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SUSTAINABLE GEOTHERMAL UTILIZATION

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ABSTRACT

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their needs. The Earth’s enormous geothermal resources have the potential to contribute significantly to sustainable energy use worldwide and to help mitigate climate change. Experience from the use of geothermal systems worldwide, lasting several decades, demonstrates that by maintaining production below a certain limit the systems reach a balance between net energy discharge and recharge that may be maintained for a long time. Therefore, a sustainability time-scale of 100 to 300 years has been proposed. Studies furthermore indicate that the effect of heavy utilization is often reversible on a time-scale comparable to the period of utilization. Geothermal resources can be used in a sustainable manner either through (1) constant production below a sustainable limit, (2) step-wise increase in production or (3) cyclic utilization schemes involving periods with production surpassing the sustainable limit alternating with recovery periods, during which other geothermal resources need to fill in the gap. The long production histories that are available for geothermal systems worldwide provide the most valuable data available for studying sustainable management of geothermal resources, and reservoir modelling is the most powerful tool available for this purpose. The paper reviews long utilization experiences from e.g. Iceland, New Zealand, El Salvador and China and presents sustainability modelling studies for a few geothermal systems in these countries. International collaboration has facilitated sustainability research and fruitful discussions as well as identifying several relevant research issues. Distinction needs to be made between sustainable production from a particular geothermal resource and the more general sustainable geothermal utilization, which involves integrated economic, social and environmental development. Developing a sustainability policy involves setting general sustainability goals and consequently defining specific sustainability indicators to measure the degree of sustainability of a given geothermal operation or progress towards sustainability.

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. There is, therefore, ample space for accelerated use of geothermal resources worldwide in the near future.

Sustainable geothermal utilization has been discussed to some degree in the literature in recent years, partly because the term "sustainable" has become quite fashionable. 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. A considerable amount of literature dealing with the issue has been published during the last decade, and some of the most relevant publications are referred to throughout this paper. The reader is in particular referred to a recent special issue of the international journal *Geothermics* (Mongillo and Axelsson, 2010).

This paper relies partly on Axelsson (2010) and Axelsson et al. (2010a). It reviews several aspects of the issue of sustainable geothermal energy utilization, such as the background of the issue, a specific logical and realistic definition, and the time-scale involved as well as a few possible modes of sustainable geothermal utilization. It also presents some long-term geothermal production histories, which yield the most important information needed to address the issue, and presents briefly the results of two modelling studies aimed at estimating the sustainable production potential of naturally permeable hydrothermal systems. Examples from Iceland, New Zealand, El Salvador and China are discussed in particular. A section of the paper is devoted to the increasing international collaboration on issues related to sustainable geothermal utilization and its role in sustainable development and in particular to a brief discussion of some of the basic research issues that need to be addressed and understood, if sustainable geothermal utilization is to be viable. Following this the steps needed in setting up a sustainability protocol are discussed, i.e. the development of sustainability goals and the consequent instatement of sustainability indicators. The paper is concluded by general conclusions and recommendations.

2. SUSTAINABLE GEOTHERMAL UTILIZATION

The definition of the term ***sustainable development***, most often referred to today, is a definition stemming from the so called Brundtland report (World Commission on Environment and Development, 1987):

> *Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs*

This is a very general definition, which is nonetheless being increasingly used to analyse most aspects of human endeavours and progress. Sustainable development, of course, includes meeting the energy-needs of mankind and geothermal resources can certainly play a role in sustainable energy development, in particular since it is recognized that they should be classified among the renewable energy sources.

Sustainable geothermal utilization has received ever increasing attention over the last decade, but the discussion has suffered from a lack of a clear definition of what it involves and from a lack of relevant policies. The word “sustainable” has in addition become quite fashionable and different authors have used it at will. A considerable amount of literature dealing with the issue has been published during the last decade, and papers by Wright (1999), Stefánsson (2000), Rybach et al. (2000), Cataldi (2001), Sanyal (2005), Stefánsson and Axelsson (2005), Ungemach et al. (2005), and O’Sullivan and Mannington (2005) provide discussions of the issue. Bromley et al. (2006) discuss sustainable utilization strategies and associated environmental issues. Rybach and Mongillo (2006) present a good review and Axelsson (2010) and Axelsson et al. (2005a) discuss relevant definitions as well as presenting information on different utilization and modelling case-histories.

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 and how enormous the energy content of the Earth’s crust is compared to the energy needs of mankind. In addition geothermal resources simply don’t fit well with non-renewable energy sources like coal and oil, for example because of much more limited greenhouse gas emissions. Geothermal energy has for example been classified as renewable by the European Parliament and the Council of the European Union (2009). Classifying geothermal resources as renewable has been disputed by some experts on the grounds that geothermal energy utilization actually involves heat-mining, see 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 discussed by Axelsson (2011) as well as the diverse renewability of different types of geothermal systems.

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 section, 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 1 or 2 centuries (chapter 3).

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. Therefore an Icelandic working group proposed a time-scale of the order of 100 – 300 years as appropriate (Axelsson et al., 2001). Others have proposed time scales of the order of 50 – 100 years. Figure 1, presented by the working group, is intended to capture the essence of its definition of sustainable production, for the time scale proposed by the group, i.e. if production is below a certain level (E_0) it can be maintained while production above the limit can't be maintained and has to be reduced before the period chosen has ended.

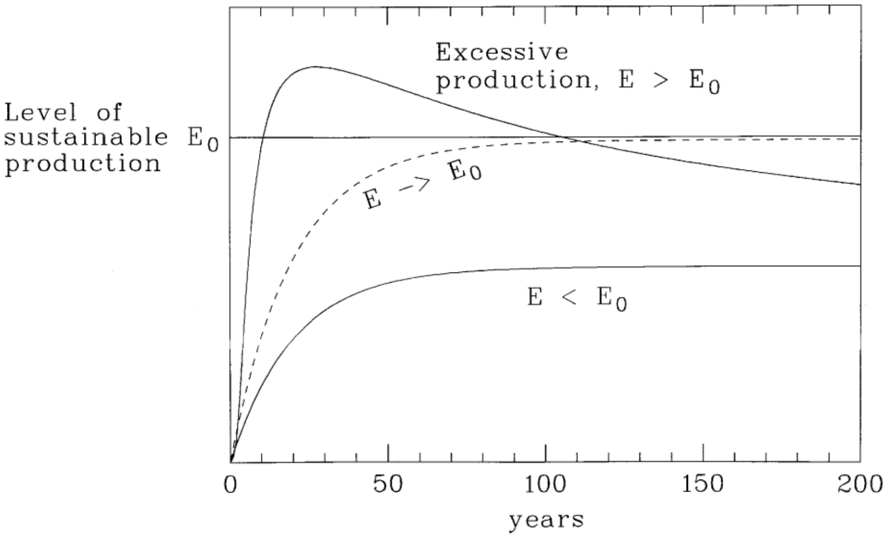

FIGURE 1: A schematic graph showing the essence of the definition of sustainable production presented by Axelsson et al. (2001). Production below the sustainable limit E_0 can be maintained for the whole period being assessed, while greater production can't be maintained.

It is important to keep in mind, however, that sustainable geothermal utilization not only involves maintaining production from each individual geothermal system. This is because sustainable development should incorporate all aspects of human needs and activity. It is also important to keep in mind that sustainable development does, in addition, not only involve preserving the environment, as sometimes assumed. In fact, sustainable utilization involves an integrated economic, social and environmental development. Therefore geothermal production can e.g. to some extent be excessive (greater than the sustainable level) for a certain period if outweighed by improved social and/or economic conditions. When taking the more narrow view of maintaining production from a single geothermal system it is recommended to refer to that as sustainable geothermal production (Ketilsson et al., 2010).

It is difficult to establish the sustainable production level, E_0, for a given geothermal system. This is because the production capacity of geothermal systems is usually very poorly known during exploration and the initial utilization step, as is well known. Even when considerable production experience has been acquired estimating accurately the production capacity, and hence the sustainable production level, can be challenging.

In spite of this downside one should bear in mind that the sustainable production level of a particular geothermal resource can be expected to increase over time with increasing knowledge on the resource, i.e. through continuous exploration and monitoring. In addition it can be expected to increase additionally through technological advances, e.g. in exploration methods, drilling technology and utilization efficiency.

When appraising the more general sustainable geothermal utilization an evaluation shouldn't necessarily focus on a single geothermal system. Either the combined overall production from several systems controlled by a single power company can be considered or several systems in a certain geographical region, even whole countries. Therefore, individual geothermal systems can e.g. be used in a cyclic manner, through which one system is rested while another is produced at a rate considerably greater than $\boldsymbol{E_0}$, and vice versa. This idea is based on an expected reclamation (recovery) of most geothermal systems when utilization is stopped, on a time-scale comparable to that of the utilization (Axelsson et al., 2005a). The recovery expectation is both based on experience and results of numerical modelling.

This brings us to the possible production modes for individual geothermal systems, which can be incorporated in a more general sustainable geothermal utilization scheme, shown in Figure 2. Mode (3) is cyclic and would require the utilization of another geothermal system, or other systems, when the primary one is being rested. Mode (4) is a variation of mode (3) in which utilization at a reduced rate is envisioned during the resting period instead of a complete stop.

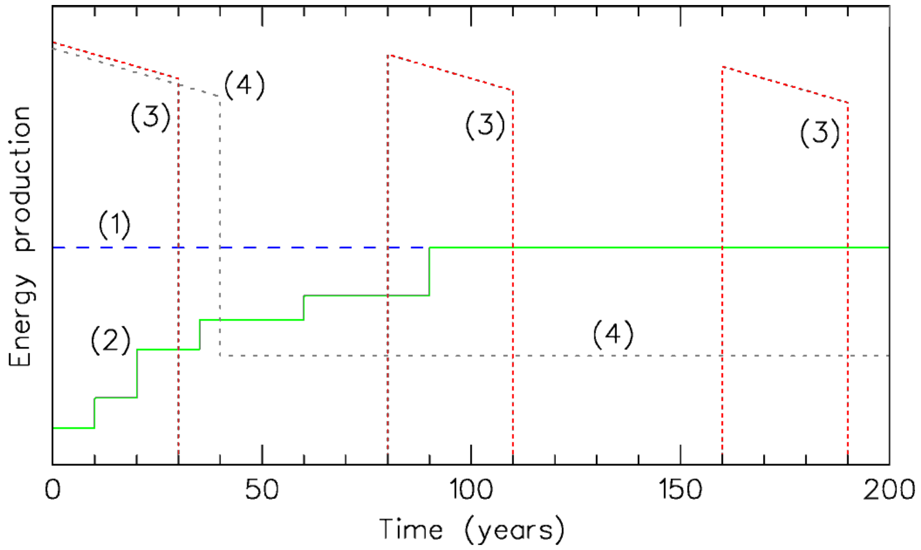

FIGURE 2: Different production modes for geothermal systems which can be incorporated into sustainable geothermal utilization scheme (based on Axelsson, 2010)

Work on sustainability issues is continuing in different parts of the world, in particular work aimed at understanding the nature of the geothermal systems and their long-term response to utilization. Some on-going work under the auspices of the Geothermal Implementing Agreement of the International Energy Agency (IEA-GIA) focuses on several relevant research issues identified (see chapter 4). Work has also started in a few countries aimed at developing sustainability goals, or protocols, to assess the progress towards sustainable geothermal development and even to find ways to introduce sustainability logically into legislation and regulatory frameworks (see chapter 5).

3. LONG UTILIZATION CASE HISTORIES AND MODELLING

3.1 Long case histories

A number of geothermal systems worldwide have been utilized for several decades. These provide the most important information on the response of geothermal systems to long-term production, and on the nature of the systems, if a comprehensive monitoring program has been in operation in the field. Such information provides the basis of understanding the issue of sustainable geothermal utilization, as well as the basis of sustainability modelling. Information on some of these can be found in the special sustainability issue of *Geothermics* (Mongillo and Axelsson, 2010). Several Icelandic low-temperature case histories are also presented by Axelsson et al. (2010b), some as long as 80 years. Axelsson (2010) lists 16 hydrothermal systems with long histories, high-temperature as well as low-temperature. Some of these are discussed below but in addition geothermal resources of the Hungarian Basin (Szanyi and Kovács, 2010) utilized since the 1930's, may be mentioned, along with Larderello in Italy (Romagnoli et al., 2010) utilized since the 1950's, Cerro Prieto in Mexico and Svartsengi in Iceland, both utilized since 1976.

The sustainable production potential of a geothermal system is either controlled by energy content or by pressure decline due to limited recharge. Many of the case histories referred to above have shown it is possible to produce geothermal energy in such a manner that a previously unexploited geothermal system reaches a new equilibrium, and this new state may be maintained for a long time. Pressure decline during production in geothermal systems can cause the recharge to the system to increase approximately in proportion to the rate at which mass is extracted. The new equilibrium is achieved when the increased recharge balances the discharge. Experience has also demonstrated that when reinjection is applied, cold-front breakthrough can be averted and thermal decline managed for decades.

One of the best examples of long-term utilization is the low-temperature Laugarnes geothermal system 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 (assuming the artesian flow to approximately equal the recharge) what it was before production started (Figure 3). A good example of a utilization of a high-temperature volcanic geothermal system maintained for several decades is the utilization of the Matsukawa geothermal system in Japan (Hanano, 2003), which has been used for more than four decades (since 1966) at a steady, average electrical generation capacity of about 23.5 MW_e (with about 60 kg/s average steam production).

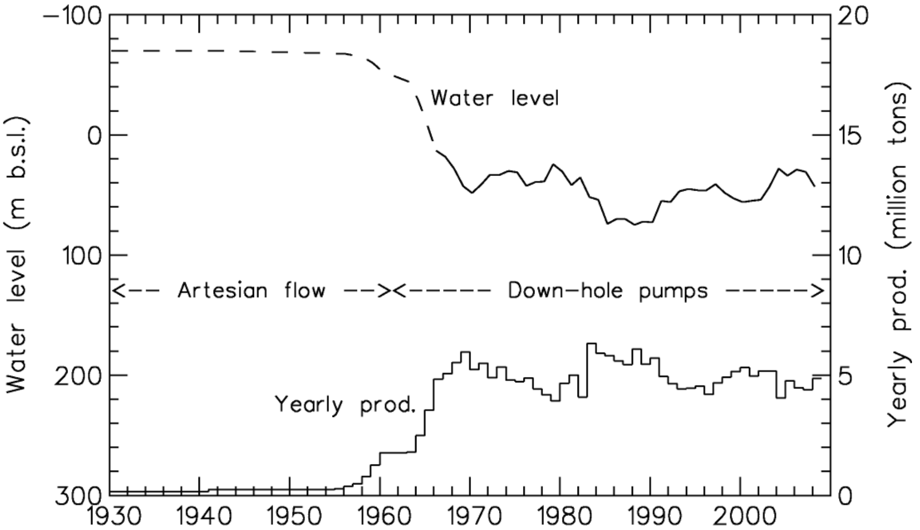

FIGURE 3: Production and water-level history of the Laugarnes low-temperature geothermal system in SW-Iceland up to 2010 (Axelsson et al., 2010b)

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 vapour-dominated Geysers geothermal system in California is a well-known example of excessive production. For a few years, the installed electric generation potential corresponded to more than 2000 MW_e, which has since been reduced by more than half because of pressure decline in the system due to insufficient fluid recharge (Barker, 2000; Goyal and Conant, 2010). Axelsson (2008b) also discuss some other examples of excessive production.

The utilization of the geothermal resources in the Paris Basin in France is another low-temperature long-term utilization example worth mentioning, although it is a sedimentary geothermal resource quite different from the better known volcanic or convective tectonic systems (Axelsson 2008a). The Paris Basin hosts a vast geothermal resource associated with the Dogger limestone formation, which stretches over 15,000 km^2 (Lopez et al., 2010). The Dogger resource is mainly used for space heating through a doublet scheme, consisting of a closed loop with one production well and one reinjection well. Utilisation of the Dogger geothermal reservoir started in 1969. The production and reinjection wells of the Paris doublets are usually separated by a distance of about 1,000 m to minimise the danger of cooling due to the reinjection. No significant cooling has taken place in any of the Paris production wells after 3 – 4 decades in spite of modelling studies having indicated that the doublets should start to cool down after 2 decades or so (Lopez et al., 2010). The extensive experience gained in the Paris Basin provides an invaluable basis for future sustainable management of the resource as well as for other geothermal resources of a comparable geological nature, utilized through a doublet scheme, e.g. in other parts of Europe and in China.

3.2 Sustainability modelling

Modelling studies, which are performed on the basis of available data on the structure and production response of geothermal systems, or simulation studies, are the most powerful tools to estimate the sustainable potential (i.e. $\boldsymbol{E_0}$) of the systems (Axelsson, 2010; Axelsson et al., 2005a). They can also be used to assess what will be the most appropriate mode of utilization in the future and to evaluate the effect of different utilization methods, such as reinjection. It is possible to use either complex numerical models, or simpler models such as lumped parameter models, for such modelling studies (Axelsson et al., 2005b). The former models can be much more accurate and they can both simulate the main features in the structure and nature of geothermal systems and their response to production. Yet lumped parameter models are very powerful for simulating pressure changes, which are in fact the changes which are the main controlling factor for the responses of geothermal systems.

The basis of reliable modelling studies is accurate and extensive data, including data on the geological structure of a system, its physical state and not least its response to production. The last mentioned information is most important when the sustainable potential of a geothermal system is being assessed and if the assessment is to be reliable the response data must extend over a few years at least, or even a few decades, as the model predictions must extend far into the future.

The sustainable potential of geothermal systems, that have still not been harnessed, can only be assessed very roughly. This is because in such situations the response data mentioned above is not available. It is, however, possible to base a rough assessment on available ideas on the size of a geothermal system and temperature conditions as well as knowledge on comparable systems. This is often done by using the so-called volumetric assessment method with the Monte Carlo method (Axelsson, 2008a; Sarmiento and Björnsson, 2007).

Axelsson (2010) presents the results of modelling studies for four geothermal systems that were performed to assess their sustainable production potential, or to provide answers to questions related to this issue. Two of these will be reviewed below, the Nesjavellir system in Iceland and the Urban system in China, while the other two are the Hamar low-temperature geothermal system in N-Iceland and the Olkaria high-temperature geothermal system in Kenya. Ofwona (2008) presents information on the production history of the Olkaria system, which has been utilized since 1981. The Hamar geothermal system has been used since 1969, and lately the average yearly production has been about 30 l/s of 65°C water. A lumped parameter model, as well as an energy content model, were used for the Hamar modelling study. The results of the calculations show the sustainable production potential of the system is probably slightly more than the present production, i.e. about 40 l/s average production, and that the sustainable energy production potential of the Hamar system is controlled by energy content and the limited size of the thermal water system, rather than by pressure decline (Axelsson, 2010).

Nesjavellir is one of the high-temperature geothermal areas in the Hengill volcanic region in southwest Iceland. It has been in use since 1990, at first for direct heating and later for cogeneration of electricity and heat. Today, the generating capacity of the Nesjavellir power plant is 120 MW_e electrical power and 300 MW_{th} thermal power. A 3D numerical simulation model, as well as a lumped parameter model, have been set up for the Nesjavellir system. The present numerical model is actually a part of a much larger and more complex numerical model of the whole Hengill-region and surroundings (Björnsson et al., 2003). The results of calculations by these models have demonstrated the present rate of utilization is not sustainable; that is, the present production cannot be maintained for the next 100 to 300 years (Figure 4). The model calculations indicate, however, the effects of the present intense production should mostly be reversible. Figure 5 shows the reservoir pressure should recover over approximately the same time scale as the period of intense production. The thermal cooling effects, which are rather limited in amplitude and not as well determined (poorly constrained in the model because no cooling has been observed yet) as the pressure effects, appear to last much longer according to the numerical model. Therefore, it should be possible to utilize the Nesjavellir system, in the long term, according to production modes (3) or (4), described above (Figure 2).

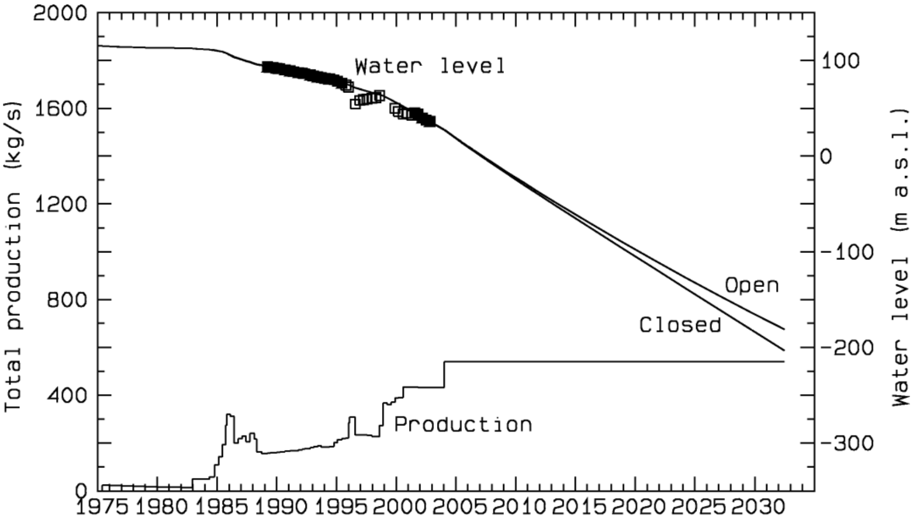

FIGURE 4: Pressure decline data (measured as water level) from an observation well at Nesjavellir simulated by a lumped parameter model and pressure decline predictions, calculated using an open (optimistic) and a closed (pessimistic) model, for a 120 MW_e future production scenario (Axelsson, 2010). The total mass extraction from the field is also shown (no injection into main reservoir).

Another two modelling studies, which are in fact sustainability modelling studies, have been carried out for the Ahuachapan high-temperature geothermal system in El Salvador and the Wairakei high-temperature geothermal system in New Zealand. The main results of these two studies are reviewed below. Both systems constitute examples of systems having quite long and well documented production and response histories. The Ahuachapan study focussed on the long term management of the geothermal system, based on monitoring data collected since its utilization started in 1976 (Monterrosa and Montalvo, 2010). Figure 6 shows simulated and predicted pressure changes in the Ahuachapan geothermal system 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, however (Monterrosa and Montalvo, 2010).

The Wairakei system in New Zealand has been utilized since 1958 and recently the electricity generation has corresponded to an average electrical generation of 170 MW_e. The sustainability modelling study for Wairakei focussed on predicting the systems response for another 50 years or so as well as predicting the recovery of the system once energy production will be stopped, after about

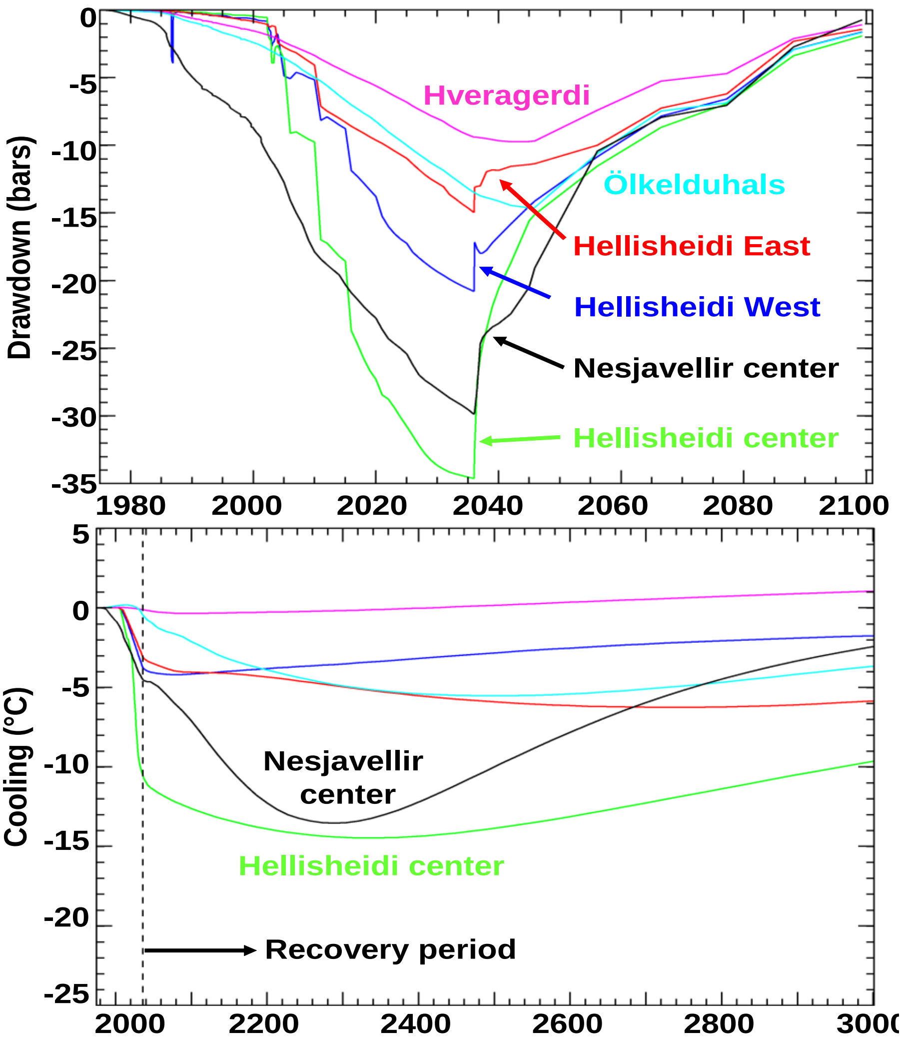

FIGURE 5: Calculated changes in reservoir pressure and temperature in different parts of the Hengill area, including the central part of the Nesjavellir geothermal reservoir, during a 30-year period of intense production, and for the following recovery (production stopped in 2036). Predicted temperature changes are not well constrained because no cooling has been observed as of 2010. Figure from Axelsson et al. (2010a); see also Björnsson et al. (2003).

100 years of utilization (O'Sullivan et al., 2010; see also O'Sullivan and Mannington, 2005). An example of the results of the study is shown in Figure 7, which shows on one hand the pressure response of the system and on the other its temperature evolution. As in the case of Nesjavellir presented above, the pressure recovers very rapidly while temperature conditions evolve much more slowly.

The fourth example of sustainability modelling presented by Axelsson (2010), referred to above, is a study done for the Beijing Urban low-temperature geothermal system. The Beijing Urban system is embedded in permeable sedimentary layers (carbonate rocks) at 1 – 4 km depth below Beijing and has been used since the 1970s (Liu et al., 2002). 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). The response of the geothermal system to this production and predictions by a lumped parameter model (Figures 8 and 9) show the production potential of the Beijing Urban system is constrained by limited water recharge to the system, but not energy content. The model calculations for the Beijing Urban system demonstrate the sustainable potential of the system is of the order of 100 l/s average yearly production. However, this depends on how much water-level drawdown will be acceptable in 100 to

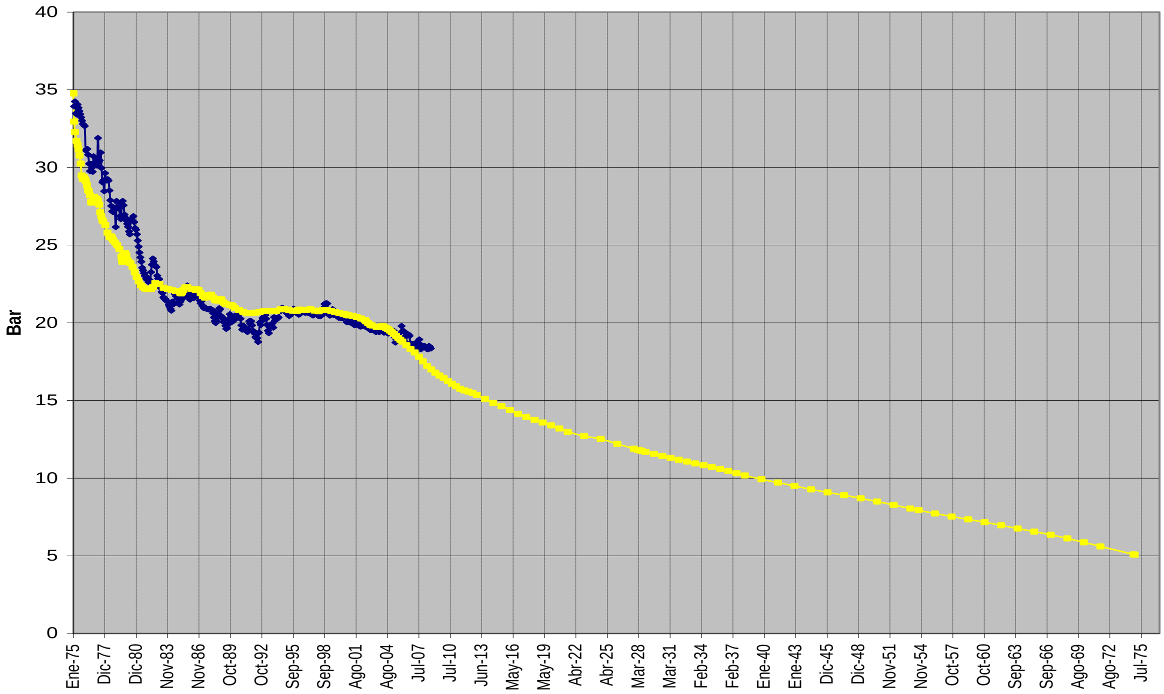

FIGURE 6: Predicted pressure changes in the Ahuachapan geothermal system in El Salvador up to 2075, for a future scenario of 95 MW_e constant production. Figure from Axelsson et al. (2010a); see also Monterrosa and Montalvo (2010).

200 years. Through a revision of the mode of utilization, which would involve reinjection of a large proportion of the water extracted, the sustainable potential could be as much as 200 l/s average yearly production. That would be a 100% increase of the production maintained from the system until now. Simple energy balance calculations show that more than sufficient thermal energy is in place in the system if the reinjection-production system is managed efficiently, as in the Paris Basin.

Axelsson et al. (2010a) discuss briefly sustainability aspects of ground-coupled, or geothermal, heat-pumps (GHP) and EGS-systems. The sustainability of GHPs depends on the particular technique applied but in all such systems it is to some extent supported by the heat supply from the atmosphere (solar radiation). In combined heating/cooling systems it is also supported by heat storage in summer and in ground-water systems by the energy carried by the ground-water flow. Rybach and Eugster (2010) discuss the theoretical and experimental basis of the sustainable utilization of borehole heat exchanger GPHs, which is the most common type today. The sustainability of EGS-systems depends on the accessible thermal energy and, in particular, on the surface area of the fracture network opened or created in such systems. Under favourable natural conditions, like at Soultz-sous-Fôrets in France, convective/advective energy re-supply can add to this (Kohl et al., 2000). Sanyal et al. (2005) discuss production longevity of EGS resources and various operational strategies that may help sustain EGS operations.

4. INTERNATIONAL COLLABORATION AND RESEARCH ISSUES

As the possible role of geothermal energy utilization in sustainable development receives increasing attention and sustainability research is stepped up, international collaboration on issues related to sustainable geothermal utilization has been increasing. Collaboration through the International Energy Agency's (IEA) Geothermal Implementing Agreement (GIA) has e.g. been significant.

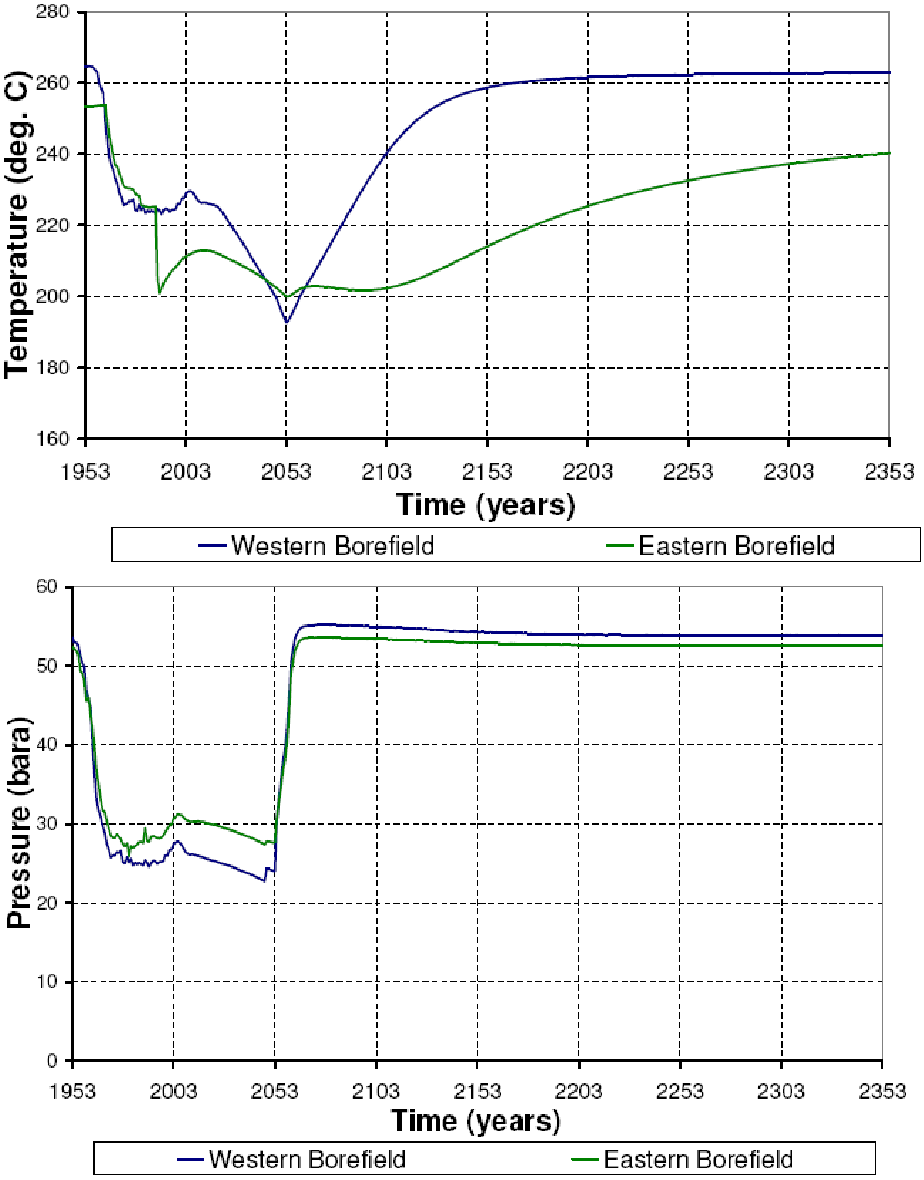

FIGURE 7: Predicted pressure and temperature recovery in the Wairakei geothermal system in New Zealand following 100 years of production. Figure from Axelsson et al. (2010); see also O'Sullivan and Mannington (2005) and O'Sullivan et al. (2010).

The GIA provides a framework for international geothermal cooperation and 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 (Axelsson et al., 2010a). 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 (see below). A number of recent papers and reports have also been assembled and made available through the IEA-GIA's website (www.iea-gia.org). 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 the geothermal research journal *Geothermics*, supported by IEA-GIA Annex I,

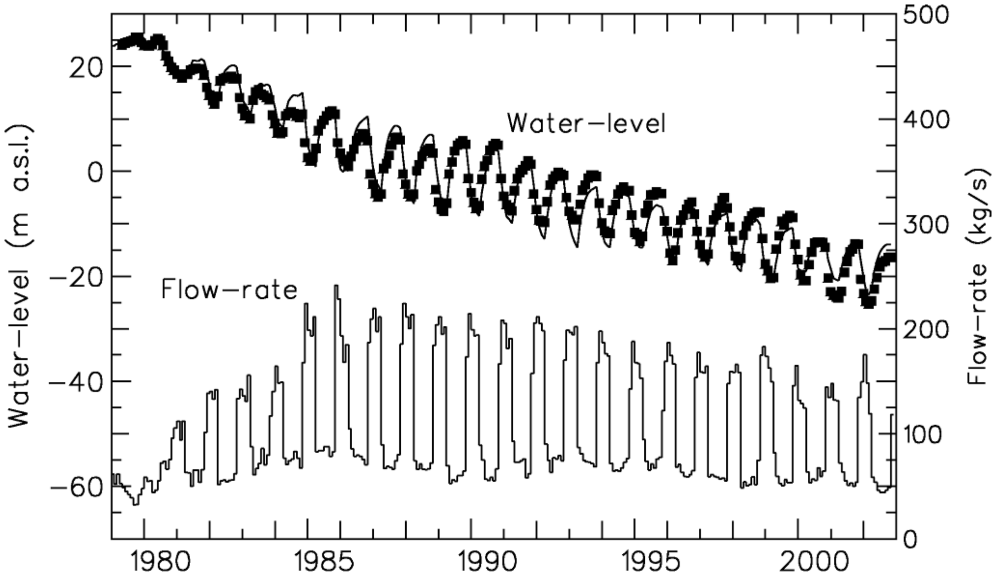

FIGURE 8: The production history of the Urban geothermal field in Beijing with the water-level history simulated by a lumped-parameter model (squares = measured data, line = simulated data). Figure from Axelsson (2010).

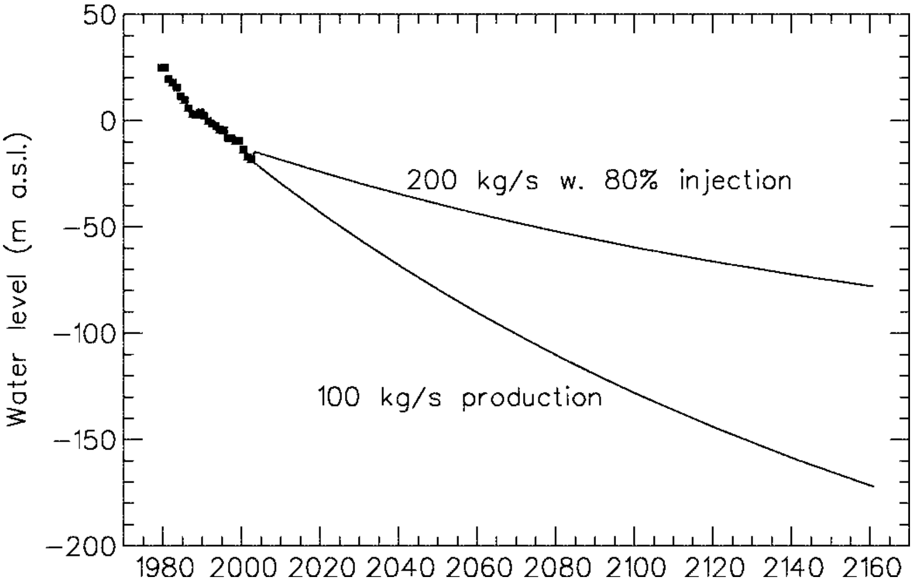

FIGURE 9: Predicted water-level changes in the urban geothermal field in Beijing for a 200-year production history (figure shows annual average values). Figure from Axelsson (2010).

devoted to sustainable geothermal utilization was published; with particular emphasis on long utilization case histories and sustainability modelling studies (Mongillo and Axelsson, 2010).

Several research issues need to be studied in conjunction with sustainability research and modelling. Some of these are listed below (from Axelsson, 2010; see also Rybach and Mongillo, 2006):

(1) What factors are most significant in controlling long-term reservoir behaviour and capacity? These include: size, permeability, boundary conditions, natural recharge, reinjection, etc.
(2) How significant and far-reaching are long-term production pressure drawdown and reinjection cooling effects? In particular, how significant is interference between adjacent geothermal areas?

(3) Which are the optimum strategies for the different modes of production presented above, such as continuous and periodic production and reinjection scenarios in different cases?
(4) How rapidly and effectively do geothermal systems recover during breaks after periods of excessive production?
(5) What is the reliability of long-term (~100 years) predictions of reservoir production response using various methods (stored heat, simple analytical models, complex 3D models, etc.)?
(6) What information should be collected at pre-exploitation and early development stages to significantly reduce uncertainties in long-term resource sustainability assessments?

5. SUSTAINABILITY GOALS AND INDICATORS

In addition to on-going work aimed at increasing the understanding of the nature and potential of geothermal resources, and how they can be utilized in a sustainable manner, work has also started in a few countries aimed at trying to incorporate sustainability into policy making at different levels as well as into legislation and regulatory frameworks.

Developing a sustainability policy involves the following two steps:

(A) Setting of general ***Sustainability Goals***, which should incorporate the main sustainability objectives aimed at, whether they are resource related, economic, environmental or social. Such goals are also referred to as policies or guidelines.
(B) Defining specific ***Sustainability Indicators*** on basis of the goals. These should be able to measure the degree of sustainability of a given operation or the progress towards sustainability. It is the authors' opinion that such indicators should neither be too many nor too complicated.

Together the goals and indicators comprise a ***Sustainability Assessment Protocol***. Comparable protocols have e.g. been developed by the hydropower industry through the International Hydropower Association (2010). Examples of such goals include eleven general goals proposed for geothermal development in Iceland, by an Icelandic working group, covering the items summarized below (Ketilsson et al., 2010):

- Resource management/renewability (2 goals)
- Efficiency
- Research and innovation
- Environmental impacts
- Social aspects
- Energy security, accessibility, availability and diversity (2 goals)
- Economic and financial viability (2 goals)
- Knowledge sharing

It may also be mentioned that individual power companies utilizing geothermal resources can also develop their own goals and indicators, such as is being done by LaGeo in El Salvador (Monterrosa and Montalvo, 2010). Examples of possible indicators can, furthermore, be found in three recent MSc-theses devoted to geothermal sustainability (Hagedoorn, 2006; Shortall, 2010; Bjarnadóttir, 2010). Another example of a geothermal sustainability assessment through the use of indicators is given by Duan et al. (2011).

Going through all the possible indicators suggested in the above references is beyond the scope of this paper, but in the authors opinion resource related indicators should address the following:

(1) ***Reservoir evolution***, i.e. reservoir pressure decline, production temperature or enthalpy evolution and change in the concentration of major chemical constituents.
(2) Assessment of ***remaining reservoir life*** at given capacity, done through reservoir modelling. Should also include an estimate of spare capacity available and the need for make-up well drilling.
(3) Assessment of ***primary energy efficiency*** in the utilization as well as of the utilization load-factor.
(4) ***Reservoir integrity***, i.e. whether irreversible damage is foreseeable such as due to either massive scaling in reservoir or massive reservoir cooling (due to cold inflow or reinjection).

The indicators, which can be both quantitative and qualitative, should serve as a gauge on how well a given geothermal operation is working; they should also help decide what direction to take if an operational problem needs to be addressed. They should be able to measure the degree of sustainability of a given operation, the progress towards sustainability and/or whether it looks like sustainable production or utilization can be maintained as proposed.

It should be mentioned that when evaluating overall sustainability two approaches can be used; weak sustainability which acknowledges the validity of growth and places equal importance on environment, social justice and economic prosperity and strong sustainability that has the environment as foundation for social justice and economic prosperity (Ketilsson et al., 2010). Thus strong sustainability focuses on the viability and health of the geothermal system to sustain utilization while weak sustainability also acknowledges economic forces and technological advances. It may also be mentioned that Ketilsson et al. (2010) describes work in progress in Iceland to find ways to introduce sustainability logically into the legislation and regulatory framework of the country, a task which is not straightforward.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper reviews several aspects of the issue of sustainable geothermal energy utilization. It is argued that geothermal resources can be utilized in a sustainable manner if a time-scale of the order of 100 – 300 years is assumed. The sustainable potential of a geothermal resource is either controlled by the pressure decline caused by production or by the energy content of the system in question, depending on the nature of the resource. Case histories of numerous geothermal systems worldwide, which have been utilized for several decades, provide the most important data for sustainability and renewability research, involving appropriate modelling and long-term future predictions. A few different sustainable utilization scenarios can be envisioned; such as through constant production below the sustainable limit, step-wise increase in production or cyclic production (intermittent excessive production with recovery periods).

It is suggested to differentiate between two terms, ***sustainable geothermal production*** and ***sustainable geothermal utilization***. The former involves the more narrow view of maintaining production from a single geothermal system while the latter is more general and involves integrated economic, social and environmental development. This is because sustainable development should incorporate all aspects of human needs and activity, not only involve maintaining a given resource use or only preserving the environment, as sometimes assumed. Therefore geothermal production can e.g. to some extent be excessive (greater than the sustainable level) for a certain period if outweighed by improved social and/or economic conditions.

Several relevant sustainability research issues have been identified and are listed in the paper. 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.

If geothermal resources are to have a place in sustainable development in different parts of the world sustainability protocols need to be set up both for individual power companies and whole countries. This involves the setting of general sustainability goals and consequently defining specific sustainability indicators to measure the degree of sustainability of a given geothermal operation or progress towards sustainability. It is the authors view that such indicators should neither be too many nor too complicated, and that they should be relatively easy to assess whether they are qualitative or quantitative.

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