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Sustainability and Renewability of Geothermal Power Capacity

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ABSTRACT

For the purposes of this paper, sustainability is defined as the ability to economically maintain the installed capacity, over the amortized life of a power plant, by taking practical steps (such as, make-up well drilling) to compensate for resource degradation (pressure drawdown and/or cooling). Renewability is defined here as the ability to maintain the installed power capacity indefinitely without encountering any resource degradation; renewable capacity is, however, often too small for commercial development. This paper also considers an additional level of commercial capacity (above the sustainable level) that is not planned to be maintained fully over the entire plant life as mitigation of resource degradation would become uneconomic or otherwise impractical at some point. This declining capacity above the sustainable level is considered commercial only if the levelized power cost is lower than that from alternative renewable, or environmentally benign, energy sources. Even if power cost at this un-sustained commercial generation level proves higher than that from fossil fuels, this additional capacity can reduce fossil fuel usage if power from renewable or environmentally benign energy resources is given adequate tax breaks or price support. Displacement of fossil fuel usage is a social imperative that would reduce environmental pollution today and preserve these fuels as raw material for organic chemicals, and for potentially cleaner power generation in the future.

Renewable capacity of a field corresponds to the power capacity equivalent of the natural heat recharge, both conductive and convective, into the system, which may increase with exploitation. Sustainable capacity is supported by mining of the stored heat in addition to natural heat recharge. With an un-sustained commercial capacity, heat mining rate is initially kept higher than can be maintained for the plant life, but is eventually allowed to decline. This paper reviews both published and unpublished results of numerical simulation and surface heat flow studies of more than half of the 65 or so liquid-dominated geothermal fields in the world that have supplied commercial power; the rate of natural heat recharge into such a reservoir has been assumed equal to the total rate of heat discharge at the surface over the thermal anomaly. The review shows that the sustainable capacity of a field is about 5 to 45 times the renewable capacity, with ten times being most likely. Commercial capacity is much more project-specific and higher than the sustainable capacity. Simple quantitative expressions are given for approximate assessment of renewable, sustainable and commercial capacities of liquid-dominated geothermal systems. A case history of approximate assessment of renewable and sustainable capacities based on actual production history is given from the Wairakei field in New Zealand. This assessment is based on a simple "lumped-parameter" model, while more accurate assessment of these capacities would call for detailed numerical simulation.

1. INTRODUCTION

In recent years many thoughtful papers have been published on the renewability and sustainability of geothermal energy (for example, Axelsson, *et al*, 2004; Rybach, 2003; Axelsson, *et al*, 2001; Stefansson, 2000; Rybach, 1999; Wright, 1995). However, no universally-accepted definitions of the words "renewability" and "sustainability" seem to exist and definitions used often have ambiguities. For example, Axelsson, et al (2001) defines "renewable" generation capacity (Figure 1) as:

> "*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.*"

And Axelsson, *et al* (2001) defines "sustainable" generation capacity as follows (Figure 1):

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

We start with an objective review of the above definitions.

2. REVIEW OF DEFINITIONS

The above definition of renewability essentially equates renewable capacity to the natural conductive plus convective heat recharge rate into a geothermal reservoir, which remains constant over geologic time (that is, tens of thousands of years) in the natural state. This recharge rate can be estimated for an actual reservoir by numerical simulation of the natural, steady-state heat flow, and temperature and pressure distributions, within the system. The renewable capacity is, however, frequently too small for commercial development because of the unfavorable economy of scale in capital and operation costs and relatively high cost of infrastructure development associated with a small power project. The above definition of sustainability may perhaps be acceptable for non-electrical uses of geothermal energy, which are of very low intensity and not capital-intensive, but the definition has inherent ambiguities and limitations for practical applications to the power industry. The difference between renewability and sustainability as defined above is a matter primarily of the time scale; as discussed later in connection with the case history, an exploitation level that can be sustained for 100 to 300 years, can most likely be sustained indefinitely. Therefore, for most fields the above two definitions are essentially identical.

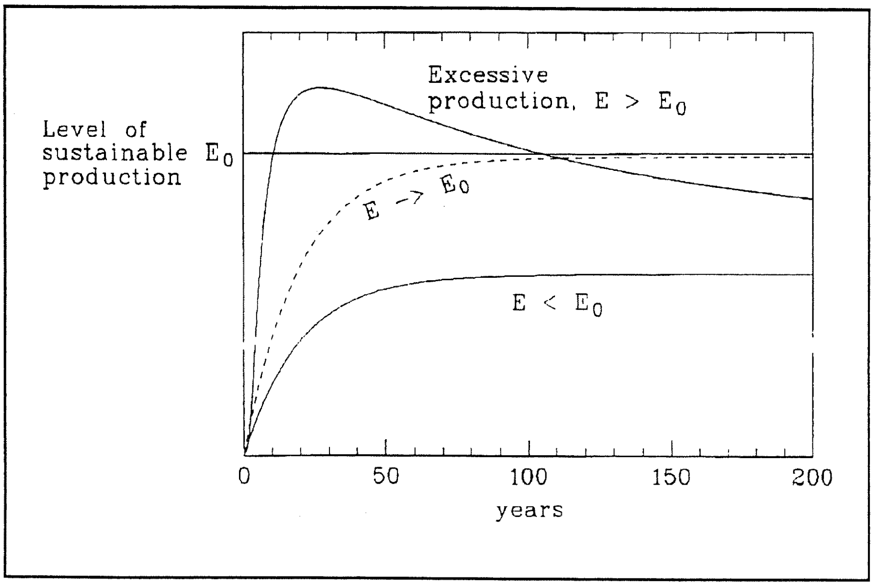

Figure 1: Illustration of the definition of sustainable and excessive production levels (according to Axelsson, *et al*, 2001)

A constant energy production rate over a time span of 100 - 300 years is reasonable for defining renewability but not sustainability. A power plant can be sustained over a typical amortized life of 30 years at a capacity level much higher than the renewable capacity level by make-up well drilling or taking other steps to mitigate resource degradation. Numerical simulation consistently shows that any resource degradation caused over a typical plant life of 30 years would essentially disappear within a 100-300 year time frame; the pressure would return to the original level in about 30 years and the temperature within 300 years, the actual time taken being dependent on the natural convective heat recharge rate (see, for example, Pritchett, 1998). Therefore, over a 100 - 300 year time span, exploitation for 30 years at the sustainable level should not leave any permanent impact on the resource base. On the other hand, it is likely that producing the reservoir at a level higher than the renewable capacity estimated from natural-state modeling would actually increase the natural recharge rate of hot water into the reservoir. This has frequently been our experience from monitoring many producing fields; the case history discussed later illustrates this point. Therefore, assessment of renewable or sustainable power capacity from the simulation of the natural state of a reservoir is conservative; substantial production history is needed to estimate these capacities with any confidence. On the other hand, unless these capacities can be determined to the satisfaction of financial institutions it is not possible to obtain long-term financing for a power plant, and unless a power plant is installed, accumulation of substantial production history is out of the question. This is a fundamental conundrum of the geothermal power industry.

Geothermal reserves are normally expressed in terms of the MWe capacity sustainable for the life of a power plant; empirical experience shows this reserve level to be an order of magnitude higher than the renewable level estimated from the natural state of the reservoir; see, for example, Table 1 (to be discussed later). Therefore, if the definition of sustainability in Figure 1, which is essentially same as renewability, is to be used, the geothermal resource base worldwide should be considered an order of magnitude smaller than is generally accepted today. In other words, exploitation of geothermal resources would be artificially constrained to an order of magnitude lower than the level at which exploitation is readily possible without long-term negative impact on the resource base. This will make development of many fields for power generation economically prohibitive. Furthermore, this cannot be a socially responsible position considering that a higher rate of exploitation can only reduce the current fossil fuel usage, thus reducing environmental pollution today and saving fossil fuel resources for future generations. There is social virtue in preserving more of fossil fuel resources for the future, and instead, maximizing the use of power from geothermal resources, which can be renewable within the 100-300 year time frame. While geothermal power today causes far less pollution than power from fossil fuels, it is inevitable that power derived from fossil fuels will become more environmentally benign in the future. Finally, unlike geothermal, fossil fuels also serve as raw material for petrochemicals and coal-based organic chemicals. While future generations may harness hitherto unforeseen sources of energy, fossil fuels will still be needed as raw material for chemicals. Therefore, one can justify a higher rate of geothermal power use today than adhering to a level that is renewable within the life-time of a power plant.

With respect to electric power capacity, this paper proposes an alternative, and more practical, definition for sustainability, and also defines a purposefully un-sustained "commercial" capacity level (Figure 2). The former is defined as the ability to economically maintain the installed capacity, over the amortized life of a power plant, by taking practical steps (such as, make-up well drilling) to compensate for resource degradation (pressure drawdown and/or cooling). The latter can be defined as a capacity level that is initially kept higher than the sustainable level but may be allowed to decline with time once make-up well drilling, or other measures to mitigate resource degradation, become uneconomic at some point in project life. In a socially responsible vein, this declining capacity starting above the sustainable level could be considered commercial only if the levelized power cost is calculated to be lower than that from alternative renewable resources. Even if the power cost at such a commercial level proves higher than that from fossil fuels, this higher capacity can displace fossil fuel usage if power from renewable or environmentally benign resources is given adequate tax breaks (such as, carbon tax credit), market access (such as, implementation of "renewable energy portfolio standards"), or price support (such as, production tax credit or any direct subsidy) by governments or international agencies.

The appropriate un-sustained but commercial level can only be arrived at by numerical simulation of the actual production behavior of the reservoir concerned and within the context of the economic realities and market forces. Such a purposefully un-sustained and commercial level is socially beneficial for a market-driven economy because it allows reduction in levelized power cost through accelerated capital recovery while helping to displace the use of fossil fuels. The cumulative energy extraction over the project life at a un-sustained but commercial level need not exceed the cumulative energy that would be extracted at the sustainable level, thus still assuring natural replenishment of the resource base in a 100 - 300 year time frame. Therefore, such a commercial development level is not only reasonable but also desirable, particularly if one considers the distinct possibility of acceleration of natural recharge of hot water into the reservoir, thus mitigating the impact of a higher initial production rate.

In discussing renewability and sustainability of geothermal energy, interesting analogies have been invoked from time to time by various authors, for example, mining, management of fisheries, utilization of hydropower, and so on. While all these analogies correspond to some aspects of geothermal energy exploitation, yet another analogy is offered here to elucidate the concept of sustainability proposed in this paper. A reasonable analogy for renewable capacity would be seasonal harvest of crops while timber harvest would be an appropriate analogy for sustainable capacity, for the timber resource would grow back within a few decades. One could harvest only the annual growth at the tips of the tree limbs and keep the forest resource constantly renewable. But is this approach to natural resource husbandry reasonable? While renewable, annual tree growth can be used as firewood or turned into paper pulp, the forest resource is more valuable to the society if mature trees are harvested for timber and then allowed to grow back. Likewise, constraining geothermal energy exploitation within a continuously renewable level, which is suitable primarily for low-intensity, non-electrical uses, is neither reasonable nor desirable from a socioeconomic viewpoint. In addition, thinning of a forest accelerates tree growth due to the penetration of more sunlight into the forest; this is a convenient metaphor for the increase in natural recharge rate due to exploitation of a geothermal resource above the so-called renewable level.

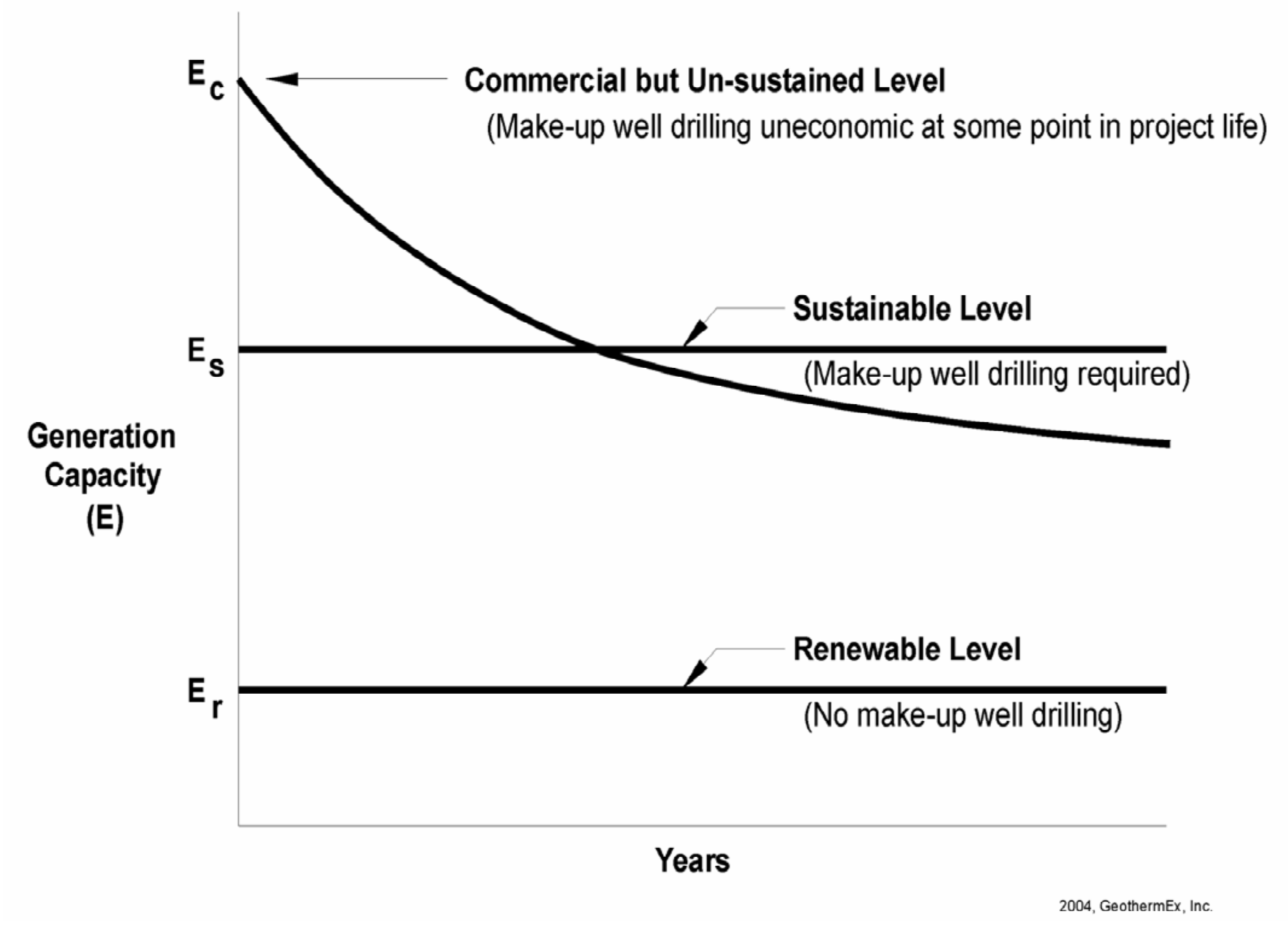

Figure 2: Proposed definitions

3. EMPIRICAL RELATION BETWEEN RENEWABLE AND SUSTAINABLE CAPACITIES

In this paper we consider only liquid-dominated geothermal fields with capacity for supplying electric power, steam-dominated fields being rare occurrences; only six steam-dominated fields have been exploited to date: The Geysers, California; Lardarello, Italy; Matsukawa, Japan; Kamojang and Darajat; Indonesia; and Los Azufres, Mexico. Based on GeothermEx's experience in monitoring many producing geothermal fields for more than three decades and conducting dozens of numerical simulation studies of actual reservoirs, the author has observed that the sustainable capacity of a liquid-dominated field is typically an order of magnitude higher than the renewable capacity. The understanding here is that the renewable capacity of a field corresponds to the power capacity equivalent of the natural heat recharge, conductive plus convective, into the system; and sustainable capacity is supported by "mining" of the stored heat in addition to natural heat recharge. To confirm this empirical observation an exhaustive review has been made of both published and unpublished results of numerical simulation and heat flow studies of more than half of the approximately 65 liquid-dominated geothermal fields in the world that have supplied commercial power and for which reasonably reliable estimate of the natural heat recharge rate could be made. The heat recharge rate was estimated from either numerical simulation or surface heat flow studies, assuming the rate of natural heat recharge into the reservoir to be equal to the total rate of heat discharge at the surface over the entire thermal anomaly.

Table 1 lists approximate estimates of the renewable and sustainable capacities of 37 fields. The electrical power equivalent (MWe) was approximated from the estimated thermal power capacity based on First and Second Laws of Thermodynamics assuming a rejection temperature of 15°C and a utilization factor of 0.45. The sustainable capacity value for a field in Table 1 was taken as the proven exploitation capacity, unless actual reservoir response and/or simulation studies had indicated the sustainable capacity to be higher. As such, the sustainable capacity values in Table 1 should in general be considered minimum estimates. As mentioned before, this table illustrates that renewable capacities are relatively small compared to sustainable capacities, the total for 37 fields being 386 MWe and 2056+ MWe, respectively. Furthermore, at the renewable level most fields would not support commercial power development; for example, if 10 MWe were the smallest commercially developable capacity, only 11 of the 37 fields would qualify.

Table 1. Empirical Data on Renewable and Sustainable Capacities

Field	Location	Renewable Capacity (MWe)	Sustainable Capacity (MWe)	Reference
Ahuachapan	El Salvador	24.8	95+	Parini, *et al* (1995)
Beowawe	Nevada	1.3	13+	Butler, *et al* (2001)
Cerro Prieto	Mexico	73.3	720	Butler, et al (2000)
Desert Peak	Nevada	14	90+	Wisian, et al (2001)
Dixie Valley	Nevada	2	55	
Heber	California	1.7	70	Lippman and Bodvarsson (1985)
Los Humeros	Mexico	2	30	
Kakkonda	Japan	26.6	80+	McGuinness, *et al* (1995)
Kawareu	New Zealand	15.5	230	White, *et al* (1997)
Krafla	Iceland	5.3	60	Tulinius and Sigurdsson (1989)
Latera	Italy	2	22.5	
Mammoth	California	25	90+	Sorey, M. L. (1985)
Mindanao	Philippines	9.6	102	Esberto, *et al* (1999)
Miravalles	Costa Rica	16.5	168	Haukwa, *et al (1992)*
Mori	Japan	5.4	50	Sakagawa, *et al* (1994)
Mutnovsky	Russia	9.2	100	Kiryukhin (2004)
Nesjavellir	Iceland	16.6	160	Steingrimsson (2000)
Ngawha	New Zealand	2.5	30	McGuinness (1998)
Oguni	Japan	8.2	20+	Yamada *et al* (2000)

Field	Location	Renewable Capacity (MWe)	Sustainable Capacity (MWe)	Reference
Okuaizu	Japan	2	45	
Onikobe	Japan	2	25	Nakanishi, *et al* (2000)
Puna	Hawaii	7	60+	
Ribeira Grande	Portugal	5	25+	
Roosevelt Hot Springs	Utah	5.3	50+	Yearsley (1994)
Salton Sea	California	16	600+	
San Emidio	Nevada	1.9	10+	Wisian, et al (2001)
Sibayak	Indonesia	11	30+	Atmojo, *et al* (2001)
Soda Lake	Nevada	1.6	15	Wisian, *et al* (2001)
Steamboat	Nevada	5	50	
Stillwater	Nevada	4	40	Wisian, et al (2001)
Sumikawa	Japan	4	50+	Pritchett, *et al (1991)*
Takigami	Japan	3	25	Furuya, *et al* (2000)
Tres Virgenes	Mexico	0.5	8	
Uenotai	Japan	2.5	25	Butler, *et al* (2004)
Wairakei	New Zealand	46	220+	Bibby, *et al* (1995)
Wasabizawa	Japan	5.6	40+	Sanyal, *et al* (2000)
Zunil	Guatemala	2.44	25	Menzies, *et al* (1991)
		Total: 386	Total: 2056+	

Figure 3 is a cross-plot of the above-listed renewable and sustainable capacities. The points with arrows in the direction of higher sustainable capacity represent fields for which the presently installed capacity appears manifestly smaller than the sustainable capacity but no estimate of the latter is available. This figure confirms our empirical observation that sustainable capacity is typically an order of magnitude higher than renewable capacity. Specifically, sustainable capacity (E_s) is a multiple, α, of renewable capacity (E_r), where α ranges from about 5 to 45, with a value of 10 most likely. We have always observed that α, which we have named "Sustainability Factor," tends to be high for a hydrothermal reservoir if the host formation is sedimentary. This is to be expected because having intergranular porosity, such a formation would display better heat transfer characteristics than a fractured non-sedimentary formation.

Wisian, *et al* (2001) concluded from surface heat flow studies of a large number of geothermal fields, that the presently installed capacity in most fields is equivalent to no more than 10 times the natural heat discharge rate at the surface. Wisian, et al (2001)'s conclusion at first seems to contradict this paper's that the sustainable capacity is 5 to 45 times the natural heat discharge rate, 10 times being most likely rather than the maximum. This difference can be explained by the fact that Wisian, *et al* (2001) considered installed plant capacity, which is in general smaller than the maximum sustainable capacity.

Finally, the empirical observation that the sustainable capacity of a reservoir is an order of magnitude higher than the renewable capacity implies that, following exploitation, the reservoir is expected to take an order of magnitude higher time span compared to the exploitation period for complete natural replenishment. This supports the earlier observation from reservoir simulation that the depletion effects of power production for 30-years would require on the order of 300 years to disappear.

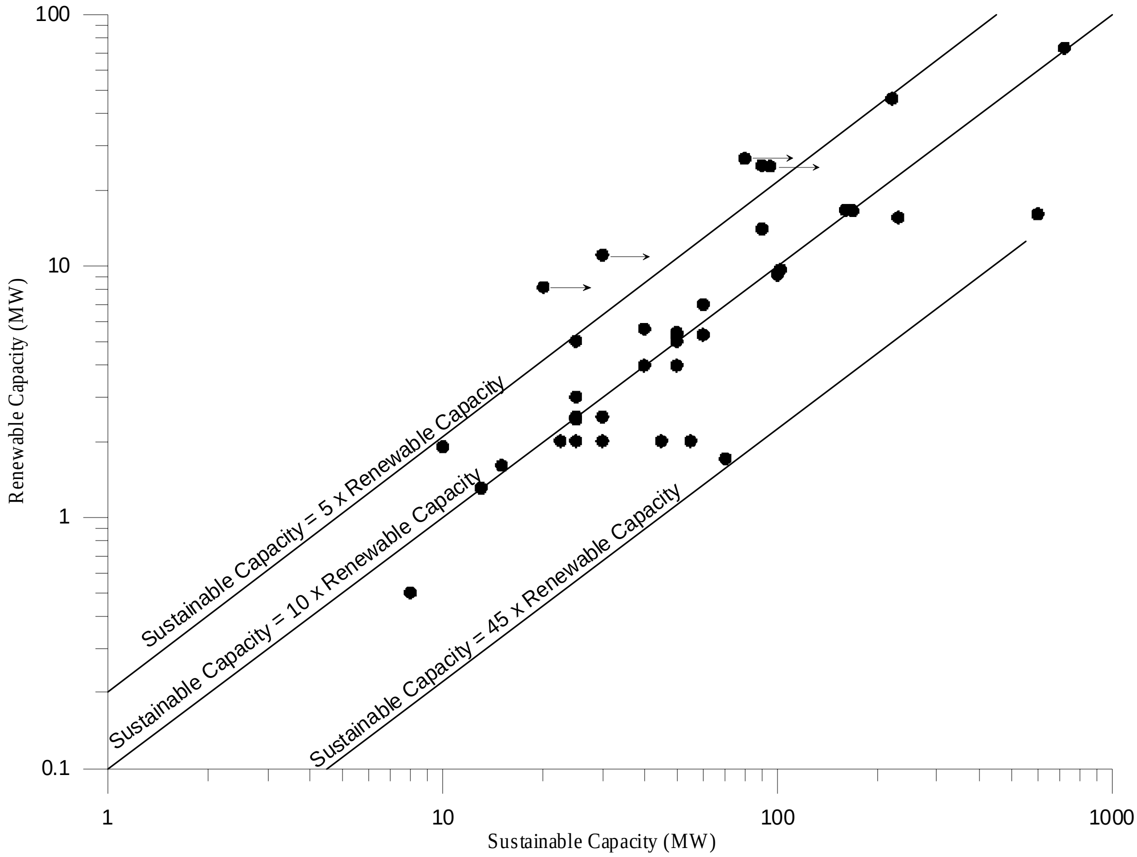

Figure 3: Renewable capacity versus sustainable capacity

4. ESTIMATING RENEWABLE, SUSTAINABLE AND COMMERCIAL CAPACITIES

The best tool for quantifying renewable capacity is a numerical simulation model that reproduces the natural state of the reservoir. But estimating sustainable and commercial capacities requires not only natural state modeling but also trial-and-error matching of the actual production history of the reservoir, and forecasting, using a reservoir simulation model. Estimation of un-sustained commercial capacity also requires market considerations and economic analysis. Assessment of even renewable capacity may require trial-and-error history matching and forecasting if recharge rate increases with reservoir pressure decline, which is often the case. Obviously, the effective use of such a numerical model requires adequate data on the natural state of the reservoir and significant production history. For some fields, renewable and sustainable capacities can be approximated by simple, "lumped-parameter" modeling of the production history. For many fields data may not be available for either numerical or even lumped-parameter modeling. For such situations, approximate formulations to quantify these capacities are presented in Sanyal, *et al* (2004) and are reproduced below.

By definition, Renewable Capacity (Sanyal, *et al*, 2004) is given by:

$$(E_r) = R = D_{cond}, \tag{1}$$

where R is heat recharge rate into the reservoir (primarily convective with a small conductive component) and D_{cond} is total heat discharge from the surface over the thermal anomaly; if the entire heat anomaly on the surface is considered, the convective component of heat discharge is usually negligible. Ideally, D_{cond} should be estimated from a "heat budget" survey of the anomaly including conductive heat loss at the surface, convective heat discharge at surface manifestations, and subsurface convective heat loss to regional aquifers.

Strictly speaking, the small rate of background (regional) heat flow should be subtracted from the estimates of renewable capacity above and sustainable capacity as presented below (Sanyal, *et al*, 2004). However, given the approximate nature of this estimation, this correction is unnecessary in most situations.

Sustainable capacity (E_s), considering both heat mining and heat recharge, is given as (Sanyal, *et al*, 2004):

$$E_s = \left\{ \left(\frac{C_v}{KL} \right) rhd \left(\frac{A_{res}}{A} \right) + 1 \right\} D_{cond}, \tag{2}$$

where C_v is volumetric specific heat of fluid-filled rock, K is thermal conductivity of the overburden, L is plant life, r is heat energy recovery factor, h is reservoir thickness, d is depth to the top of the reservoir, A_{res} is reservoir area, and A is the area of the entire thermal anomaly.

A conservative definition of commercial capacity (E_c) is that $E_c > E_s$ initially, but eventually falls below E_s, such that the total energy recovered over the plant life is same as would be for production at the sustainable level. With this definition, and harmonic decline in well productivity it can be shown (Sanyal, *et al*, 2004):

$$E_c = \frac{E_s L D_i}{\ln(1+D_i L)}, \qquad (3)$$

where D_i is initial decline rate in well productivity. E_c can be considerably higher than E_s, depending on economic factors. The higher the margin by which E_c exceeds E_s, the higher is D_i.

Let us consider an actual example, that of the Beowawe field in the State of Nevada, United States. For this field,

$$\left(\frac{A_{res}}{A}\right) \approx 0.1,$$

d = 900m, and h = 1,500m.

From Butler, *et al* (2001), for this field R = 1.3 Mwe ≈ D_{cond} (ignoring background heat flow).

Therefore, Renewable Capacity = 1.3 Mwe

Typical values of the other parameters are: C_v = 2,700 kJ/m^3/°C, K = 3.1 W/m/°C, L = 30 years and r = 0.1.

Therefore, from (2), Sustainable Capacity ≈ 18 Mwe (ignoring background heat flow).

Most-likely reserves for this field, from Klein, *et al* (2004) = 58 Mwe

Therefore, commercial capacity would fall somewhere between 18 and 58 MWe, depending on the economic factors. For example, if no make-up well drilling is contemplated and an initial productivity decline rate of 10% is economically acceptable, from (3), E_c = 40 MWe.

The above discussion shows that renewable development level for the Beowawe field is only 1.3 MWe, which is entirely uneconomic. While a sustainable capacity of 18 MWe is commercial, a capacity of 40 MWe may even be more attractive economically, and yet would cause no further energy draw from the reservoir, and consequently, the reservoir should still be replenished naturally, in a 100-300 year time frame. It should be noted that a plant capacity of 13 MWe has already been sustained in this field over the past two decades.

5. A CASE HISTORY FROM THE WAIRAKEI FIELD, NEW ZEALAND

This is a case history of estimating renewable and sustainable capacities of a field from its production history using a simple "lumped parameter" model. The Wairakei field presents a good case history because: (a) it has more than 50 years of production history, longer than that of any other liquid-dominated field in the world; (b) it offers an extensive database that is publicly available (for example, Clotworthy, 2000); and (c) since the average temperature of this reservoir has not declined significantly over its long production history, its pressure behavior can be reasonably modeled by considering material balance only (rather than coupled materials-and-energy balance).

Numerical simulation and heat flow studies of this field have shown the steady-state recharge rate in natural state to be about 31 ktonnes/day; in other words, the minimum renewable depletion capacity (E_r) is 31 ktonnes/day. Figure 4 presents a plot of the mass depletion rate (m), defined as production rate minus injection rate, versus time. As of 1956 (2000 days from the initiation of production in 1950) the reservoir pressure in the deep liquid zone in the Western Borefield (the portion of the field eventually most exploited) was about 52 bar-a, and negligible production had taken place before that time. Therefore, from equation (A-4) in Appendix, reservoir pressure (p) is given as:

$$p = 52.0 - \frac{(m-31)}{r}\left[1 - e^{-\frac{r}{s}(t-2000)}\right], \qquad (4)$$

where m is assumed constant with time (t, days), r is a recharge coefficient (ktonnes/day/bar) and s is a reservoir storage coefficient (ktonnes/bar).

Figure 5 shows the cumulative depletion history of the field. Between 2000 days and the present, a reasonably linear trend can be defined with a slope of 135 ktonnes/day. Therefore, we can approximate a constant value of m after 2000 days as 135 ktonnes/day. The unknowns r and s in equation (4) can be estimated by trial-and-error; Figure 6 shows the best fit the author obtained between the observed pressure (continuous curve) at the deep liquid zone of the Western Borefield and the computed pressures (solid circles) as a function of time; this fit required an s value of 11,000 ktonnes/bar and an r value of 4.2 ktonnes/day/bar. The fit in Figure 6 is good between 5,000 and 18,000 days, a span of 36 years; a look at Figure 5 shows that the poor match before and after this period is to be expected as the depletion trend had deviated significantly from the linear in the very early and very recent periods.

The overall recharge rate at any time is the sum of the steady-state recharge rate (m_{sr}) and the pressure dependent component of recharge rate (m_r), the latter being given, from (A-2) and (A-4) in the Appendix. Using the r and s values derived above, the historical rate of recharge at Wairakei has been estimated as shown in Figure 7. Overall, fluid recharge at Wairakei to date appears to have been generally hot because negligible overall cooling of the reservoir has been noted in 50 years, and recharge has steadily increased in response to pressure drawdown (Figure 7). For this reason, the renewable level of depletion of this reservoir has become steadily higher than the steady-state depletion rate of 31 ktonnes/day derived from natural-state modeling. In fact, the recharge rate by 17,000 days has nearly equaled the depletion rate; if the entire recharge here indeed represents hot fluid entry from depth, then a depletion level of 135 ktonnes/day, rather than 31, can be considered renewable.

Now, what is the sustainable depletion capacity (E_s) of this reservoir? If the minimum static reservoir pressure at which wells in this field can still flow commercially can be estimated, then one can calculate E_s for any assumed project life. Wellbore simulation for wells producing from the deep liquid zone at Wairakei indicates this minimum pressure value to be about 15 bar-a. Therefore, we can calculate the sustainable capacity, assuming only hot recharge, for any assumed project life from (4).

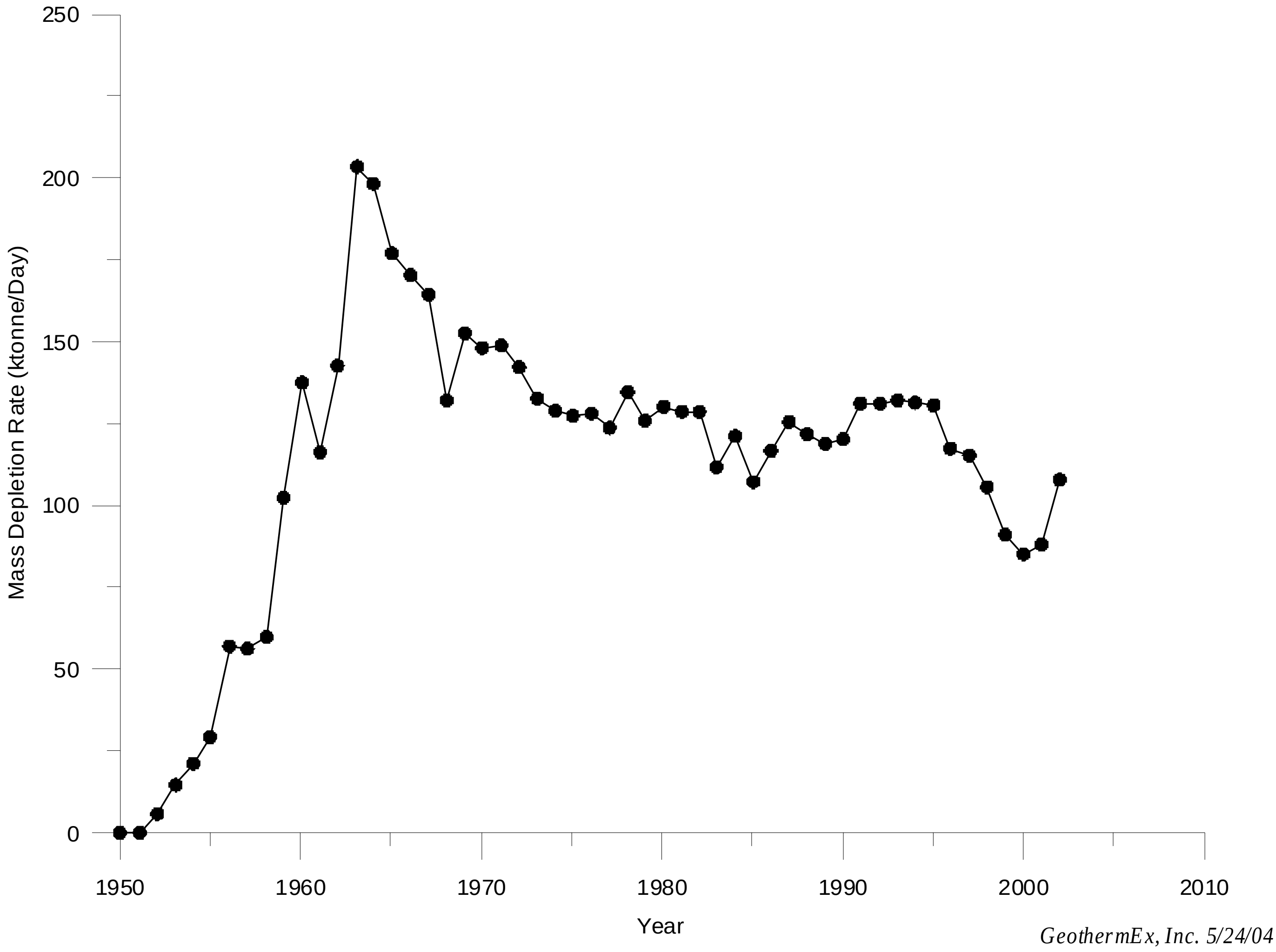

Figure 4: Mass depletion history

The above equation gives very similar values of E_s for a 30-year or a 300-year project life, 188.8 and 186.5 ktonnes/day, respectively. This relative insensitivity of E_s to project life is due to the very high recharge coefficient and the apparent preponderance to date of hot rather than cool recharge at Wairakei; this latter fact is also supported by numerical simulation. Since recharge rate in most fields is lower than at Wairakei, an assessment was made of how E_s would have changed as a function of project life if the recharge coefficient at Wairakei were smaller. Figure 8 shows the calculated E_s value versus project life for a range of hypothetical recharge coefficients expressed as fractions of the actual recharge coefficient at Wairakei. Figure 8 shows that as the recharge coefficient becomes smaller so does sustainability and the latter becomes more sensitive to project life. Figure 9 shows the same data as in Figure 8 represented as sustainable capacity versus recharge coefficient for project lives of both 30 years and 300 years. This figure illustrates that the difference between renewable and sustainable capacities for 30-year and 300-year project lives becomes less as recharge coefficient increases, for Wairakei this difference (corresponding to an r of 4.2 ktonnes/day) being negligible.

Finally, it should be noted that sustainability factor (α), as defined before, for Wairakei is 188.8/31, or 6.1. Why is this value of sustainability factor at the low end of the range of 5 to 45 mentioned earlier? The reason is that until recently, there was no injection in the this field. Therefore, the above analysis is based on depletion being equal to production. If injection is practised, the effective depletion rate will be lower than production rate, and therefore, a higher production capacity can be sustained. For example, if 50% of the produced fluid were injected, the sustainable production rate would be double the sustainable depletion rate (188.8 ktonnes/day), that is, 377.6 ktonnes/day, assuming the recharge to be predominately hot. Therefore, sustainability factor would be 377.6/31 or 12.2; this sustainable production capacity is an order of magnitude higher than the renewable capacity of 31 ktonnes/day.

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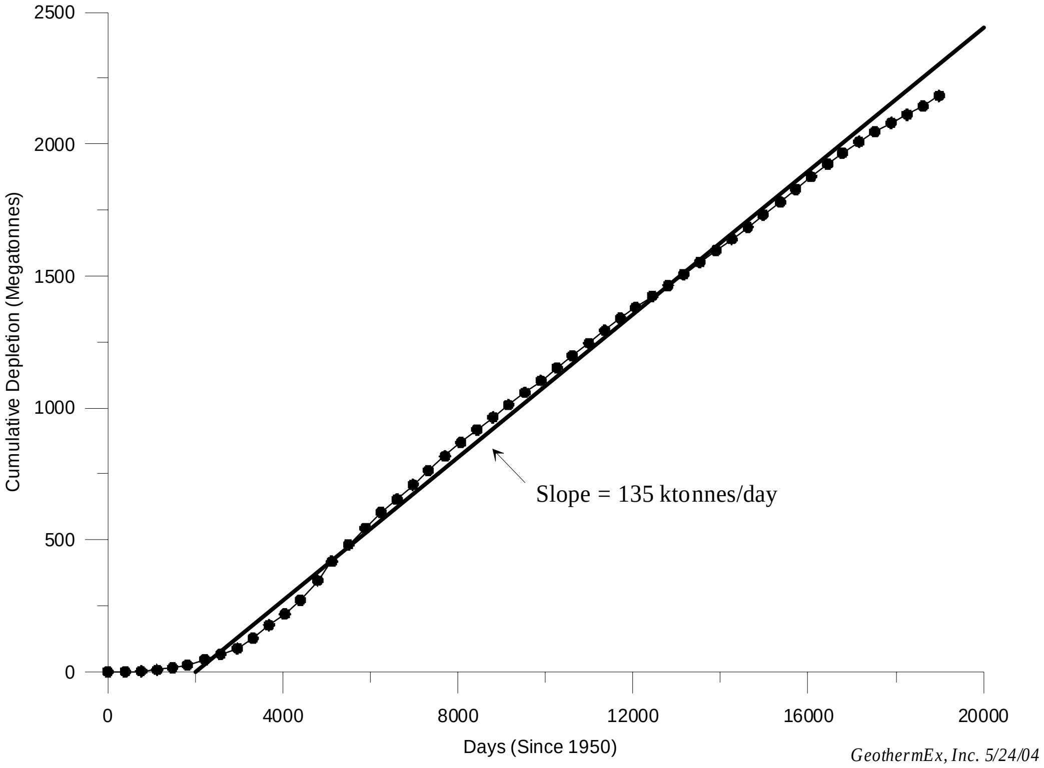

Figure 5: Cumulative depletion history

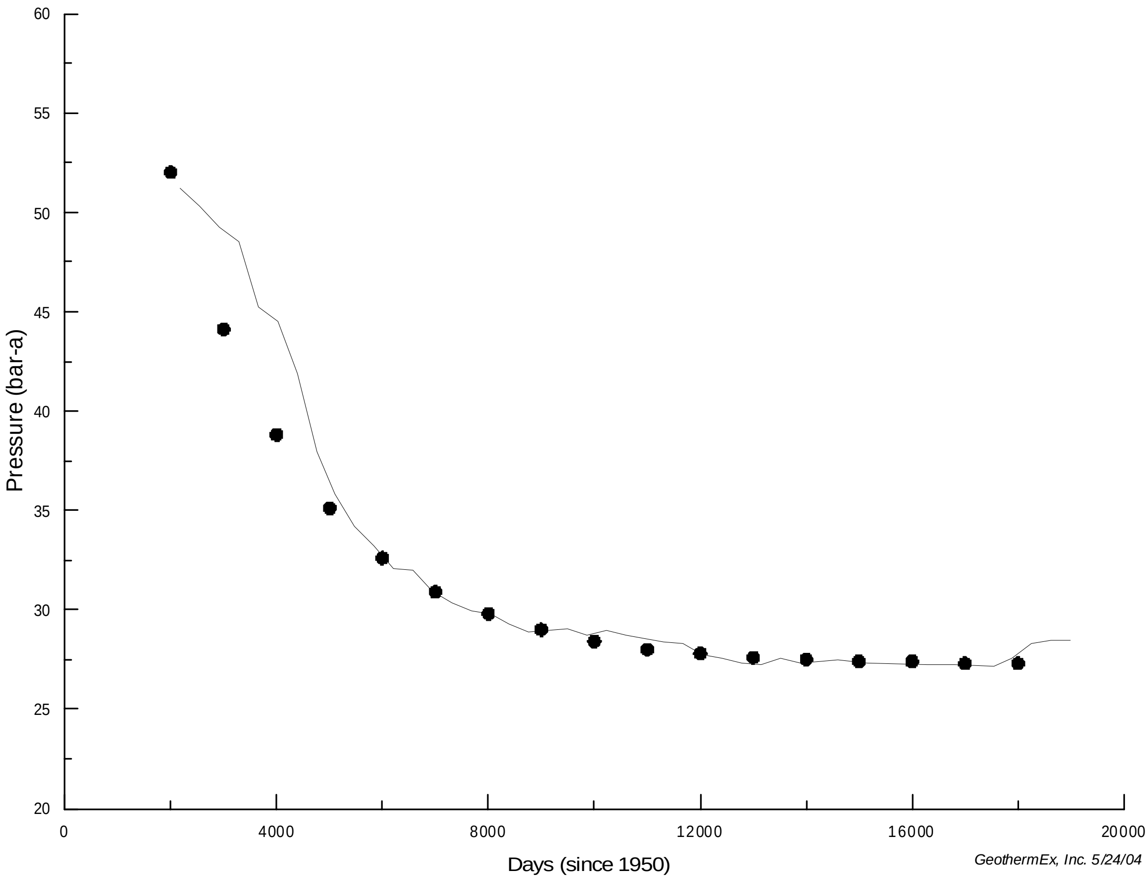

Figure 6: Observation and computed liquid pressures, Western Borefield

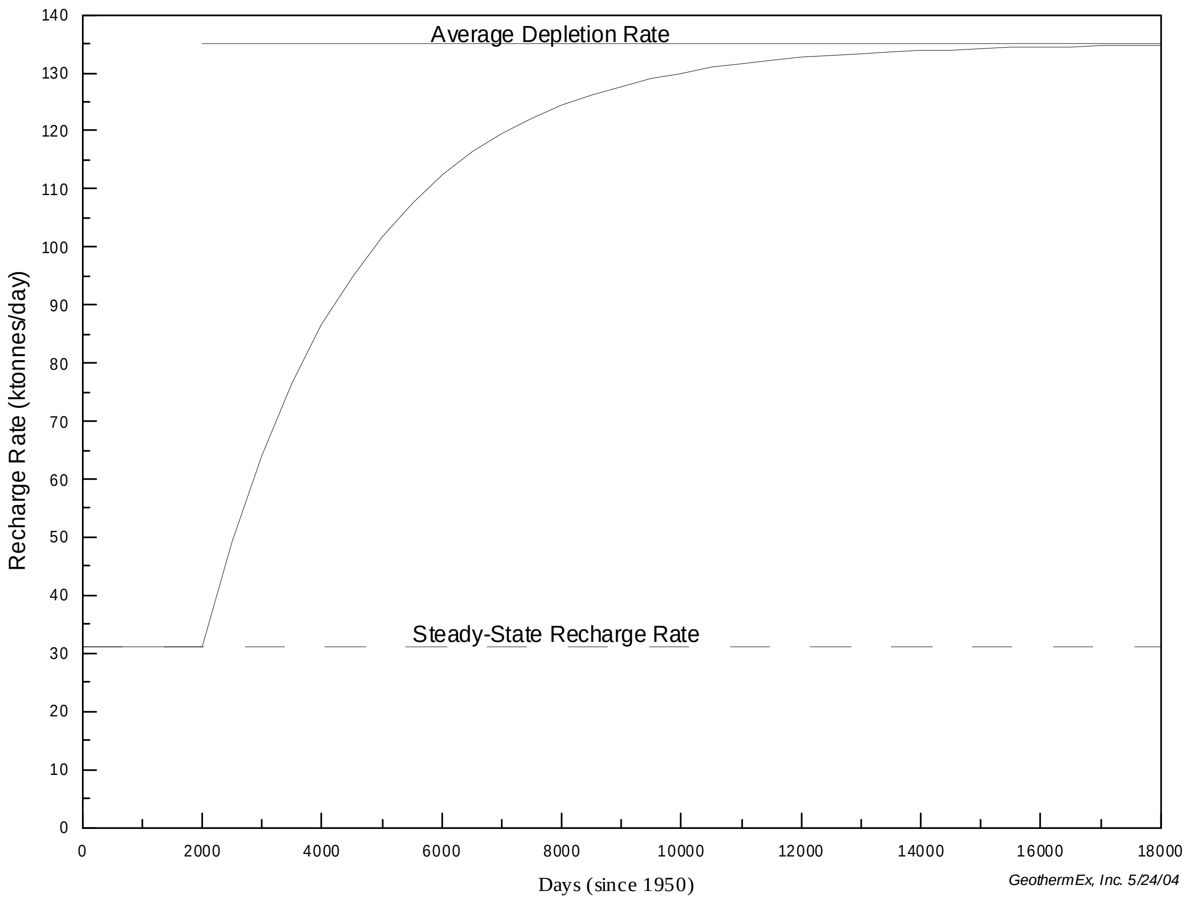

Figure 7. Recharge versus time, Wairakei field

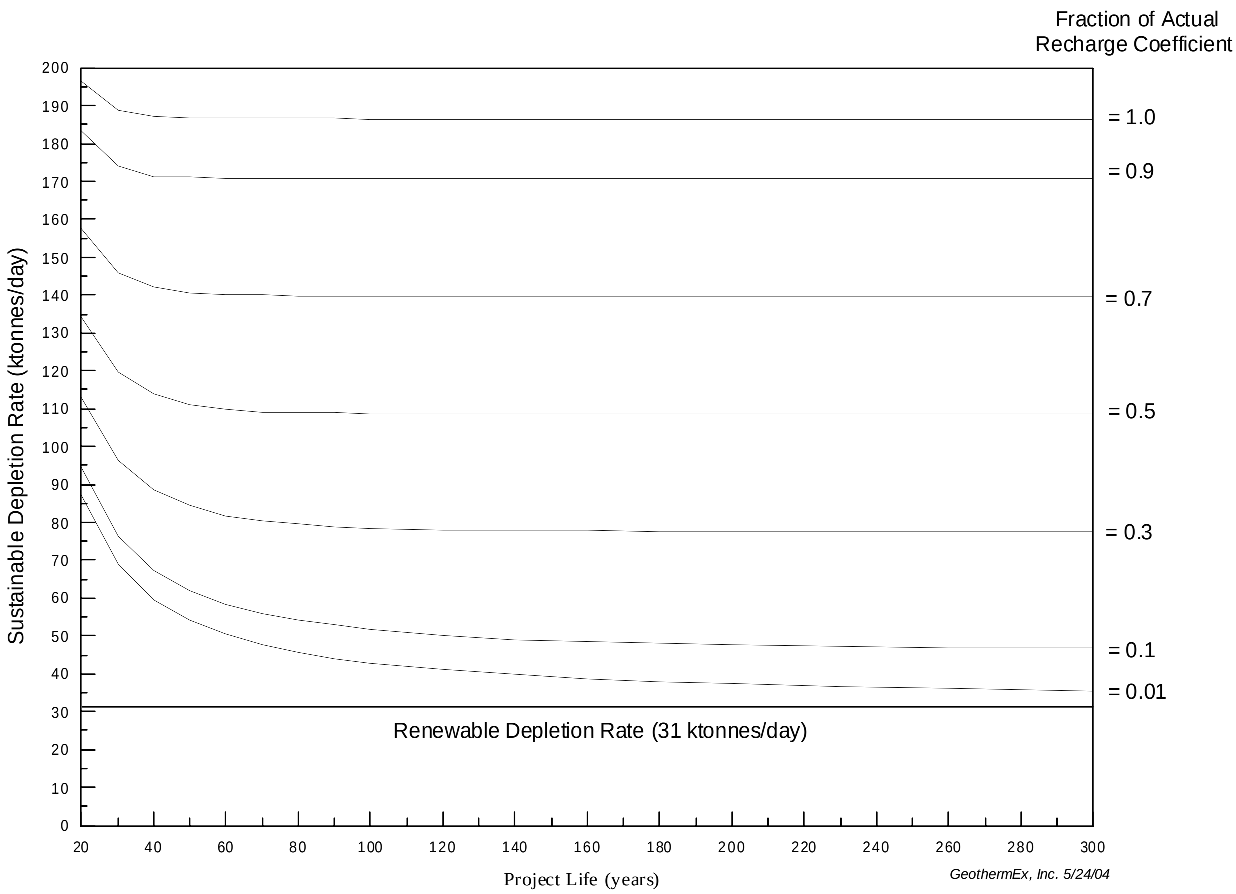

Figure 8. Sustainable depletion rate versus project life, Wairakei field

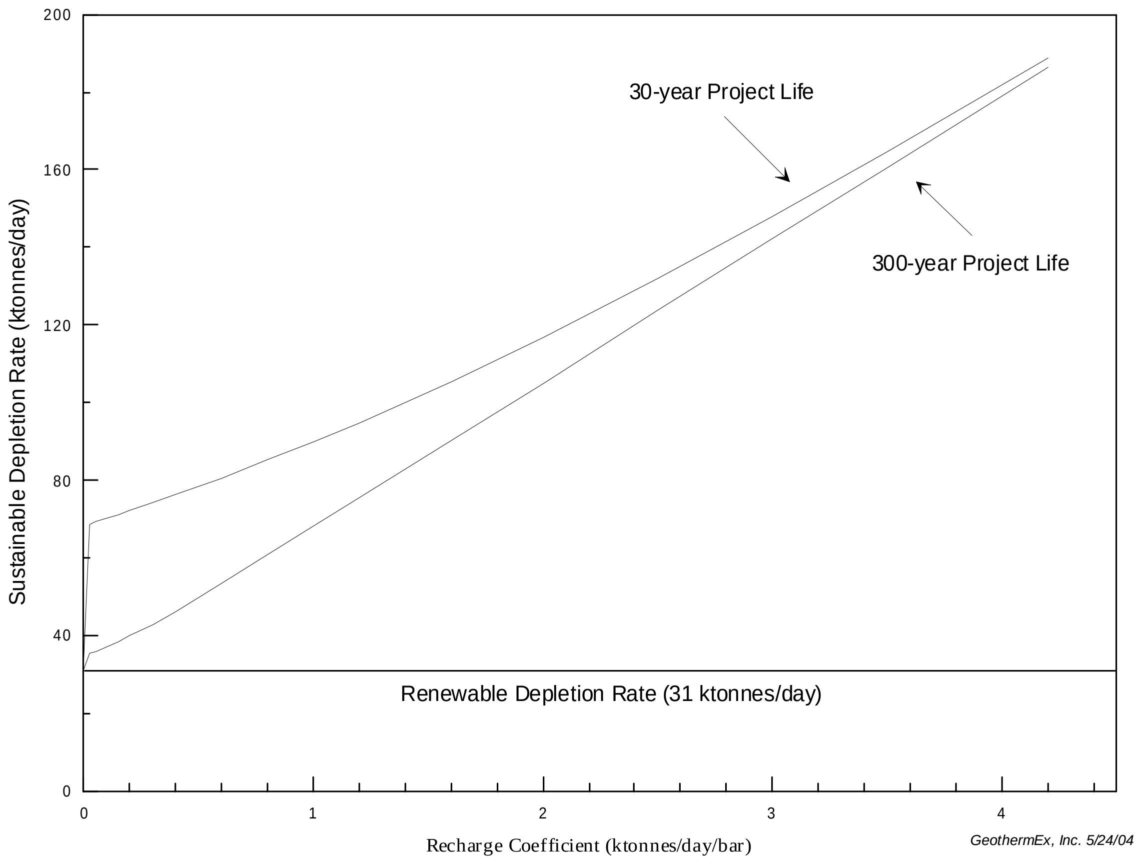

Figure 9: Sustainable capacity versus recharge coefficient

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APPENDIX: LUMPED PARAMETER MODEL USED

Considering material balance,

$$m - m_{sr} = -s\left(\frac{dp}{dt}\right) + m_r \quad \text{(A-1)}$$

where *m* is mass depletion rate (ktonnes/day), equal to production rate minus injection rate, m_{sr} is rate of the steady-state component of recharge into the reservoir in natural state (ktonnes/day), assumed to be independent of exploitation, m_r is rate of the pressure-dependent component of recharge into the reservoir that increases as reservoir pressure declines (ktonnes/day per bar), *s* is a storage coefficient for rock and fluids, that is, fluid mass contributed to production by the expansion of rock, water and steam as reservoir pressure declines (ktonnes/bar), *p* is static reservoir pressure (bar-a), and *t* is time since the start of exploitation (days).

Assuming a typical linear relation between recharge rate and reservoir pressure decline at time *t*,

$$m_r = r(p_i - p), \quad \text{(A-2)}$$

where p_i is initial reservoir pressure (bar-a), *p* is reservoir pressure at time t (bar-a), and *r* is a recharge coefficient (ktonnes/day per bar).

Combining (A-1) and (A-2),

$$-s\left(\frac{dp}{dt}\right)+r(p_i - p)-m+m_{sr}=0, \qquad \text{(A-3)}$$

Solving the above ordinary differential equation,

$$p = p_i - \frac{(m-m_{sr})}{r}\left[1-e^{-\frac{r}{s}t}\right]. \qquad \text{(A-4)}$$