Using Long Case Histories to Study Hydrothermal Renewability and Sustainable Utilization

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Keywords

Geothermal, renewability, sustainable use, production response, production capacity, case history, boundary conditions

ABSTRACT

A number of long and well documented utilization and response case histories of hydrothermal systems are available worldwide, many spanning more than 30 years. These are extremely valuable for studying the long-term response and hence production capacity of geothermal resources, as well as their renewability and possible sustainable utilization. Simple evaluations, and associated calculations, for a few low-temperature (< 150°C) case histories presented, demonstrate this. The cases histories reveal that the associated geothermal systems can often be classified as either open or closed as regards production induced recharge. Fluid volumes extracted over several decades range from being much less to being approximately equal to the estimated pore volumes of the reservoirs in question. This may explain why significant chemical changes haven't been observed in the cases presented. In addition volume estimates based on long-term pressure changes are often very large compared to the estimated volumes of the hot reservoirs. A slow pressure decline for many closed systems and a slow cooling of many open systems demonstrate their potential sustainable utilization.

1. Introduction

Geothermal resources are distributed throughout the Earth's crust with the greatest energy concentration associated with hydrothermal systems in volcanic regions at crustal plate boundaries. Yet exploitable geothermal resources may be found in most countries, either as warm ground-water in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available world-wide and attempts are underway at developing enhanced geothermal systems (EGS) in places where limited permeability precludes natural hydrothermal activity. Saemundsson *et al.* (2009) discuss the classification and geological setting of geothermal systems in considerable detail.

The potential of the Earth's geothermal resources is enormous when compared to its use today and to the future energy needs of mankind. Stefánsson (2005) estimated the technically feasible electrical generation potential of identified geothermal resources to be 240 GW_e (1 GW = 10^9 W), which are likely to be only a small fraction of hidden, or as yet unidentified, resources. He also indicated the most likely direct use potential of lower temperature resources (< 150°C) to be 140 EJ/yr (1 EJ = 10^{18} J). The Earth's ultimate geothermal potential is, however, impossible to estimate accurately at the present stage of knowledge and technology. Even though geothermal energy utilization has been growing rapidly in recent years, it is still miniscule compared with the Earth's potential. Bertani (2010) estimated the worldwide installed geothermal electricity generation capacity to have been about 10.7 GW_e in 2010 and Lund *et al.* (2010) estimated the direct geothermal utilization in 2009 to have amounted to 438 PJ/yr (1 PJ = 10^{15} J). Fridleifsson *et al.* (2008) have estimated that by 2050 the electrical generation capacity may reach 70 GW_e and the direct use 5.1 EJ/yr.

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their needs. Geothermal resources have the potential to contribute significantly to sustainable energy use worldwide in coming decades as well as to help mitigate climate change. Sustainable geothermal utilization has received ever increasing attention over the last decade (see e.g. Axelsson, 2010). The discussion has nevertheless suffered from a lack of a clear definition of what it involves and from a lack of relevant policies as well as a lack of research on the subject. The word "sustainable" has in addition become quite fashionable and different authors have used it at will. The terms *renewable* and *sustainable* are moreover often confused. The former simply refers to the nature of a resource, while the latter should refer to how it is used.

There have also been considerable discussions on the renewability of geothermal resources and whether to classify them amongst the renewable energy resources or the non-renewable ones. They are generally classified as renewable because they are maintained by a continuous energy current. Geothermal energy has for example been classified as renewable by the European Parliament and the Council of the European Union (2009). This has been disputed by some scientists, for example in Iceland, on the grounds that geothermal energy utilization actually involves heat-mining.

The key to understanding the nature of geothermal resources, including their renewability, as well as estimating their long-term response to utilization, production capacity and possible contribution to sustainable energy development, is comprehensive and focussed research, often based on extensive exploration and monitoring data. The purpose of this paper is to point out the extremely valuable information contained in well documented and monitored utilization case histories. A number of such case histories for hydrothermal systems are available, many spanning more than 30 years. These are also particularly valuable for studying the renewability and possible sustainable utilization of geothermal resources.

The paper starts out by discussing the renewability and sustainable use of geothermal resources followed by an examination of the factors controlling their nature and production capacity. Subsequently four long low-temperature (< 150°C) case histories are presented, three from Iceland and one from China. After this some simple evaluation methods are presented and applied to the case histories. The paper is concluded by a discussion of other applicable research methods as well as conclusions and recommendations. It should be emphasized that the purpose of the paper is not a thorough evaluation, or detailed calculations, on basis of the case histories, but rather to point the way for more detailed studies.

2. Renewability of Geothermal Resources and their Sustainable Use

This section reviews briefly the renewability of geothermal resources and their sustainable use with emphasis on what can be learned from long utilization case histories. The dispute on renewability will also be addressed. The distinction between the two aspects must be stressed again, i.e. that renewability refers to the nature of the resource in question while sustainability refers to how it is utilized, a distinction which isn't always clear to authors discussing them.

2.1 Renewability

Geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current and how enormous the energy content of the Earth's crust is compared to the energy needs of mankind. This is in accordance with the definition that the energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy with the replacement taking place on a time-scale comparable to that of the extraction time-scale (Stefánsson, 2000). In addition they simply don't fit well with non-renewable energy sources like coal and oil, for example because of much more limited greenhouse gas emissions.

But this classification has been disputed, as mentioned above. In addition to the discussions in Iceland mentioned above various authors have referred to geothermal energy utilization as "heat mining", for example Sanyal (2010). The author of this paper claims that this dispute simply arises from a need to force a complex natural phenomenon into an inadequate classification scheme. The claim that geothermal resources are non-renewable has, moreover, been used as an argument against increased geothermal development. The foundation for increased geothermal utilization worldwide is, however, improved understanding through amplified research.

Classifying geothermal resources as renewable may also be an oversimplification. This is because 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 (Axelsson *et al.*, 2005a). 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. During production the renewable component (the energy current) is greater than the recharge to the systems in the natural state, however, because production induces in most cases an additional inflow of mass and energy into the systems (Stefánsson, 2000).

The double nature of geothermal resources is strikingly apparent through different assessments of the geothermal resources of Iceland carried out in the 1980's by different investigators. Bödvarsson (1982) estimated the size of the total heat flow through the crust while Pálmason *et al.* (1985) estimated the amount of thermal energy stored in the crust. Stefánsson (2000) combined the results of the two studies in a unified presentation, however, 15 years later (Fig. 1).

The renewability of different types of geothermal systems (see classification by Saemundsson *et al.*, 2009) is quite diverse. This is because the relative importance of the energy current compared with the stored energy is highly variable for the different types. In *volcanic systems* the energy current is usually quite powerful, comprising both magmatic and hot fluid inflow. In *convective systems of the open type*, i.e. systems with strong recharge, the energy current (hot fluid inflow) is also highly significant. But the inflow can either originate as hot inflow from depth or as shallower inflow, colder in origin. In shallow inflow situations the inflow

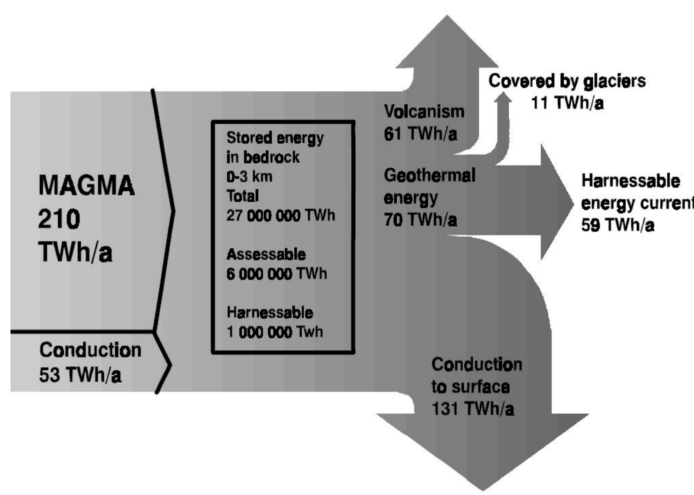

Figure 1. Simplified sketch of the geothermal resources of Iceland, reflecting their double nature. Based on combining an assessment of the terrestrial energy current in Iceland and an assessment of the heat stored in the crust (Stefánsson, 2000).

is heated up by heat extraction from hot rocks at the outskirts of the system in question. The renewability of such systems is then supported by the usually immense energy content of the hot rocks of the systems. In *convective systems of the closed type*, i.e. with limited or no recharge, the renewability is more questionable. The energy extracted from the reservoir rocks through reinjection in such situations is only slowly renewed through heat conduction, but again the energy content of the systems is usually enormous. They can, therefore, be considered slowly renewable in nature.

Sedimentary systems, which are mostly utilized through doublet operations, are comparable to the closed convective systems as the energy current is usually relatively insignificant compared to the stored energy. Their renewability is, therefore, mainly supported by heat conduction and hence is relatively slow. The same applies to *EGS*- or *hot dry rock systems*. Both these types can thus also be considered slowly renewable. In most such cases the stored energy component is extremely large because of the large extent and volume of the systems. Rybach and Eugster (2010) and Rybach *et al.* (2000) discuss the theoretical and experimental basis of the renewability and sustainable utilization of borehole heat exchanger ground-source heat-pumps (GHPs), with particular emphasis on work done in Switzerland. Their results show that GHPs cause a highly localized temperature disturbance and that the disturbance increases very slowly over long time periods. The results, furthermore, show that the ground temperature recovers almost fully over a period of comparable length to that of the utilization.

Sustainable geothermal utilization is discussed in the following section. It depends to a large extent on the nature of the geothermal resource in question and hence its renewability. If energy production from a geothermal system is within some kind of sustainable limits (see below) one may expect that the stored energy is depleted relatively slowly and that the energy in the reservoir is renewed at a rate comparable to the extraction rate.

2.2 Sustainable Use

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their needs (so-called Bruntland definition; see World Commission on Environment and Development, 1987). This is a very general definition, which is nonetheless being increasingly used to analyse most aspects of human endeavours and progress. Sustainable development includes meeting the energy-needs of mankind and geothermal resources can certainly play a role in sustainable energy development. Sustainable development is based on three main pillars; the environment, social justice and economic prosperity. Distinction is made between two approaches: *Strong sustainability* implies development that doesn't involve negative impact on, or decay of, any of the pillars (Ketilsson *et al.*, 2010). Under this approach geothermal energy production must be sustainable, and the underlying resource can't decay significantly, on a given timescale. *Weak sustainability* on the other hand allows some decay of one of the main pillars provided the overall development yields macro-economic, social growth. Some decay of a geothermal resource, reflected in declining energy production on the timescale in question, would then be acceptable if it results in significant social and economic gain.

Two main issues are of principal significance when geothermal sustainability is being discussed and evaluated. These are (1) the question whether geothermal resources can be used in some kind of sustainable manner at all and (2) the issue of defining an appropriate time-scale. Long utilization histories, such as those discussed in the following, clearly indicate that geothermal systems can be utilized for several decades without significant decline in output due to the fact that they often appear to attain a sort of semi-equilibrium in physical conditions during long-term energy-extraction. In other cases physical changes in geothermal systems are so slow that their output is not affected for decades. Modelling studies have, consequently, extended the periods to one or more centuries (Axelsson, 2010).

The second issue is the time-scale. It is clear that the short time-scale of 25–30 years usually used for assessing the economic feasibility of geothermal projects is too short to reflect the essence of the Bruntland definition, even though economic considerations are an essential part of sustainability. It is furthermore self-evident that a time-scale with a geological connotation, such as of the order of millions of years, is much too long. This is because at such a time scale the sustainable potential of a geothermal system would only equal the natural flow through the system. Predicting human activity and development for the next few hundred years is also almost impossible. Therefore an Icelandic working group proposed a time-scale of the order of 100–300 years as appropriate (Axelsson *et al.*, 2001a). Others have proposed time scales of 50–100 years.

A detailed evaluation of all aspects of sustainable geothermal utilization is beyond the scope of this paper. The reader is instead referred to the papers by Axelsson (2010) and Rybach and Mongillo (2006) for more details, as well as various other papers in the international geothermal literature. Yet it should be mentioned that Axelsson (2010) points out that production modes other than constant production below the sustainable limit can be envisioned as parts of sustainable utilization schemes. This includes development involving step-wise increase in production, cyclic utilization involving intermittent excessive production with breaks and reduced production after a shorter period of heavy production. Modelling studies have for example indicated that the effect of heavy utilization, such as during a cyclic utilization scheme, is often reversible on a time-scale comparable to the period of utilization.

Several research issues need to be studied in conjunction with sustainability research and modelling. Some of these are identified and listed by Axelsson *et al.* (2010a). The most important are boundary conditions for volcanic or fractured convection systems, which control recharge to the systems, and the overall thermal management of sedimentary and EGS systems, where full reinjection is applied. The management is aimed at efficient use of the thermal energy in-place in the reservoir rocks while avoiding rapid cooling of production wells.

3. Nature and Production Capacity

The long-term response and hence production capacity of geothermal systems is mainly controlled by (1) their size and energy content, (2) permeability structure, (3) boundary conditions (i.e. significance of natural and production induced recharge) and (4) reinjection management. Their energy production potential, in particular in the case of hydrothermal systems, is predominantly determined by pressure decline due to production. This is because there are technical limits to how great a pressure decline in a well is allowable; because of pump depth or spontaneous discharge through boiling, for example. The production potential is also determined by the available energy content of the system, i.e. by the temperature or enthalpy of the extracted mass. The pressure decline is determined by the rate of production, on one hand, and the nature and characteristics of the geothermal system, on the other hand.

Natural geothermal reservoirs can be classified as either ***open*** or ***closed***, with drastically different long-term behaviour, depending on their boundary conditions (see also Fig. 2):

(A) Pressure declines continuously with time, at constant production, in systems that are ***closed*** or with small recharge (relative to the production). In such systems the production potential is limited by lack of water rather than lack of thermal energy. Such systems are ideal for reinjection, which provides man-made recharge. Examples are many sedimentary geothermal systems, systems in areas with limited tectonic activity or systems sealed off from surrounding hydrological systems by chemical precipitation.

(B) Pressure stabilizes in ***open*** systems because recharge eventually equilibrates with the mass extraction. The recharge may be both hot deep recharge and colder shallow recharge. The latter will eventually cause reservoir temperature to decline and production wells to cool down. In such systems the production potential is limited by the reservoir energy content (temperature and size) as the energy stored in the reservoir rocks will heat up the colder recharge as long as it is available/accessible.

The situation is somewhat different for ***EGS-systems*** and sedimentary systems utilized through production-reinjection ***doublets*** (well-pairs) and heat-exchangers with 100% reinjection. Then the production potential is predominantly controlled by the energy content of the systems involved. But permeability, and therefore pressure variations, is also of controlling significance in such situations. This is because it controls the pressure response of the wells and how much flow can be achieved and maintained, for example through the doublets involved (it's customary to talk about intra-well impedance for EGS-systems, based on the electrical analogy). In sedimentary systems the permeability is natural but in EGS-systems the permeability is to a large degree man-made, or at least enhanced.

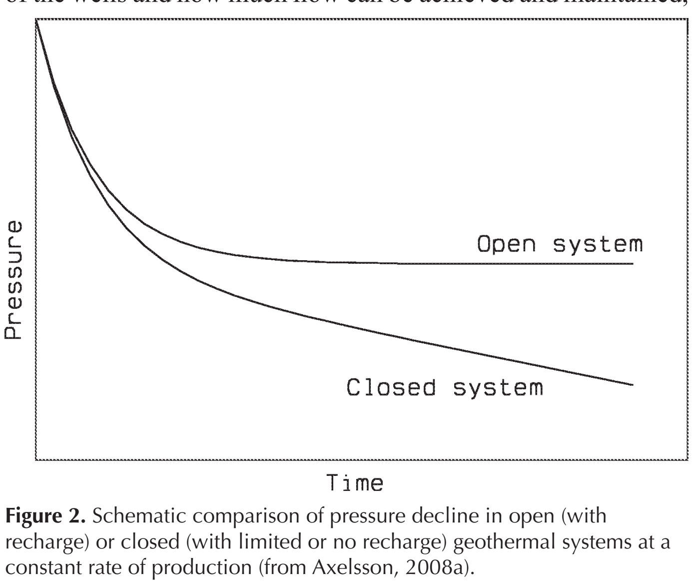

Figure 2. Schematic comparison of pressure decline in open (with recharge) or closed (with limited or no recharge) geothermal systems at a constant rate of production (from Axelsson, 2008a).

The long-term response and hence production capacity of hydrothermal systems is mainly controlled by (1) size and energy content, (2) permeability structure, (3) boundary conditions (i.e. significance of natural and production induced recharge) and (4) reinjection management. A number of long and well documented utilization and response case histories are available worldwide, many spanning more than 30 years. These are extremely valuable for studying the renewability of geothermal resources and their possible sustainable utilization. Simple evaluations, and associated calculations, for a few low-temperature case histories presented demonstrate this.

4. Long Case Histories

A number of long and well documented hydrothermal utilization and response case histories are available worldwide, many spanning more than 30 years, which are extremely valuable for studying geothermal resource utilization and management, as already mentioned. This section presents four such low temperature histories, as examples. Three of these are case histories for Icelandic low temperature systems (from Axelsson *et al.*, 2010b), in basaltic crust, while the fourth one is from China, from a geothermal system completely different in nature:

(1) The Laugarnes geothermal system is located in central Reykjavík, Iceland, in young and hot crustal rocks. Exploitation for space heating started in 1930 with utilization of free-flow from a number of shallow wells, while drilling of both deeper and larger diameter wells commenced in 1958. This together with the introduction of large capacity down-hole pumps enabled the hot water production in Laugarnes to be increased by an order of magnitude. Ten production wells are in operation today with the deepest extending down to 2700 m. The reservoir temperature in the Laugarnes system is about 120–140°C. The last few years the yearly average production from the system has been more than 150 l/s. Laugarnes is among the more productive low-temperature systems utilized in Iceland.

(2) The Gata (or Laugaland) system is located in the Holt district of the south Iceland lowlands, a few kilometres south of the highly active South-Iceland seismic zone. In spite of its proximity to the seismic zone, the permeability of the Gata system is unusually low and the system has poor productivity. The Gata geothermal system has been utilized since 1946. Up to 1982, the utilization was for local heating and a swimming pool, but after 1982, a district heating system (hitaveita) for the towns of Hella and Hvolsvöllur, east of Gata, was added. The geothermal system has a reservoir temperature of 100-105°C. The average yearly production rate has varied between 10 and 22 l/s, while it has been about 15 l/s the last few years. One primary production well, 1000 m deep, has been in use since 1982. Because of Gata's limited productivity a new production area was connected to the hitaveita in early 2000, which enabled

a drastic reduction in production from the Gata system. At the same time, limited (10-20% of the production) re-injection was started at Gata. A major earthquake (M_s = 6.6) shook the Holt district on 17 June 2000, only a few kilometres north of Gata, followed by another one a few days later further to the west. They caused drastic changes in hydrological systems all over the southern lowlands of Iceland and a modelling study indicates that the observed water level after the earthquakes is, in fact, 40–80 m higher than the modelled level (Axelsson et al., 2005b). This is believed to be the result of reservoir permeability at Gata, as well as fluid recharge, having increased considerably because of the earthquakes.

(3) The Skútudalur low-temperature system is located in the Siglufjördur fjord in north-central Iceland and serves the town of Siglufjördur. It is in a region of relatively old crust that is tectonically quite active, explaining the low-temperature geothermal activity in the region. The system has a reservoir temperature of approximately 70°C and has been utilized since 1975. The Skútudalur system is not highly productive, but it does reach quasi-equilibrium during constant production. The water level appears to drop more over the last few years than would be expected on the basis of the production (Fig. 5). It has been speculated this may be due to a recently constructed road-tunnel through the mountains above Skútudalur with the road-tunnel draining water from, and lowering pressure in, the groundwater system in the mountains, which is thought to provide recharge for the geothermal system.

(4) The Beijing Urban geothermal system is embedded in permeable sedimentary layers (carbonate rocks) at 1 – 4 km depth below Beijing, China, and has been used since the 1970s, mainly for space-heating but also for other direct uses (Liu *et al.*, 2002). About 70 production wells, ranging in depth from 1000 to 3600 m, have been drilled into the system. The average yearly production from the system has been a little over 100 l/s of 40 to 90 °C water (mainly used during the four coldest months of the year).

Figures 3 – 6 show the production and pressure histories (presented as water level) of the four geothermal systems. Production increased drastically in Laugarnes in the 1960s due to the introduction of down-hole pumps, resulting in a pressure decline corresponding to about 120 m water level drop (Fig. 3). Production and water level have, however, remained relatively

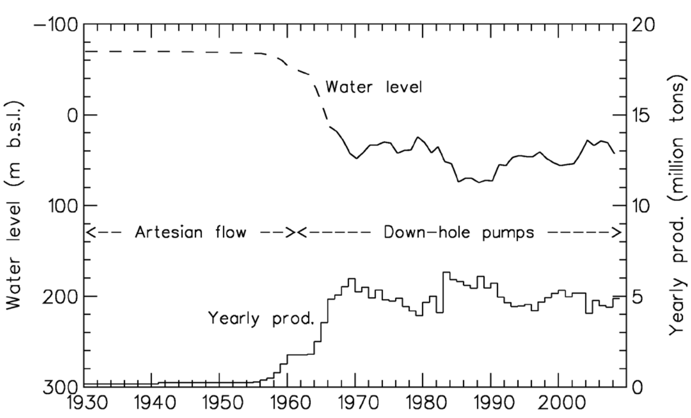

Figure 3. Production and water level (winter minima) history of the Laugarnes low-temperature geothermal system within Reykjavík, SW-Iceland, from 1930 to 2008. The broken line indicates estimated water level. From Axelsson et al. (2010b).

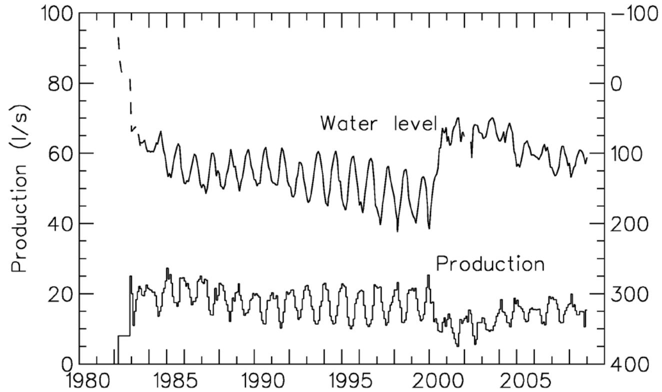

Figure 4. Production and water level history of the Gata low-temperature geothermal system in the Holt district of southern Iceland from 1982 to 2008. The broken line indicates estimated water level. From Axelsson et al. (2010b).

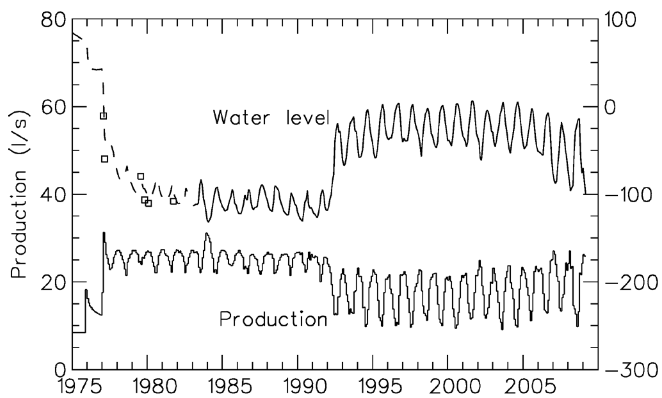

Figure 5. Production and water level history of the Skútudalur low-temperature geothermal system in Siglufjördur, N-Iceland, from 1975 to 2008. The broken line indicates estimated water level and the boxes isolated water level readings. From Axelsson et al. (2010b).

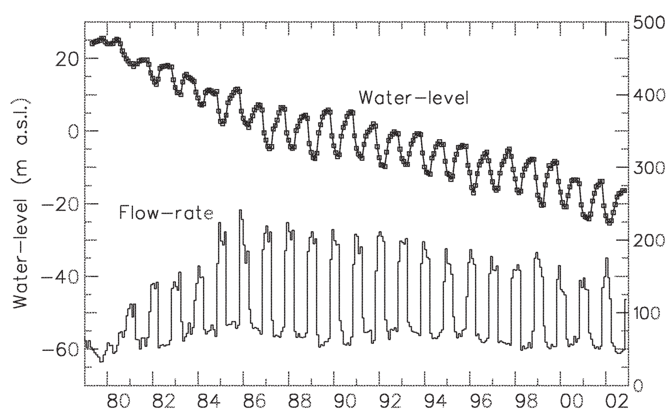

Figure 6. Production and water level history of the Beijing Urban sedimentary low-temperature geothermal system in China from 1979 to 2002. Based on Liu et al. (2002).

stable during the last four decades. This indicates the reservoir has found a new quasi-equilibrium, with about ten times the natural recharge. The water level recovery at Gata in 2000 is believed to be a combination of reduced production, reinjection and beneficial hydrological effects of the earthquakes already mentioned (Fig. 4). The Skútudalur case history demonstrates the approximate equilibrium reached during constant production, as well as the apparently degrading effect of the road-tunnel mentioned before (Fig. 5). Finally the Beijing history demonstrates a continuously declining reservoir pressure, at approximately constant yearly average production, reflecting a hydrothermal system with very limited recharge (Fig. 6).

In addition to the data presented in the figures, which of course are of primary importance, other significant data are also available, which can help further in understanding the nature and characteristics of the hydrothermal systems. These data are not presented here, but include data on chemical content, in particular on changes in the content, throughout the production histories. Geological and geophysical exploration data are also important, and so are all temperature distribution data.

In addition to the four low-temperature systems presented above quite a number of other hydrothermal case histories exist, which are available for research as proposed here. Information on some of these can be found in a recent special issue of the international journal *Geothermics* (Mongillo and Axelsson, 2010). Several other Icelandic low-temperature case histories are presented by Axelsson *et al.* (2010b) and (Axelsson, 2010) lists 16 hydrothermal systems with long histories, high-temperature as well as low-temperature. These include Ahuachapan in El Salvador (Monterrosa and Montalvo, 2010), utilized since 1976, the Paris Basin in France (Lopez *et al.*, 2010), utilized since 1969, Svartsengi in Iceland, utilized since 1976, Matsukawa in Japan, utilized since 1966 and Wairakei in New Zealand (O'Sullivan *et al.*, 2010), utilized since 1958, to name only a few.

5. Evaluation

5.1 Possible Evaluation Methods

This section presents and discusses the evaluation methods, which are particularly applicable to long case histories such as the ones presented above, and can be used to study the long-term response and hence production capacity of geothermal resources, as well as their renewability and possible sustainable utilization. The methods are consequently applied, in a rudimentary manner, to the four response histories of the Laugarnes, Gata, Skútudalur and Beijing Urban systems.

The following are the main evaluation and calculation (modelling) methods proposed:

(1) Evaluate boundary conditions (BC's) based on long-term pressure decline data, i.e. weather system is open or closed (see Fig. 2). Can be done visually if production history is simple or through modelling. Lumped parameter modelling is ideal for this purpose (Axelsson et al., 2005b).

(2) Estimate size (volume) of hot part of geothermal system based on geological data, geophysical surveying, in particular resistivity, temperature log data, etc.

(3) Compare total extracted fluid volume (corrected to reservoir conditions) with pore-space volume according to (2). Requires average porosity to be estimated.

(4) Estimate hydrological size from long-term, linear pressure decline rate (dp/dt, see Fig. 2) and average production, for systems with closed BC's. This actually refers to the volume influenced by pressure changes, i.e. the volume controlling the pressure changes, which is not the same volume as in (2). This depends on the storativity of the reservoir in question, which can either be controlled by compressibility, free-surface mobility in systems with unconfined sections or phase-changes in two-phase systems. Lumped parameter modelling is again an ideal tool for this estimate.

(5) Estimate maximum possible size of the reservoir volume cooled by cold recharge for systems with open BC's. The simple model of Bödvarsson (1972) can be used for this purpose. Such an estimate assumes that all production induced recharge is cold, which is quite pessimistic. Hence it provides an estimate of the maximum cooled volume.

Other response aspects add to the above evaluation and calculation methods, yet more indirectly:

- Chemical changes, which may be presumed to be due to production induced recharge by colder fluid and/or fluid of chemical composition different from that of the reservoir fluid.
- Temperature decline, which may be presumed to be due to production induced colder fluid recharge.

No such changes have been observed in the case histories presented here, and they are in fact rather rare. Therefore, it can be stated that calibration of temperature changes in reservoir modelling can often be considered inadequate, because of lack of temperature decline data.

It should be mentioned that Vitai (2010) and O'Sullivan *et al.* (2010) have performed what may be called renewability evaluations, based on modelling, for a few low-temperature systems in Iceland and for the Wairakei system in New Zealand, respectively.

5.2 Simple Evaluation of the Four Response Histories

The results of a rudimentary application of the methods listed above to the four case histories presented here are presented in Table 1 below. It should be emphasised that they are only presented to demonstrate their application, but that they should not

Table 1. Results of a rudimentary application of the evaluation and calculation methods suggested in the paper to four low-temperature case histories (see figures 3 – 6). For more information on each item see list above.

System	BC	Min. hot volume	Min. pore space volume	Extracted volume	Max. volume acc. to dp/dt[1)]	Max. cooled volume
Laugarnes	Open	~10 km^3	~1 km^3	0.25 km^3	-	0.9 km^3
Gata	Semi-closed	>0.1 km^3	>0.01 km^3	0.014 km^3	140 km^3	-
Skútudalur	Open	>0.2 km^3	>0.02 km^3	0.024 km^3	-	0.08 km^3
Beijing Urban	Closed	~70 km^3	~3 km^3	0.080 km^3	4700 km^3	-

1) Assuming compressibility controlled storage.

be considered as accurate. More thorough evaluation and modelling are required for that purpose. In addition significant chemical changes have not been observed in any of the four cases.

The table shows that two of the systems are classified as open and two as closed, as regards production induced recharge. The open ones are both in Iceland while the Chinese sedimentary system behaves as closed, which can't be considered surprising. For the two larger systems, Laugaland and Beijing Urban, the fluid volumes extracted over several decades are much less than the estimated pore volumes of the reservoirs. This may explain why significant chemical changes haven't been observed there. For the two smaller systems, Gata and Skútudalur, the fluid volumes extracted approximately equal the estimated pore volumes, which may indicate that the production induced recharge is to a large extent hot fluid, at least fluid of comparable composition.

The volume estimates based on long-term pressure changes for the two closed systems are very large compared to the estimated volumes of the hot reservoirs. In the case of the Beijing system the estimated size is much greater than its surface area of about 390 km^2 (Axelsson *et al.*, 2002). It is however comparable to the combined area of all the geothermal systems of the Beijing basin, which is about 2300 km^2, assuming a thickness of about 2 km. This may indicate that they are all hydrologically linked. In the case of Gata the large size can only be explained by the system being hydrologically linked to unconfined reservoirs (shallower geothermal or groundwater) with free-surface mobility storage. Finally the estimated cooled volumes of the two open systems are much less than the minimum hot volumes, which concurs with the fact that no cooling has been observed in the corresponding reservoirs, as of yet.

5.3. Other Relevant Data and Research

For completeness the following data and research methods, which can also contribute to the renewability and sustainability research being proposed here, is mentioned:

(A) Repeated gravity and elevation surveying, which can provide important information on the overall mass-balance in geothermal systems during utilization.

(B) Conventional numerical reservoir modelling focussing on temperature and pressure conditions as well as reservoir monitoring data.

(C) Numerical modelling (B) with additional geophysical constraints, in particular resistivity data, gravity and elevation data as well as seismic data.

6. Concluding Remarks

In addition to discussing the renewability of geothermal resources and their sustainable use this paper has emphasised how extremely valuable long-term (several decades) hydrothermal production and response histories are for studying the long-term response and hence production capacity of geothermal resources, as well as their renewability and possible sustainable use. The following concluding remarks can be added, partly based on the case histories studied in the paper:

- The cases histories reveal that the associated geothermal systems can often be classified as either open or closed as regards production induced recharge.
- Fluid volumes extracted over several decades range from being much less to being approximately equal to the estimated pore volumes of the reservoirs in question. This may explain why significant chemical changes haven't been observed in the cases presented.
- Estimates of volumes presumably cooled by colder fluid recharge (production induced) are only a fraction of estimated hot reservoir volumes agreeing with the fact no cooling has been observed in these cases.
- Volume estimates based on long-term pressure changes, for closed systems, are often very large compared to the estimated volumes of the hot reservoirs. This may be the result of either the systems being connected with much larger or unconfined hydrological systems.
- A slow pressure decline for many closed systems and a slow cooling of many open systems demonstrate their potential sustainable utilization.
- Systems with closed boundary conditions will require substantial reinjection for sustainable management (Axelsson *et al.*, 2008b)
- Finally it may be mentioned that modelling studies and actual experience has shown that hydrothermal systems recover thermodynamically during breaks in production (Axelsson, 2010; O'Sullivan *et al.*, 2010). This has important implications regarding the possible modes of sustainable geothermal production.

Acknowledgements

The author would like to thank Reykjavík Energy, Skagafjardarveitur and Rarik in Iceland for allowing publication of data from the geothermal systems discussed here.

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