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Modelling Sustainable Geothermal Energy Utilization

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Abstract

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their needs. The Earth's enormous geothermal resources have the potential to contribute significantly to sustainable energy use worldwide and to help mitigate climate change. Experience from the use of geothermal systems world-wide, lasting several decades, demonstrates that by maintaining production below a certain limit the systems reach a balance between net energy discharge and recharge that may be maintained for a long time. Therefore, a sustainability time-scale of 100 to 300 years has been proposed. Modelling studies furthermore indicate that the effect of heavy utilization is often reversible on a time-scale comparable to the period of utilization. The long production histories that are available for geothermal systems worldwide provide the most valuable data available for studying sustainable management of geothermal resources, and reservoir modelling is the most powerful tool available for this purpose. Long utilization experiences from e.g. Iceland, New Zealand, El Salvador, Kenya and China are reviewed and sustainability modelling studies for a few geothermal systems in these countries presented.

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 enormous when compared to its use today and to the future energy needs of mankind and even though geothermal energy utilization has been growing rapidly in recent years it is still miniscule compared with the Earth's potential. There is, therefore, ample space for accelerated use of geothermal resources worldwide in the near future.

Sustainable development has been receiving ever increasing attention and emphasis world-wide and it's become clear that some kind of sustainable development is essential for the future of mankind, both because of the Earth's limited resources and for environmental reasons. The Earth's geothermal resources have in fact the potential to contribute significantly to sustainable energy use worldwide and to help mitigate climate change. Two main issues are of principal significance when sustainable geothermal utilization is being considered; (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. The first issue can only be addressed on the basis of comprehensive knowledge on the geothermal system in question; both on its inherent nature and on its production capacity. Modelling plays a key role in assimilating that knowledge.

The energy production potential of geothermal systems, in particular hydrothermal systems, is predominantly determined by pressure decline due to production (Axelsson, 2008). This is because there are technical limits to how great a pressure decline in a well can be for it to remain productive. The production potential is also determined by the available energy content of the system, i.e. by temperature or enthalpy and size. The pressure decline is determined by the rate of production, on one hand, and the nature and characteristics (size, permeability, boundary conditions, etc.) of the geothermal system, on the other hand. Natural geothermal reservoirs can most often be classified as either ***open*** or ***closed***, with drastically different long-term behaviour, depending on their boundary conditions.

Pressure declines continuously with time, at constant production, in closed systems or ones with small recharge (relative to the production). In such systems the production potential is limited by lack of water rather than lack of thermal energy. Pressure stabilizes in contrast in open systems because recharge eventually equilibrates with the mass extraction. The recharge may be both hot deep recharge and colder shallow recharge. The latter will eventually cause reservoir temperature to decline and production wells to cool down. In such systems the production potential is limited by the reservoir energy content (temperature and size) as the energy stored in the reservoir rocks will heat up the colder recharge as long as it is available/accessible. The situation is somewhat different for EGS-systems and sedimentary systems utilized through production-reinjection doublets and heat-exchangers with 100% reinjection. Then the production potential is predominantly controlled by the energy content of the systems involved. But permeability, and therefore pressure variations, are also of controlling significant in such situations.

Experience from the use of geothermal systems worldwide, lasting several decades (long utilization histories), 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. Various modelling methods, applicable to geothermal systems, are the principal tools available to study the possible sustainable utilization of geothermal resources and modelling studies have, in fact, extended the case histories to 1 or 2 centuries. Such modelling studies are the subject matter of this paper.

Sustainable geothermal utilization has been discussed to some degree in recent years, often without a clear vision of what the term "sustainable" entails. A general and logical definition has been missing. 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, with Axelsson (2010) providing information on several relevant references. The reader is, furthermore, referred to a recent special issue of the international journal *Geothermics* (Mongillo and Axelsson, 2010). The following chapter is devoted to a review of several aspects of the issue of sustainable geothermal energy utilization.

2. Sustainable Geothermal Utilization

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

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

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

Two main issues are of principal significance when geothermal sustainability is being discussed and evaluated. These are (1) the question whether geothermal resources can be used in some kind of sustainable manner at all and (2) the issue of defining an appropriate time-scale. Long utilization histories, such as those discussed later, 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. Modelling studies have, consequently, extended the periods to 1 or 2 centuries, as already mentioned.

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. Fig. 1, presented by the working group, is intended to capture the essence of its definition of sustainable production, for the time scale proposed by the group, i.e. if production is below a certain level (E_0) it can be maintained while production above the limit can't be maintained and has to be reduced before the period chosen has ended.

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.

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

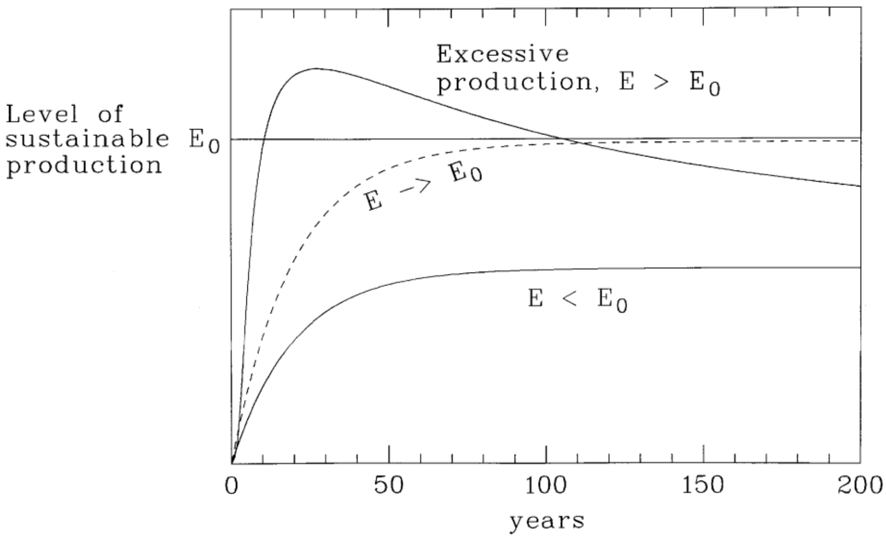

Figure 1. *A schematic graph showing the essence of the definition of sustainable production presented by Axelsson* et al. *(2001). Production below the sustainable limit* $\mathbf{E_0}$ *can be maintained for the whole period being assessed, while greater production can't be maintained.*

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

When appraising the more general sustainable geothermal utilization an evaluation shouldn't necessarily focus on a single geothermal system. Either the combined overall production from several systems controlled by a single power company can be considered or several systems in a certain geographical region, even whole countries. Therefore, individual geothermal systems can e.g. be used in a cyclic manner, through which one system is rested while another is produced at a rate considerably greater than 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.

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

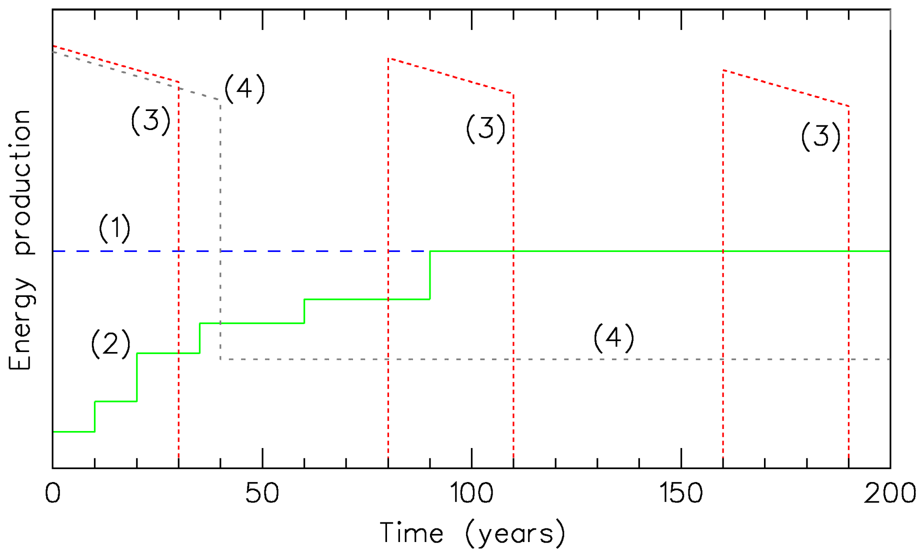

Figure 2. *Different production modes for geothermal systems which can be incorporated into sustainable geothermal utilization scheme (based on Axelsson, 2010).*

3. Sustainability Modelling

3.1 The Basis – 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. Axelsson (2010) lists a number of well-known examples of systems that have been in use for 30 or more years. 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).

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

One of the best examples of long-term utilization is the low-temperature Laugarnes geothermal systems in Reykjavík, Iceland, where a semi-equilibrium has been maintained the last four decades indicating that the inflow, or recharge, to the systems is now about tenfold (assuming the artesian flow to approximately equal the recharge) what it was before production started. In other cases geothermal production has been excessive and it has not been possible to maintain it in the long-term. The utilization of the vapour-dominated Geysers geothermal system in California is a well-known example of excessive production. For a few years, the installed electric generation potential corresponded to more than 2000

MW_e, which has since been reduced by more than half because of pressure decline in the system due to insufficient fluid recharge (Goyal and Conant, 2010).

Another low-temperature long-term utilization example is worth mentioning, or the sedimentary geothermal resources in the Paris Basin. Sedimentary geothermal resources are, quite different from volcanic or convective tectonic systems because of how extensive in area they are. 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 and following the two oil crises more than fifty geothermal plants had been constructed in the Paris Basin. Some of the doublets have been abandoned, mostly due to economic reasons, at least temporarily. Today some doublets are being revitalized and new ones are being drilled. The production and reinjection wells of the Paris doublets are usually separated by a distance of about 1,000 m to minimise the danger of cooling due to the reinjection. Experience, lasting 3 – 4 decades, has shown that no significant cooling has yet taken place in any of the Paris production wells. This is in spite of various modelling studies, which have indicated that the doublets should start to cool down after 2 decades or so (Lopez *et al.*, 2010).

Axelsson (2010), furthermore, lists several high-temperature, volcanic type geothermal systems with long utilization case histories that should provide important data to base sustainability modelling on. These include:

- Ahuachapan, El Salvador, used since 1976
- Cerro Prieto, Mexico, used since 1973
- Larderello, Italy, used since the 1950s
- Krafla, Iceland, used since 1976
- Svartsengi, Iceland, used since 1976
- Olkaria, Kenya, used since 1981
- Matsukawa, Japan, used since 1966
- Palinpinion, Philippines, used since 1983
- Tiwi, Philippines, used since 1979
- Wairakei, New Zealand, used since 1958

3.2 Long-term 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. 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 (Axelsson *et al.*, 2005). 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, 2008).

Axelsson (2010) presents 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. Two of these are the Hamar geothermal system in Svarfadar-dalur in north Iceland, which is used for space heating and other direct uses in the town of Dalvík and in the surrounding region, and the Beijing Urban geothermal system below the city of Beijing in China, which is used for heating and other direct uses in the city.

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, were used for the Hamar modelling study (see figures 3 to 5). 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. 4). It appears, however, 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, as can be seen from Fig. 5.

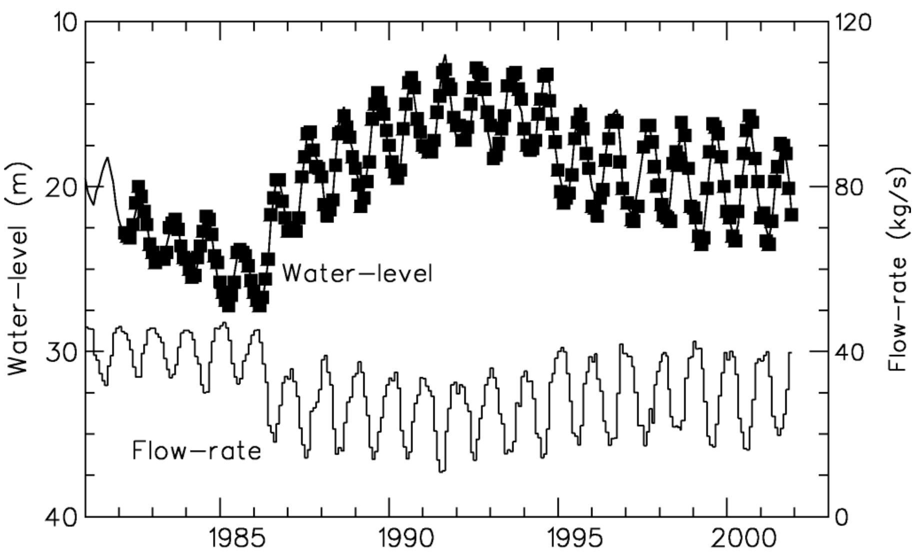

Figure 3. *Production history of the Hamar geothermal system in N-Iceland. The water-level history was simulated by a lumped-parameter model (squares = measured data, line = simulated data). From Axelsson (2010).*

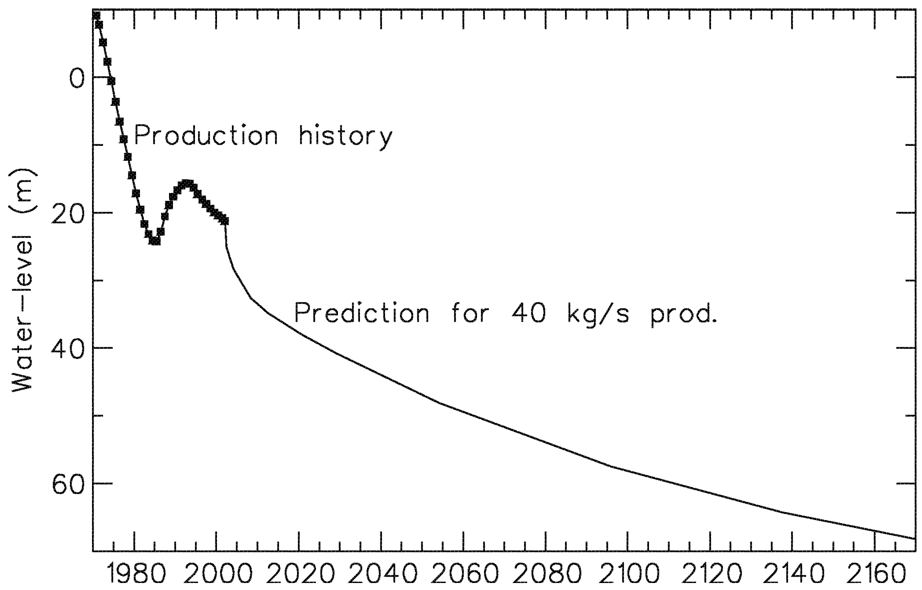

Figure 4. *Predicted water-level changes in the Hamar geothermal system for a 200-year production history (figure shows annual average values). From Axelsson (2010).*

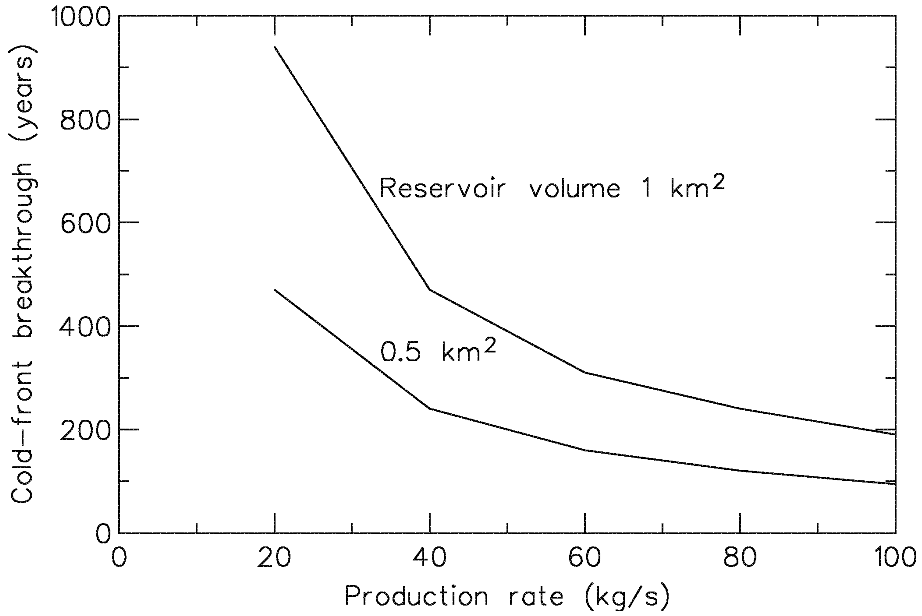

Figure 5. *Estimated cold-front breakthrough times for the Hamar geothermal system based on the model of Bödvarsson (1972). From Axelsson (2010).*

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 the 1970s (Liu *et al.*, 2002). The average yearly production from the system has been a little over 100 l/s of 40 to 90 °C water (mainly used during the four coldest months of the year). The response of the geothermal system to this production and predictions by a lumped parameter model (see figures 6 and 7) show the production potential of the Beijing Urban system is constrained by limited water recharge to the system, but not energy content.

The model calculations for the Beijing Urban system demonstrate the sustainable potential of the system is less than 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, as in the Paris Basin.

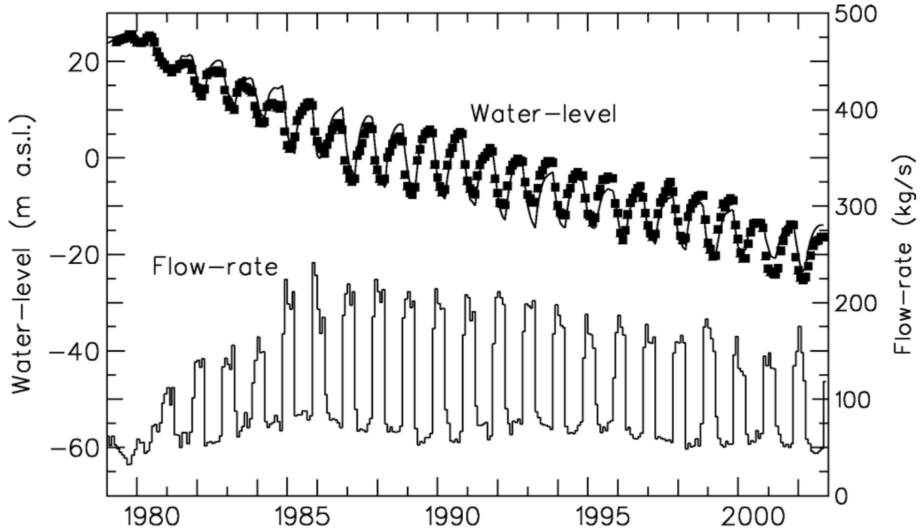

Figure 6. *The production history of the Urban geothermal field in Beijing with the water-level history simulated by a lumped-parameter model (squares = measured data, line = simulated data). From Axelsson (2010).*

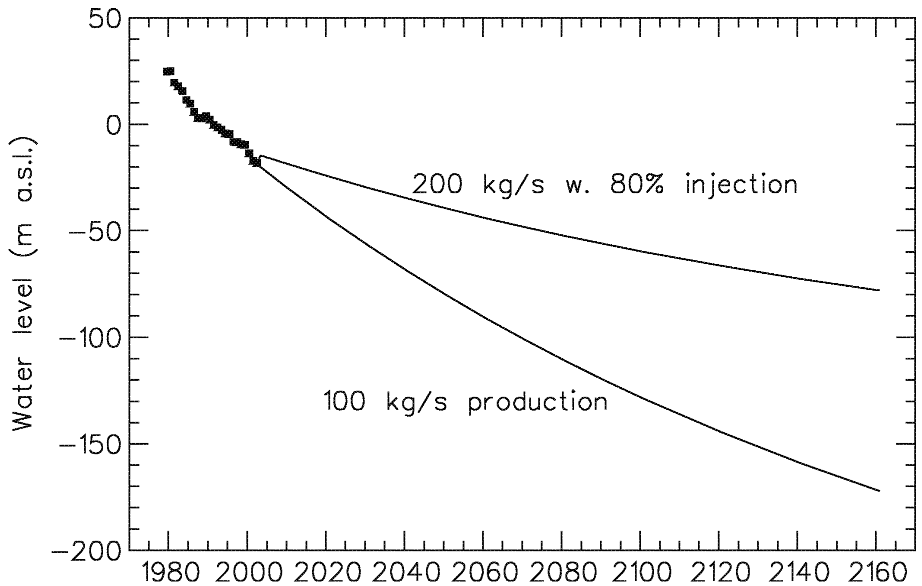

Figure 7. *Predicted water-level changes in the Urban geothermal field in Beijing for a 200-year production history (figure shows annual average values). From Axelsson (2010).*

Nesjavellir is one of the high-temperature geothermal areas in the Hengill volcanic region in southwest Iceland. It has been in use since 1990, at first for direct heating and later for cogeneration of electricity and heat. Today, the generating capacity of the Nesjavellir power plant is 120 MW_e electrical power and 300 MW_{th} thermal power. A 3D numerical simulation model, as well as a lumped parameter model, have been set up for the Nesjavellir system.

The present numerical model is actually a part of a much larger and more complex numerical model of the whole Hengill-region and surroundings (Björnsson *et al.*, 2003). The results of calculations by these models have demonstrated the present rate of utilization is not sustainable; that is, the present production cannot be maintained for the next 100 to 300 years (Fig. 8). The model calculations indicate, however, the effects of the present intense production should mostly be reversible. Figure 9 shows the reservoir pressure should recover over approximately the same time scale as the period of intense production. The thermal cooling effects, which are rather limited in amplitude and not as well determined (poorly constrained in the model because no cooling has been observed yet) as the pressure effects, appear to last much longer according to the numerical model. Therefore, it should be possible to utilize the Nesjavellir system, in the long term, according to production modes (3) or (4), described above (Fig. 2).

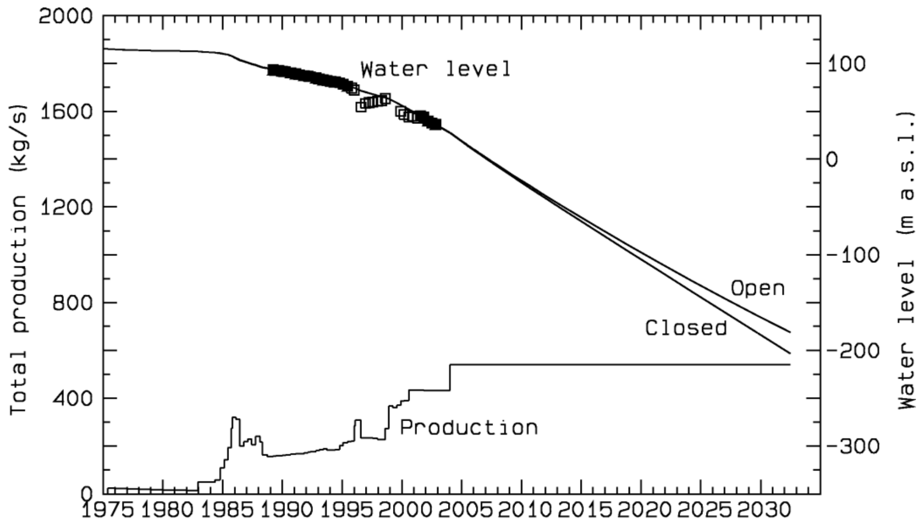

Figure 8. *Pressure decline data (measured as water level) from an observation well at Nesjavellir simulated by a lumped parameter model and pressure decline predictions, calculated using an open (optimistic) and a closed (pessimistic) model, for a 120 MWe future production scenario (Axelsson, 2010). The total mass extraction from the field is also shown (no injection into main reservoir).*

Another two modelling studies, which are in fact sustainability modelling studies, have been carried out for the Ahuachapan high-temperature geothermal system in El Salvador and the Wairakei high-temperature geothermal system in New Zealand. The main results of these two studies are reviewed below. Both systems constitute examples of systems having quite long and well documented production and response histories. The Ahuachapan study focussed on the long term management of the geothermal system, based on monitoring data collected since its utilization started in 1976 (Monterrosa and Montalvo, 2010). Figure 10 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 future modification of power plant conditions, such as some lowering of turbine inlet pressure, however (Monterrosa and Montalvo, 2010).

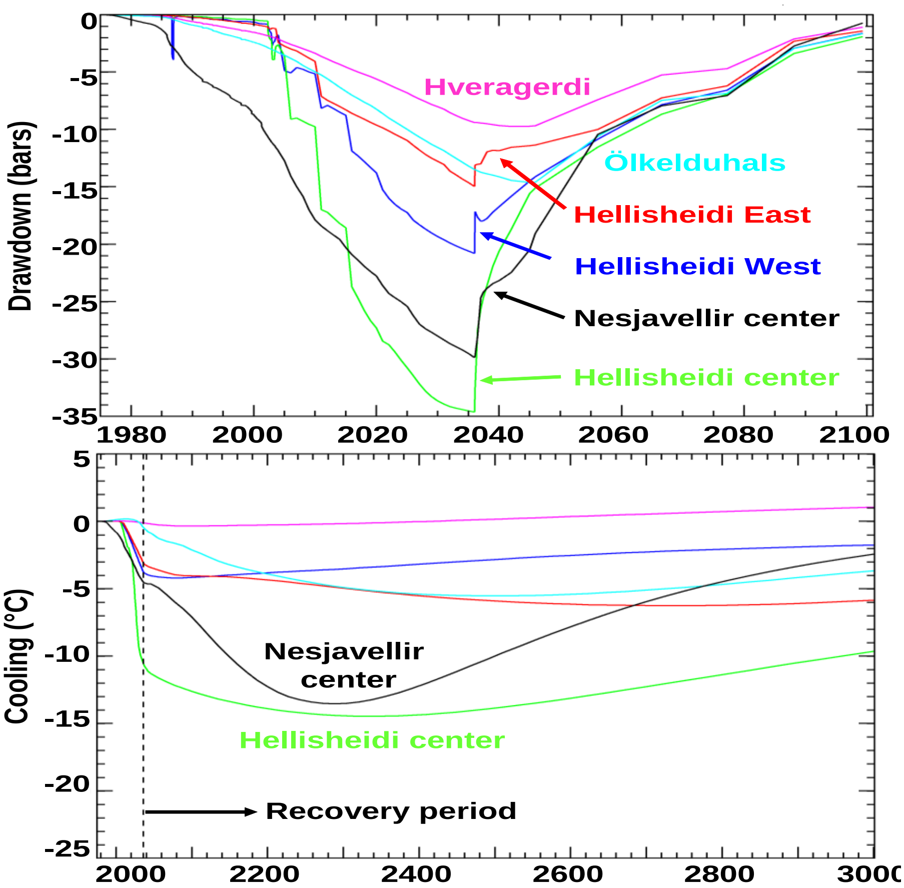

Figure 9: *Calculated changes in reservoir pressure and temperature in different parts of the Hengill area, including the central part of the Nesjavellir geothermal reservoir, during a 30-year period of intense production, and for the following recovery (production stopped in 2036). Predicted temperature changes are not well constrained because no cooling has been observed as of 2010. Figure from Axelsson* et al. *(2010b); see also Björnsson* et al. *(2003).*

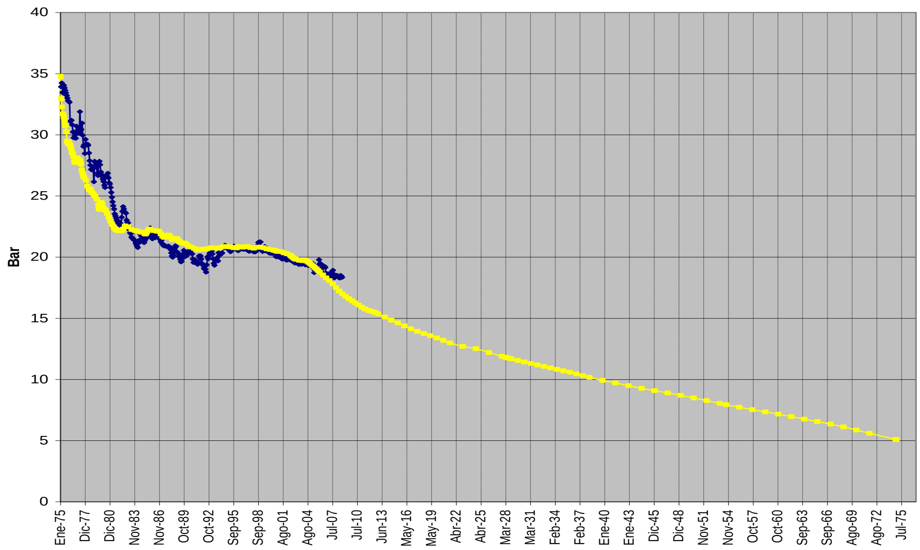

Figure 10: *Predicted pressure changes in the Ahuachapan geothermal system in El Salvador up to 2075, for a future scenario of 95 MWe constant production. Figure from Axelsson* et al. *(2010b); see also Monterrosa and Montalvo (2010).*

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; see also O'Sullivan and Mannington, 2005). An example of the results of the study is shown in Fig. 11, which shows on one hand the pressure response of the system and on the other its temperature evolution. As in the case of Nesjavellir presented above, the pressure recovers very rapidly while temperature conditions evolve much more slowly.

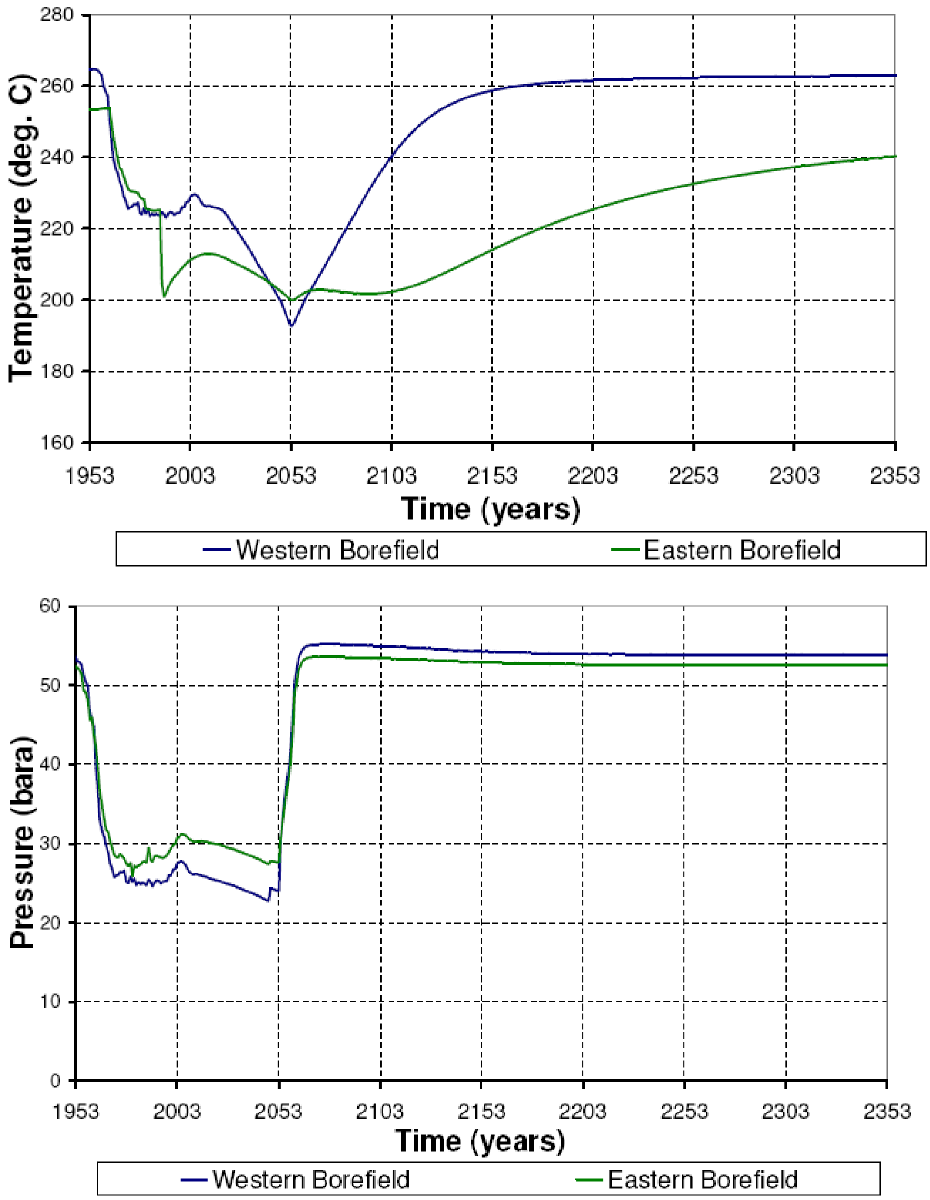

Figure 11: *Predicted pressure and temperature recovery in the Wairakei geothermal system in New Zealand following 100 years of production. Figure from Axelsson* et al. *(2010b); see also O'Sullivan and Mannington (2005) and O'Sullivan* et al. *(2010).*

Finally it may be mentioned that Rybach *et al.* (2000) and Ungemach *et al.* (2005) have performed sustainability modelling studies for ground source heat pump applications and the doublet operations in the Paris Basin, respectively. Reviewing those studies is beyond the scope of this paper. Axelsson (2010) also presents the results of a simple sustainability modelling study for the Olkaria-I sector of the Olkaria high-temperature, volcanic geothermal system in Kenya.

4. Conclusions

It is argued that geothermal resources can be utilized in a sustainable manner if a time-scale of the order of 100 – 300 years is assumed. This paper has discussed the issue of sustainability modelling and presented several examples of such work, focussing on this long time-scale. The modelling examples either focus on long-term predictions or the recovery of geothermal systems following periods of heavy utilization. The sustainable energy production potential of a geothermal resource is either controlled by the reservoir pressure decline caused by production or by the energy content of the system in question, both depending on the nature of the resource in question. Case histories of numerous geothermal systems world-wide, which have been utilized for several decades, provide the most important data for sustainability and renewability research, including sustainability modelling.

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. A specific task of the GIA has in recent years focussed on collecting information, identifying research needs, facilitating international collaboration on the issue through workshops and meetings, as well as facilitating the publication of scientific papers and reports on geothermal sustainability studies and research (Axelsson *et al*., 2010b).

Several research issues, which have been identified through the IEA-GIA sustainability work, need to be studied in conjunction with sustainability research and modelling. Some of these are listed below (from Axelsson, 2010; see also Rybach and Mongillo, 2006):

(1) What factors are most significant in controlling long-term reservoir behaviour and capacity? These include: size, permeability, boundary conditions, natural recharge, reinjection, etc.
(2) How significant and far-reaching are long-term production pressure drawdown and reinjection cooling effects? In particular, how significant is interference between adjacent geothermal areas?
(3) Which are the optimum strategies for the different modes of production presented above, such as continuous and periodic production and reinjection scenarios in different cases?
(4) How rapidly and effectively do geothermal systems recover during breaks after periods of excessive production?
(5) What is the reliability of long-term (~100 years) predictions of reservoir production response using various methods (stored heat, simple analytical models, complex 3D models, etc.)?
(6) What information should be collected at pre-exploitation and early development stages to significantly reduce uncertainties in long-term resource sustainability assessments?

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