:

- Determination of "true" sustainable production levels for geothermal resources and techniques for defining them at the earliest possible stages of development.
- Compilation and analysis of the successful examples for stabilizing reservoir performance during production for both high enthalpy (Larderello, Italy [Cappetti, 2004];

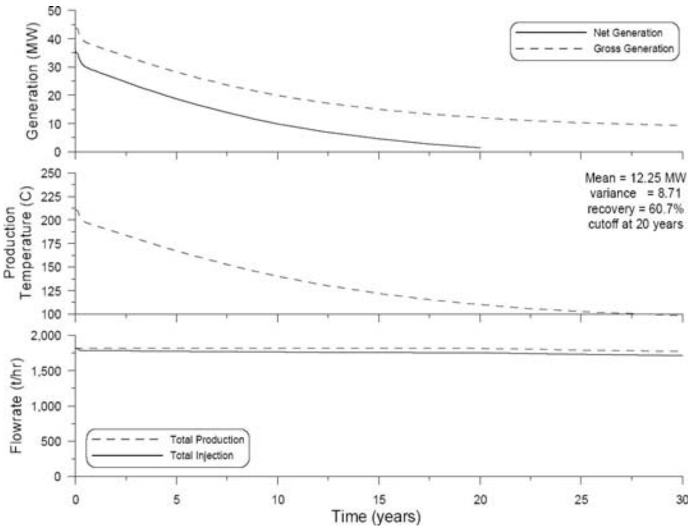

Figure 5. Power generation from an EGS system with high circulation rate (500 l/s) starts with 45 MW_e capacity but terminates after 20 years with a total generation of 245 MW_eyears (from Sanyal and Butler, 2005).

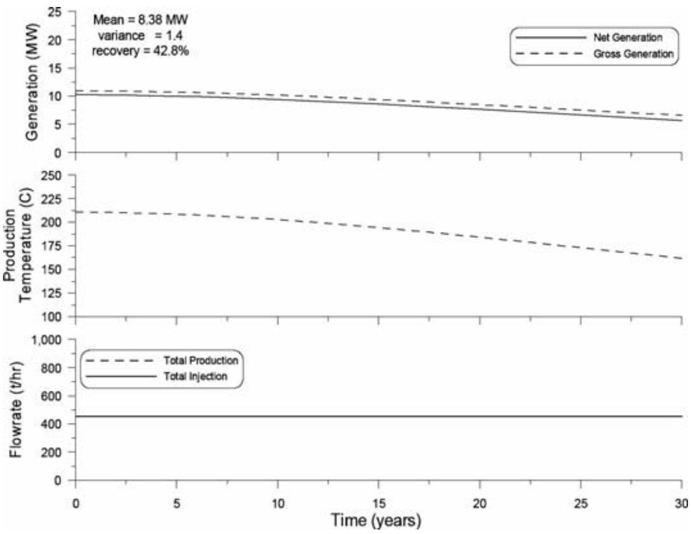

Figure 6. Lower circulation rate (126 l/s) yields long-lasting power production with total generation of 250 MW_eyears (from Sanyal and Butler, 2005).

Kawerau, New Zealand [Bromley, 2006a]; Wairakei, New Zealand [Bromley, 2006b]) and low enthalpy systems (Laugarness, Iceland [Axelsson, et al., 2005]; Paris Basin, France [Ungemach, et al., 2005]).

- Synoptic treatment of numerically modelled production technologies (steam-turbine power plant, geothermal doublet, ground-source heat pump) through a unified approach looking at the regeneration time-scales.
- Numerical modelling of EGS considering long-term production/recovery, by different production scenarios like combined heat and power (CHP) production, load-following operation, etc.
- Determination of "dynamic" recovery factors: these must account for enhanced recharge driven by the strong hydraulic and thermal gradients created by fluid/heat extraction.

Conclusions

- Any "balanced" fluid/heat production by a geothermal utilisation scheme, i.e. which does not produce more than the natural recharge re-supplies, can be considered "fully" sustainable. A natural thermal spring, issuing since Roman times, is an impressive example.
- Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content, but also increases the natural recharge rate into created pressure and temperature sinks (i.e. dynamic recovery). A new and sustainable equilibrium condition can be established. Production rates that exceed the long-term rate of recharge will eventually lead to reservoir depletion, which could stop economic production.
- The continuous production of geothermal fluid and/or heat creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn– both during and after termination of production– generate fluid/heat inflow towards re-establishing the pre-production state.
- Unlike for mining (e.g. mining out an ore body), there will be geothermal resource regeneration. The recovery typically shows asymptotic behaviour, being strong at the beginning and slowing down subsequently, the original state being re-established theoretically only after infinite time. However, practical replenishment (e.g. 95% recovery) will be reached relatively early, generally on a time-scale of the same order as the lifetime of geothermal production systems.
- Recovery of high-enthalpy reservoirs is accomplished at the same site at which the fluid/heat is extracted. In addition, for the doublet and heat pump systems, truly sustainable production can be achieved. Thus geothermal resources can be considered renewable on time-scales of technological/societal systems, and do not need geological times as fossil fuel reserves do (coal, oil, gas).
- For geothermal energy utilization, sustainability means the ability of the production system applied to sustain the production level over long times. Sustainable production of geothermal energy therefore secures the longevity of the resource, at a lower production level.
- Long-term production from geothermal resources should be limited to sustainable levels, although short periods of extra production may be an appropriate means of rapidly establishing pressure and temperature sinks, and thereby encouraging greater flows of hot recharge from much larger underlying or peripheral resources.
- The level of sustainable production depends on the utilization technology as well as on the local geothermal resource characteristics. Its determination needs specific studies, especially model simulations of long-term production strategies, for which exploration, monitoring and production data are required.
- Further sustainability research is needed in several areas, as stated above.

One of the aims of this paper is to stimulate discussion of sustainable geothermal energy utilization amongst the geothermal community, with a major outcome being the development of an International Energy Agency- Geothermal Implementing Agreement position on this issue. Consequently, the authors encourage and invite comments to be sent to Mike Mongillo (mongillom@reap.org.nz) before 30 November 2006.

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C ANHANG III

Stellungnahme von L. Rybach zu „White paper“ und „Draft Protocol“, IEA GIA Annex I (Environmental Impacts of Geothermal Energy Development), Subtask D (Seismic Risk From Fluid Injection Into Enhanced Geothermal Systems)

Comments of L. Rybach on IEA GIA Annex I Subtask D White Paper

Induced Seismicity Associated with Enhanced Geothermal Systems
E. Majer, R. Baria, M. Stark, B. Smith, S. Oates, J. Bommer, and H. Asanuma

(”White Paper”; distributed by GIA Secretary M. Mongillo on 20 September 2006)

The White Paper presents an excellent overview of the current knowledge about induced seismicity (man-made earthquakes, MEQ) in general and about MEQ related to EGS in particular. It also clearly identifies the gaps in knowledge and suggests investigations that could help to close these gaps.

Still a lot remains to be done. The suggested investigations are numerous and will need considerabe research efforts. There are still further issues to be clarified; below I list – from my point of view– additional tasks that should be included in future investigations.

1. *Search for means to discriminate EGS-related MEQ from natural seismic events*: Identify and characterize attributes typical of EGS-caused events (duration, frequency content, dominant frequency....)

2. *Looking into possible seismic effects during long-term EGS operation (production phase):*
   Can it be expected that the level of seismicity due to production will be lower than that during stimulation? So far there is no (or not much) experience about thermoelastic effects (cooling cracks) on the long term.

3. *How far can relevant stress field pertubations reach out from EGS operations?*
   Pore pressure build-up propagates generally quickly but reduces with distance.

4. *Related to the above issue: What safety distance is needed between an EGS reservoir and a nearby ”capable fault”?* (The planned reservoir of the DHM project in Basel would be located ~ 2 km west of the major listric Eastern Boundary Fault of the Rhine Graben)

5. *Substantiation and generalization (if possible) of the findings of Italian researchers in Tuscany (Barbier 1997):*
   - increasing volumes of reinjected fluids do not lead to larger earthquakes, but to more frequent events;
   - reinjection has possibly a positive effect, by releasing stress in numerous smaller events, which acts against stress accumulation for a large single earthquake.

6. *Further studies on post shut-in seismicity:*
   MEQ could happen after a production stop implemented according to the “Traffic light” concept.

7. *The research efforts should ultimately provide means for a safe, responsible management of EGS-related MEQ:*
   How to design and implement downhole EGS operations to remain below permissible/tolerable levels of ground shaking? The management scheme must rely on technical factors like volume, rate, temperature of fluid injection. These will depend on the local conditions at depth. The nature and degree of dependency is still unclear.

The White Paper does admittedly not intend to prioritize the (numerous) research needs and actions to be taken. Nevertheless a prioritization will be needed, in view of limited budgets and the time pressure dictated by the ongoing or starting EGS projects. A discussion should be initiated and a consensus shall be reached within the EGS community. The IEA GIA could provide a platform for this, and/or the EU project ENGINE.

Finally I would like to point out that possible synergies could be generated and side benefits created together with other technology domains that apply large-scale injections (production from high-enthalpy geothermal fields, enhanced hydrocarbon recovery, CO_2 sequestration). Links and ties to these activity fields should be envisaged and established.

Zurich, 30 November 2006 L. Rybach

Comments of L. Rybach on IEA GIA Annex I Subtask D ***Protocol***

(DRAFT FOR DISCUSSION)
PROTOCOL FOR INDUCED SEISMICITY ASSOCIATED WITH ENHANCED GEOTHERMAL SYSTEMS

(”Protocol”; distributed by GIA Secretary M. Mongillo on 20 September 2006)

Should geothermal energy utilization by EGS reach its full potential the issue of induced seismicity (=Man-made earthquakes, MEQ) must be addressed to the point of public acceptance. Therefore general confidence and public acceptance are key EGS issues. The Protocol aims to define and describe means and actions to be taken by EGS developers and project managers to deal and communicate with local authorities and the public. It describes possible steps to be undertaken before and during EGS development. Below some remarks are given, without addressing the suggested steps individually.

The Protocol’s main handling and action scheme (=steps) remains reactive. It suggests measures like those included in the ”Traffic light” action plan, which can only be implemented after a seismic event has already happened. What would really be needed is a procedure to prevent –or at least reduce– future, disturbing ($M \geq 3$) seismic events related to EGS operations.

Complete avoidance of MEQ during EGS operations is impossible and not foreseen: microseismic activity due to stimulation is a key process to map EGS reservoir development in space and time, thus badly needed and highly beneficial. The most revelant issue is the level of perceptible / permissible ground shaking. It is customary to quantify ground shaking in terms of ground peak velocity (PGV; cm/s). There are numerical values of PGV presented and discussed in the literature for various human activities that can cause ground shaking (traffic, blasting, foundation piling); the ”White Paper” presents such information.

For EGS operations the role and position of regulating authorities is crucial. For the Deep Heat Mining (DHM) project in Basel/Switzerland the responsible local authority is the Office of Environment and Energy, Canton Basel City. This Office was responsible for fixing of limits and issuing injunctionas as well as restrictions within the Environmental Impact Procedure. For ground vibrations the Office has set the limits of PGV at 0.04 cm/s (daytime) and 0.03 cm/s (night), respectively. The limits are compared with actually measured values and weekly displayed on the website of the Office (http://www.aue.bs.ch/fachbereiche/laerm/dhm.htm) .

To my knowledge there have been no limits set (yet?) by the local authority for EGS-related ground shaking in Basel. The Draft Traffic Light Scheme of the DHM project (as presented at the 3rd IEA GIA Annex I Subtask D Workshop (January 2006) envisages actions only above PGV=2.0 cm/s, which is 50 times higher than the level set for ground vibrations.

Public perception is equally important and can be crucial. Fears and expectations must be taken serious (e.g the fear that small but repeated MEQ could accumulate energy in the ground and trigger –earlier than by nature– a large seismic event). Therefore constant, transparent and unbiased information is indispensable in order to achieve pubic acceptance as far as possible. The DHM project at Basel found an excellent solution for this: the EGS seismicity issue is fully handled by the Swiss Seismological Service; the special DHM website (**http://www.seismo.ethz.ch/basel/**) demonstrates exemplarily what kind of information and with what frequency needs to be given to the general public.

Still a lot remains to be done. EGS development must proceed in parallel with basic research on EGS-induced seismicity (for open questions and corresponding investigations see the "White paper"). It will be crucial to have firm ground for MEQ handling and EGS operation management before a significant number of EGS systems goes into production.

Zurich, 30 November 2006 L. Rybach