Presented at “SDG Short Course I on Sustainability and Environmental Management of Geothermal Resource Utilization and the Role of Geothermal in Combating Climate Change”, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, September 4-10, 2016.

UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

LaGeo
GrupoCEL

SUSTAINABLE MANAGEMENT OF GEOTHERMAL RESOURCES

Gudni Axelsson
Iceland GeoSurvey (ÍSOR)
and University of Iceland
Reykjavík
ICELAND
gax@isor.is

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 semi-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. Sustainable management basically involves setting up and maintaining a specific long-term production scheme. It also involves the basic ingredients of successful geothermal resource management, i.e. reinjection, monitoring and modelling. The most ideal way to utilize a geothermal resource in a sustainable manner is through a step-wise increase in production, even though other sustainable utilization schemes can be envisioned. The long production histories that are available for geothermal systems worldwide provide the most valuable data available for studying sustainable geothermal utilization, 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. 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. A sustainability policy is based on general sustainability goals and includes specific sustainability indicators to measure the degree of sustainability of a given geothermal operation.

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. The potential of the Earth's geothermal resources is, furthermore, enormous when compared to their use today, and to the future energy needs of mankind. There is, therefore, ample space for accelerated use of geothermal resources worldwide in the near future and it has been envisaged that by 2050 geothermal electrical generation capacity may reach 70 GW_e, or about 5 times the present capacity, and direct use 5 EJ/yr, which is about 10 times the present use. The nature and use of the world's geothermal resources is discussed in more detail in another paper presented at this short course (Axelsson, 2016).

It is evident that increased utilization of geothermal resources can contribute to the world's sustainable development, both as a long-term source of energy and by being relatively environmentally benign. Sustainable geothermal production has been studied and discussed to a considerable degree in the literature in recent years, to some extent 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 relevant publications are referred to throughout the paper.

This paper is based on earlier papers by the author, mainly Axelsson (2012) and Axelsson (2010). It reviews several aspects of the issue of sustainable geothermal energy utilization, such as the background of the issue and a specific definition of the term "sustainable production", which is considered both logical and realistic, along with the time-scale involved. The paper, furthermore, discusses what's involved in the sustainable management of geothermal resources along with a few possible modes of long-term utilization. It also discusses some long-term geothermal production histories, which yield the most important information needed to address the issue, and presents briefly the results of modelling studies aimed at estimating the sustainable production potential of naturally permeable hydrothermal systems. Examples from Iceland, France, New Zealand, El Salvador and China are discussed in particular. A section of the paper is devoted 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.

Sustainable geothermal utilization doesn't only involve maintaining production from a given geothermal system for a long time. It also involves environmental and social criteria that need to be considered, along with economic aspects. Environmental and social aspects of sustainable geothermal utilization are discussed in numerous presentations at this short course. It should also be mentioned that at the short course the nature and assessment of geothermal resources are reviewed in a presentation by Axelsson (2016) and the development of sustainability protocols by Shortall et al. (2016).

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 conditions, 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 or two, 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 this period, as reviewed by Rybach and Mongillo (2006) and Axelsson (2012). The literature includes an early discussion by Wright (1999), a discussion of sustainable utilization strategies and associated environmental issues by Bromley et al. (2006) and an analysis of relevant definitions as well as a presentation of different utilization and modelling case-histories (Axelsson, 2010).

There have also been considerable discussions on the renewability of geothermal systems and whether to classify them amongst the renewable energy resources or the non-renewable ones, as discussed by Axelsson (2016) at this short course. They are generally classified as renewable, while this may be an oversimplification, 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, 2011). 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.

Two main issues are of principal significance when geothermal sustainability is being discussed and evaluated (Axelsson, 2012). 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 later in this paper (sub-chapter 4.1), 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 (see also later in sub-chapter 4.2).

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 ($\boldsymbol{E_0}$) it can be maintained while production above the limit can’t be maintained and has to be reduced before the period chosen has ended.

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 narrower view of maintaining production from a single geothermal system it is recommended to refer to that as sustainable geothermal production (Axelsson, 2012). Other aspects of the potential contribution of geothermal resources to sustainable development, e.g. environmental and social issues, as well as the battle against climate change, are discussed in several other presentations at this short course.

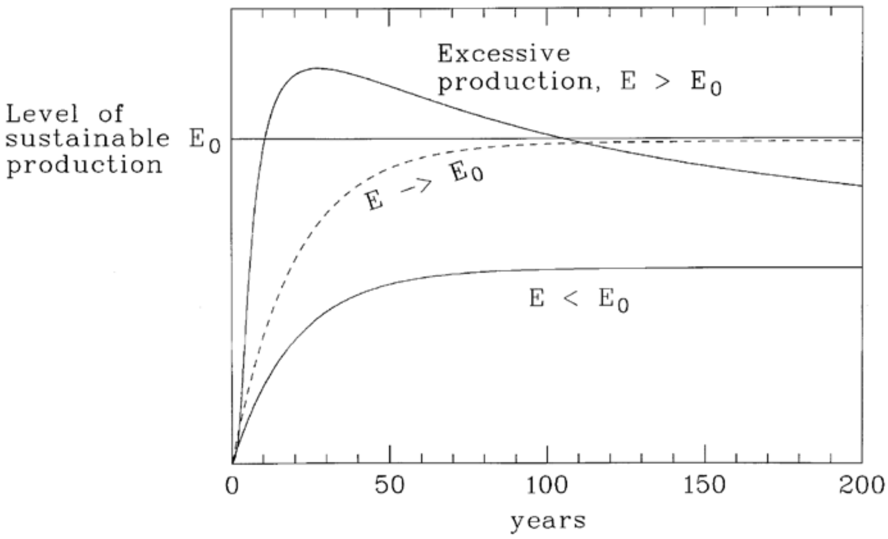

FIGURE 1: A schematic graph showing the essence of the definition of sustainable production presented by Axelsson et al. (2001). Production below the sustainable limit E_0 can be maintained for the whole period being assessed, while greater production can't be maintained

It is difficult to establish the sustainable production level, $\boldsymbol{E_0}$, 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, and requires comprehensive knowledge on the nature, properties and utilization response of a system.

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. This includes e.g. deeper drilling, such as near, or into, the deep roots of volcanic geothermal systems where greater production capacity may be expected per well (Axelsson, 2016).

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, 2010). The recovery expectation is both based on experience and results of numerical modelling.

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 (Axelsson 2012). Some relevant research issues are discussed briefly later in this paper (see sub-chapter 4.3). Work has also started on developing geothermal sustainability assessment framework, or protocols, for geothermal energy projects, based on general sustainability goals and specific indicators, to assess the progress towards sustainable geothermal development, as will be discussed later (see chapter 5).

3. SUSTAINABLE MANAGEMENT

Sustainable management basically involves setting up specific long-term production schemes and maintaining them for an expected production period, through different management actions. Possible sustainable production modes for individual geothermal systems, which can be incorporated in a more general sustainable geothermal utilization scheme, are presented and discussed by Axelsson (2010). These involve constant production at, or below, the sustainable limit of the system in question. This mode can't really be considered realistic as the sustainable limit is unknown, or at best only roughly known, at the onset of long-term production. Another mode involves a step-wise increase in production, shown in Figure 2, and discussed further below. The third mode involves cyclic production, where the production is excessive for short periods (20 – 40 years), followed by production-breaks of comparable length. This mode would require the utilization of another geothermal system, or other systems, when the primary one is being rested. The fourth mode is a variation of the third one, in which an initial period of excessive production is followed by production at a reduced rate (less than the otherwise sustainable potential), instead of a complete stop. Figure 2 also demonstrates the possible effect of improved modes of production and technological advances (see above).

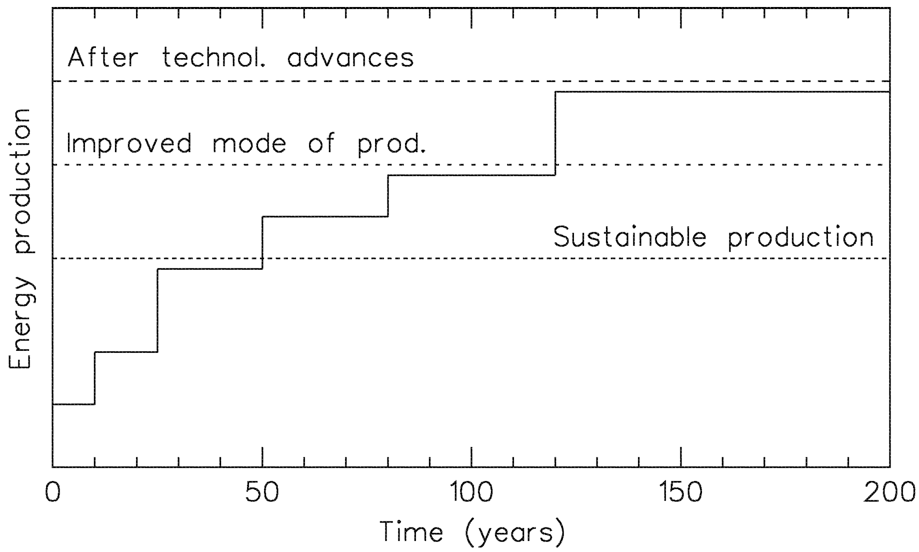

FIGURE 2: A simple schematic graph demonstrating how the sustainable production potential of a geothermal system is dependent on the mode of production, as well as technological advances. The figure also demonstrates how the energy production may be increased in steps towards a sustainable limit, which in turn will probably increase with time (Axelsson, 2010).

Stefánsson and Axelsson (2005) discuss how economic feasibility studies usually only consider a few decades of utilization. They point out that by increasing the energy production from a geothermal system in steps (see Figure 2), two objectives can be achieved simultaneously. First, such steps are economical due to a relatively low risk of failure and relatively small increments of investment. Second, such steps can be used to estimate the sustainable potential of a given system. During each step the optimum level of the next step may be estimated, increasingly better data on reservoir performance collected, and thus, the maximum sustainable level of production slowly approached. Step-wise development can, therefore, be considered to be the ideal way of developing and utilizing a geothermal resource in a sustainable manner.

Axelsson (2008) reviews geothermal management in some detail and presents references to other relevant publications. Such management basically involves various actions aimed at maintaining a certain geothermal energy production, such as through the drilling of make-up or step-out wells, addressing issues that may arise because of the chemical content of the geothermal fluid, mainly scaling and corrosion, and engineering solutions aimed maintaining output in spite of changing thermodynamic conditions, to name a few examples. It also includes some of the key ingredients of successful geothermal resource management, i.e. reinjection, monitoring and modelling. Reinjection chiefly helps maintain reservoir pressure through supplementing the natural recharge; its management is aimed at efficient use of the thermal energy in-place in the reservoir rocks while avoiding rapid cooling of production wells. Monitoring provides essential data for understanding the nature and utilization response of a geothermal system, which in turn is used to calibrate models and calculate future predictions, essential for successful management. Consequently, modelling is the primary reservoir engineering tool used in geothermal resource management, as it can be used to predict the outcome of various management actions. Finally, it should be mentioned that geothermal development and utilization has both environmental and social impacts, which need the appropriate attention (see other presentations at this short course).

4. LONG UTILIZATION CASE HISTORIES, MODELLING AND RESEARCH ISSUES

4.1 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. (2010a), 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, or both (Axelsson, 2016). 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. In other cases, physical changes in geothermal systems are so slow that their output is not affected for decades, as already mentioned. Experience and modelling have, furthermore, demonstrated that when reinjection is applied, cold-front breakthrough can be averted and thermal decline managed for decades.

An outstanding example of long-term geothermal 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). The Laugarnes system is a fracture-controlled convective system (Axelsson, 2016) believed to extend down to at least 2.5 km depth. At present there are no indications of deterioration of the system, in one way or another, which would otherwise reduce the production capacity of the system in coming years/decades (Axelsson et al., 2010a).

In other case histories 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 natural fluid recharge (Goyal and Conant, 2010). Through injection of steam condensate, surface-water and treated sewage piped from communities in the general area energy production has been approximately stabilized.

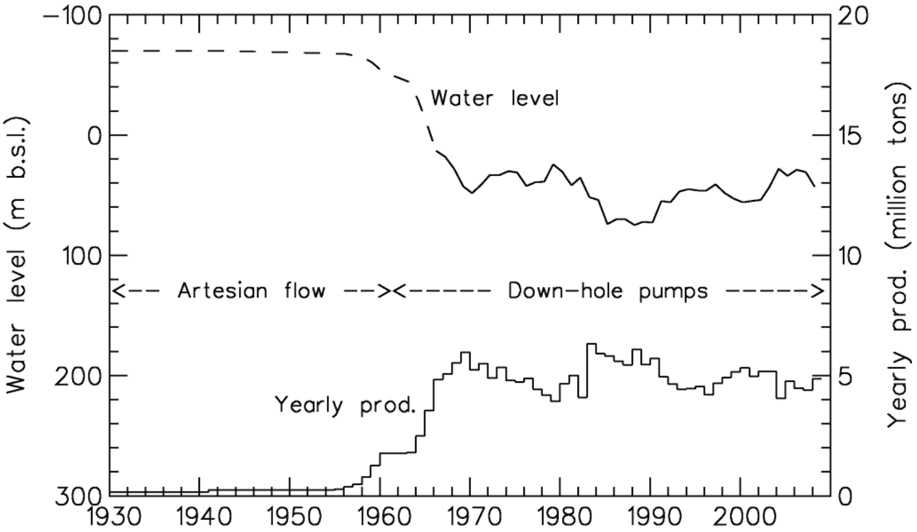

FIGURE 3: Production and water-level (reservoir pressure) history of the Laugarnes low-temperature geothermal system in SW-Iceland up to 2010 (Axelsson et al., 2010a)

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. 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 km, or more, 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.

4.2 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). 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, as is presented in another presentation at this short course (Axelsson, 2016). 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, 2016).

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. These are the Hamar low-temperature fracture controlled convective geothermal system in N-Iceland, the Nesjavellir high-temperature volcanic geothermal system in SW-Iceland, the Urban low-temperature sedimentary geothermal system in Beijing, China, and the Olkaria high-temperature volcanic geothermal system in Kenya. The results of these studies will be reviewed to a varying degree below, apart from those for the Olkaria geothermal system (see instead Axelsson et al., 2013)

The Hamar geothermal system has been used since 1969, mainly for space-heating, 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 results of calculations by these models have demonstrated that the present rate of utilization is not sustainable; that is, the present production cannot be maintained for the next 100 years or more. The model calculations indicate, however, the effects of the present intense production should mostly be reversible. They show that the reservoir pressure should recover over approximately the same time scale as the period of intense production (see Figure 13 in Axelsson, 2016). 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 the cyclic production mode described above (chapter 2).

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 1970's (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 4 and 5) show that 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 that 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 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.

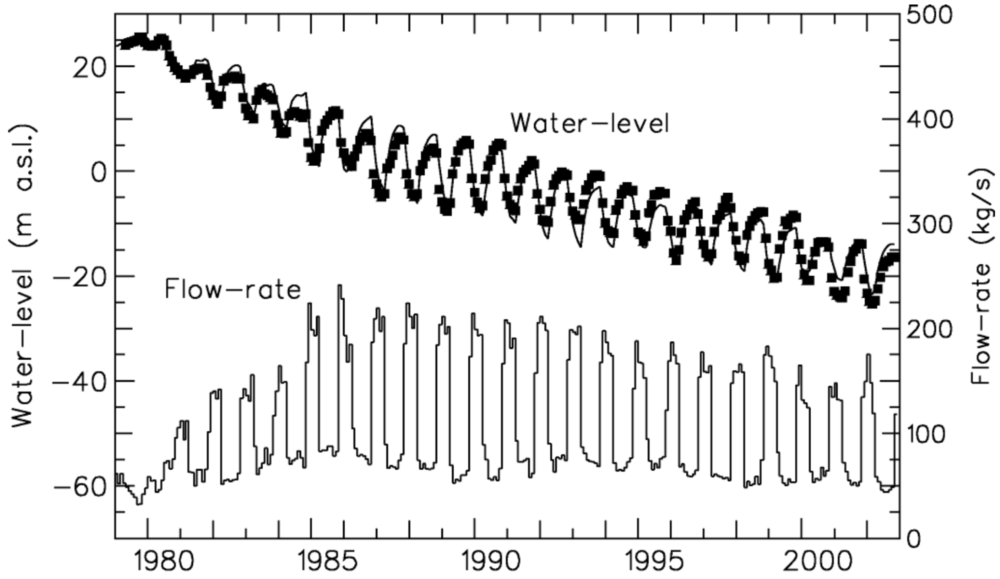

FIGURE 4: The production history of the Urban geothermal field in Beijing with the water-level history simulated by a lumped-parameter model (squares = measured data, line = simulated data). Figure from Axelsson (2010).

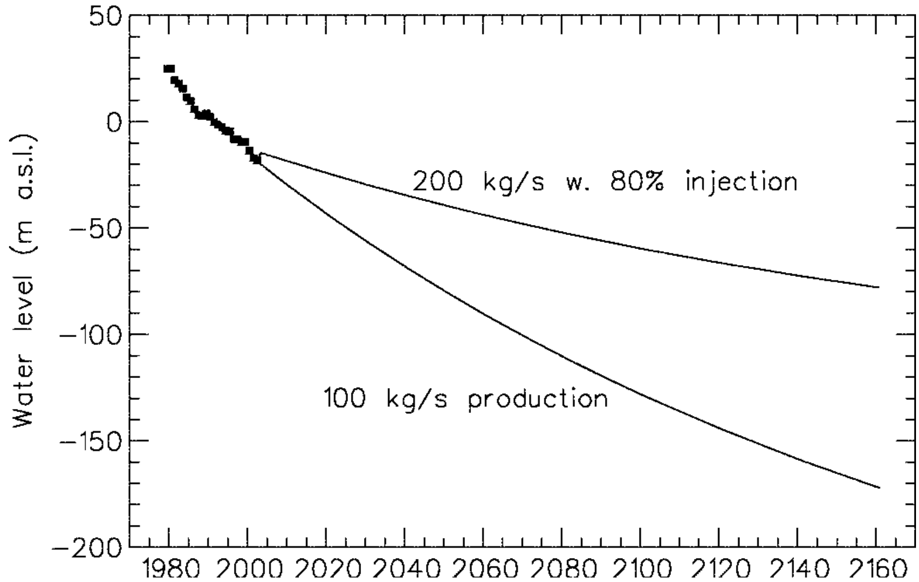

FIGURE 5: Predicted water-level changes in the Urban geothermal field in Beijing for a 200-year production history (figure shows annual average values). Figure from Axelsson (2010).

Another two modelling studies, which are also sustainability modelling studies in fact, have been carried out for the Ahuachapan and Wairakei high-temperature volcanic geothermal systems in El Salvador and New Zealand, respectively. 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 100 years of utilization (O'Sullivan et al., 2010). 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 discussed above, the pressure recovers very rapidly while temperature conditions evolve much more slowly.

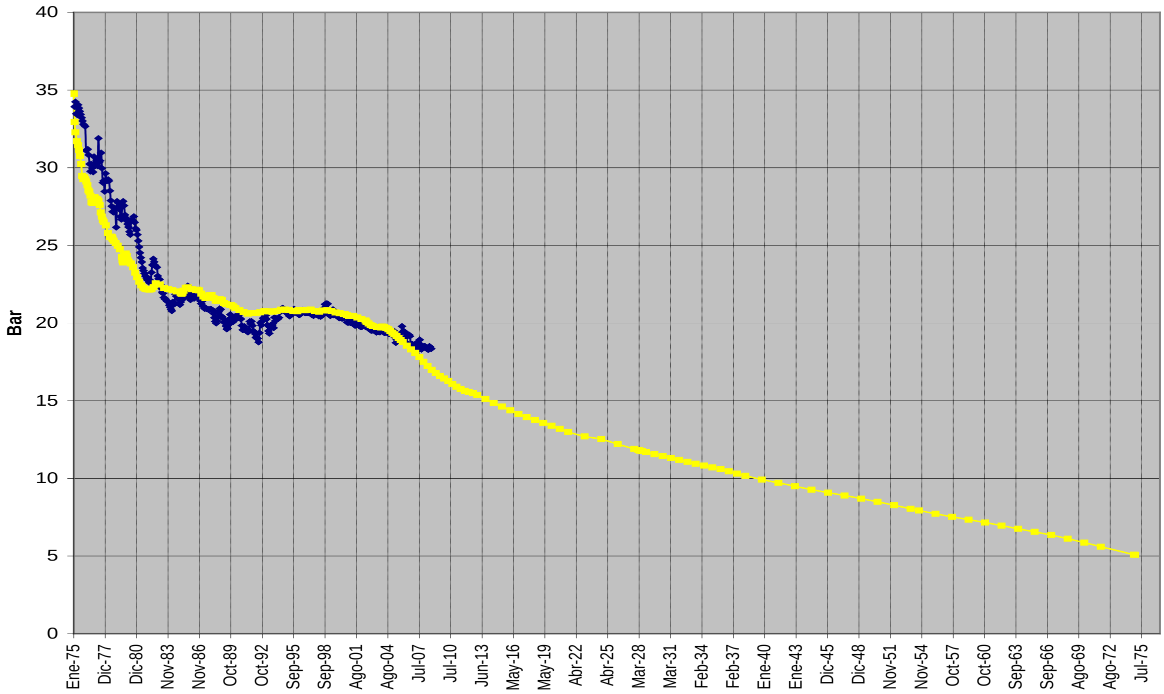

FIGURE 6: Predicted pressure changes in the Ahua¬chapan geothermal system in El Salvador up to 2075, for a future scenario of 95 MWe constant production. Figure from Axelsson et al. (2010b); see also Monterrosa and Montalvo (2010).

It should also be noted that Axelsson (2012) discuss briefly sustainability aspects of ground-coupled, or geothermal, heat-pumps (GHP) and EGS-systems.

4.3 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. The GIA provides a framework for international geothermal cooperation and the promotion of sustainable utilization of geothermal energy is one the main aims of the IEA-GIA. The recent sustainability tasks of the GIA are described by (Axelsson et al., 2010b). Those have included a literature compilation, meetings and workshops as well as the publication of a 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 (Mongillo and Axelsson, 2010).

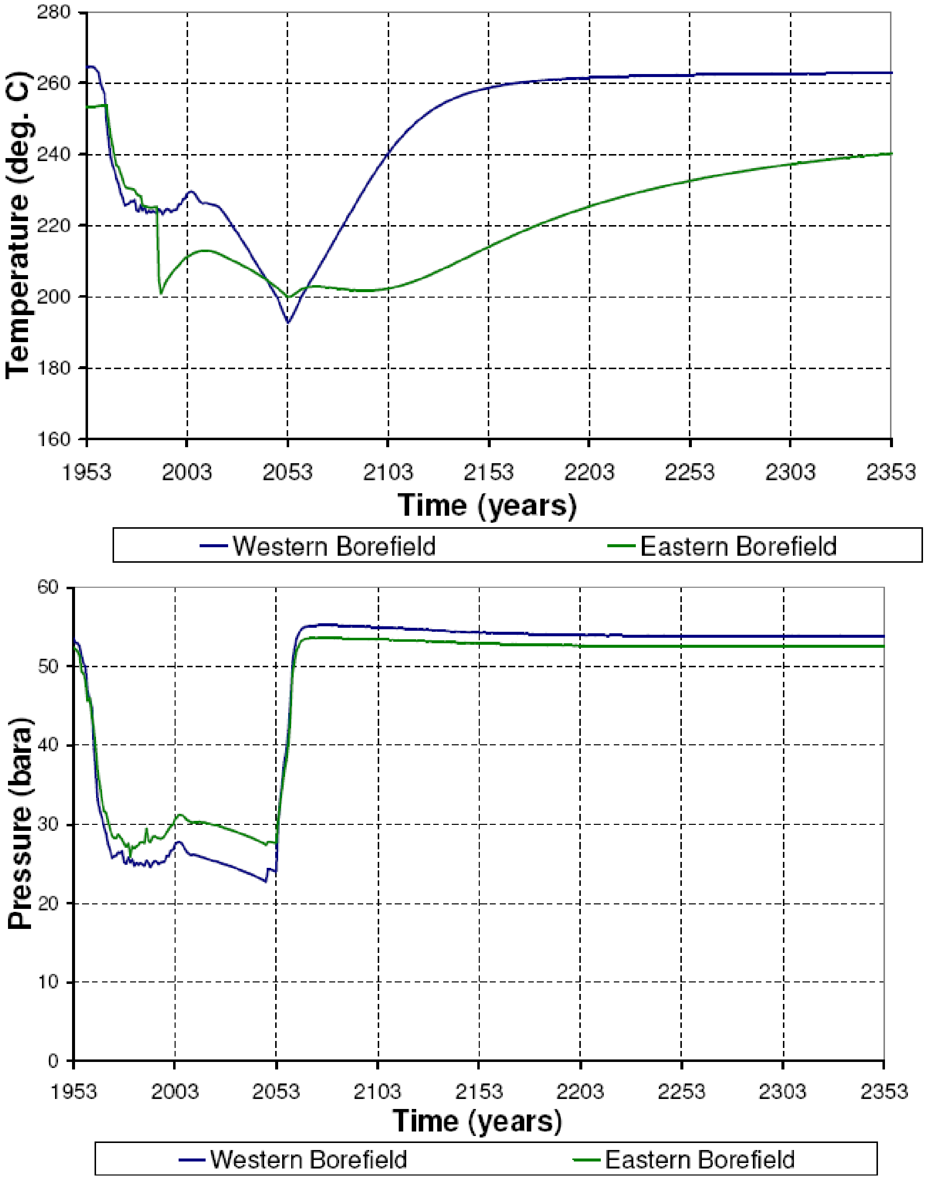

FIGURE 7: Predicted pressure and temperature recovery in the Wairakei geothermal system in New Zealand following 100 years of production. Figure from Axelsson et al. (2010b); see also O'Sullivan et al. (2010).

Axelsson (2012) summarizes several research issues that need to be studied in conjunction with sustainability research and modelling. These include:

(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, described above, work has recently been ongoing 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***. Examples of sustainability 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); and
- Knowledge sharing.

It may also be mentioned that individual power companies utilizing geothermal resources can also develop their own goals and indicators, such as has been done by LaGeo in El Salvador (Monterrosa and Montalvo, 2010). Axelsson (2012) mentions some other examples of indicator development attempts, available or ongoing at that time. More comprehensive work has been completed since and the reader is, in particular, referred to the presentation by Shortall et al. (2016) at this short course and the more detailed references, also by Shortall and co-authors, listed in that paper.

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

This paper reviews several aspects of the issue of sustainable geothermal resource utilization and management. It is based on earlier papers by the author, including a paper presented at an earlier El Salvador short course. The paper is, furthermore, founded on the contention 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.

From the resource point of view sustainable production involves the narrower view of maintaining production from a single geothermal system while the term geothermal utilization 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. Environmental and social aspects of sustainable geothermal utilization are discussed in other presentations at the present short course.

Sustainable geothermal resource management basically involves setting up and maintaining specific long-term production schemes. It also involves the key ingredients of successful geothermal resource management, i.e. reinjection, monitoring and modelling. The most ideal way to utilize a geothermal resource in a sustainable manner is through a step-wise increase in production, even though other sustainable utilization schemes can be envisioned, e.g. constant production at, or below, the sustainable production limit and cyclic production with intermittent excessive production connected by recovery periods of approximately the same time-length.

Several relevant sustainability research issues are reviewed in the paper. The most important ones include boundary conditions (controlling recharge) 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 thermal 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 assessment frameworks, or sustainability protocols, need to be set up for individual power companies, regions and whole countries. This involves the setting of general sustainability goals and the consequent definition of specific sustainability indicators to measure the degree of sustainability of a given geothermal operation or its progress towards sustainability. Such indicators should neither be too many nor too complicated, and that they should be relatively easy to assess, regardless of whether they are qualitative or quantitative.

ACKNOWLEDGEMENTS

The author would like to acknowledge numerous colleagues for fruitful discussions during the last decade or two, on the issue of sustainable geothermal utilization, most of them in Iceland, but also with colleagues at the IEA-GIA, especially Mr. Chris Bromley, and at LaGeo in El Salvador, particularly Mr. Manuel Monterrosa. The author would also like to acknowledge the late Valgardur Stefánsson, who was a pioneer on the issue of sustainable geothermal utilization and management. The relevant geothermal utilities and power companies are also acknowledged for allowing publication of the case-history data presented here.

REFERENCES

Axelsson, G., 2008: Management of geothermal resources. *Papers presented at "Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED,* Tianjin, China, 15 pp.

Axelsson, G., 2010: Sustainable geothermal utilization – Case histories, definitions, research issues and modelling. *Geothermics, 39,* 283–291.

Axelsson, G., 2011: Using long case histories to study hydrothermal renewability and sustainable utilization. *Geothermal Resources Council Transactions, 35,* 1393–1400.

Axelsson, G., 2012: Sustainable geothermal utilization. *Papers presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo,* Santa Tecla, El Salvador, 19 pp.

Axelsson, G., 2016: Nature and assessment of geothermal resources. *Papers presented at "Short Course on Sustainability and Environmental Management of Geothermal Resource Utilization and the Role of Geothermal in Combating Climate Change", organized by UNU-GTP and LaGeo,* Santa Tecla, El Salvador, 23 pp.

Axelsson, G., Arnaldsson, A., Gylfadóttir, S.S., Halldórsdóttir, S., Mortensen, A.K., Bore, C., Karingithi, C., Koech, V., Mbithi, U., Muchemi, G., Mwarania, F., Opondo, K., Ouma, P., 2013: Conceptual model and resource assessment for the Olkaria geothermal system, Kenya. *Papers presented at "Short Course on Conceptual Modelling of Geothermal Systems", organized by UNU-GTP and LaGeo,* Santa Tecla, El Salvador, 21 pp.

Axelsson, G., Gunnlaugsson, E., Jónasson, Th., and Ólafsson, M., 2010a: Low-temperature geothermal utilization in Iceland – Decades of experience. *Geothermics, 39,* 329–338.

Axelsson, G., Bromley, C., Mongillo, M., and Rybach, L., 2010b: The sustainability task of the International Energy Agency's Geothermal Implementing Agreement. *Proceedings World Geothermal Congress 2010, Bali, Indonesia,* 8 pp.

Axelsson, G., Gudmundsson, Á., Steingrímsson, B., Pálmason, G., Ármannsson, H., Tulinus, H., Flóvenz, Ó.G., Björnsson, S., and Stefánsson, V., 2001: Sustainable production of geothermal energy: suggested definition. *IGA-News,* Quarterly No. 43, 1–2.

Bromley, C.J., Mongillo, M., and Rybach, L., 2006: Sustainable utilization strategies and promotion of beneficial environmental effects – Having your cake and eating it too. *Proceedings of the New Zealand Geothermal Workshop 2006,* Auckland, New Zealand, 5 pp.

Goyal, K.P. and Conant, T.T., 2010: Performance history of The Geysers steam field, California, USA. *Geothermics, 39,* 321–328.

Ketilsson, J., Axelsson, G., Björnsson, A., Björnsson, G., Pálsson, B., Sveinbjörnsdóttir, Á.E., and Saemundsson, K., 2009: Introducing the concept of sustainable geothermal utilization in Icelandic Legislation. *Proceedings World Geothermal Congress 2010,* Bali, Indonesia, 8 pp.

Liu, J., Pan, X., Yang, Y., Liu, Z., Wang, X., Zhang, L., and Xu, W., 2002: Potential assessment of the Urban geothermal field, Beijing, China. *Proceedings of the International Symposium on Geothermal and the 2008 Olympics in Beijing,* Beijing, China, 211–217.

Lopez, S., Hamm, V., Le Brun, M., Schaper, L., Boissier, F., Cotiche, C., and Giuglaris, E., 2010: 40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France. *Geothermics, 39*, 339–356.

Mongillo, M.A., and Axelsson, A. (guest editors), 2010: Special issue on sustainable geothermal utilization. *Geothermics, 39,* 279–402.

Monterrosa, M., and Montalvo, F., 2010: Sustainability analysis of the Ahuachapan geothermal field – Management and modelling. *Geothermics*, *39,* 370–381.

O'Sullivan, M., Yeh, A., and Mannington, W., 2010: Renewability of geothermal resources. *Geothermics*, *39,* 314–320.

Romagnoli, P., Arias, A., Barelli, A., Cei, M., and Casini, M., 2010: An updated numerical model of the Larderello–Travale geothermal system, Italy. *Geothermics*, *39,* 292–313.

Rybach, L., and Mongillo, M., 2006: Geothermal sustainability – A review with identified research needs. *Geothermal Resources Council Transactions, 30,* 1083–1090.

Shortall, R., Davidsdóttir, B., and Axelsson, G., 2016: A geothermal sustainability assessment framework for geothermal energy projects. *Papers presented at "Short Course on Sustainability and Environmental Management of Geothermal Resource Utilization and the Role of Geothermal in Combating Climate Change", organized by UNU-GTP and LaGeo*, Santa Tecla, El Salvador, 7 pp.

Stefánsson, V., and Axelsson, G., 2005: Sustainable utilization of geothermal resources through stepwise development. *Proceedings World Geothermal Congress 2005,* Antalya, Turkey, 5 pp.

Szanyi, J., and Kovács, B., 2010: Forty years utilization experience for geothermal systems in South-East Hungary. *Geothermics*, *39,* 357–364.

World Commission on Environment and Development, 1987: *Our Common Future*. Oxford University Press, Oxford, UK, 400 pp.

Wright, P.M., 1999: *The sustainability of production from geothermal resources*. Lectures presented at the United Nations University Geothermal Training Programme, Reykjavík, Iceland, 42 pp.