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Sustainable Utilization of Geothermal Resources through Stepwise Development

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ABSTRACT

Geothermal energy is a renewable energy source that can be utilized in a sustainable or excessive manner. Excessive production from a geothermal resource can only be maintained for a relatively short time. Therefore, excessive production from a field can indicate overinvestment in wells and power-plant equipment. Sooner or later a field operator is forced to reduce the production to the level of maximum sustainable use. Stepwise development of geothermal resources is a methodology that takes into consideration the individual conditions of each geothermal system and minimizes the long-term production cost. The cost of drilling is a substantial component both in the exploration and the development of geothermal fields. With the stepwise development method, production from the field is initiated relatively shortly after the first successful wells have been drilled and the production- and response history of the reservoir during the first development step is used to estimate the size of the next development step. In this way, favorable conditions are achieved for the timing of the investment in relation to the timing of the revenue, resulting in lower long-term production costs than can be achieved by developing the field in one step. Merging the step-wise development method, with the concept of sustainable development of geothermal resources, results in an attractive and economical way to utilize geothermal energy resources.

1. INTRODUCTION

Development of geothermal resources can be done in large or small steps. Many authors have assumed that the benefit of size is valid for geothermal power plants and that large development steps are more economical than smaller steps. However, a review of the actual cost of several power projects in Iceland indicates that this effect is not present for power plants in the range of 20 – 60 MW_e (Stefansson, 2002).

A prerequisite for a large geothermal development step is knowledge on the generating capacity of the reservoir. Such knowledge requires that a certain number of wells is drilled and the capacity of the field is tested prior to the actual investment in the field. Such a procedure requires considerable investment in the field prior to the construction phase and a long time before any income from the energy production is obtained. Large geothermal steps are therefore front loaded from the economic point of view.

Sustainable production from a geothermal system can be maintained if the production does not exceed a certain limit, characteristic for each individual geothermal system and each mode of utilization (Axelsson et al., 2001). The level of maximum sustainable production can not be determined prior to production from a resource. Therefore, both economic considerations and sustainable resource management considerations favor development of geothermal resources in relatively small steps.

2. DEFINITION OF RENEWABILITY AND SUSTAINABILITY

The use of the term sustainable development became fashionable after the publication of the Bruntland 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*. This definition is inherently rather vague and has often been understood in different ways.

In the attempt to link the concepts of the Bruntland report to the management of resources, a mix-up of the concepts renewable and sustainable sometimes occurs. Our understanding of these terms is that *renewable* describes a property of the resource, namely the ability of the resource to replace what is taken out of the resource, whereas the term *sustainable* describes the mode of utilization of the resource. We can use the terms renewable energy source and sustainable use of a resource, but expressions like "sustainable resource" and "renewable use of a resource" are meaningless expressions in our opinion.

Axelsson et al. (2001) propose 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 exist 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 does neither consider economical aspects, environmental issues, nor do technological advances, all of which may be expected to fluctuate with the times.

The definition given above applies to the total extractable energy and depends in principle on the nature of the geothermal system considered, but not on load-factors or utilization efficiency. It also depends on the mode of production that may involve spontaneous discharge, pumping, injection, or periodic production.

The value of E_0 is not known a priory, but it may be estimated on the basis of exploration and production data as they become available. It should be noted that the maximum level of sustainable use is not necessarily equal to the natural recharge to an undisturbed geothermal system. In many cases, the exploitation of the resource enhances the recharge to the geothermal system.

Stefansson and Axelsson (2003) have proposed the following definition of a renewable energy source:

The energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy, and the replacement takes place on a similar time scale as that of the extraction.

Renewable energy sources are in one way or another linked to some continuous energy process in nature. The conditions must be such that the action of extracting energy from the natural process will not influence the process of energy circulation in nature. Furthermore, it is necessary to constrain the definition to the cases where the replacement is taking place on a similar time scale as the extraction from the resource. It could be argued that oil and gas are renewable on a geological time scale, but this geological time scale is so long in relation to the human time scale that there is a common agreement to classify oil and gas as finite energy resources

Strictly speaking, it is only the time scale that divides the energy resources into renewable resources and finite resources. Human time scale is used as reference for this purpose. It is known that hydrocarbon reservoirs are formed in the crust in a time span of some 50-100 million years, but this time is so long compared to the time scale used by human beings that the maturation of hydrocarbon reservoirs is defined as not renewable on the time scale of the activities carried out by mankind. It is possible to extract the energy from a hydrocarbon reservoir in a time that is a million times shorter than the time required to form the resource.

Also, it can be argued that the natural processes that are the basis for renewable energy resources are finite, if a very long time scale is considered. Most of the renewable energy resources like solar, wind, and hydro depend on the energy radiation from the sun. The lifetime of the sun is, however, limited even though this time is even longer than the geological time needed for the formation of oil reservoirs. Furthermore, it can be argued that the thermal energy of the interior of the earth is also of finite size causing geothermal energy also to be a finite resource, if a very long time is considered.

The requirement that the human time scale should be used as the reference point in the definition of renewable versus non-renewable energy resources can create some gray areas, where it might not be clear whether the resource should be classified as renewable or non-renewable. Geothermal energy is an example where such ambiguity can be noted.

The reason for the apparent ambiguity is the different mode of energy transport within the crust. The energy transport within the crust takes place by three processes:

- Advection of magma.
- Advection of geothermal fluid.
- Thermal conduction.

The transport of energy from the mantle takes place simultaneously through all three processes, and the relative contribution of each transport mode also changes from one place to another in the crust. Energy (heat) transport with advection of magma and thermal water is a relatively fast process. Time constants in the range of days or months are suitable to describe these processes. On the other hand, thermal conduction is a relatively slow process where a time constant of the order of hundreds of years is needed to characterize the process. The utilization of geothermal energy from natural geothermal systems is primarily governed by the advection of thermal fluid in the crust.

If the energy transport is only by thermal conduction on the other hand, it is hardly possible to talk about a “renewable” energy source because the time constant of the energy replacement is much longer than the time constant required for the exploitation. All conventional exploitation of geothermal energy is based on energy extraction from natural geothermal systems where water transports the energy within and towards the systems, and water also transports the energy to the surface where the utilization takes place. Production causes a pressure decline in the geothermal system, which results in increased recharge of water and energy to the system under exploitation. These conditions are typical for renewable energy sources where the replacement of energy takes place on a similar time scale as the extraction.

The exception from this rule is hot dry rock and the extraction of connate water from some deep sediment. In the case of hot dry rock, the idea is to create an artificial geothermal system in impermeable rocks by injecting water into one well and extracting the heat stored in the rocks through another well. If the rock is completely impermeable, the replacement of energy to the reservoir will only take place as thermal conduction, and the replacement of the heat energy will take such a long time that it is questionable whether the resource can be classified as renewable in this case. Similar conditions might be present in sedimentary systems with no natural recharge. In most cases, however, there is some recharge to the sediments. Furthermore, the concept of hot dry rock is now changing rapidly to the concept of enhanced geothermal systems. For these enhanced systems, there is some natural recharge to the reservoirs, such that the energy recharge will partly take place through advection of thermal fluid and partly through thermal conduction. The question of renewability of the hot dry rock utilization mode will probably be of minor importance in the future.

It is interesting to note that the ambiguity of the renewability of geothermal energy results from the utilization mode applied. It might be possible to find cases where the definition of a renewable energy source is hardly applicable. In all other cases, there is a common agreement that geothermal energy should be classified as a renewable energy source.

3. LARGE OR SMALL DEVELOPMENT STEPS

Direct observations of the internal conditions of a geothermal system can only be obtained by producing from the system. The response of the system to production gives information on how the system will behave in the future and an estimate of the generating capacity of the system can be made, for example by applying reservoir simulation. The confidence level of such predictions depends on the length of the observations made in the field and on the amount of the production from the resource. If the production in the field test is only a small fraction of the capacity of the field, there will be large uncertainty in the predicted capacity of the field. Furthermore, the accuracy of the predictions is strongly dependent on the prediction time applied. Simulation methods can give reasonable predictions for some 10-30 years, but predictions made for some 100-300 years are usually associated with large uncertainties.

The time constants applied in financial considerations are usually of the order of 20-30 years, whereas a time constant of some 100-300 years is used in the definition of sustainable use of geothermal resources presented by Axelsson et al. (2001).

Both for the financial considerations (time constant 20 years) and for the resource management considerations (time constant 200 years) it is appropriate to use stepwise development in order to estimate the financial capacity of the resource and the maximum level of sustainable use. The sizes of the steps are site specific but for the development of high temperature resources in Iceland, 20-40 MW_e seems to be a suitable step from economic point of view.

4. ECONOMIC CONSIDERATIONS FOR STEPWISE DEVELOPMENT

The geothermal industry in Iceland has adopted the stepwise development strategy for the development of high temperature resources. The main reasons for this choice are the following:

- Short time between drilling and production is of great importance for the viability of all geothermal projects.
- Reservoir response is tested with actual production from the field. In this way, testing of the field capacity is not delaying the earning from the energy production.
- Overinvestment in the field is avoided.
- Enthalpy changes due to production will not cause mismatch between equipment and field properties.

The stepwise development strategy applied in Iceland has been successful and the production cost of electricity from geothermal power plants in Iceland is quite favorable compared to other places in the world (Stefansson, 2002).

The stepwise development strategy has been applied in Iceland for the last decade or so. Figure 1 shows the comparison between the old and the new development strategies applied.

The benefits of the stepwise development strategy are reflected in the increase of electricity production by geothermal power plants in Iceland during the last decade (Figure 2).

By applying the stepwise development strategy, the production cost of electricity from geothermal power plants has turned out to be lower than the production cost of electricity from hydro. Therefore, the geothermal alternative became more attractive than hydro for new power plants. At present, there are geothermal power plants under construction in Iceland that will double the geothermal capacity within the next 3 years.

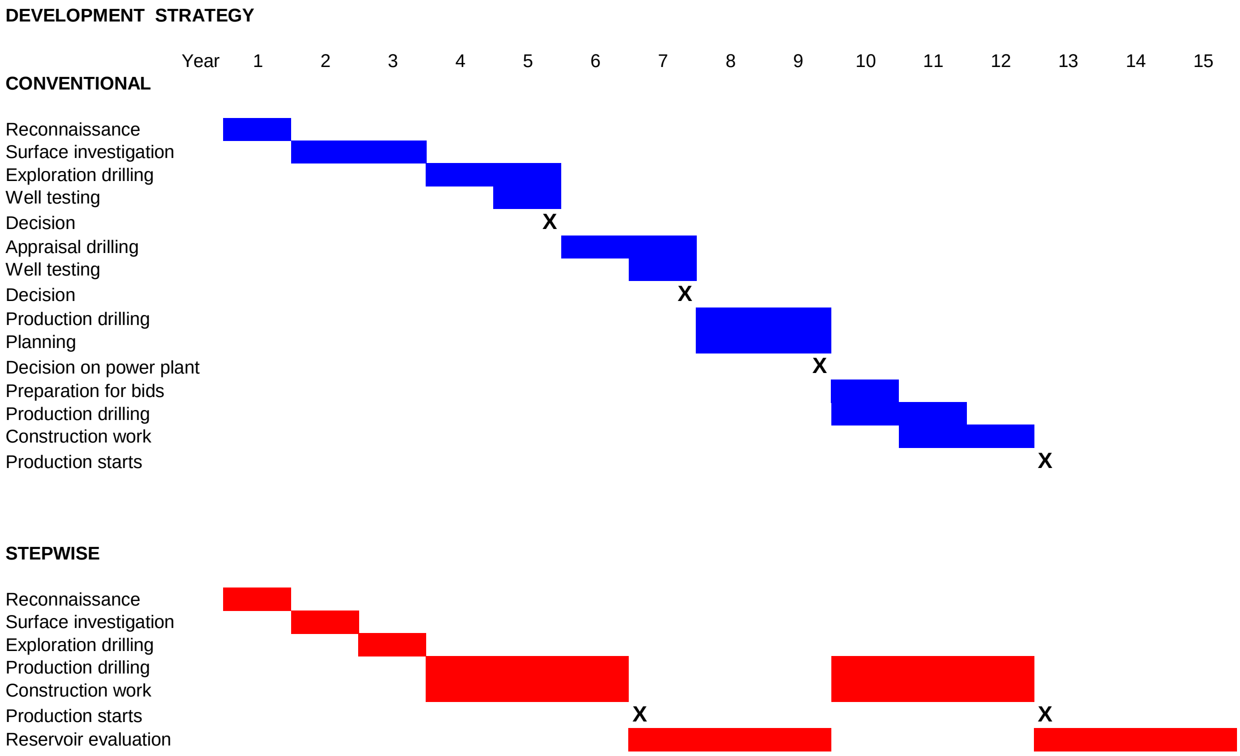

Figure 1: Comparison of the stepwise development strategy (lower part of the figure) and the conventional development strategy (upper part of the figure).

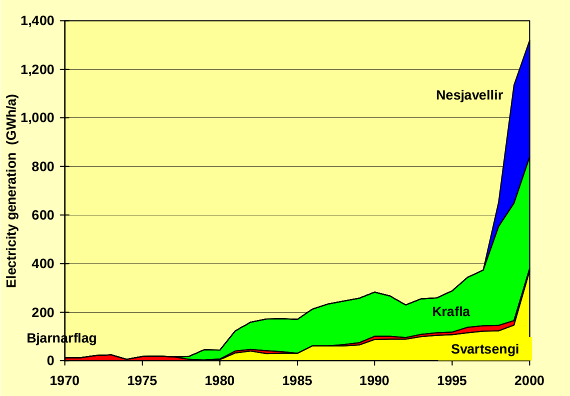

Figure 2: Generation of electricity from geothermal power plants in Iceland during 1970-2000.

5. SUSTAINABLE USE OF GEOTHERMAL RESOURCES

In the definition of sustainable use of geothermal resources presented by Axelsson et al. (2001) reference is made to a constant energy production from the resource for a very long time (100-300 years). This definition is made in order to describe the nature and the meaning of the concept "sustainable use". The definition does not state that excessive production is forbidden or that excessive production will harm the resource. The definition only state that if excessive production is selected and applied, it will not be possible to maintain that level of production for a very long time. Furthermore, both field observations and model simulations indicate that although excessive production is applied for limited time, the resource will usually recover if allowed to rest for some time after the excessive production has been applied (Axelsson et al., 2004; Pritchett, 1998).

Sustainable use of a geothermal resource does not necessarily have to be considered the most profitable or economic mode to exploit a resource. In all societies applying interest rate on capital, time periods beyond some 30-50 years are of minor economic importance. Note for ex. that in a society with interest rate of 5% per year, the present value of a dollar that will be paid after 50 years is 9 cents. If the interest rate is 10% per year, the corresponding present value of a dollar is less than 1 cent. Therefore, it is not practical to use economic considerations for longer time periods than some 30-50 years. It should be noted also that with the interest rate of 0% per year, the sustainable use of a resource is the most economic mode of utilization.

Periodical utilization of a geothermal resource, meaning that the resource is allowed to produce for some time, and then allowed to rest for some time and so on, might be a reasonable management method in our market economy. For a limited time (< 30 years), the production from the resource is larger than the maximum sustainable use, but the average production over a time length of some 200-300 years will be less than the maximum sustainable use.

Figure 3 shows a possible arrangement for periodic production of geothermal resources. Excessive production can be applied for a limited time if the resource is allowed to recover in-between the production periods.

It is not necessarily a prudent management plan to require that the production from a geothermal resource is all the time below the level of maximum sustainable use. The Waikato Regional Council in New Zealand seems to be requiring that production from geothermal fields should be sustainable on a time scale of 100 years (Environment Waikato, 2003), but resources consents can only be issued for maximum 30 years at the time, according to the laws in New Zealand. The management policy of the Waikato Regional Council is not necessarily the most economic exploitation of geothermal resources in the Waikato Region.

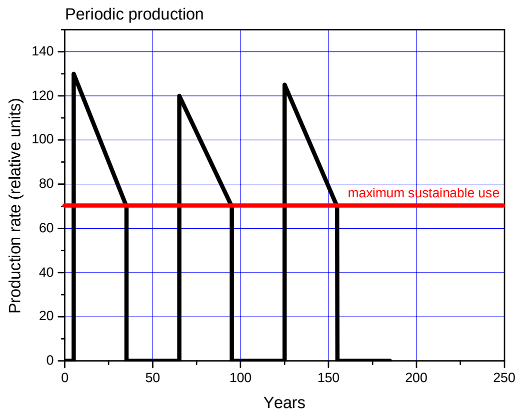

Figure 3: Possible arrangement of periodic production from a geothermal resource.

The level of maximum sustainable use depends on two parameters: the energy stored within the system under consideration and the energy recharge to the system. In the simulation of the natural state of a geothermal system it is usually assumed that the natural recharge is a constant value, independent of time. During exploitation, the internal conditions of the system change, however, and these changes may influence the rate of recharge to the geothermal system. By lowering the pressure in a geothermal reservoir, conditions for increased recharge are favorable. Such increased recharge will occur place if there is fluid outside the boundary of the system that can flow towards the decreased pressure created by exploitation. In the early stage of geothermal exploitation, boundary conditions of a geothermal system are poorly known, such that predictions of increased recharge can usually not be made until production from the resource has been going on for some ten years or more.

Increased recharge to a geothermal system can be either in the form of hot or cold fluid. Therefore, it is only in few cases that actual increase in energy recharge has been demonstrated. The Laugarnes field inside Reykjavik in Iceland is one of these cases. Figure 4 shows the production history of that field.

The production from the Lauganes field started 75 years ago and for the first 30 years, the production was limited to free flow from wells. In the sixties of the last century, the production was increased by an order of magnitude through the introduction of down-hole pumps. This resulted in a reservoir pressure drop corresponding to about 120 m of water level. Production and water level have, however, remained relatively stable during the last three decades. This indicates that the reservoir has found a new semi-equilibrium, with ten times the natural recharge. No change in the temperature has been observed in the reservoir fluid during the 35 years of operation of the new equilibrium state. Therefore, it can be concluded that the energy recharge has increased tenfold as compared to the natural recharge to the geothermal system in Laugarnes.

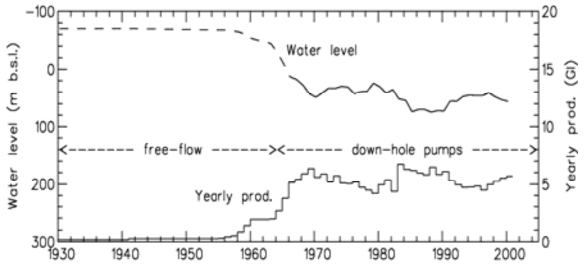

Figure 4: The production and water-level history of the Laugarnes geothermal system in SW-Iceland.

Estimates of the natural recharge to geothermal systems give the minimum recharge value that can be expected during exploitation. In some cases, the pressure draw-down in the reservoir can stimulate increased energy recharge to the system, but in most cases the increase in energy recharge seems to be small.

Relatively long production time is required in order to reveal the boundary conditions of a geothermal system. In many cases some 5-10 years of continuous monitoring are required to estimate these parameters. Furthermore, the draw-down in a geothermal reservoir may increase the energy recharge to the system under consideration. Therefore, stepwise development of a geothermal field is a development strategy that fits the nature of geothermal resources. Figure 5 shows a possible arrangement for a stepwise geothermal development.

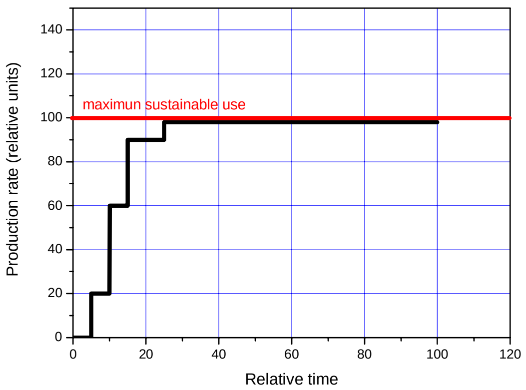

Figure 5: Typical stepwise development of a geothermal resource.

By applying stepwise development strategy, overinvestment in the field is avoided. On the other hand, it will take some time before the revenue of the field will reach the maximum value.

By selecting more rapid development for a the field, revenue from the field will be obtained sooner, but the risk for overinvestment in the field is high. If this happens, some of the equipment will become idle after some time and the revenue of the investment in the equipment will reduce.

Figure 6 shows production and reinjection in The Geysers field in California during 1968 to 2000. It is evident from this figure that the field can only sustain a production of 100 million tons for a short time. At present some of the power plants in the field are not in use due to lack of steam. At the same time efforts are made to increase reinjection in order to maintain the present level of electricity generation at The Geysers.

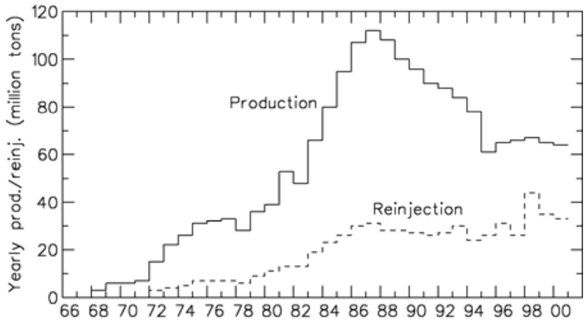

Figure 6: Production- and reinjection history of The Geysers geothermal field in California. After Baker (2000).

A relatively stable production has been maintained since 1995, partly through reinjection. The recharge to the Geysers field appears to limit the production that can be maintained in the long run. It is still an open question what is the maximum sustainable production level of The Geysers field for the production mode including reinjection.

6. CONCLUSIONS

Sustainable use and generating capacity are related concepts but different time constants are involved. Generating capacity is linked to economic considerations of the geothermal development and time constants in excess of some 30-50 years are of little interest in economic considerations.

The level of maximum sustainable use of geothermal resources, on the other hand, is related to the possibilities for future generations to benefit from the same geothermal resources as used to-day. For practical considerations, a time constant of some 200-300 years seems to be appropriate for these purposes. We refer to this time frame as very long time. For many human beings, this time frame appears close to infinity, but recalling the fact that the Earth and the Sun are believed to have existed for a finite length of time, we avoid using the term infinity in our discussion.

Both generating capacity and the level of maximum sustainable use are estimated from the response of the resource to load (production from the resource). In both cases, the method of stepwise development is a suitable method to deduce both the level of generating capacity (level of economical exploitation for some 30-50 years) and the level of maximum sustainable production (continuous exploitation for a very long time).

Experience seems to indicate that temporary excessive production does not cause permanent harm to a geothermal resource and the resource will recover if it is allowed to rest for some time or if the production is reduced considerably below the maximum level of sustainable use. Therefore, it might be possible to find an economic scenario that allows excessive production from a field for a limited time, but such arrangements include a time where part of the surface equipment will be idle.

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