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Sustainable Management of Geothermal Production

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ABSTRACT

Geothermal resources are of a double nature, a combination of an energy current (through heat convection and conduction) and of stored energy. 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. Production from geothermal resources is, therefore, not a mining process. Unlike in ore mining or hydrocarbon extraction, the heat/fluid removed from the resources is continuously replaced at the site of production. Experience from the use of geothermal systems worldwide, lasting several decades (in some cases half a century or more), demonstrates that the systems often appear to attain a sort of semi-equilibrium in physical conditions during long-term production. In some cases, this equilibrium is found by gradually increasing production rate and in other cases equilibrium is found after a limited period of higher extraction rates. In yet other cases, physical changes in geothermal systems are so slow that their output is not affected for decades. 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 geothermal management basically involves setting up and maintaining a specific long-term production scheme. The most practical 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 (like moderate circulation flow-rates in EGS or variable production to follow load coming from wind and solar utilization). Distinction needs to be made between sustainable production from a particular geothermal resource and the more general sustainable geothermal utilization, which involves integrated resource, economic, social and environmental development. Yet, the key element of sustainable geothermal utilization is sustainable production from a given resource. A sustainability policy (protocol) should be based on general sustainability goals and include 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 groundwater in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available worldwide 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 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 (Fridleifsson et al., 2008).

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 two decades, 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 (2016). 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; Rybach et al., 1999).

Distinction needs to be made between sustainable production from a particular geothermal resource and the more general sustainable geothermal utilization, which involves integrated resource, economic, social and environmental development. The latter needs to be controlled through a sustainability policy (protocol), which should be based on general sustainability goals and include specific sustainability metrics, or indicators, to measure the degree of sustainability of a given geothermal operation. Clear metrics are needed to define the sustainable production from geothermal resources, in particular, which is the key issue on which all other aspects of sustainable geothermal utilization is founded. These metrics should be benchmarked for green field and brown field reservoirs, for low and high enthalpy geothermal systems, as well as for electricity generation and direct use. When this has been achieved, it is suggested that these resource focused metrics be given more weight in general sustainability assessment when compared to other factors. It is our opinion that resource metrics (indicators) are lacking in some available sustainability protocols.

This paper starts out by deliberating the renewability of geothermal resources and why their utilization should not be compared/equated with a mining process. It then continues to discuss the main aspects of sustainable geothermal utilization as well as possible different utilization modes and the regeneration of geothermal resources following large-scale utilization. After that a separate chapter discusses the concept of sustainable production level, the key issue of the more general sustainable geothermal utilization, while the last chapter considers sustainability protocols.

2. RENEWABILITY OF GEOTHERMAL RESOURCES – THEIR UTILIZATION DOES NOT CONSTITUTE MINING

2.1 Renewability of geothermal resources

Geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current and because how enormous the energy content of the Earth's crust is compared to the energy needs of mankind. In addition, they simply don't fit well with non-renewable energy sources, like e.g. coal and oil, because of much more limited environmental load (greenhouse gas emissions, etc.).

But this classification has been disputed, by experts and laypersons alike. The authors of this paper claim that this dispute simply arises from a need to force a complex natural phenomenon into an inadequate classification scheme. The claim that geothermal resources are non-renewable has, moreover, been used as an argument against increased geothermal development. The foundation for increased geothermal utilization worldwide is, however, improved understanding through intensified research.

Classifying geothermal resources as renewable may also be an oversimplification. This is because geothermal resources are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and stored energy (Axelsson, 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 (Stefánsson, 2000; Rybach et al., 2000).

The renewability of different types of geothermal systems is quite diverse (see e.g. Axelsson, 2016, for a classification of the different types of geothermal systems). This is because the relative importance of the energy current compared with the stored energy is highly variable for the different types. In volcanic systems the energy current is usually quite powerful, comprising both magmatic and hot fluid inflow. In convective systems of the open type, i.e. systems with strong recharge, the energy current (hot fluid inflow) is also highly significant. But the inflow can either originate as hot inflow from depth or as shallower inflow, colder in origin. In shallow inflow situations the inflow is heated up by heat extraction from hot rocks at the outskirts of the system in question. The renewability of such systems is then supported by the usually immense energy content of the hot rocks of the systems. In convective systems of the closed type, i.e. with limited or no fluid recharge, the renewability is more questionable. The energy extracted from the reservoir rocks through reinjection in such situations is only slowly renewed through heat conduction, but again the energy content of the systems is usually vast. They can, therefore, be considered slowly renewable in nature.

Sedimentary systems, which are mostly utilized through doublet operations, are comparable to the closed convective systems as the energy current is usually relatively insignificant compared to the stored energy. Their renewability is, therefore, mainly supported by heat conduction and hence is relatively slow. The same applies to EGS- or hot dry rock systems. Both these types can thus also be considered slowly renewable. In most such cases the stored energy component is extremely large because of the large extent and volume of the systems.

It is important to stress the difference between sustainability and renewability, i.e. that renewability refers to the nature of the resource in question while sustainability refers to how it is utilized, a distinction which isn't always clear to authors discussing them. Sustainable geothermal utilization depends to a large extent on the nature of the geothermal resource in question and hence its renewability. If energy production from a geothermal system is within some kind of sustainable limits (see later) one may expect that the stored energy is depleted relatively slowly and that the energy in the reservoir is renewed at a rate comparable to the extraction rate.

It is also necessary to distinguish between recharge and recovery: Recharge brings fluid and/or heat back to the reservoir, whereas temperature and/or pressure recover(s) after production stop (pressure quicker than temperature).

2.2 "Mining" of geothermal resources?

In many brochures, publications, presentations etc. geothermal heat and/or fluid extraction is described as "mining". It must be strongly emphasized that this analogy is absolutely wrong. Besides, mining activities cause often severe environmental problems and the reputation of mining operations in the general public is correspondingly bad. When a mineral deposit is mined and the ore has been taken out, it will be gone forever. Not so in geothermal: the replenishment of geothermal resources (heat and fluid) will always take place, albeit at sometimes low rates. These will be addressed below. One would, for example, not classify the seasonal drawdown of a hydro reservoir as "hydro-mining", and the same should apply to geothermal. The wrong analogy leads also to legal problems and obstacles: in many countries, geothermal is often regulated by the mining law and permits are issued by mining authorities. In reality, geothermal energy cannot be defined in physical terms as a mineral resource; the mining offices in general are not specially trained to deal with geothermal problems.

The regeneration of geothermal resources is a process, which operates at various time scales, depending on the type and size of the production system, the rate of extraction, and on local conditions. In general, the production goes on over a certain length of time. After production stop the resources recover by natural processes: The production of geothermal fluid and/or heat successively creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn – after termination of production – generate fluid/heat inflow to re-establish the pre-production state. The question of regeneration boils down to the rate of fluid/heat resupply.

3. SUSTAINABLE GEOTHERMAL UTILIZATION

3.1 Main issues, including the time-scale

Two main issues are of principal significance when geothermal sustainability is being discussed and evaluated (Axelsson, 2010). 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 by Axelsson (2016b), 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 Axelsson, 2016b).

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

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, as well as contributing to the battle against climate change. Therefore, sustainable geothermal utilization 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 benefit. 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, 2010).

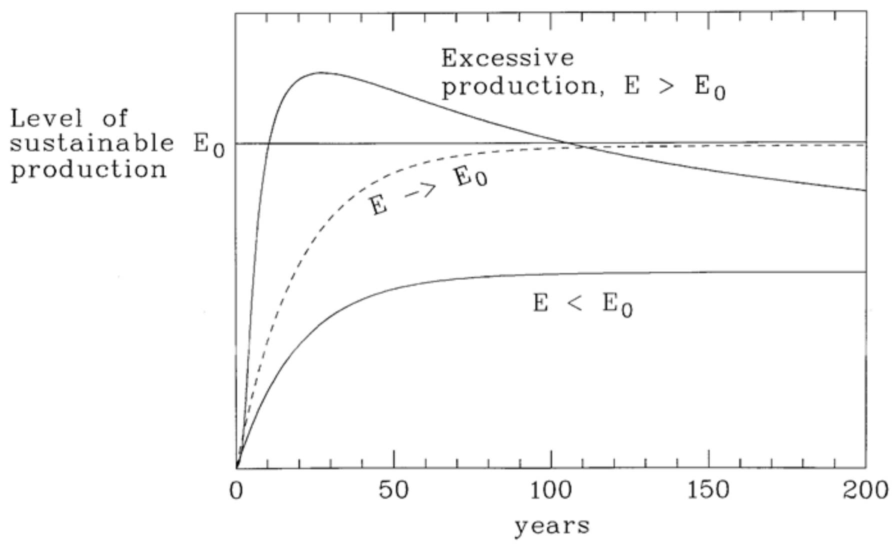

Figure 1: A schematic graph showing the essence of the definition of sustainable production presented by Axelsson et al. (2001). Production below the sustainable limit E0 can be maintained for the whole period being assessed, while greater production can't be maintained.

It is difficult to establish the sustainable production level, E0, 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.

Despite 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.

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 E0, 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.

3.2 Long case histories and modelling

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, as well as Ahuachapan in El Salvador utilized since the late 1970's (Monterrosa and Montalvo, 2010).

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 2). The Laugarnes system is a fracture-controlled convective system 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., 2010).

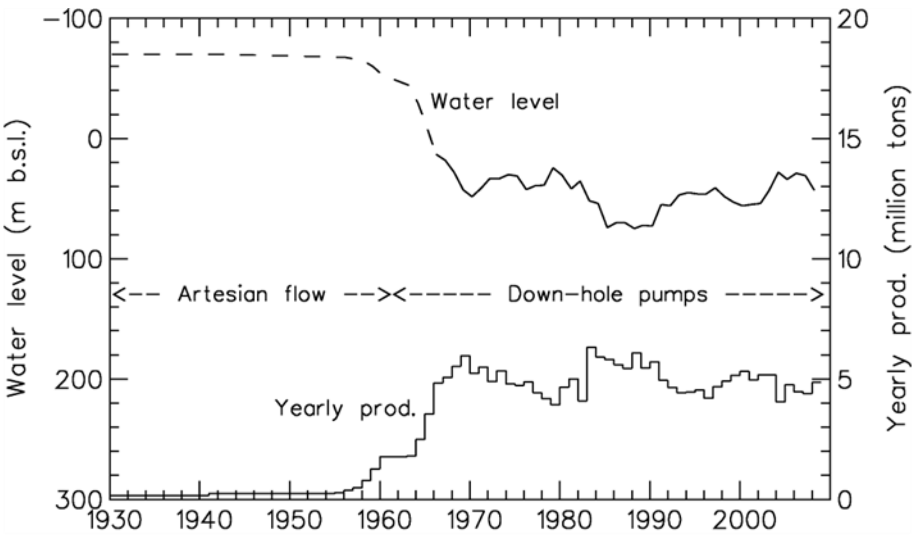

Figure 2: Production and water-level (reservoir pressure) history of the Laugarnes low-temperature geothermal system in SW-Iceland up to 2010. Figure from Axelsson et al. (2010).

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 MWe, 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. The Geysers example also indicates that a sustainable production rate can be achieved after an earlier term of excessive production (the rate may however be lower than otherwise, in some cases) – whether that is a sensible strategy is mostly an economic question.

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. Significant cooling has not taken place in any of the Paris production wells after 3 – 4 decades. 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.

Modelling studies, which are performed on 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 (see e.g. Gylfadottir, 2013), or simpler models such as lumped parameter models, for such modelling studies (see e.g. Axelsson, 2016 and Júlíusson and Axelsson, 2018). 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 either the so-called power density method or the so-called volumetric assessment method with Monte Carlo simulation.

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 the Urban system study will be presented briefly below, as an example.

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. The average yearly production from the system had been a little over 100 l/s of 40 to 90 °C water (mainly used during the four coldest months of the year) at the time of the study. The response of the geothermal system to this production and predictions by a lumped parameter model (figures 3 and 4) 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 up to the beginning of the present century. 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.

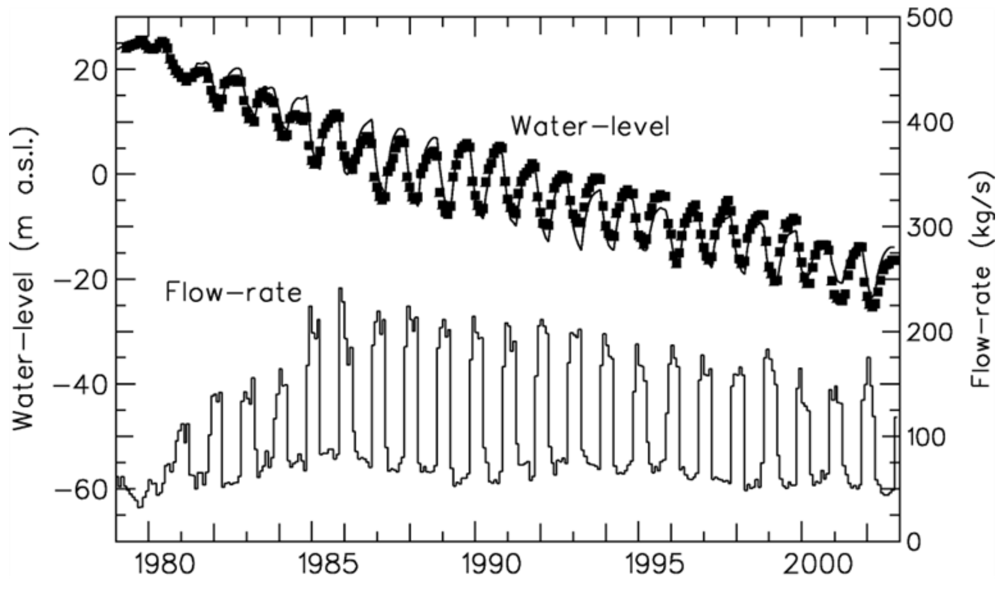

Figure 3: The production history of the Urban geothermal field in Beijing with the water-level history simulated by a lumped-parameter model (squares = measured data, line = simulated data). Figure from Axelsson (2010).

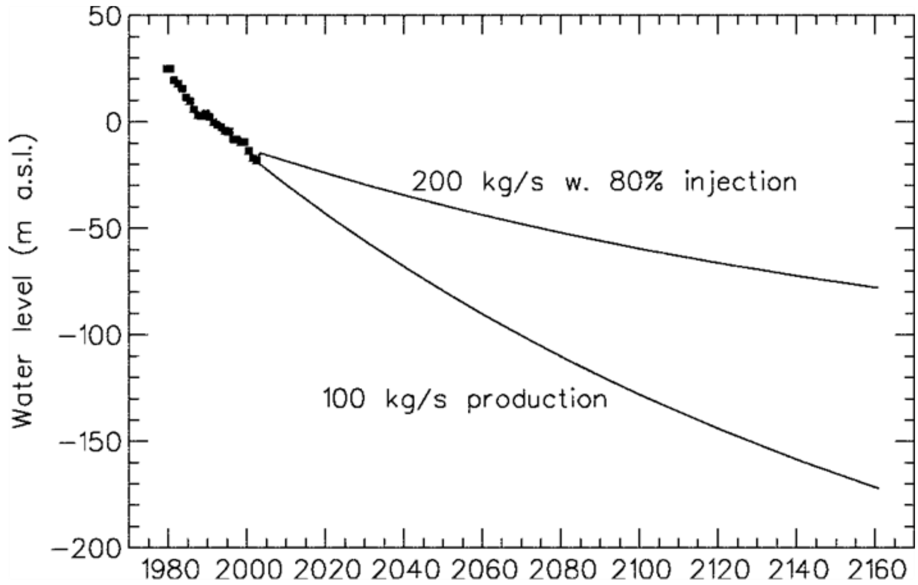

Figure 4: Predicted water-level changes in the Urban geothermal field in Beijing for a 200-year production history (figure shows annual average values). Figure from Axelsson (2010).

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 MWe. A 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 5, 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 by Axelsson (2010), the pressure recovers very rapidly while temperature conditions evolve much more slowly.

Geothermal heat pumps (GHP), using shallow resources (<400m deep), represent by far the fastest growing market in geothermal development, and is also one of the fastest growing renewable technologies: the annual growth rate of globally installed capacities between 1995 and 2015 was 20 % (Rybach and Sanner, 2017).

GHPs can be (and generally are) operated in a sustainable manner (Rybach and Eugster, 2002) since the ground is a heat source as well as a heat sink. In fact, ground temperatures are generally higher in winter and lower in summer than ambient air temperature. Therefore, GPH systems are used for space heating and cooling (for details see Rybach and Eugster, 2010).

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.

4. UTILIZATION MODES AND REGENERATION

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 6, 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 utilisation of another geo-thermal 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 (possibly less than the otherwise sustainable potential), instead of a complete stop. Figure 6 also demonstrates the possible effect of improved modes of production and technological advances (see above).

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 6), two objectives can be achieved simultaneously. First, such steps are practical due to relative ease of permitting, 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 an appropriate level for 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 most practical way of developing and utilizing a geothermal resource in a sustainable manner.

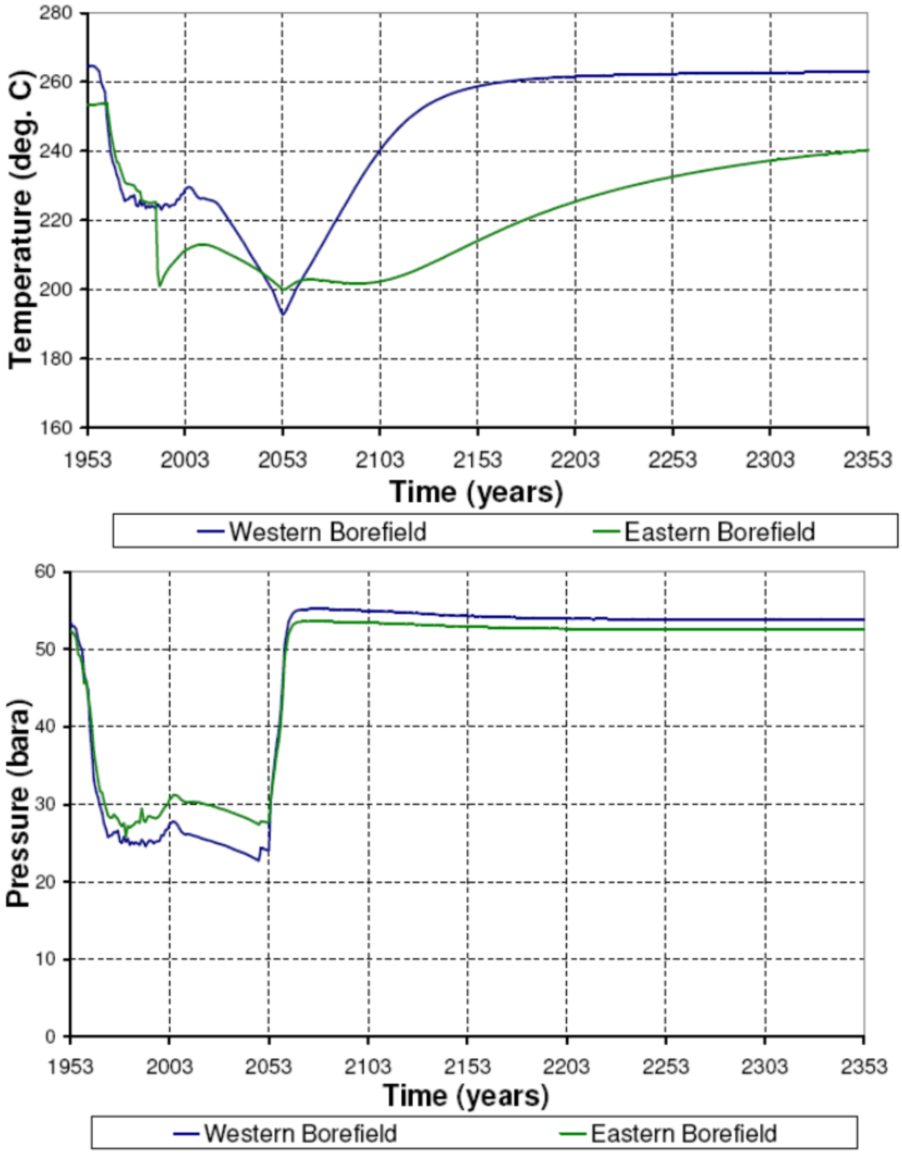

Figure 5: Predicted pressure and temperature recovery in the Wairakei geothermal system in New Zealand following 100 years of production. Modified from O'Sullivan et al. (2010).

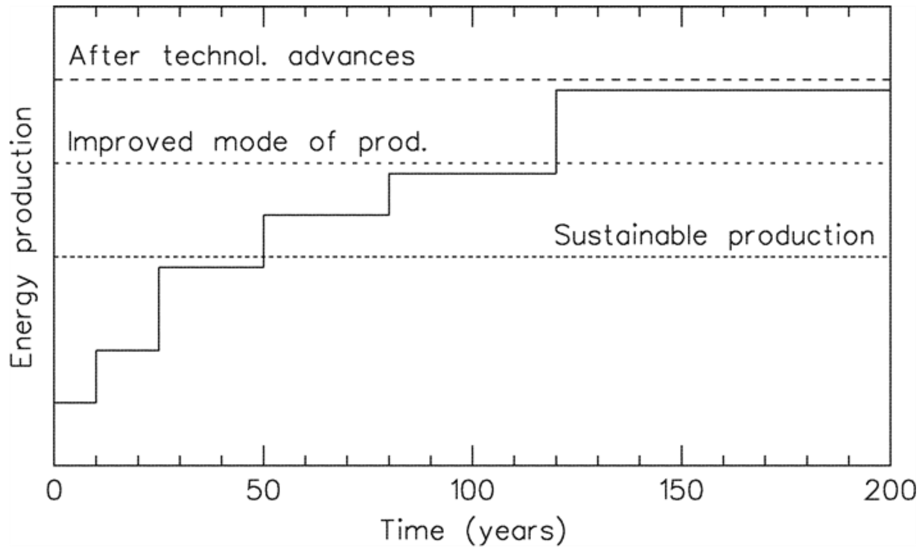

Figure 6: A simple schematic graph demonstrating how the sustainable production potential of a geothermal system is dependent on the mode of production, as well as technological advances. The figure also demonstrates how the energy production may be increased in steps towards a sustainable limit, which in turn will probably increase with time (Axelsson, 2010).

Júlíusson et al. (2011) present a simple stock model that illustrates well the combined consumption of stored and regenerated energy from a geothermal resource. The present how different restrictions on power plant size and project lifetime lead to different production strategies. Notably, the economically optimal strategies found, involved an initial period of excessive (sometimes mildly and sometimes strongly) production that later led to an asymptotical decline towards a strongly sustainable production rate (i.e. production rate equal to recharge rate). The recharge rate for the model chosen for this investigation, had a rather large impact on the production strategy, as it was assumed to be quite strong. For example, this study produced optimal strategies that were close to strong sustainability even after a mere 30 years of production. In each one of the scenarios the recharged energy contributed to more than half of the energy consumed over the project lifetime (30 or 100 years).

In a more recent study (Júlíusson and Axelsson, 2018) looked at similar stock models for geothermal resources in Iceland. These models indicated that the recharged energy contributed a much smaller portion (around 10%) of the total energy consumption. Unfortunately, data are generally not available to constrain the recharge assumptions of these models well. Therefore, it is difficult to make conclusive remarks about how long-term production will play out. The most common way is to assume that there is very limited recharge, which then leads to more conservative production strategies. The bottom line is that, considering both the stored energy and the recharged energy is of importance in determining a sensible strategy for sustainable utilization, but this strategy will also be strongly influenced by resource uncertainty and economic incentives.

The following general comments can be made about geothermal regeneration. Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content, but also increases the natural recharge rate into created pressure and temperature sinks (i.e. dynamic recovery). Thus, a new and sustainable equilibrium condition can be established. The recovery process begins after production stops, driven by natural forces resulting from pressure and temperature gradients. The recovery typically shows asymptotic behaviour, being strong at the beginning and slowing down subsequently, with the original state being re-established theoretically only after an infinite time. However, practical replenishment (e.g. 95% recovery) will be reached much earlier, generally on time-scales of the same order as the lifetime of the geothermal production systems.

Two examples are given below:

A. Continuous operation of a geothermal heat pump system with borehole heat exchangers (BHEs) in annual heating seasons creates measurable temperature deficit around the BHEs. The thermal recovery time (to reach pre-production conditions) corresponds to the production time, e.g. about 30 years for 30 heating seasons.
B. This rule applies also to other geothermal heat extraction systems operating by heat conduction, like EGS.

For details see Figure 7 and Rybach and Kohl (2018).

5. THE SUSTAINABLE PRODUCTION LEVEL – THE KEY ISSUE

The key element of sustainable geothermal utilization and development is sustainable production from a given resource, as has already been mentioned. A sustainable production level can be reached via many different utilization strategies, some may focus on project practicality while others might emphasize maximum economic output or minimal load variation. Having a metric that could capture the sustainable production for each of these would be useful.

When producing from a geothermal resource the sustainability will depend on the initial heat and fluid content and their regeneration (Wright, 1995). Besides, the reaction of the resource to production will largely depend on the rate of heat/fluid extraction. With high extraction rates the energy yield will be correspondingly high at the beginning (and with it the economic reward) but the energy delivery will significantly decrease with time which can put strain on the longer-term operation of the project and cause market imbalance issues. The total energy yield during the operational period will amount to a certain number; for power generation this will be the total produced GWh_e.

Lower production rates can secure the longevity of production, i.e. a relatively constant production rate can be sustained. But as illustrated by Lovekin (2000), "*there can be real economic and social advantages in developing geothermal resources to their full potential, rather than insisting that constant electrical output throughout the project life must be assured.*" Lovekin compared two development scenarios for a hypothetical reservoir (figures 8 and 9). The base scenario was a 30 MW development with moderate decline rates (less than 2%) and constant output for a 30-year period. The comparative scenario was a 90 MW development with much higher well decline rates (20% tapering down to 3% in year 30), but after 20 years output was allowed to decline to about 64 MW in year 30. The make-up well requirement for the latter case was about 2.5 times greater than for the base case.

The example above, illustrates the social benefit that can be gained from allowing temporarily excessive production schemes. Therefore, it is important to allow such schemes fit under the umbrella of sustainable utilization and look upon these favourably from a regulatory perspective.

A definition of sustainability that can encompass and allow temporary excessive production could for example state that the sustainable production level is the average production level over a long period, say 100 years. Some limit on variability might also be added, e.g. that the production level at any given time should be within $\pm$100% of the average production level over this 100 year period.

Lovekin (2000) mentions that market constraints are often more limiting that the physical constraints of the reservoir. This rhymes well with the findings of Júlíusson et al. (2011) and calls for a sustainability metric that can relate the market to production from the reservoir. One way to achieve this would be to create a standardized way to compute the variable cost of production from the reservoir that could be compared to an estimate of future market prices for electricity. This cost could combine many cost factors, e.g. labour cost, predicted decline, induced recharge, brine reinjection and CO_2 emissions. As long as this cost is predicted to remain at or below future market prices for electricity, the operation would be considered sustainable.

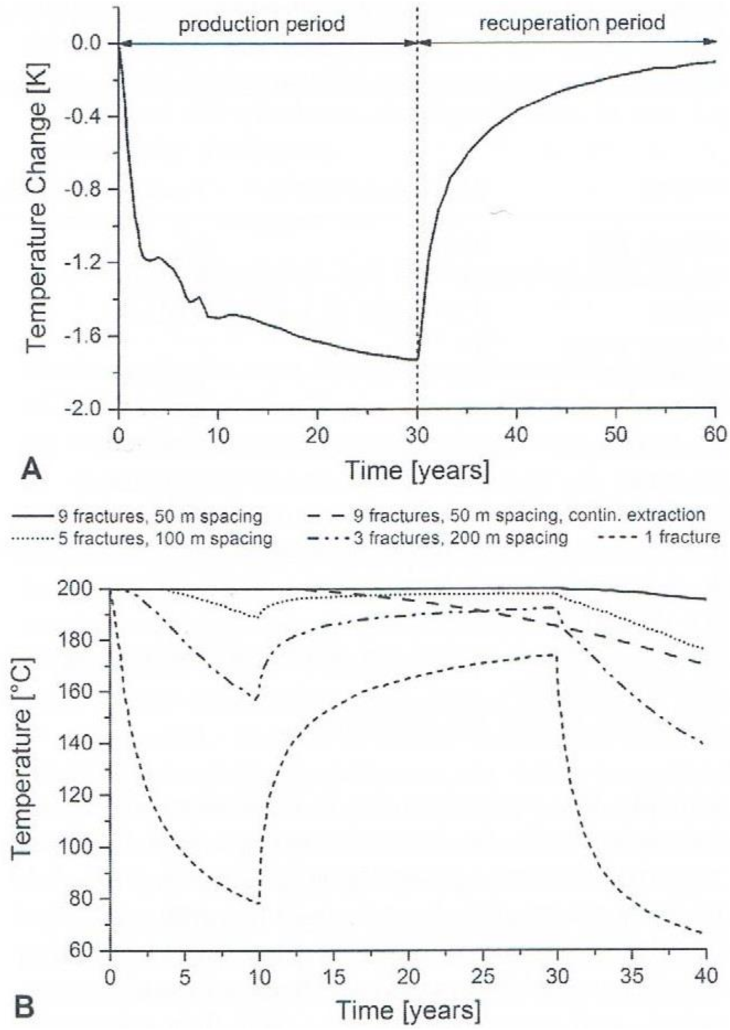

Figure 7: Typical depletion and recovery curves. A: ground temperature changes at 50 m depth and 1-m distance from an operating 100-m-long BHE – the first 10 years measured, the rest modelled (from Rybach et al., 1999). B: EGS fluid production temperatures with various heat exchanger fracture configurations (after Fox et al., 2013). The similarity of the curve shapes is remarkable.

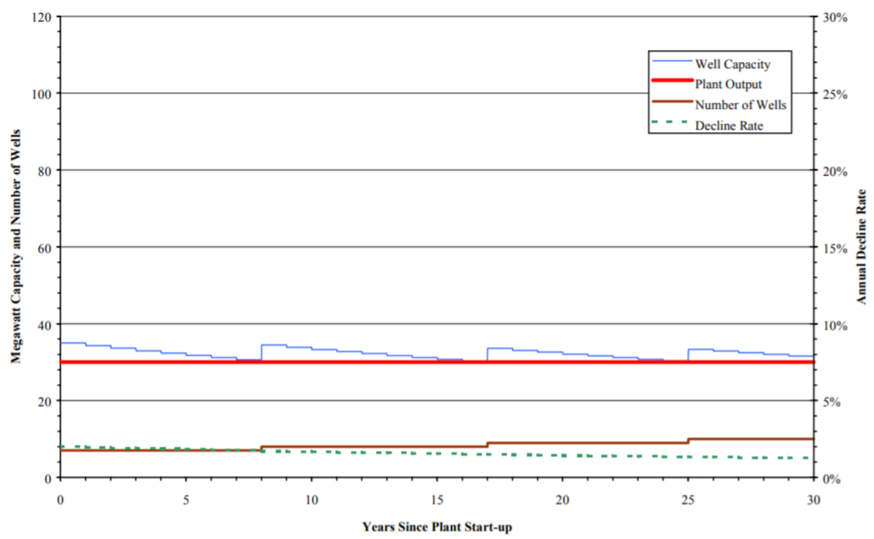

Figure 8: Conservative (base) scenario as defined by Lovekin (2000).

The outcome of Lovekin's study was that both the return on investment and net present value of production was considerably higher for the 90 MW scenario. Moreover, a considerably larger amount of energy was produced, and more wells were drilled, thus inducing more recharge and allowing better access to the resource. In the words of Lovekin: "*the developer gets a better return on investment, and society gets a greater amount of environmentally beneficial power at a lower cost per kW.*"

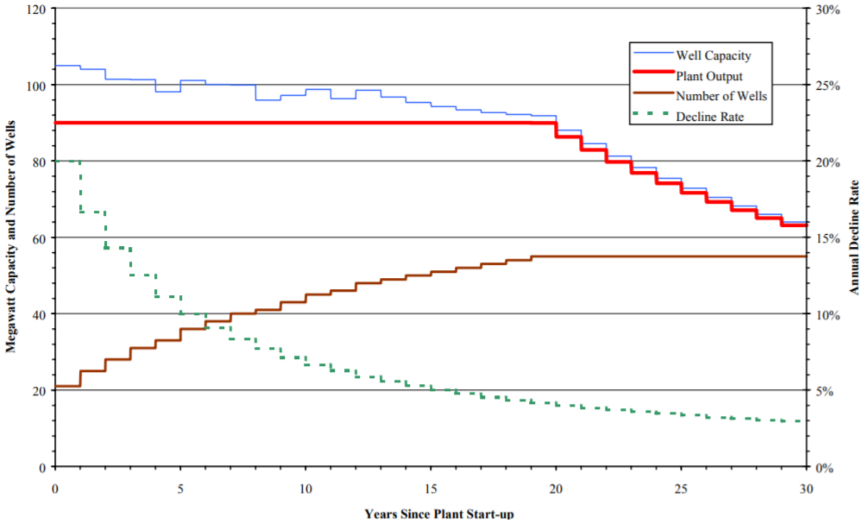

Figure 9: Aggressive (comparative) scenario as defined by Lovekin (2000).

It will be shown below that with the moderate production rate to provide resource sustainability similar total energy yields can be achieved.

To demonstrate this, the results of a specific study (Sanyal and Butler, 2005) will be summarized. In particular, a high and a low-level production from an EGS model are compared. The model reservoir domain has a volume 3.66 x 3.66 km with a vertical extension between 1.22 and 2.74 km depth. The average initial reservoir temperature was set at 210°C. Further details can be found in Sanyal and Butler (2005). The authors applied a three-dimensional, double-porosity, finite-difference numerical scheme to calculate power generation from this hypothetical EGS reservoir. For a five-spot borehole array (an injector at the model centre and a production well at each corner of a square) two fluid circulation rates, a high (1800 t/hr) and a lower (475 t/hr) rate, have been considered (injection flow rate = production flow rate).

Production at the high rate yielded higher power generation capacity at the beginning (45 MW_e). A parasitic load of nearly 10 MW_e was needed to pump the high fluid circulation rate through the system. The fluid production temperature decreased with time and reservoir depletion resulted in production stopping after 20 years (Figure 10). The total energy produced amounts to 245 MW_eyear.

At the lower circulation rate, the starting capacity was only 12 MW_e (Figure 11), but the pumping load was nearly negligible. The temperature decline was also much less and the power generation capacity prevailed well beyond 30 years. The total energy produced over 30 years, 250 MW_eyear, was very similar to that from the excessive production.

This demonstrates that with lower extraction rates the longevity of the resource, and thus sustainable production, can be achieved and still generate as much energy as from excessive production. The level of sustainable production depends on the utilization technology as well as on the local geological conditions and resource characteristics. Its determination needs specific studies, especially model simulations of long-term production strategies.

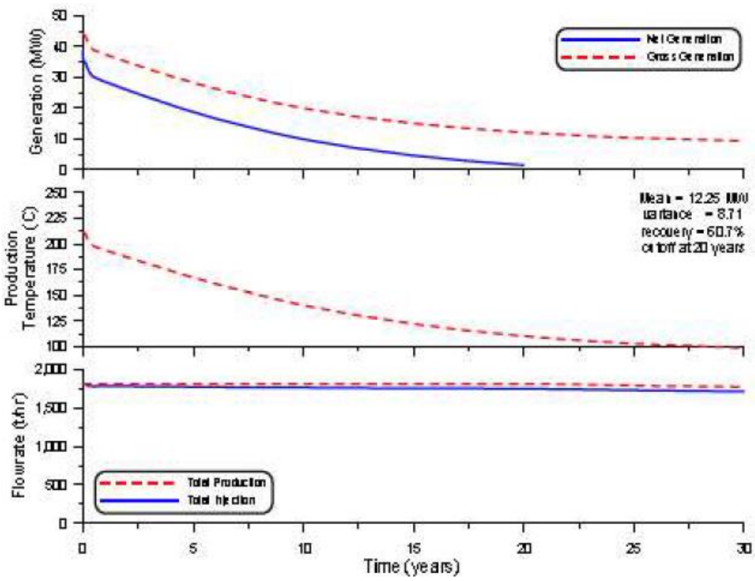

Figure 10: Power generation from an EGS system with high circulation rate (500 l/s) starts with 55 MW_e capacity but terminates after 20 years, with a total generation of 245 MW_eyears (from Sanyal and Butler, 2005).

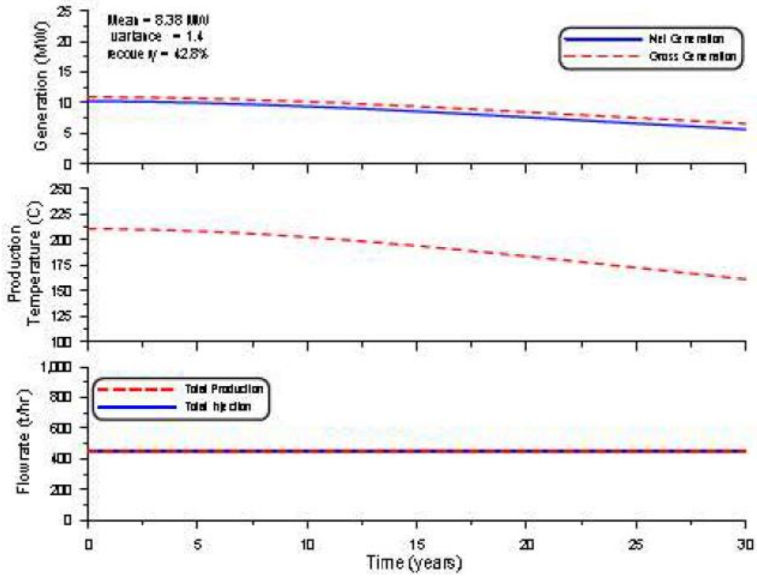

Figure 11: Lower circulation rate (126 l/s) yields long-lasting power production, with total generation of 250 MW_eyears (from Sanyal and Butler, 2005).

6. SUSTAINABILITY PROTOCOLS

Evaluation of the different aspects of sustainable geothermal utilization and development, i.e. resource, environmental, economic and social ones, can be unified through developing geothermal sustainability assessment frameworks, or protocols. In recent years such work has started, based on general sustainability goals and specific indicators, with the purpose of assessing the progress towards sustainable geothermal development. Such work is also 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.

In continuation of this work, the Icelandic Energy Authority (OS) and the Environmental Authority (UST), in collaboration with the Icelandic energy companies, Landsvirkjun, HS Orka and Reykjavik Energy (OR), took on the development of a Geothermal Sustainability Assessment Protocol (GSAP). The protocol was developed both for development projects and operational projects. It was tested on the 90 MW_e Þeistareykir project developed by Landsvirkjun and the 303 MW_e Hellisheiði operation owned by OR. The results and further discussion will be presented in a WGC 2020 publication by Jóhannesson et al. (2020).

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). Quite comprehensive work regarding sustainability protocol development has been performed at the University of Iceland and the reader is referred to short review paper by Shortall et al. (2016) 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.

7. CONCLUSIONS

Sustainable development 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.

Clear metrics are needed to define the sustainable production from geothermal resources. These metrics should be benchmarked for green field and brown field reservoirs, for low and high enthalpy geothermal systems, as well as for electricity generation and direct use.

Sustainable geothermal utilization depends to a large extent on the nature of the geothermal resource in question and hence its renewability. If energy production from a geothermal system is within some kind of sustainable limits, then the stored energy is depleted relatively slowly and the energy in the reservoir is renewed at a rate comparable to the extraction rate. The regeneration of geothermal resources is a process, which operates at various time scales, depending on the type and size of the production system, the rate of extraction, and on local conditions. In general, the production goes on over a certain length of time. After production stop the resources recover by natural processes.

Experience from the use of geothermal systems worldwide, lasting several decades, demonstrates that by maintaining production below a certain limit the systems often appear to attain a sort of semi-equilibrium in physical conditions during long-term production. In other cases, physical changes in geothermal systems are so slow that their output is not affected for decades. Therefore, a sustainability time-scale of 100 to 300 years has been proposed.

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 can be incorporated in a more general sustainable geothermal utilization scheme. A number of successful case histories world-wide are assembled in a Special Issue of Geothermics (2010, Vol. 39, Issue 4).

Evaluation of the different aspects of sustainable geothermal utilization and development, i.e. resource, environmental, economic and social ones, can be unified through developing geothermal sustainability assessment frameworks, or protocols. In recent years such work has started, and many metrics have been suggested. In fact, so many metrics have been suggested (often presented in spider charts) that it becomes difficult to determine the most important ones, especially as there seems to be some reluctance to giving specific weight to different aspects.

Above we have suggested the development of a cost metric for sustainable production that would tie together various aspects of sustainability, e.g. resource decline, environmental cost and market conditions. As long as this cost remains competitive in comparison to other alternatives in the energy market, the production should be sustained. This could be a practical way to engage developers and guide in sustainable practices when creating and running geothermal projects. It would also appeal to the financing world, which is a major enabler of future growth of geothermal energy.

The key element of sustainable geothermal utilization is ***sustainable production from a given resource*** and a clear metric is needed to define sustainable production from geothermal resources. These metrics should be benchmarked for green field and brown field reservoirs, for low and high enthalpy geothermal systems, as well as for electricity generation and direct use. When this has been achieved, it is suggested that these resource focused metrics be given more weight in general sustainability assessment when compared to other factors. It is our opinion that resource metrics (indicators) are lacking in some available sustainability protocols. We, therefore, call for wider collaboration on how to achieve definitions that work for the international geothermal community.

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