Geothermics 39 (2010) 283–291

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Sustainable geothermal utilization – Case histories; definitions; research issues and modelling

Gudni Axelsson [a,b,*]

[a] Iceland GeoSurvey (ÍSOR), Grensásvegur 9, IS-108 Reykjavík, Iceland
[b] University of Iceland, Saemundargötu 6, IS-101 Reykjavík, Iceland

ARTICLE INFO

Article history:
Received 28 June 2009
Accepted 25 August 2010
Available online 13 October 2010

Keywords:
Geothermal
Sustainable utilization
Renewability
Case history
Utilization mode
Research
Modelling

ABSTRACT

Sustainable development by definition meets the needs of the present without compromising the ability of future generations to meet their own needs. The Earth's enormous geothermal resources have the potential to contribute significantly to sustainable energy use worldwide as well as to help mitigate climate change. Experience from the use of numerous 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 (100–300 years). Modelling studies indicate that the effect of heavy utilization is often reversible on a time-scale comparable to the period of utilization. Thus, geothermal resources can be used in a sustainable manner either through (1) constant production below the sustainable limit, (2) step-wise increase in production, (3) intermittent excessive production with breaks, and (4) reduced production after a shorter period of heavy production. The long production histories that are available for low-temperature as well as high-temperature geothermal systems distributed throughout the world, 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 presents sustainability modelling studies for the Hamar and Nesjavellir geothermal systems in Iceland, the Beijing Urban system in China and the Olkaria system in Kenya as examples. Several relevant research issues have also been identified, such as the relevance of system boundary conditions during long-term utilization, how far reaching interference from utilization is, how effectively geothermal systems recover after heavy utilization and the reliability of long-term (more than 100 years) model predictions.

1. Introduction

The term sustainable development first emerged with the publication of the Brundtland report in 1987 (World Commission on Environment and Development, 1987). There, sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Since then, sustainable development has been receiving increased attention, and the importance of sustainable use of the Earth's natural resources has become increasingly clear. Geothermal energy is one of the energy resources that can be used in a sustainable manner, as well as help to mitigate climate change.

The potential of 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 is 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). In comparison, the worldwide installed geothermal electricity generation capacity was about 10 GW_e in 2007. The direct geothermal utilization amounted to 330 PJ/yr (1 PJ = 10^{15} J), according to the International Energy Agency's Geothermal Implementing Agreement (2008). About one third of the direct use is through ground-source heat-pumps. Fridleifsson et al. (2008) have estimated that by 2050 the electrical generation potential 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 use 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

* Tel.: +354 528 1500; fax: +354 528 1699.
E-mail address: gax@isor.is.

0375-6505/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.geothermics.2010.08.001

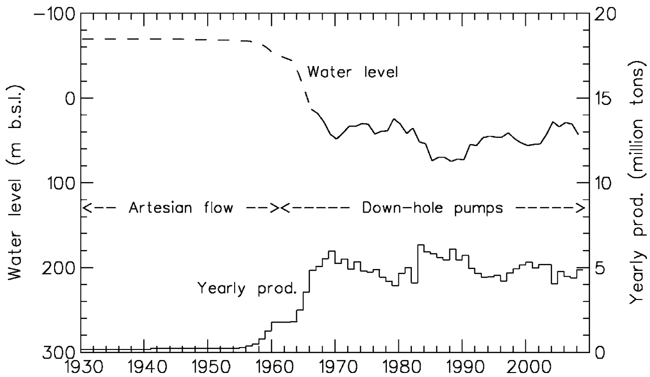

Fig. 1. Production and water-level history of the Laugarnes geothermal system in SW-Iceland up to 2010.
Updated from Axelsson et al. (2002).

the latter should refer to how it is used. 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. Rybach and Mongillo (2006) present a good review. Axelsson et al. (2005) discuss sustainable geothermal utilization for 100–300 years and present the results of a few relevant modelling studies. Bromley et al. (2006) discuss sustainable utilization strategies and associated environmental issues.

This paper reviews several aspects of the issue of sustainable geothermal utilization, such as the background of the issue, a specific logical and realistic definition, and the time-scale involved. It also discusses long-term geothermal production response histories, which yield the most important information needed to address the issue, as well as a few possible modes of sustainable geothermal utilization. Furthermore, we discuss some of the basic research issues that need to be addressed and understood, if sustainable geothermal utilization is to be viable and present briefly the results of a few modelling studies focussing on the sustainability issue; in particular studies aimed at estimating the sustainable production potential of naturally permeable hydrothermal systems. However, the reader is advised that specific issues related to sustainable long-term production potential of engineered or enhanced geothermal systems (EGS), or ground-source heat pump installations (where recharge is predominantly by conductive heating), are not addressed in this paper.

2. Background

Experience from the utilization of numerous geothermal systems over the past few decades has 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 injection is applied, cold-front breakthrough can be averted and thermal decline managed for decades.

Axelsson and Stefánsson (2003) and Axelsson et al. (2005, 2010a) discuss a few examples of equilibrium between production and recharge. One of the best examples is the Laugarnes geothermal systems in Reykjavík (see also Section 3, Fig. 1), from which the average yearly mass extraction has been about 5 Mm^3 (about 160 l/s average production) for the past four decades. This has not caused a substantial pressure decline in the system, except during the first few years after pumping started. Therefore, the inflow, or recharge, to the system is now believed to be an order of magnitude greater than the pre-production recharge. Another good example is the Matsukawa geothermal system in Japan (Hanano, 2003), which also has been used for about four decades for an electricity generation (about 60 kg/s average steam production). The use of the Dogger reservoir in the Paris Basin is a further example involving low-temperature utilization through an extensive doublet-scheme for four decades (Lopez, 2008).

In other cases, geothermal production has, for a period of time, been excessive, and it has not been possible to maintain in the long-term. The utilization of the Geysers area in California is a well-known example of excessive production. For a few years, the total electric generation corresponded to more than 2000 MW_e, which has since been reduced by about half because of pressure decline in the system due to insufficient fluid recharge (Barker, 2000; Axelsson et al., 2005).

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

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

This definition applies to the total extractable energy, and it depends in principle on the nature of the geothermal system in question. It does not, however, consider load factors, utilization efficiency, economics aspects, environmental issues or technological advances. The value of E_0 may be expected to increase with time through technological advances, such as deeper drilling. In addition, the definition is dependent on different modes of production, which may involve artesian flow, pumping, injection or periodic production.

The definition quoted above is based on a much longer time scale than the customary economical time frame for geothermal power plants (often on the order of 20–30 years), which is generally used as the time frame when the production potential of geothermal systems is being assessed, particularly for investment purposes. By contrast, alternative time frames for a sustainable production definition could be as long as 1000 years (the time since Iceland was settled), or a period on the geological time scale, such as 10,000 years (the time since the end of the last ice age). However, such long time frames are considered unrealistic in view of the time scale of human endeavours, especially those leading to technological advancements in energy utilization. Therefore, a time frame within the bounds of these different time scales (100–300 years), which represents several generations of human endeavour, was chosen (Axelsson et al., 2001).

Even though geothermal resources are classified as renewable energy sources, because they are maintained by a continuous energy flow, such a classification is an oversimplification. Geothermal resources have, in essence, dual characteristics; that is, a combination of an energy flow (through heat convection, advection, and conduction) and stored energy. The renewability of these two aspects is quite different as the energy flow is quasi-steady and fully renewable, while part of the stored energy is renewable only on a very long time-scale. This is because the part renewed by heat conduction occurs relatively slow compared to fluid flow (advection and convection). The quasi-equilibrium reached in cases such as Laugarnes and Matsukawa affirms the renewability of the corresponding geothermal resources. The renewable component (the energy flow) is greater than the natural state recharge to the systems because production has induced an additional inflow of mass and energy into the systems (Stefánsson, 2000). In the case of Laugarnes, the recharge may have increased by an order of magnitude.

The value of E_0 is not known a priori, but it may be estimated, through modelling, on the basis of exploration and production data as they become available. Examples of such modelling are presented later in this paper. Although this definition of sustainability is based on the Brundtland definition, it does not imply economic sustainability, which normally is considered on a much shorter time scale, typically of the order of 30 years.

If energy production from a geothermal system is to be sustainable, the stored energy must be depleted at a relatively slow rate, and after a transient period, the energy recharge to the reservoir must approximately equal the energy extraction rate. Once again the Laugarnes system (Fig. 1) provides a good example. Maintaining such a semisteady-state for a long time generally requires the producing reservoir to be well connected to a relatively large source of hot recharge fluid. Consequently, in these cases, the "volume of influence" of the geothermal energy extraction is likely very large, and the renewability is supported by indirect energy extraction from the outer and deeper parts of the geothermal system which are not tapped directly by production boreholes.

3. Long utilization 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 (see later). The list below of geothermal systems that have been in use for 28 or more years is not exhaustive, but presents some well-known examples; some of which are described in more detail elsewhere within this Special Issue. A number of low-temperature (<150 °C) geothermal systems in Iceland have been used for even longer than three decades; their production histories are presented in Axelsson et al. (2010a).

1. Ahuachapan, El Salvador, used since 1976 (Monterrosa and Montalvo, 2006).
2. Cerro Prieto, Mexico, used since 1973.
3. Geysers, California, USA, used since 1960s (Barker, 2000).
4. Larderello, Italy, used since 1950s (Capetti et al., 1995).
5. Paris Basin, France, used since 1969 (Lopez, 2008).
6. Hungarian Basin, Hungary, used since 1930s.
7. Laugarnes, Iceland, used since 1930 (Axelsson and Stefánsson, 2003).
8. Hamar, Iceland, used since 1969 (Axelsson et al., 2005).
9. Krafla, Iceland, used since 1976.
10. Svartsengi, Iceland, used since 1976.
11. Olkaria, Kenya, used since 1981 (Ofwona, 2008).
12. Beijing Urban Area, China, used since the late 1970s (Liu et al., 2002).
13. Matsukawa, Japan, used since 1966 (Hanano, 2003).
14. Palinpinion, Philippines, used since 1983 (Aquí et al., 2005).
15. Tiwi, Philippines, used since 1979 (Barker et al., 1990).
16. Wairakei, New Zealand, used since 1958 (O'Sullivan and Mannington, 2005).

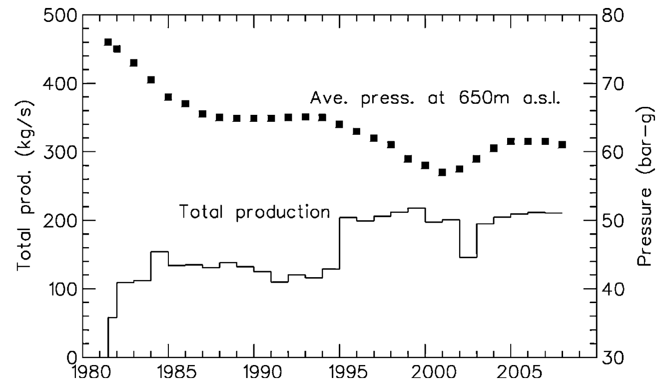

Fig. 2. Production and pressure history (smoothed) of the Olkaria-East geothermal system in Kenya from 1981 to 2007.
Figure based on Ofwona (2008).

The majority of these are high-temperature, or high-enthalpy, systems. Exceptions are the Paris Basin, Hungarian Basin, Laugarnes, Hamar and Beijing systems, which are low-temperature systems.

Figs. 1–3 present examples of three long production- and pressure- (water level) response histories: first, the very long history of the Laugarnes system in SW-Iceland, which has been discussed by Axelsson et al. (2002, 2005); second, the 27-year history of Olkaria-East in Kenya (Ofwona, 2008); and third, the 32-year history of Krafla in NE-Iceland (up to 2008). Notably, the overall reservoir pressure at Krafla seems to have been slowly increasing for this period, while the local, production-induced, pressure decline is superimposed on this steady background increase. This may partly result from the system-pressure recovering after a major volcanic and tectonic episode, which started in 1975, and partly from a shift in production load. The results of a simple modelling study for Olkaria are presented later in this paper, along with three other modelling cases, including studies for Beijing and Hamar (referenced in the list above).

4. Possible modes of utilization

Geothermal resources can be utilized through many different modes of operation, all of which may adhere to the sustainability definition presented above. In view of this, the following must be kept in mind:

A. The sustainable production potential of geothermal systems is unknown at the onset of production, but it may be estimated

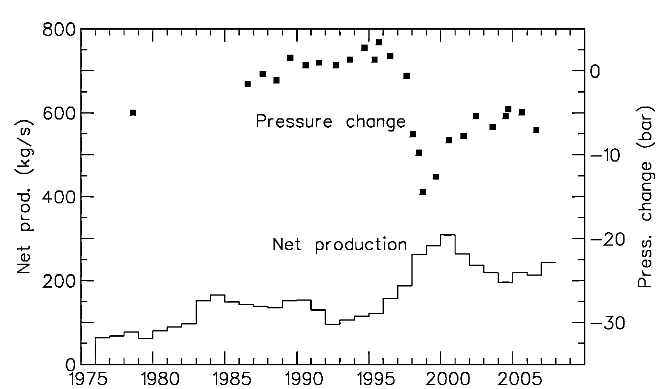

Fig. 3. Net production (production–injection) and pressure change history of the Krafla geothermal system in NE-Iceland from 1976 to 2007. Pressure changes measured at 800 and 1150 m depth in well K-6. Since 2002, about 20% of produced fluid has been injected.

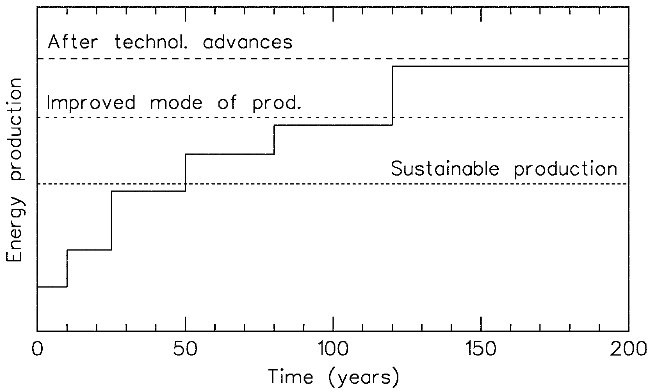

Fig. 4. Sustainable production potential of a geothermal system is dependent on the mode of production (e.g., injection) and technological advances (e.g., deeper drilling). From Axelsson et al. (2006). The figure also shows how geothermal production can be increased in steps as proposed by Stefánsson and Axelsson (2005).

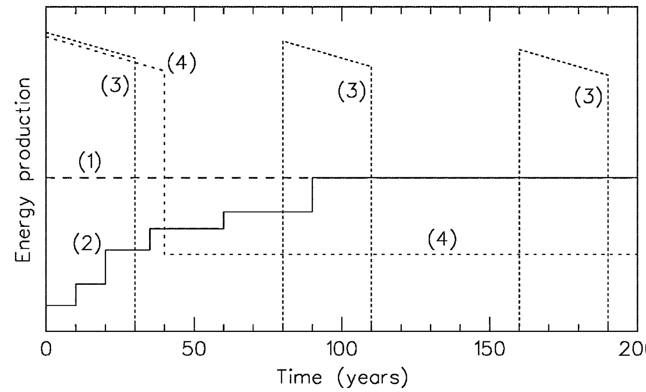

Fig. 5. Examples of different modes of sustainable geothermal system utilization. From Axelsson et al. (2006). The numbers refer to the production modes discussed in the paper.

from the internal structure and nature of the systems and their response to production, as will be discussed later in this paper. Such estimates become more and more reliable as the production history of the corresponding geothermal system becomes longer.

B. The sustainable potential is, in addition, dependent on utilization technology, both the mode of utilization and technological advances. As an example, in most situations, injection of return water (including waste liquid from heat exchangers, brine from separators, and surplus condensed steam from power-plant cooling circuits), or supplementary make-up water to replace vapour losses to the atmosphere, increases the production potential of geothermal systems (Axelsson, 2008b). It is also to be expected that through deeper drilling in the future (4–5 km instead of the common 2–3 km today), more energy may be extracted from many geothermal systems; in particular high-temperature systems associated with volcanic centres (Fridleifsson et al., 2005).

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, 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.

Fig. 4 shows a simple schematic graph, which is intended to demonstrate how the sustainable production potential is dependent on the mode of production, as well as technological advances. In addition, this figure also demonstrates how the energy production may be increased in steps towards a sustainable limit (which will probably increase with time and acquired knowledge).

The discussion above refers to two possible modes of sustainable geothermal utilization: first, step-wise increasing production up to the sustainable limit, and second, utilization where the production remains approximately constant from the outset. In addition, much more aggressive utilization modes can be envisioned, by either initially or intermittently extracting energy (partly from the stored component) at relatively high rates. Modelling studies have demonstrated that, because of increased recharge following a period of excessive production, geothermal systems are able to recover approximately back to their preproduction state. That is, the effects of intense production are mostly reversible (see Section 6.3). Such production modes are typical of the use of many high-temperature geothermal systems today; the resources are often harnessed in relatively large steps. The excessive extraction rates are unlikely to be sustainable for a long time, but large installations are more economically feasible due to economies of scale. Such installations also meet a demand for electrical power that grows in large steps, such as with the demands of power-intensive industry.

The main modes of sustainable geothermal utilization that may be envisioned over a 100- to 300-year period are thus the following:

1. Constant production (aside from variations during temporary demand cycles such as annual variations) for several hundred years. This is seldom a practical option because the sustainable production capacity of geothermal systems is generally unknown beforehand. Therefore, a test period is required initially to assess the sustainable potential.
2. Production increased in a few steps until the sustainable potential has been assessed and the sustainable limit attained.
3. Cyclic production with excessive production (not continuously sustainable) for a few decades (perhaps about 30 years) with total breaks in between (perhaps about 30–50 years), so the geothermal system is able to recover almost fully (>90%).
4. Excessive production for 30–50 years followed by a steady, but reduced production for the next 150–170 years. The production following the excessive period would typically be less than the sustainable potential at constant production [mode (1)], but this depends on the amount of increased steady-state recharge induced by the pressure and temperature drawdown during the period of excessive production.

A schematic diagram demonstrating these four modes is presented in Fig. 5.

The sustainable development of regional geothermal energy resources must be viewed in a broader context than for single geothermal systems independent of other systems. The methods that have been discussed here can, indeed, be used to assess the sustainable production potential of all known geothermal systems in a given region of the country, or in the country as a whole. The following must be kept in mind:

1. During long-term use, some pressure or temperature interference effects may be observed between adjacent geothermal fields. These possible effects could be significant even over distances of tens of kilometres, and should be taken into consideration when planning or modelling regional development strategies.

2. If single geothermal systems are being used in an intense or excessive manner during a certain period, other geothermal systems may need to be explored and proven to be available in the same general region. These could then be used while the former systems are being allowed to recover. Thus, the overall geothermal resource utilization in the region may be managed as sustainable, even though single geothermal systems are only used intermittently.
3. If geothermal development in a region is, on the other hand, conducted in a step-wise manner, development may be required to be ongoing in several geothermal fields simultaneously, because the energy production from each field is likely to be relatively small.

5. Research issues

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

1. What factors are most significant in controlling long-term behaviour/capacity? These include size, permeability, boundary conditions, inflow/recharge, injection, etc.
2. How significant and far-reaching are long-term production pressure drawdown and injection cooling effects? In particular, how significant is interference between adjacent geothermal areas?
3. Which are the optimum strategies for the different modes of production presented above, such as continuous and periodic production/injection 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 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?

Issue (1) is, of course, a key issue in geothermal development and a controlling factor regarding sustainable utilization of geothermal systems for periods of 100–300 years. This issue has been discussed by various authors for decades, and Axelsson (2008a) concludes the production capacity of geothermal systems is mainly controlled by the reservoir pressure decline caused by production, which, in turn, is determined by the size of a geothermal reservoir, its permeability and storage capacity, hydraulic boundary conditions (water recharge), and geological structure. The boundary conditions are of singular importance during long-term production.

Issue (2) has not received great attention until now, partly because interference between adjacent areas is difficult to distinguish from natural variations. Clear examples of such interference are well known, however. A good example from Iceland is the interference observed 15 km to the NE of the Reykir low-temperature area in SW-Iceland. An annual water-level variation of 10–20 m is observed there, resulting from an annual variation in production at Reykir on the order of 500–600 l/s (Björnsson et al., 2000). In theory, such interference is highly dependent on the storage mechanism controlling the response of the geothermal system in question, whether it is fluid/rock compressibility, free-surface mobility (when a part of the whole hydrological system is unconfined), or two-phase storativity. In the case of two-phase storativity, such interference may be expected to extend over much shorter distances than in the case of liquid systems (more than an order of magnitude difference). In effect, when two-phase zones are created by pressure decline and boiling, they tend to 'buffer' or reduce the rate of vertical and horizontal transmission of pressure transients through a liquid-dominated reservoir.

Issues (3), (4) and (5) are best studied through modelling based on the longest available case histories. Ideally item (3) should be studied through combined modelling of the geothermal resources, surface operations (power plants etc.), and economic aspects. Lovekin (2000) has studied the economics of sustainable geothermal utilization. Recovery rates (item 4) have not been studied extensively, but some examples of specific case studies include the Nesjavellir high-enthalpy study (as presented in Section 6.3 below); the recovery studies of ground-source heat pump operations (Rybach et al., 2000); the long-term recovery of a hypothetical two-phase geothermal system with limited natural fluid recharge (Pritchett, 1998); and recovery of the highly-permeable, Wairakei liquid-dominated system (O'Sullivan and Mannington, 2005). The many numerical reservoir models that have been developed for high-enthalpy geothermal systems worldwide can easily be used for such recovery studies.

Issue (6) relates in particular to parameters providing information on Issue (1) for each particular geothermal system, especially parameters that can help delineate boundary conditions and recharge, as well as the actual size of a system.

Finally, injection research and modelling are of great significance, since the cooling effect of injected fluids may be expected to be very far-reaching during 100–300 years of operation. Therefore, alternative injection zones have to be pre-selected and back-up injection strategies set up, to minimize the adverse effects of injection.

6. Sustainability modelling

Modelling studies, which are performed on the basis of available data on the structure and production response of geothermal systems, are the most powerful tools for estimating the sustainable potential. They can also be used to determine the most appropriate mode of utilization in the future and to evaluate the effect of different utilization methods, such as injection, as well as for assessing the possible interference between nearby systems during long-term utilization.

Either complex numerical models or simpler models, such as lumped parameter models, can be used for such modelling studies (Axelsson et al., 2005). The former models can be much more accurate because they can simulate both 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 one of the main controlling factors for the short- and long-term responses of geothermal systems. The basis of reliable modelling studies is accurate and extensive data, including data on the geological structure of a system, their physical state and, not least, their 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 at least a few years. Ideally, available data should extend over several decades, if reliable model predictions are to extend for a comparable period into the future.

The sustainable potential of geothermal systems which have not been harnessed can only be assessed very approximately. This is because, in such situations, the response data mentioned above is not available. It is, however, possible to base an approximate assessment on available conceptual ideas regarding the size of a geothermal system and its fluid state (pressure, temperature, gas content, and salinity), as well as knowledge of the characteristics of comparable systems.

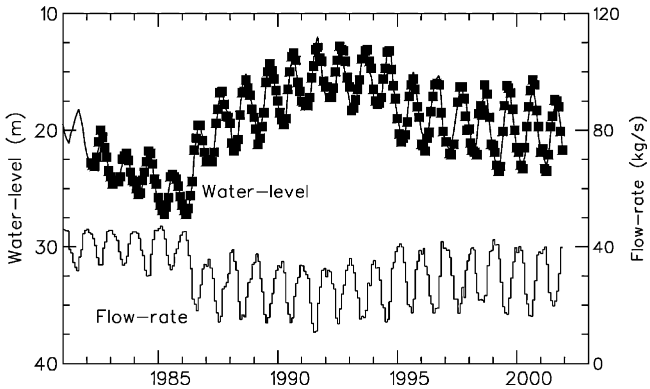

Fig. 6. Production history of the Hamar geothermal system. The water-level history was simulated by a lumped-parameter model (squares = measured data, line = simulated data).
From Axelsson et al. (2005).

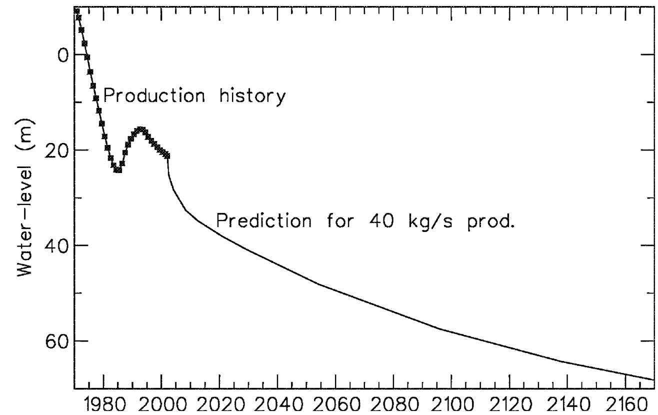

Fig. 7. Predicted water-level (pressure) changes in the Hamar geothermal system for a 200-year production history (the figure shows annual average values).
From Axelsson et al. (2005).

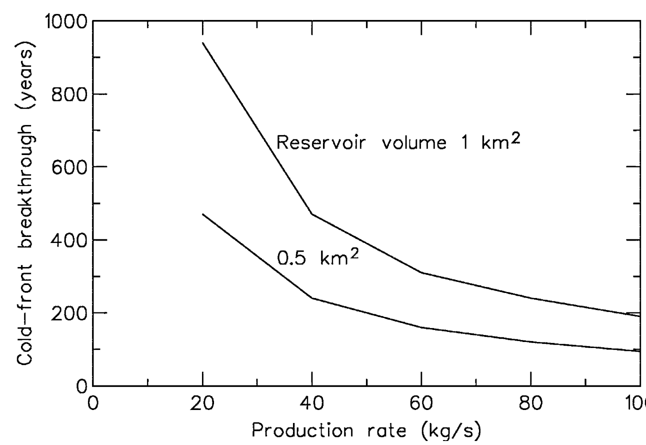

Fig. 8. Estimated cold-front breakthrough times for the Hamar geothermal system based on the model of Bodvarsson (1972).
From Axelsson et al. (2005).

Rybach et al. (2000) and Ungemach et al. (2005) performed sustainability modelling studies for ground source heat pump applications and the doublet operations in the Paris Basin, respectively. Sustainability of the Wairakei geothermal system was investigated by O'Sullivan and Mannington (2005). Axelsson et al. (2005) present the results of modelling studies for three 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 geothermal system in Svarfadardalur in north Iceland, which is used for space heating and other direct uses in the town of Dalvík and in the surrounding region; the Beijing Urban geothermal system below the city of Beijing in China, which is used for direct energy in the city; and finally, the Nesjavellir geothermal system in the Hengill volcanic region, east of Reykjavík in southwest Iceland, which is used for both electricity generation and direct heat. The two former systems are low-temperature systems while the Nesjavellir system is a high-temperature system. The results for these three systems are summarized briefly below, but Axelsson et al. (2005) provide more detail. In addition, we also present preliminary results of lumped parameter modelling studies for the Olkaria systems.

6.1. The Hamar geothermal system, N-Iceland

The Hamar geothermal system has been used since 1969, and during the last few years 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, was used for the Hamar modelling study (see Figs. 6–8). The results of the calculations show the sustainable production potential of the system is probably a little bit more than the present production, i.e. about 40 l/s average production (see water-level predictions until the year 2170 in Fig. 7). It appears, however, 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, as can be seen from Fig. 8.

6.2. Geothermal resources under Beijing, PR of China

The Beijing Urban geothermal system is embedded in permeable sedimentary layers (carbonate rocks) at 1–4 km depth below Beijing and has been used since 1970s (Liu et al., 2002). The average yearly production from the system has been a little over 100 l/s of 40–90 °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 (see Figs. 9 and 10) 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 demonstrate the sustainable potential of the system is less than 100 l/s average yearly production. However, this depends on how much water-level drawdown will be acceptable in 100–200 years. Through a revision of the mode of utilization, which would involve injection of a large proportion of

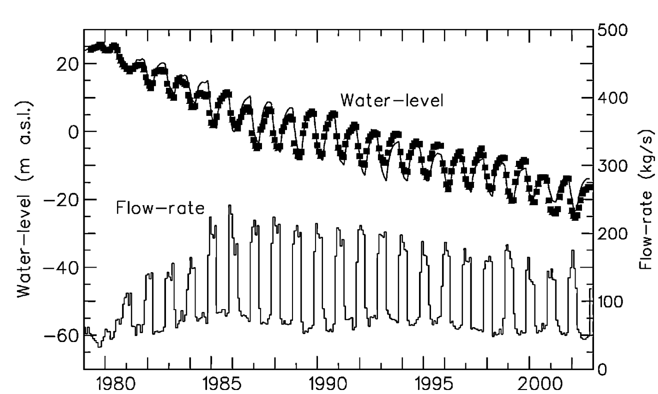

Fig. 9. The production history of the Urban geothermal field in Beijing with the water-level history simulated by a lumped-parameter model (squares = measured data, line = simulated data).
From Axelsson et al. (2005).

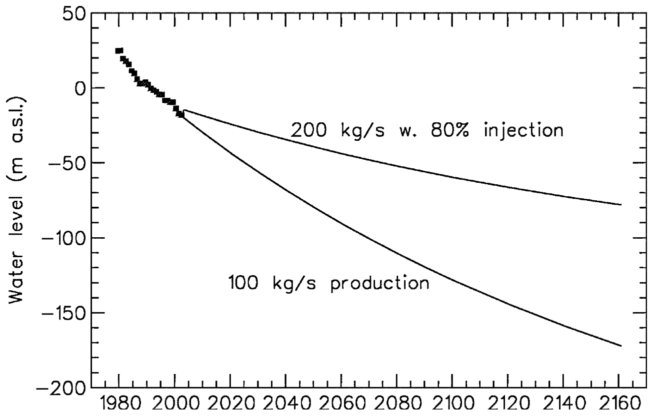

Fig. 10. Predicted water-level (pressure) changes in the Urban geothermal field in Beijing for a 200-year production history (the figure shows annual average values). From Axelsson et al. (2005).

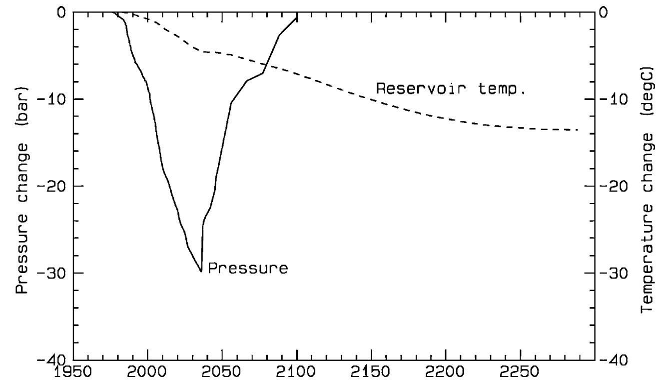

Fig. 12. Calculated changes in reservoir pressure and temperature in the central part of the Nesjavellir geothermal reservoir during the 30-year period of intense production (Fig. 11), and for the following 250 years of recovery (production stopped in 2036). Predicted temperature changes are not well constrained because no cooling has been observed as of 2010.
Based on Björnsson and Hjartarson (2003).

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 injection/production system is managed efficiently, as e.g. in the Paris Basin.

6.3. The Nesjavellir high-enthalpy systems, SW-Iceland

Nesjavellir is one of the 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 electrical power and 300 MW 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 and Hjartarson, 2003; 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 100–300 years (Fig. 11). The model calculations indicate, however, the effects of the present intense production should mostly be reversible. Fig. 12 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 mode (3) or mode (4), as described above (see Fig. 13).

6.4. The Olkaria high-enthalpy system, Kenya

The Greater Olkaria geothermal area is located in the Kenya Rift within the East African Rift System. It is divided into seven fields or subareas. One of these is the Olkaria East (Olkaria-I) field, which has been used since 1981. At present, the installed capacity at Olkaria East is 45 MW_e and according to Ofwona (2008) the Olkaria East reservoir has performed well up to now.

A numerical reservoir model for the Greater Olkaria area is presently being updated. This model may be used for sustainability modelling, along the lines discussed above. This has not been done yet, but instead the preliminary results of a simple lumped parameter modelling study are presented here. The pressure change data presented above (Fig. 2) were simulated and predictions calculated for 200 years using two production scenarios: first, 300 kg/s constant production, and second periodic 350 kg/s production for 50 years followed by equally long total breaks in production. The current production is of the order of 200 kg/s. The results are presented

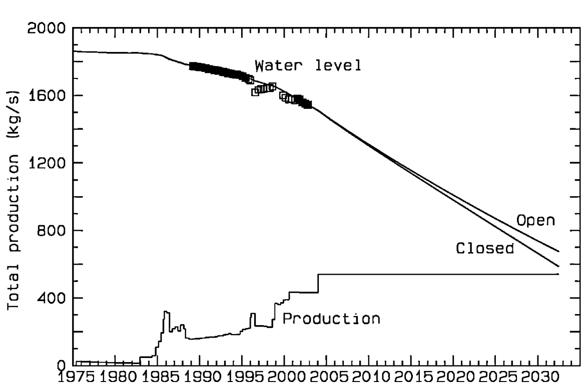

Fig. 11. Pressure decline data (measured as water level) from an observation well (NJ-15) at Nesjavellir simulated by a lumped parameter model and pressure decline predictions, calculated using an open (optimistic) and a closed (pessimistic) model, for a 120 MW_e future production scenario. Also shown is the total mass extraction from the field (no injection into main reservoir).
From Axelsson et al. (2005).

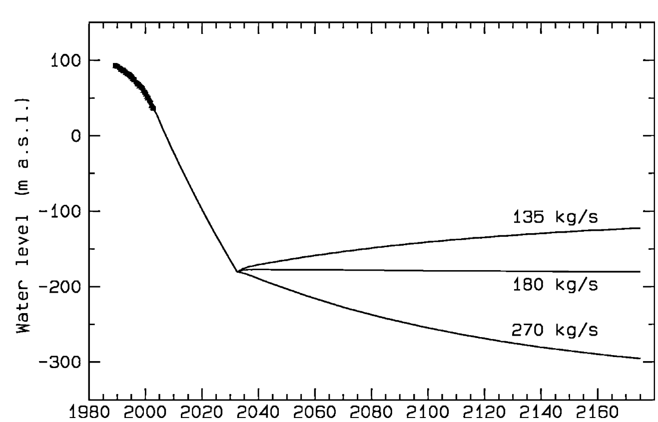

Fig. 13. Predicted pressure changes (presented as water level changes) in the Nesjavellir systems during a 200-year production history with intense/excessive production (540 kg/s) up to 2036.
From Axelsson et al. (2006).

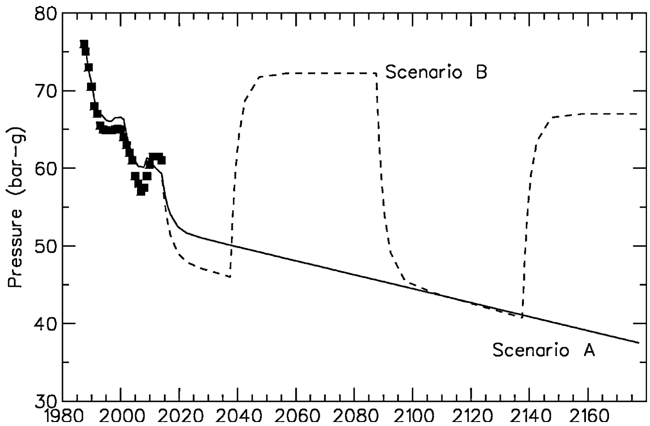

Fig. 14. Average reservoir pressure at 650 m a.s.l. in the Olkaria-I reservoir (filled squares), simulated by a lumped parameter model, along with predictions for two future production scenarios (see text).

in Fig. 14, which indicates both these production scenarios should be sustainable.

In the case of the Greater Olkaria area, possible interference between adjacent production fields needs to be kept in mind. However, this can likely be minimized by well-planned injection.

7. Concluding remarks

This paper has discussed several issues relevant to sustainable geothermal utilization. It illustrates geothermal systems, in particular natural hydrothermal systems, can be used in a sustainable manner according to a definition that considers a time scale of 100–300 years. Case histories, from a selection of geothermal systems worldwide that have been used for 25–80 years, provide important data on which to perform system-specific sustainability studies and research aimed at better understanding the renewability of geothermal resources. Such studies should involve appropriate modelling and long-term future predictions. They would be of great value to the geothermal industry where long-term sustainability and renewability are receiving ever increasing attention.

We propose four possible sustainable utilization modes. These need to be studied through modelling for specific geothermal systems, both from the reservoir management standpoint and economics point of view, to weigh the different utilization options. Reservoir modelling will also serve as a vital tool in studying the various research issues discussed in the paper. We present four distinct sustainability modelling studies as examples: two of them for high-temperature volcanic systems, one for a low-temperature convective system in Iceland and one for a low-temperature sedimentary system in China. The studies consider how these systems may be used in a sustainable manner and how the sustainable production potential of a geothermal system can be controlled either by energy content or pressure decline due to limited recharge. In the latter case, properly managed injection could increase the sustainable production potential considerably. Thermal modelling is usually not as well constrained as fluid-flow and pressure modelling, however, because of lack of actual temperature-decline data.

Finally, work on sustainability issues is continuing in different parts of the world, as exemplified by this special issue of *Geothermics*. Work aimed at understanding the nature of the geothermal systems and their long-term response to utilization continues in Iceland, and work in progress is intended to find ways to introduce sustainability logically into the legislation and regulatory framework of the country (Ketilsson et al., 2010). Considerable work is also in progress under the auspices of the geothermal Implementing Agreement of the International Energy Agency (see Axelsson et al., 2010b for details).

Acknowledgements

The author would first like to acknowledge the late Dr. Valgardur Stefánsson who was a pioneer in studying the possible sustainable utilization of geothermal resources, and who stimulated many of the ideas, and much of the research, presented here. The author would also like to thank the relevant geothermal utilities and power companies for allowing publication of the case-history data presented here. Mr. Cornel Ofwona at KenGen in Kenya is, in particular, acknowledged for providing the data for the Olkaria field. Finally, Chris Bromley, Mike Mongillo, and John Garnish are acknowledged for thorough reviews of the paper and helpful comments.

References

Aquí, A.R., Aragones, J.S., Amistoso, A.E., 2005. Optimization of Palinpinon-1 production field based on energy analysis – the Southern Negros geothermal field, Philippines. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 7 pp.

Axelsson, G., 2008a. Production capacity of geothermal systems. In: Proceedings of the Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia, Tianjin, China, 14 pp.

Axelsson, G., 2008b. Importance of geothermal reinjection. In: Proceedings of the Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia, Tianjin, China, 16 pp.

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

Axelsson, G., Stefánsson, V., Xu, Y., 2002. Sustainable management of geothermal resources. In: Proceedings of the International Symposium on Geothermal and the 2008 Olympics in Beijing, Beijing, pp. 277–283.

Axelsson, G., Stefánsson, V., 2003. Sustainable management of geothermal resources. In: Proceedings of the International Geothermal Conference 2003, Reykjavík, Iceland, pp. 40–48.

Axelsson, G., Stefánsson, V., Björnsson, G., Liu, J., 2005. Sustainable utilization of geothermal resources for 100–300 years. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 8 pp.

Axelsson, G., Björnsson, S., Stefánsson, V., 2006. How can geothermal resources be utilized in a sustainable manner, and how to estimate their sustainable potential? In: Proceedings of the Energy Conference 2006, Reykjavík, Iceland, 11 pp. (in Icelandic).

Axelsson, G., Jónasson, Th., Ólafsson, M., Ragnarsson, Á., 2010a. Successful utilization of low-temperature geothermal resources in Iceland for district heating for 80 years. In: Proceedings of the World Geothermal Congress 2010, Nusa Dua, Bali, Indonesia, 8 pp.

Axelsson, G., Bromley, C., Mongillo, M., Rybach, L., 2010b. The sustainability task of the international energy agency's geothermal implementing agreement. In: Proceedings of the World Geothermal Congress 2010, Nusa Dua, Bali, Indonesia, 8 pp.

Barker, B.J., 2000. The Geysers: past and future. Geothermal Resources Council Bulletin 29, 163–171.

Barker, B.J., Atkinson, P.G., Powell, T.S., 1990. Development and production performance of the Tiwi field. In: Proceedings of the 15th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA, pp. 245–251.

Björnsson, G., Hjartarson, A., 2003. Reservoir model for the Hengill geothermal systems and future predictions for 120 MW electrical production at Nesjavellir and Hellisheidi (in Icelandic). Iceland GeoSurvey, Report ÍSOR-2003/009, Reykjavík, Iceland, 150 pp.

Björnsson, G., Thordarson, S., Steingrímsson, B., 2000. Temperature distribution and conceptual reservoir model for geothermal fields in and around the city of Reykjavík, Iceland. In: Proceedings of the 25th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA, 7 pp.

Björnsson, G., Hjartarson, A., Bodvarsson, G.S., Steingrímsson, B., 2003. Development of a 3-D geothermal reservoir model for the greater Hengill volcano in SW-Iceland. In: Proceedings of the TOUGH Symposium 2003, Berkeley, CA, USA, 12 pp.

Bodvarsson, G., 1972. Thermal problems in the siting of reinjection wells. Geothermics 1, 63–66.

Bromley, C.J., Mongillo, M., Rybach, L., 2006. Sustainable utilization strategies and promotion of beneficial environmental effects – having your cake and eating it too. In: Proceedings of the 28th New Zealand Geothermal Workshop, Auckland, New Zealand, 5 pp.

Capetti, G., Parisi, L., Ridolfi, A., Stefani, G., 1995. Fifteen years of reinjection in the Larderello-Valle Secolo area: analysis of the production data. In: Proceedings of the World Geothermal Congress 1995, Florence, Italy, pp. 1997–2000.

Cataldi, R., 2001. Sustainability and renewability of geothermal energy. In: Proceedings of the International Scientific Conference on Geothermal Energy in Underground Mines, Ustron, Poland, 4 pp.

Fridleifsson, G.Ó., Elders, W.A., Thórhallsson, S., Albertsson, A., 2005. The Iceland deep drilling project – a search for unconventional (supercritical) geothermal resources. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 8 pp.

Fridleifsson, I.B., Bertani, R., Huenges, E., Lund, J.W., Ragnarsson, Á., Rybach, L., 2008. The possible role and contribution of geothermal energy to the mitigation of climate change. In: Hohmeyer, O., Trittin, T. (Eds.), Proceedings of the IPCC Scoping Meeting on Renewable Energy Sources. Luebeck, Germany, pp. 59–80.

Hanano, M., 2003. Sustainable steam production in the Matsukawa geothermal field, Japan. Geothermics 32, 311–324.

International Energy Agency, 2008. Geothermal Implementing Agreement (IEA-GIA), 2007 IEA-GIA Annual Report (available at: http://www.iea-gia.org/publications.asp), 238 pp.

Ketilsson, J., Axelsson, G., Björnsson, A., Björnsson, G., Pálsson, B., Sveinbjörnsdóttir, Á.E., Saemundsson, K., 2010. Introducing the concept of sustainable geothermal utilization in Icelandic legislation. In: Proceedings of the World Geothermal Congress, Nusa Dua, Bali, Indonesia, 7 pp.

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

Lopez, S., 2008. Forty years of Dogger aquifer management in Ile-de-France, Paris Basin, France. In: Draft Paper Presented at the International Geothermal Sustainability Modelling Workshop, Taupo, New Zealand, 16 pp.

Lovekin, J., 2000. The economics of sustainable geothermal development. In: Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan, pp. 834–848.

Monterrosa, M., Montalvo, F., 2006. Geothermal reservoir management in El Salvador – Case histories of Ahuachapán and Berlín. In: Proceedings of the Workshop for Decision Makers on Geothermal Projects in Central America, San Salvador, El Salvador, 15 pp.

O'Sullivan, M., Mannington, W., 2005. Renewability of the Wairakei-Tauhara geothermal resource. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 8 pp.

Ofwona, C., 2008. Olkaria I reservoir after 26 years of production. In: Proceedings of the UNU Geothermal Training Programme's 30th Anniversary Workshop, Reykjavík, Iceland, 8 pp.

Pritchett, J.W., 1998. Modeling post-abandonment electrical capacity recovery for a two-phase geothermal reservoir. Geothermal Resources Council Transactions 22, 521–528.

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

Rybach, L., Megel, T., Eugster, W.J., 2000. At what scale are geothermal resources renewable? In: Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan, pp. 867–872.

Sanyal, S.K., 2005. Sustainability and renewability of geothermal power capacity. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 13 pp.

Stefánsson, V., 2000. The renewability of geothermal energy. In: Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan, pp. 883–888.

Stefánsson, V., 2005. World geothermal assessment. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 5 pp.

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

Ungemach, P., Antics, M., Papachristou, M., 2005. Sustainable geothermal reservoir management. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey.

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

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