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The Sustainability Task of the International Energy Agency's Geothermal Implementing Agreement

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ABSTRACT

The Geothermal Implementing Agreement (GIA) provides a framework for international geothermal cooperation under the auspices of the International Energy Agency (IEA). The promotion of sustainable utilization of geothermal energy is the main aim of the IEA-GIA's current 5-year term. Therefore, a task was set up under Annex I (Environmental Impacts of Geothermal Development) of the IEA-GIA dealing with sustainable geothermal utilization. The aim of the Task is to collect information, identify research needs, facilitate international collaboration on the issue through workshops and meetings, as well as facilitate the publication of scientific papers and reports on geothermal sustainability studies and research. To date, the sustainability issue has been discussed at several Annex I meetings; with some relevant definitions established and several significant research needs identified. A number of recent papers and reports have also been assembled and made available through the IEA-GIA's website. In addition, a successful one-day international workshop dealing with sustainability modelling was held in late 2008, in Taupo, New Zealand, with over 40 participants and 17 presentations from 7 countries. As a result a special issue of a geothermal research journal, supported by the IEA-GIA Annex I, devoted to sustainable geothermal utilization has been prepared; with particular emphasis on long utilization case histories and sustainability modelling studies. Further workshops devoted to the sustainability issue and continued information gathering and dissemination are also planned. Another achievement of the Task is the lively sustainability discussions it has stimulated within the geothermal community.

1. INTRODUCTION

The potential of the Earth's geothermal resources is enormous, both compared with its utilization today and the future energy-needs of mankind. Stefánsson (2005) estimated that the technically feasible potential of identified geothermal resources is 240 GW_e (1 GW = 10^9 W), which is only a small fraction of hidden, or as yet unidentified, resources. He also estimates that the most likely direct use potential of lower temperature resources is 140 EJ/yr (1 EJ = 10^{18} J). In comparison the worldwide installed geothermal electricity generation capacity was about 10 GW_e in 2007 and the direct geothermal utilization amounted to 330 PJ/yr (1 PJ = 10^{15} J) according to IEA-GIA (2008a). About 1/3 of the direct use is through ground-source heat-pumps. Fridleifsson *et al.* (2008) have estimated that by 2050 the electrical generation potential may have reached 70 GW_e and the direct use 5.1 EJ/yr, 600 and 1450 % increase, respectively. There is, therefore, ample space for accelerated use of geothermal resources worldwide in the near future. Geothermal resources also have the potential of contributing significantly to sustainable development and to help mitigate climate change.

The Geothermal Implementing Agreement (GIA) provides a framework for international geothermal cooperation under the auspices of the International Energy Agency (IEA). The promotion of sustainable utilization of geothermal energy is the main aim of the GIA's current 5-year term. Therefore, a task was set up under Annex I (Environmental Impacts of Geothermal Development) of the GIA dealing with sustainable geothermal utilization.

This paper describes the work conducted under the Sustainability Task of the IEA-GIA. It starts out with a brief description of the IEA-GIA, followed by a discussion of the concept of sustainable geothermal utilization and a discussion of the work associated with the Sustainability Task. Mongillo *et al.* (2010) describe the IEA and the IEA-GIA in detail, only a short review is presented here. A more detailed analysis of sustainable geothermal utilization is presented by Axelsson (2009).

2. IEA AND IEA-GIA

The International Energy Agency (IEA) is an intergovernmental organization founded in 1974 (in response to the first oil-crisis) and based in Paris (Mongillo *et al.*, 2010). The IEA now acts as an energy policy advisor to its 28 member countries dealing with energy security, economic development, environmental protection, alternative energy sources and energy efficiency, to name a few issues. The IEA operates an extensive programme of data compilation, energy research, publication and public dissemination.

IEA coordinates collaboration through a network of 41 Implementing Agreements (IAs) that guide the IEA's collaborative program activities (Mongillo *et al.*, 2010). IA members are either representatives of member countries or industrial- or organizational sponsors. IA activities, named Tasks, are organized in Annexes. An Executive Committee (ExCo), consisting of one representative from each member, manages the activities of each IA and is responsible for disseminating results and reporting to the IEA. Each Annex is led by an Operating Agent that is usually an institution.

The Geothermal Implementing Agreement (GIA) was established in 1997 and as of 2007 it's in its third 5-year term (Mongillo *et al.*, 2010). The general scope of the GIA is to strengthen international collaboration to: compile and exchange information on global geothermal energy R&D,

develop improved technologies for geothermal energy use, improve the understanding of the environmental benefits of geothermal energy utilization and develop ways to minimize its environmental impacts. Presently (May 2009) the IEA-GIA has nineteen members, including 12 country-members (Australia, France, Germany, Iceland, Italy, Japan, Mexico, New Zealand, Republic of Korea, Spain, Switzerland, United States), the EC, four industrial-members and two organizational-members.

The GIA ExCo, which consists of one voting representative from each of the above 19 Members, supervises the overall operation of the organization. It meets twice a year to report on geothermal activity of the members and discuss the organization's activities. Separate Annex meetings are frequently held in association with the ExCo meetings.

The IEA-GIA's Annexes operating at present are:

- Annex I: Environmental impacts of geothermal energy development.
- Annex III: Enhanced geothermal systems (EGS).
- Annex VII: Advanced geothermal drilling techniques
- Annex VIII: Direct use of geothermal energy.

The studies conducted in each Annex are organized under several Tasks. Mongillo *et al.* (2010) describe Annexes III, VII and VIII as well as the overall organization and operation of the IEA-GIA, dissemination of the results of its activities as well as participation in meetings, workshops and conferences. The IEA-GIA's public website (www.iea-gia.org) provides access to various GIA documents, other relevant international publications as well as allowing comments to be made on these documents. The focus of this paper is on Annex I, however.

The goals of Annex I are:

- To encourage the sustainable development of geothermal energy resources in an economic and environmentally responsible manner.
- To quantify any adverse or beneficial impacts that geothermal energy development may have on the environment.
- To identify ways of avoiding, remedying or mitigating such adverse effects.

The activity associated with these goals is organized into the following Annex I Tasks that are currently active (IEA-GIA, 2008b)

A) **Impacts on natural features**. This Task aims at documenting impacts of geothermal developments on natural features with the aim to provide a sound basis on which to devise methods to mitigate the impacts.
B) **Discharge and reinjection problems**. This Task aims at evaluating the effectiveness of countermeasures used to mitigate adverse environmental effects and at developing recommendations for improved, and less costly, mitigation methods. The focus is on chemicals in waste fluids, gases, cooling and subsidence.
C) **Methods of impact mitigation and environmental manual**. The aim of this Task is to develop an effective, standard environmental analysis process based on identifying successful policies and strategies in effect.
D) **Seismic risk from fluid injection into enhanced geothermal systems.** The aim of this Task is to analyze large seismic events induced during EGS reservoir development to obtain a better understanding of why they occur so that they can either be avoided or mitigated.
E) **Sustainable utilization strategies**.

The sustainability Task is described in detail in a later section.

3. SUSTAINABLE GEOTHERMAL UTILIZATION

3.1 General

The term *sustainable development* became fashionable after the publication of the Brundtland report in 1987 (World Commission on Environment and Development, 1987). There, sustainable development is defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. This definition is inherently rather vague and it has often been understood somewhat differently.

At the core of the issue of sustainable development is the utilization of the various natural resources available to us today, including the worlds' energy resources. Sustainable geothermal utilization has been discussed to some degree in the literature in recent years. A general and logical definition has been missing, however, and the term has been used at will. In addition the terms renewable and sustainable are often confused. The former should refer to the nature of a resource while the latter should refer to how it is used. Information on recent papers on the issue is presented in a later section. The following publications may be mentioned, however: Wright (1999) presents a general discussion of the issue. Axelsson *et al.* (2005) discuss sustainable geothermal utilization for 100 – 300 years and present the results of a few relevant modelling studies. Bromley *et al.* (2006) discuss sustainable utilization strategies and associated environmental issues. Finally Rybach and Mongillo (2006) present a thorough review of recent sustainability research and identify different research needs (see later).

Experience from utilization of numerous geothermal systems the last few decades has shown that it's possible to produce geothermal energy in such a manner that a geothermal system, which previously was in an undisturbed natural state, reaches a new equilibrium after massive production starts, which may be maintained for a long time. Pressure decline in geothermal systems, due to production, can cause the recharge to the systems to increase approximately in proportion to the rate at which mass is extracted.

Axelsson and Stefánsson (2003) and Axelsson *et al.* (2005) discuss a few such examples. One of the best examples is the Laugarnes geothermal systems in Reykjavík, Iceland, where a semi-equilibrium has been maintained the last four decades indicating that the inflow, or recharge, to the systems is now about tenfold what it was before production started. Another good example is the Matsukawa geothermal system in Japan (Hanano, 2003), which also has been utilized for about four decades for an approximately steady electricity generation. In other cases geothermal production has been excessive and it has not been possible to maintain it in the long-term. The utilization of the Geysers area in California is a good example of excessive production (Barker, 2000; Axelsson *et al.*, 2005).

3.2 Definition

It seems natural to classify sustainable geothermal utilization as energy production that somehow can be maintained for a very long time. Based on this understanding and case histories, such as the ones above, Axelsson *et al.* (2001) proposed the following definition for the term "sustainable production of geothermal energy from an individual geothermal system":

*For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, $\boldsymbol{E_0}$, below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years). If the production rate is greater than $\boldsymbol{E_0}$ it cannot be maintained for this length of time. Geothermal energy production below, or equal to $\boldsymbol{E_0}$, is termed **sustainable production** while production greater than $\boldsymbol{E_0}$ is termed **excessive production.***

This definition neither considers load-factors, utilization efficiency, economical aspects, environmental issues nor technological advances. The value of $\mathbf{E_0}$ depends on the mode of production and may be expected to increase with time through technological advances (e.g. deeper drilling). The value of $\mathbf{E_0}$ is not known a priori, but it may be estimated, through modelling, on the basis of exploration and production data as they become available (see later section).

The definition is based on a much longer time-scale than the customary economical time-frame for geothermal power plants (often of the order of 30 years), which often is used as the time-frame when the production potential of geothermal systems is being assessed. In contrast, a geological time-scale (>10.000 years) was considered unrealistic in view of the time-scale of human endeavours. Therefore, a time-frame within the bounds of these different time-scales was chosen (Axelsson *et al.*, 2001).

Even though geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current, such a classification may be an oversimplification. Geothermal resources are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and stored energy. The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. The semi-equilibrium reached in cases such as Laugarnes and Matsukawa may reflect the renewability of the corresponding geothermal resources. The renewable component (the energy current) is greater than the recharge to the systems in the natural state, however, because production has induced an additional inflow of mass and energy into the systems (Stefansson, 2000).

If energy production from a geothermal system is within the sustainable limit defined above one may assume that the stored energy is depleted relatively slowly and that the energy in the reservoir is renewed at approximately the same rate as it is extracted at. To maintain a semi-steady state for a long time thus requires the renewable part of the underlying resource to be relatively powerful. Yet it is likely that the "volume of influence" of the geothermal energy extraction is very large and that the renewability is to some degree supported by energy extraction from the outer and deeper parts of the geothermal system in question.

3.3 Sustainable Operation of Geothermal Heat Pumps

Geothermal heat pumps (GHP) are the key to utilize the ubiquitous shallow geothermal resources. GHPs 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 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 resupply of fluid is secured by the hydrologic cycle (infiltration of precipitation) and the heat comes either "from above" (atmosphere) and/or "from below" (geothermal heat flow); the relative proportions depend on aquifer depth. This leads to a 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.

Nowadays the GHP systems with borehole heat exchangers (BHE) are the most commonly used types. Theoretical and experimental studies, performed in Switzerland over several years, established a solid scientific base of reliable long-term operation of borehole heat exchanger-coupled heat pump systems. Proper design, taking into account local conditions like ground properties and building needs, secures the sustainability of production from systems with single and multiple borehole heat exchangers. Long-term experience acquired at operational objects confirms the predictions (Rybach and Eugster, 2009).

3.4 EGS Sustainability

Enhanced geothermal system (EGS) sustainability relates to the 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).

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. Production longevity from an EGS resource can be achieved by applying sustainable production rates (Sanyal and Butler, 2005). Various operational strategies such as load following, variable well flow rates, innovative reservoir/power plant management (e.g. by matching power plant design to reservoir production) could help to sustain EGS functioning, but need to be tested.

4. ANNEX I WORK

4.1 General

The IEA-GIA has identified sustainable development as one of the geothermal industry's most significant issues (Mongillo *et al.*, 2010). It has identified the importance of promoting sustainable geothermal development in order to realize the huge global geothermal potential as a clean, economic and secure energy resource that can contribute to the mitigation of climate change. This is at the core of the IEA-GIA's Third Term Mission, as accepted by the IEA (Mongillo *et al.*, 2010):

To promote the sustainable utilization of geothermal energy throughout the world by improving existing and developing new technologies to render exploitable the vast and widespread global geothermal resources, by facilitating the transfer of know-how, by providing high quality informa-

tion and by widely communicating geothermal energy's strategic, economic and environmental benefits.

Therefore, Task E was set up under Annex I in late 2006, dealing with sustainable geothermal utilization. The aim of the Task is to collect information, identify research needs, facilitate international collaboration on the issue through workshops and meetings, as well as facilitate the publication of scientific papers and reports on geothermal sustainability studies and research. To date, the sustainability issue has been discussed at several Annex I meetings and a number of significant research needs identified as well as possible sustainable utilization modes discussed. Information on recent relevant publications has also been assembled. Some relevant definitions have been established or adopted, including the definition presented above.

Task E on sustainable utilization continues to be very active and productive. The activity and achievements are discussed below.

4.2 Literature Compilation

In 2006 an initial investigation into developing a GIA sustainability policy was initiated and a review paper that examined the renewable characteristics of geothermal resources, and their sustainable development, with associated identified research needs was prepared (Rybach and Mongillo, 2006). This paper stimulated much discussion that was useful for Task E.

As a continuation of the publication of the paper, information on numerous papers, and other publications, dealing with sustainability of geothermal utilization and related issues has been collected. The resulting reference-list is accessible through the IEA-GIA website (IEA-GIA, 2008c). Some of the papers/publications are, in addition, available through the website.

4.3 Possible Modes of Sustainable Utilization

Geothermal resources can be utilised through various different modes of operation, all of which may adhere to the sustainability definition presented above. In addition to utilisation modes in which production is always below the sustainable limit much more aggressive utilisation modes can be envisioned (with maximum utilization not sustainable in the long-term), either initially or intermittently. Modelling studies have demonstrated that following a period of excessive production geothermal systems are able to recover approximately back to their pre-production state, i.e. the effects of intense production are mostly reversible (Axelsson *et al.*, 2005). Such production modes are more in-line with the utilisation of many high-temperature geothermal systems today. They are harnessed in great steps, which are unlikely to be sustainable along the lines of the definition above, but are economically feasible due to their size.

The main methods/modes of sustainable geothermal utilisation that may be envisioned, and have been discussed within Task E of Annex I, are the following (see Fig. 1):

(1) Constant production (aside from variations due to temporary demand such as annual variations) for 100 – 300 years. This is hardly a realistic option because the sustainable production capacity of geothermal systems is unknown beforehand. Therefore, a kind of test-period is required initially until the sustainable potential has been assessed.

(2) Production increased in a few steps until the sustainable potential has been assessed and the sustainable limit attained (see e.g. Stefánsson and Axelsson, 2005).

(3) Excessive production (not sustainable) for a few decades (perhaps about 30 years) with total breaks in-between, perhaps a little longer than the production periods (about 50 years), wherein a geothermal system is able to recover almost fully.

(4) Excessive production for 30 – 50 years followed by steady, but much reduced production for the next 150 – 270 years. The production following the excessive period would thus be considerably less than the sustainable potential at constant production (mode (1)).

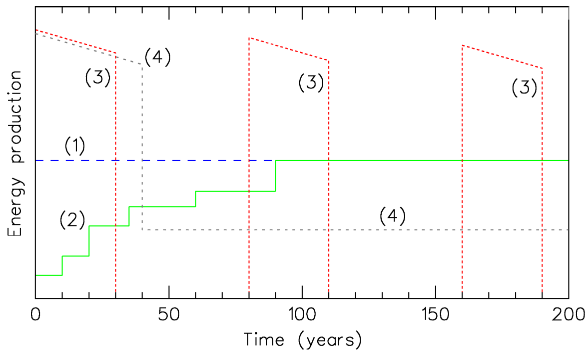

Figure 1: A schematic figure showing examples of different methods/modes of sustainable geothermal system utilization. The numbers refer to the production methods/modes discussed in the paper.

It should be pointed out that the sustainable development of energy resource utilisation must eventually be viewed in a broader context than for single geothermal systems independent of other systems. The following must be kept in mind:

(i) During long-term utilisation some interference, even considerable, may be expected between adjacent geothermal fields being used, even over considerable distances (tens of km). This possible interference must be kept in mind.

(ii) If single geothermal systems are being utilised in an intense/excessive manner during a certain period other geothermal systems may need to be available in the same general region, which could then be utilised while the former systems are being rested. Thus the overall geothermal resource utilisation in the region may be managed as sustainable, even though single geothermal systems are not.

(iii) If geothermal development in a region is, on the other hand, in a step-wise manner the development may be required to be ongoing in several geothermal fields at the same time, because the steps in each field are likely to be so small.

4.4 Research Issues

Through the work of Task E of IEA-GIA's Annex I several research issues, and questions, that need to be studied in conjunction with sustainability research and modelling have been identified. Rybach and Mongillo (2006) list the following research needs:

- 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 (e.g. Larderello, Italy; Kawerau, New Zealand; Wairakei, New Zealand).
- 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.
- Deriving "dynamic" recovery factors: these have to account for enhanced regeneration, driven by the strong hydraulic and thermal gradients created by fluid/heat extraction.

Further issues and questions identified in conjunction with the work of Task E are the following:

(a) What factors are most significant in controlling long-term behaviour/capacity? Size, permeability, boundary conditions, inflow/recharge, reinjection, etc.
(b) How significant and far-reaching are long-term production pressure drawdown and injection cooling effects. In particular, how significant is interference between adjacent geothermal areas?
(c) Comparison of the different modes of production presented above, such as continuous and periodic production/injection scenarios. Which are the optimum strategies in different cases?
(d) How rapidly and effectively do geothermal systems recover during breaks after periods of excessive production?
(e) What is the reliability of long term predictions of reservoir production response using various methods (stored heat, simple analytical models, complex 3D models, etc)?
(f) What information should be collected at pre-exploitation and early development stages to significantly reduce uncertainties in long-term resource sustainability assessments?

These issues are discussed in detail by Axelsson (2009), but issue (a) is, of course, a controlling factor regarding sustainable geothermal utilization. This issue has been discussed by various authors for decades (see e.g. Axelsson, 2008). It may be mentioned that geothermal system boundary conditions are of singular importance during long-term production. Issue (b) has not received great attention up to now, partly because interference between adjacent areas is difficult to distinguish from internal interference and natural variations. Clear examples of such interference are well known, however.

Issues (c), (d) and (e), which are best studied through modelling based on the longest available case histories, were extensively discussed at a sustainability modelling workshop in New Zealand in 2008 presented below. In addition Lovekin (2000) has studied the economics of sustainable geothermal utilization, and Pritchett (1998), Rybach *et al.* (2000) as well as Axelsson *et al.* (2005), present the results of recovery studies.

Issue (f) relates in particular to parameters providing information on issue (a) for specific geothermal systems, in particular parameters that can help delineate boundary conditions and recharge as well as the actual size of systems. Finally, it should be mentioned that reinjection research and modelling are of great significance here since the cooling effect of reinjection may be expected to be very far-reaching during 100 – 300 years of operation.

5. TAUPO 2008 WORKSHOP AND GEOTHERMICS SPECIAL ISSUE

In November 2008, the IEA-GIA's Annex I sponsored a one-day international workshop devoted to sustainability modelling in Taupo, New Zealand, in association with the 2008 New Zealand Geothermal Workshop and the 50th Anniversary of the Wairakei Power Station. There were over 40 participants at the workshop, with 17 presentations from 7 countries, examining geothermal development strategies, geothermal modelling and other related issues. Table 1 provides a list of the speakers and presentations, which have all been made available through the IEA-GIA website (http://www.iea-gia.org/publications.asp).

Table 1: List of speakers and presentations at the November 2008 Taupo workshop on sustainability modelling of geothermal systems.

Speaker	Subject
M. Mongillo	Introduction to IEA-GIA
C. Bromley	Outline of sustainability issues
G. Axelsson	Case histories, research issues and modelling (**Fig. 2**)
M. O'Sullivan	Sustainability modelling for Wairakei (New Zealand) (**Fig 3**)
W. Kissing	Deeper, larger-scale modelling
S. Zarrouk	Ohaaki (New Zealand) modelling
A. Clotworthy	Geothermal development end point (example from Nicaragua)
M. Monterrosa	Assessing sustainability, the Ahuachapan (El Salvador) case (**Fig. 4**)
T. Dwikorianto	Kamojang (Indonesia) case history
P. White	Groundwater management and sustainability
B. Cumming	Geothermal decision making and risk
E. Kaya	Reinjection modelling
P. Leary	Surveying fracture heterogeneity
S. Onacha	Integration of geophysical data in reservoir modelling (Olkaria/Kenya)
G. Siddiqi	Direct geothermal use in Switzerland
S. Ehara	Sustainable development at Hatchobaru (Japan) based on gravity monitoring
G. Björnsson	Sustainable power production in Hengill (Iceland) (**Fig. 5**)

Figures 2 through 5 show examples of long-term (100 – 400 years) predictions predicted at the workshop. Fig. 2 shows the predicted water-level (pressure) changes in the Urban geothermal system under Beijing, the capital of China, up to 2160, which demonstrate clearly the benefit of reinjection for a closed reservoir system.

Figures 3 and 5 show the pressure and temperature recovery of the Wairakei (New Zealand) and Hengill (Iceland) geothermal systems, respectively, after long periods of production. They both show that pressure (fluid) recovers rapidly while temperature (energy) recovers more slowly.

Fig. 4 shows predicted pressure changes in the Ahuachapan geothermal field in El Salvador up to 2075 assuming production at full power plant capacity of 95 MW_e (gross). The Figure shows a modest decline in reservoir pressure. The decline may require a future modification of power plant conditions, such as some lowering of turbine inlet pressure.

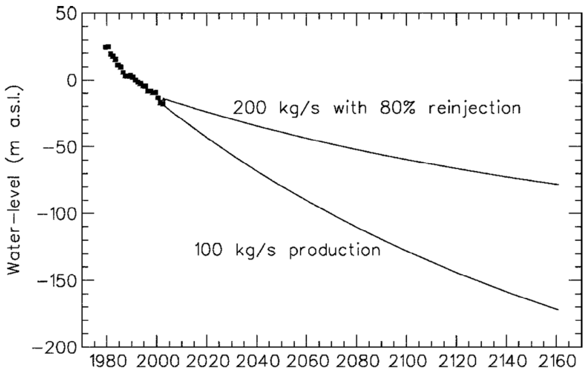

Figure 2: Predicted water-level (pressure) changes in the Urban geothermal system under Beijing, the capital of China, up to 2160, for two future scenarios, one with reinjection and double the production of the other scenario, which is without reinjection. Figure from Taupo presentation of G. Axelsson (Table 1).

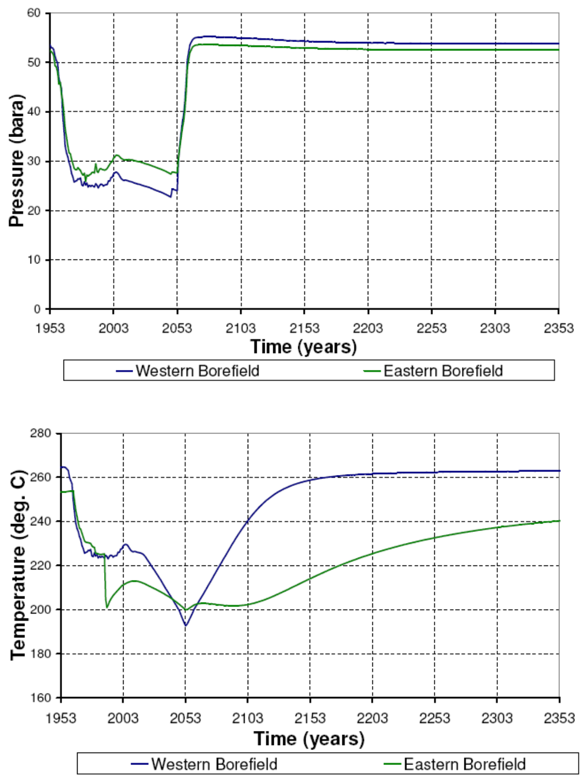

Figure 3: Predicted pressure and temperature recovery in the Wairakei geothermal system in New Zealand following 100 years of production. Figure from Taupo presentation of M. O'Sullivan (Table 1).

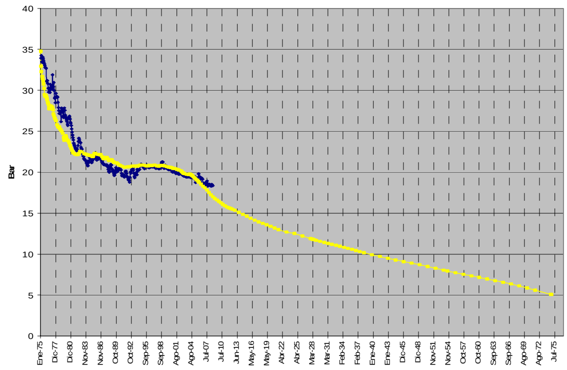

Figure 4: Predicted pressure changes in the Ahuachapan geothermal system in El Salvador up to 2075, for a future scenario of 95 MW$_e$ constant production. Figure from Taupo presentation of M. Monterrosa (Table 1).

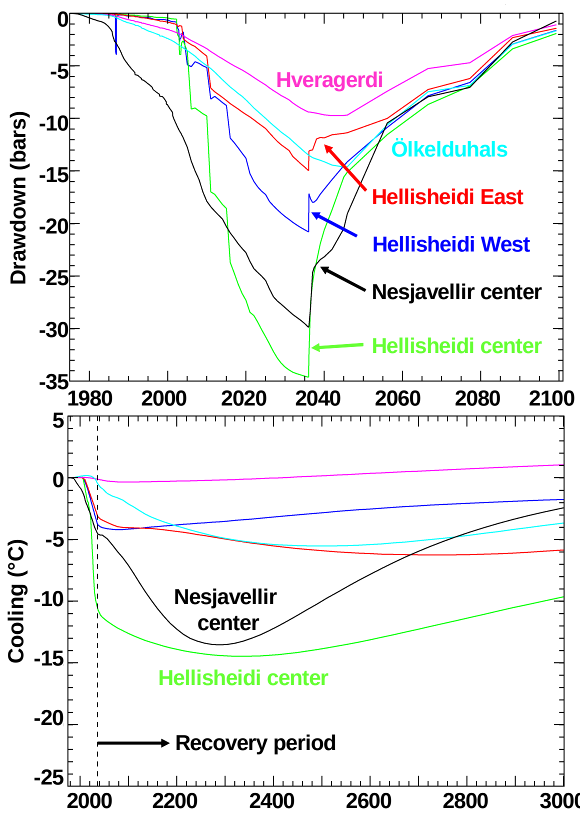

Figure 5: Predicted pressure and temperature recovery in the Hengill geothermal system in Iceland following 50 years of production. Figure from Taupo presentation of G. Björnsson (Table 1).

The above just provide 4 specific examples of results presented at the Taupo workshop. Various other results and ideas were presented and discussions were quite lively and informative. The following practical strategies for geothermal system management were e.g. suggested and discussed, as the means towards optimizing long-term sustainability (see also possible utilization modes above):

1. Cyclic utilization (see mode (3) above) involving depletion and recovery, relying on enhanced mass and heat recharge. Allocation of standby reserves may be needed for use during recovery periods.

2. Optimization of total energy yield considering both economics and risk. Use high extraction rates over short duration cycles, or low extraction rates for long duration cycles?
3. Use ‘adaptive’ reinjection to support pressure and replace fluid, while trying to avoid premature cooling or suppressing natural hot recharge. Also use reinjection to suppress acid fluid production, and excess enthalpy steam.
4. Drill replacement or make-up wells to retain surplus production/injection capacity for optimum flexibility and to extend knowledge on reservoir boundaries.
5. Stage development sizes incrementally to test boundary conditions and recharge parameters, and to reduce risk.

The following modelling issues, to some extent involving prediction reliability, were also discussed at the workshop:

- Are dynamic modelling assessments conservative compared to stored heat (volumetric) assessments (see comparison by Sarmiento and Bjornsson, 2007)?
- How can geophysical-, geochemical- and shallow exploration well data improve reliability of conceptual geo-scientific models?
- Are boundary conditions (recharge) better constrained by natural state models or subsequent exploitation models (response history matching)?
- There is need to distinguish between pressure stabilisation caused by steam cap development and that caused enhanced recharge of hot fluid through deep boundaries.
- How many years are needed per step in staged increment development (mode (2) above)?
- What is the cost vs. benefit of drilling boundary monitoring wells to improve modelling reliability?
- What is the value of tracer tests for estimating overall permeability structure, gravity surveys for monitoring mass- and saturation changes, and chemical monitoring for evaluating injected fluid returns?
- How can recovery factor estimates be made more reliable? Are recovery factors used realistic and in agreement with modelling results?
- How to manage problems concerning enthalpy, scaling and acid fluids? Can detailed models of particular injection/production scenarios help solve specific problems?
- How do initial model boundary condition assumptions affect calculated recharge and pressure recovery rates?

Finally the role of reinjection strategies in sustainable development was discussed at the workshop, the following items in particular:

- Reinjection sustains reservoir pressures, but fractured reservoirs, in particular, are susceptible to premature thermal break-through of cooler reinjected fluid.
- If two-phase zones are allowed to develop, by limiting reinjection fluid returns, stored energy in the rock is extracted more efficiently. The duration of the recovery stage must be longer to allow for this energy to be replaced.
- Injection into steam zones may be needed to recover pressures and avoid excess enthalpy effects.
- The key is flexible and adaptive reinjection: infield, outfield (peripheral) or targeted (shallow or deep).

As a continuation of the Task E work, which culminated in the workshop describe above, preparations started on the publication of a special issue of an international geothermal research journal, supported by Annex I of the IEA-GIA, devoted to sustainable geothermal utilization. Geothermics (see www.elsevier.com/locate/geothermics), published by Elsevier, agreed to publish the issue. The special issue is planned for publication in early 2010. It will be devoted to long utilization case histories and sustainability modelling studies and contributions are mostly based on selected presentations at the Taupo workshop. A few additional papers are included dealing with case-histories, or studies, not presented at the workshop.

The special issue contains fourteen papers, twelve of which are based on long production case histories of geothermal systems in different parts of the world (El Salvador, Mexico, USA, Iceland, France, Switzerland, Hungary, Indonesia, China, Japan, The Philippines and New Zealand). A majority of the systems presented are high-temperature systems utilized for electricity generation while a few are low temperature ones used directly. Eight papers also present long-term modelling studies while two are more general overview papers.

6. CONCLUSIONS

This paper has described the background and achievements of the Sustainability Task of the International Energy Agency’s Geothermal Implementing Agreement (IEA-GIA). The Task was set up in late 2006 with the aim to collect information, identify research needs and facilitate international collaboration on the sustainability issue through workshops and meetings, as well as facilitate the publication of scientific papers and reports on geothermal sustainability studies and research.

Since the initiation of the Task the sustainability issue has been discussed at several Annex I (the Annex hosting the Task) meetings. A specific definition of the term “sustainable utilization” has been adopted and the aspects of the nature of geothermal resources, which enable their sustainable utilization according to the definition, have been reviewed. A number of possible sustainable utilization modes have, furthermore, been analysed and several highly relevant research issues identified. Information on quite a number of recent papers and reports dealing with the issue has also been assembled and made available through the IEA-GIA’s website along with direct access to some of the publications.

A one-day international workshop supported by Annex I of the IEA-GIA, dealing with sustainability modelling, was held in late 2008, in Taupo, New Zealand, with over 40 participants and 17 presentations from 7 countries. The Taupo workshop was quite successful. The presentations were very informative and the discussions they aroused quite enlightening. Various pertinent future research issues were also identified through discussions at the workshop.

As a result, work is now underway on preparing a IEA-GIA Annex I supported special issue of the geothermal research journal Geothermics, devoted to sustainable geothermal utilization; with particular emphasis on long utilization case histories and sustainability modelling studies. The papers of the issue are mostly based on presentations at the Taupo workshop.

The final achievement of the Task, which warrants being mentioned, is the lively sustainability discussions it has stimulated within the geothermal community. Further workshops devoted to the sustainability issue and continued information gathering and dissemination are also planned.

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