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Sustainable and Environmentally-Sound Development Strategies Addressed Through International Collaboration

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ABSTRACT

Collaborative research into sustainable and environmentally-sound development strategies is carried out under the auspices of the IEA Geothermal Implementing Agreement (IEA-Geothermal) (www.iea-gia.org), through the Tasks of its Annex 1, Environmental Impacts of Geothermal Development. Cooperation amongst member countries facilitates knowledge sharing and exchanges of geothermal operational and modeling experience. This is vital in order to learn from past successes and mistakes. By growing investor confidence in the long-term sustainable development of geothermal resources, and avoiding or mitigating adverse local environmental effects, we can materially advance global efforts to mitigate the much more serious adverse effects of climate change resulting from fossil-fuel carbon emissions.

Analysis of long-term historical performance of developed geothermal reservoirs, together with simulations of their likely future performance using reservoir models, leads to important conclusions regarding optimizing sustainable strategies for future development. A key factor is the choice of initial and subsequent staged capacity installments; these are justified by increasingly more-sophisticated reservoir simulation models. The objective is to avoid excessive pressure or temperature draw-down, but to allow for sufficient reservoir response to provide good history matching. A second key factor is the ability to adapt reinjection strategies (location, depth, fluid chemistry and temperature) as new information from monitoring of production/injection effects becomes available. The third key factor is the early recognition of the dynamic response of a resource to its utilization, with good information collected on the source location, chemistry and temperature of induced recharge fluids. Improved tracer technology helps characterize parameters such as permeability, diffusion and fluid storage between injection and production sectors. Better calibration of reservoir models improves characterization of the permeability structure and boundary recharge parameters that dictate long-term reservoir behavior. Over very long timescales (>100 years) reservoirs are likely to trend toward a pseudo steady-state wherein induced mass and heat recharge almost balance the net mass and heat that can be extracted. Other options for sustainable development, however, might involve cyclic or intermittent energy extraction ('heat grazing') wherein parts of a large heat resource may be developed and recovered in rotation. Strategies must also take into account potentially adverse local environmental effects.

An alternative long-term strategy is to use the acquired knowledge and simulated behavior from early production stages to plan deeper drilling, by targeting the primary up-flows. Over time, the shallow parts of a resource are 'retired' and bore-holes tap directly into higher enthalpy and more productive sectors of the resource. Challenges associated with this strategy include the need to reduce the cost of deep drilling, and to develop technologies to deal with super-critical and potentially corrosive reservoir fluids. However, the rewards could be significant.

1. INTRODUCTION

Sustainability of production is a key issue in assessing the potential contribution of geothermal resources to mitigation of climate change (Bromley et al., 2010, Goldstein et al., 2011). Axelsson (2010) helped define the meaning of sustainable production of geothermal fields, through a theoretical analysis, supported by modeling of different types of geothermal fields, from a variety of geological settings. He identified the research issues and suggested that recovery of a production reservoir can be achieved on a time-scale comparable to the period of utilization, that is, at the 100-300 year time scale.

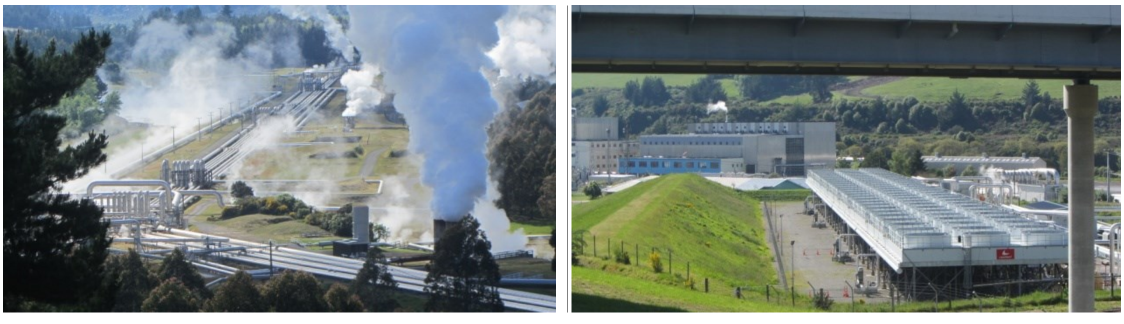

Figure 1: Wairakei borefield and power station: 57 years of sustained resource use, by applying adaptive management.

This paper provides an overview of collaborative work undertaken by IEA-Geothermal Annex 1 participants to investigate this topic, in the context of the wider objectives of avoiding, minimizing or mitigating adverse environmental effects.

2. SUSTAINABLE DEVELOPMENT STRATEGIES

Strategies to sustain heat and power generation output, by successfully managing geothermal fields over the longer term (i.e. 100 years and beyond), are considered to be crucial to the future of geothermal as a renewable source of energy (Stefánsson, 2000; Sanyal, 2005; Rybach and Mongillo, 2006). These strategies may involve staged development (Stefánsson and Axelsson, 2005) and some form of 'cyclic utilization' or 'rotational heat grazing' to allow recovery of depleted reserves (Axelsson et al., 2005; Axelsson, 2010; Bromley et al, 2006). This recovery originates from surrounding or deeper recharge zones. To achieve continuous geothermal generation across a region, it will be necessary to identify reserve sources of generation for use during the recovery periods. This requires prior exploration and identification of additional geothermal systems.

2.1 Adaptive management

Adaptive management of geothermal production, by adjusting locations and rates of fluid extraction and injection, are also needed to optimize sustainable utilization of each system. This requires flexibility. Most geothermal developments that have been operating for more than 20 years have undergone changes in production-injection strategy as the result of resource effects identified through monitoring. Planners and regulators need to accommodate this. Also, developers should maintain some surplus production and injection capacity throughout development. A range of future options are needed in order for adaptive and flexible management to work. Effective monitoring of reservoir conditions (temperature, pressure, phase, fluid chemistry) are also essential components of this strategy in order to identify injection returns, cool groundwater inflows, etc. Monitoring tools include bore-hole measurements, micro-gravity, seismicity, tracer studies, and pressure interference testing. The monitoring results are used to calibrate reservoir simulation models which are used for planning.

Reservoir management strategies should also emphasize the achievement of environmental balance through avoiding, remedying or mitigating adverse effects, and encouraging beneficial effects. This will achieve greater community support. In this regard, there are some successful international experiences in developing of resources using environmentally-sensitive strategies. These help to promote geothermal utilization, and provide excellent role models for current and future developers. Global awareness of these successes can be improved through information sharing and international collaboration. A suggested flow-chart for optimizing development strategy is shown in Table 1.

Table 2: Development strategy flow-chart for optimal sustainable utilization of renewable geothermal resources

1. Exploration - Resource Assessment	2. Initial Capacity for Staged Approach	3. Natural-State Simulation Model
6. Timing of Multiple Stage Expansions	5. Calibrate Reservoir Simulation Model	4. Produce- Monitor Reservoir Response
7. Force Resource Response	8. Achieve Enhanced Hot Recharge	9. Adaptive Reinjection Strategy
12. Long-term Rotation (heat-grazing)	11. Make-up Drilling Options: in or out	10. Refine Simulations (loop back to 6);
13. Refine Resource Boundary Conditions	14. Improve Simulations (loop back to 11)	15. SUCCESS!

2.2 Role of IEA-Geothermal

IEA-Geothermal provides an opportunity for international collaboration on various aspects of resource development, including environmental and sustainable management issues (Mongillo et al., 2010, www.iea-gia.org). A series of workshops (Bromley, 2012), discussion documents, and Geothermics Special Issue papers (Mongillo and Axelsson, 2010) have been produced on topical issues. These include: protecting and enhancing natural thermal features; minimizing adverse effects from disposal of geothermal fluids and gases; providing policy advice; dealing with induced seismicity and subsidence; and improving sustainability of geothermal production, particularly through adaptive injection.

Within Annex I, IEA-Geothermal participants (from: New Zealand, Iceland, Japan, Italy, Mexico, Australia, USA, Switzerland and Norway) undertake tasks to identify environmental effects of geothermal development and devise and adopt methods to avoid or minimize their impact (Bromley, 2010). These tasks include: a) to investigate the impacts on natural features; b) to study the problems associated with discharge and reinjection of geothermal fluids; c) to examine methods of impact mitigation and produce environmental guidelines; and d) to develop sustainable utilization strategies (Axelsson et al., 2010). Annex XI (Induced Seismicity) investigates seismic risk from EGS fluid injection. This work has identified practical environmental strategies including: 1) improved discharges from surface thermal features by targeted fluid injection, 2) creation of enhanced thermal habitats, and 3) treatment or injection of toxic chemicals or gases. Good monitoring programs allow the establishment of pre-production baseline information to help properly identify effects from such strategies.

2.3 Cyclic or 'heat grazing' extraction strategy

Sustainable geothermal energy production is achieved by properly managing fluid production and injection rates and locations. Total energy yields achieved using low extraction rates over long duration cycles can be similar to those achieved with high extraction rates for short duration cycles. Balanced fluid/heat production that does not exceed the recharge (natural and induced) can be considered indefinitely sustainable. If extraction rates exceed the rate of recharge, reservoir depletion will occur, but following termination of production, geothermal resources will undergo asymptotic recovery towards their pre-production pressure and temperature states. Practical replenishment (~95% recovery) will occur on time scales of the same order as the lifetime of the geothermal production cycle (typically ~50 to 300 years). This is illustrated in Figure 2, and has been tested using reservoir simulations. A useful formula for estimating the full thermal recovery time, from O'Sullivan and Mannington (2005), is as follows:

T (rec) = (PR-1) T(ext)

where T(rec) is the recovery time needed for a geothermal system to be restored to its pre-development condition; T(ext) is the time period of geothermal fluid extraction; and PR is the ratio of heat extraction rate to natural heat discharge rate. If, for example, the heat extraction rate is twice the natural heat discharge, then the recovery time matches the extraction time. In a practical situation, because the recovery process is asymptotic, a new cycle of energy extraction can begin well before full thermal recovery is achieved.

The optimum level of long-term sustainable production depends on the utilization technology (reinjection strategy, in particular) as well as on the geothermal resource characteristics.

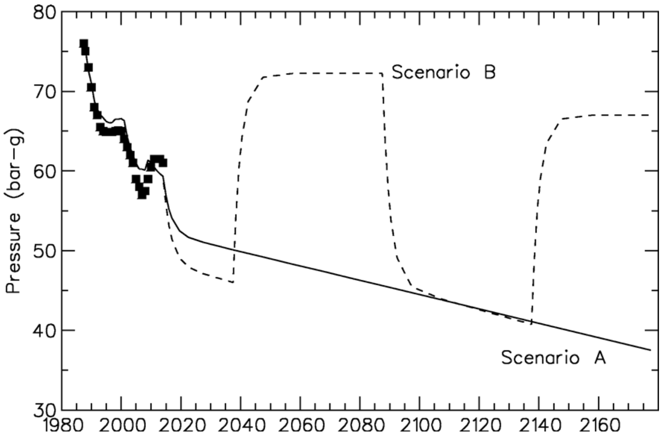

Figure 2: An example from Olkaria (Axelsson, 2010) of the 'cyclic' development concept. In Scenario B, the short term production is greater (350 kg/s), but cycles on/off. Average pressures are better supported in B than in A, by improving the balance between mass/energy extraction and recharge.

2.4 Successful examples

Examples, from IEA-Geothermal participating countries, of successful sustainable geothermal developments, where reservoir performance has stabilized over more than 35 years of production, include both higher enthalpy systems (e.g. Wairakei & Kawerau in New Zealand, Svartsengi in Iceland, and Larderello in Italy) and lower enthalpy systems (e.g. Laugarnes in Iceland, and the Paris Basin in France). Dynamic recovery factors determine the long term response of the system to energy extraction; they change with time. Recovery is influenced by an enhanced recharge driven by the strong pressure and temperature gradients initially created by the fluid and heat extraction. Because of this dynamic recovery process, rotational utilization of geothermal resources is a viable long-term strategy, and an economic and sustainable alternative to the strategy of simply limiting extraction to maintain continuous steady-state reservoir conditions. Utilization duration can be tailored to meet demand cycles (daily or seasonal), or can be extended out to periods of the order of 100 years. A term that appropriately describes this process is heat 'grazing', a concept that has also been suggested for EGS projects where fracture permeability is stimulated but limited in extent.

Figure 3: Examples of sustainable development: a) Larderello -103 years (with some grey-haired IEA-Geothermal members), and b) Svartsengi - 38 years geothermal heat-park in Iceland, a combined heat & power plant, with spa ('Blue Lagoon').

2.5 Near-surface environmental effects

In high-enthalpy, liquid-dominated systems (e.g. Wairakei, New Zealand; Svartsengi, Iceland; and Cerro Prieto, Mexico), a consequence of drawing down reservoir pressure, and increasing hot deep recharge, is that fluids may boil and possibly form two-phase zones. Conversely, re-saturation of two-phase zones may occur in reinjection sectors. This can affect the relative upflows of hot liquid and steam to the surface. Changes may include a decline in mineralized hot springs and an increase in steam-heated thermal features above production sectors, while the converse may occur above injection sectors. For reservoirs that are steam-dominated (e.g. The Geysers and Larderello), a decline in reservoir pressure may reduce the natural upflow of steam to surface features. Such changes can have both adverse and beneficial effects on established users of the surface thermal features (such as hot spring resorts), and the associated thermal ecosystems.

2.6 New environmentally sustainable management techniques

Recent strategies of geothermal environmental management have emphasized the achievement of an overall balance of effects, through avoiding adverse effects and promoting beneficial effects (Bromley et al., 2006). The objective of the strategy is to devise practical mitigation schemes to achieve these outcomes. Production and reinjection well layouts and inter-connections should be planned with built-in flexibility in order to allow rapid reaction to induced adverse effects, without compromising the efficient utilization of the resource.

Examples of adverse effects might include: reductions in natural spring discharges, increasing subsidence, excessive large magnitude seismicity, or increasing gas emissions. In many cases, technology can be applied for their avoidance, remediation or mitigation, as appropriate. Some examples of local environmental benefits deriving from adaptive production/injection strategies might include: hot stream and thermal feature creation or restoration using separated brine, increased steam-heated ground from liquid pressure drawdown, and increased hot spring discharge from shallow reinjection (if locally desirable). Indirect environmental benefits have included wetland creation in subsidence areas, and enhanced thermal ecological habitats where thermal features have increased. As stated above, the key to achieving a successful balance is to adopt an adaptive resource management strategy (see Table 1).

3. CONCLUSIONS

To summarize, an optimum level of long-term sustainable production can be achieved through adaptive management and the judicious use of simulation modeling. The degree of success depends on the utilization technology and the capability for flexible reservoir management, as well as on the geothermal resource characteristics. Long-term sustainability can be achieved by properly managing fluid production and injection rates and locations. Following temporary shutdown, practical replenishment occurs on time scales of the same order as the lifetime of the production cycle. The recovery factors that determine the long term response of these systems to fluid and energy extraction are not static but dynamic (for example, increased recovery rate through stimulated permeability increase in the hot recharge zone). Recovery rates are influenced by enhanced recharge, driven by the strong pressure and temperature gradients, created during the early stages of fluid and heat extraction.

Sustainable reservoir management also involves countering the adverse effects of premature temperature and pressure decline with appropriate and flexible production and injection strategies. Such strategies need to be adjusted at times, in order to achieve the correct balance. A key means of achieving a successful outcome is to plan for a high degree of flexibility in locating and utilizing future injection wells, both inside and outside the hydrological edges of a geothermal system. Furthermore, optimized strategies for geothermal environmental management can achieve a balance through avoiding or mitigating adverse effects and promoting beneficial ones.

Improved tracer technology helps characterize parameters such as permeability, diffusion and fluid storage between injection and production sectors. Better calibration of reservoir models improves characterization of the permeability structure and boundary recharge parameters that dictate long-term reservoir behavior.

Another successful long-term development strategy is to progressively develop the deeper parts of a known resource. The acquired knowledge and simulated behavior from early production stages is used to plan deeper drilling, by targeting the primary fluid up-flows, and by selecting injection sectors to maximize pressure maintenance while minimizing premature cooling. Over time, the shallow parts of a known resource can be 'retired' and bore-holes drilled to tap directly into higher enthalpy and more productive sectors of the resource. The rewards could be significant, but there are challenges associated with this strategy, including the need to improve the economics by reducing the cost of deep drilling, and the requirement to develop technologies to deal with super-critical and potentially corrosive reservoir fluids.

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