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Renewability of geothermal resources

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ABSTRACT

In almost all geothermal projects worldwide, the rate of extraction of heat energy exceeds the pre-exploitation rate of heat flow from depth. For example, current production of geothermal heat from the Wairakei–Tauhara system exceeds the natural recharge of heat by a factor of 4.75. Thus, the current rate of heat extraction from Wairakei–Tauhara is not sustainable on a continuous basis, and the same statement applies to most other geothermal projects. Nevertheless, geothermal energy resources are renewable in the long-term because they would fully recover to their pre-exploitation state after an extended shut-down period. The present paper considers the general issue of the renewability of geothermal resources and uses computer modeling to investigate the renewability of the Wairakei–Tauhara system. In particular, modeling is used to simulate the recovery of Wairakei–Tauhara after it is shut down in 2053 after a hundred years of production.

1. Introduction

The average heat flux through the surface of the continents is 65 mW/m^2 and through the oceanic floor it is 101 mW/m^2 (see Pollack et al., 1993; Stefansson, 2005). Thus, the weighted average for Earth is 87 mW/m^2. In warm water geothermal systems, the heat flux is two to three times the world average and the only heat transfer mechanism is conduction. However, in vigorous convective geothermal systems such as Wairakei (New Zealand), the heat flux is much larger and is accompanied by a large convective mass flow as well. In its pre-production or natural state, the total mass flux at Wairakei was in the range of 350–550 kg/s (Allis, 1981) and the corresponding energy flow was 400–620 MW$_{th}$ (in our computer model of Wairakei–Tauhara we use a value of 560 MW$_{th}$). However recently at Wairakei the electrical output has been approximately 170 MW$_e$ produced from an average mass take of approximately 135 ktonnes/day with a corresponding energy flow of 1900 MW$_{th}$. As shown in Fig. 1, the mass production at Wairakei–Tauhara has been relatively constant for almost 30 years but the electrical output has increased slowly as plant modifications have improved the conversion efficiency. More recently in 1997, a second small power station (approximately 40 MW$_e$) was added at Poihipi Road, and in 2005 a 16 MW$_e$ binary plant was commissioned. More details of the history of Wairakei–Tauhara geothermal field are given by Clotworthy et al. (1999), Thain and Carey (2009), and Bixley et al. (2009).

The amount of thermal energy extracted from a geothermal system compared with the natural through-flow of energy is very important with regard to the sustainability of the resource. For convenience we introduce the term "production ratio" or PR defined by:

$$\mathrm{PR} = \frac{(\text{produced energy flow})}{(\text{natural energy flow})} \tag{1}$$

Using the lowest figure from Allis (1981), a production ratio (PR) of 4.75 is calculated for Wairakei. Thus, heat is currently being removed from the Wairakei–Tauhara system faster than it is being replaced by deep recharge and obviously, the present rate of electricity generation cannot be sustained forever. Computer modeling studies show that the present rate of steam production at Wairakei–Tauhara can be sustained for at least 50 years (see O'Sullivan et al., 1998; Mannington et al., 2000, 2004; O'Sullivan and Yeh, 2007; O'Sullivan, 2009) but the question remains as to what happens after that. The purpose of this paper is to investigate the following two matters:

(i) How long will it take for Wairakei–Tauhara to fully recover to its original state after shut-down at some time in the future?
(ii) What changes will occur during the recovery process?

The first question will be addressed initially by considering a simple lumped parameter model of the Wairakei–Tauhara geothermal system. Then both questions will be investigated with a large, complex, three-dimensional computer model. A preliminary version of the modeling results was previously presented by O'Sullivan and Mannington (2005). Here, an updated model (O'Sullivan and

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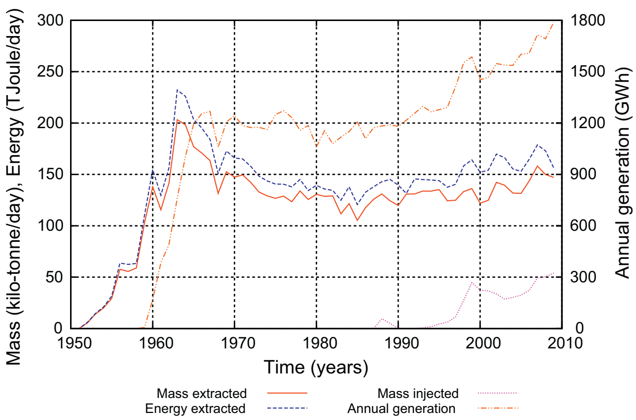

Fig. 1. Production history at Wairakei.

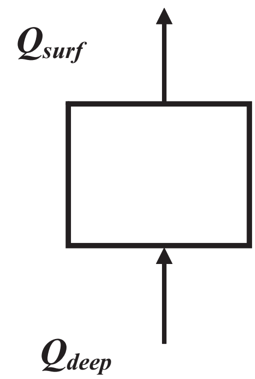

Fig. 2. Diagrammatic sketch of the natural state of a geothermal system.

Yeh, 2007, 2010) is used in a simulation study of Wairakei–Tauhara, and the general discussion of the renewability of geothermal resources is extended to all types of geothermal systems.

Wairakei–Tauhara is a very vigorously convecting geothermal system with a large natural-state surface heat and mass flows not typical of all geothermal systems. Therefore, other types of geothermal systems are considered here to cover the entire spectrum. The system parameters for some typical geothermal fields are summarized in Table 1. The parameters are from: O'Sullivan and Yeh (2010) for Wairakei–Tauhara; Riney et al. (1979) and Sonnelitter et al. (2000) for East Mesa; and Alamsyah et al. (2005) and Hoang et al. (2005) for Darajat. The parameters for Cooper Basin were taken from Hutchings and Wyborn (2006) and Voros et al. (2007).

A lumped parameter approach described in Section 2 below shows that the recovery time for a geothermal system after 100 years of production is given approximately by (PR-1) × 100. This formula was used to calculate the recovery times in Table 1. The large range in the recovery times can be explained by considering the heat flow mechanisms that are active in each type of geothermal system. In a hot water system like East Mesa (Riney et al., 1979; Sonnelitter et al., 2000) the dominant heat transfer mechanism is conduction. The contribution from convection is small (or zero in some similar cases) and thus the total heat flux is comparatively small. Over 100 years of production, most of the heat required for electricity production comes from storage, not from the natural flow from depth. Once production ceases, the mechanisms for replenishing the stored heat are conduction and a low rate of convection, both of which are slow processes.

For Wairakei–Tauhara, the dominant heat transfer mechanism is convection while conduction plays only a minor role. In this case the heat flow required for electricity production does exceed the natural heat flow, but by a smaller factor than for the other types of geothermal system. After production ceases the recovery is relatively fast driven by strong convective heat transfer.

In a vapor-dominated system like Darajat, the through-flows of heat and mass are quite small. In the vapor zone the counter flow of steam upwards and water downwards accounts for most of the flow of heat. Some of this is lost to the surface via small discharges of steam through fractures in the capping layers, while the rest is lost through conduction. The very deep flow of heat is mainly from conduction and therefore, the heat mined by production wells will be only slowly replaced.

For EGS or hot dry rock projects, most of the heat flow is by conduction with heat being generated by radiogenic decay in rocks such as granites and often thick overlying sediments act as low conductivity thermal insulators (e.g., see Beardsmore, 2004). Therefore, the heat flows are small and replenishment of mined heat will be very slow.

2. Lumped parameter model

In the pre-production or natural state, a geothermal system can be represented by the lumped-parameter model shown in Fig. 2.

Here the surface outflow of heat Q_{surf} is equal to the deep inflow Q_{deep}, i.e.:

$$Q_{surf} = Q_{deep} \tag{2}$$

It should be noted that it is often difficult to accurately estimate Q_{surf}, as the obvious surface manifestations may be small and some of the deep upflow of heat may be lost to shallow groundwater aquifers.

During production, energy is extracted at a rate, Q_{prod}, by the production wells. Some additional convective flow and deep hot recharge, Q_{rech}, may be stimulated by the production induced pressure decline. Thus the rate at which heat is being extracted from the system, Q_{extr}, is given by:

$$Q_{extr} = Q_{prod} + Q'_{surf} - Q_{deep} - Q_{rech} \tag{3}$$

Note that in (3) the energy flow from the surface, Q'_{surf}, is not the same as in the natural state. At Wairakei, after production began,

Table 1
Parameters for a range of geothermal systems.

Name	Type	Area (km^2)	Natural heat flow (MW)	Heat flux (W/m^2)	Electricity production (MW)	Production heat flow[a] (MW)	PR	Recovery time[b] (years)
East Mesa	Hot water	215[c]	32	0.149	50	2000	63	6200
Wairakei–Tauhara	Liquid-dominated, two-phase	30	400	13.3	190	1900	4.8	380
Darajat	Vapor-dominated, two-phase	16	80	5.0	150	1500	19	1800
Cooper Basin[d]	EGS (hot dry rock)	40	4.2	0.105	280	5600	1300	130000

[a] Approximate only, based on 10% for the efficiency of conversion from heat to electricity for the high enthalpy systems and 5% for the low enthalpy systems.
[b] Calculated for 100 years of production.
[c] Includes some area outside the bore-field.
[d] Proposed project.

the surface heat flows decreased in the features supplied by hot water, e.g., Geyser Valley, and increased in some steam-fed features such as Karapiti, but overall heat flows are similar to their pre-production values (Allis, 1981). It is not obvious how much induced recharge is occurring at Wairakei, although computer modeling indicates it may be significant (Mannington et al., 2004; O'Sullivan and Yeh, 2007). Here an approximate approach is taken and the surface energy flow and the induced recharge are ignored (or assumed to cancel one another) and (3) becomes:

$$Q_{extr} \approx Q_{prod} - Q_{deep} \approx (PR - 1)Q_{deep} \tag{4}$$

If deep induced recharge is included at a fraction f of the original deep upflow, then (4) is only slightly changed:

$$Q_{extr} \approx Q_{prod} - Q_{deep} - Q_{rech} \approx (PR - 1 - f)Q_{deep} \tag{5}$$

The present production regime at Wairakei is mining energy from the water, steam and rock at the top of the large natural convective plume that existed in the pre-production state at a rate of approximately 3.75 times the natural energy supply. As hot water and steam have been produced, cold water has flowed both laterally and vertically downwards to replace it. This recharge was initially heated by energy in the rock matrix, but eventually the cold water has encroached into the production horizon(s). This has resulted in the cooling off of some of the production wells (Clotworthy et al., 1999; Bixley et al., 2009).

This type of production strategy is not unique to Wairakei. Most developed geothermal fields are exploited at a rate faster than the energy is replaced by the pre-production flow (e.g., Williamson et al., 2001). Because of this fact, the concept of sustainability or renewability of geothermal systems is complicated.

Clearly, geothermal systems cannot be produced at a rate corresponding to the installed capacity of their power plants on a continuous basis forever. Thus, in this sense they are not sustainable. However, if after a time, the power plants are shut down, the natural energy flow will slowly replenish the geothermal system and it will again be available for production. Therefore, when operated on a periodic basis, with production followed by recovery, geothermal systems are renewable and indefinitely sustainable. Again using the simple, lumped-parameter energy balance above, the rate of energy recovery, Q_{reco}, will be given by:

$$Q_{reco} = -Q''_{surf} + Q_{deep} + Q_{rech} \tag{6}$$

If we assume that the surface flow Q''_{surf} and the induced recharge Q_{rech} are small and can be ignored then:

$$Q_{reco} \approx Q_{deep} \tag{7}$$

By equating the total heat extracted to the total heat recovered it follows that:

$$Q_{reco}t_{reco} \approx Q_{extr}t_{extr} \tag{8}$$

Here t_{reco} is the recovery time and t_{extr} is the duration of past production.

Then (4), (7) and (8) together give

$$t_{reco} \approx (PR - 1)t_{extr} \tag{9}$$

Thus, the ratio of the recovery duration to the production period should be approximately one less than the ratio of production energy flow to natural energy through-flow [the PR defined in Eq. (1) above]. The detailed recovery process will depend on the state of the reservoir and will require three-dimensional modeling for accurate assessment, but Eq. (8) should give a reasonable estimate.

3. Previous investigations

Several other authors have recognized the requirement for a production/recovery cycle in the long-term exploitation of geothermal systems. A quantitative study of the topic was carried out by Pritchett (1998) in a computer modeling study of a generic geothermal reservoir. His model had a high permeability upflow leading into a reservoir zone with horizontal and vertical permeability of 10 md. The maximum permeability of 10 md used in the model is lower than that at Wairakei and many other fields, nevertheless the predicted post-abandonment behavior is of general interest. In Pritchett's reservoir, the natural state inflows are 100 kg/s and 133 MW_{th} (330 °C water), and the reservoir was produced for 50 years at an average rate of 60 MW_e. This corresponds to 166.7 kg/s of separated steam (5.5 bars well head pressure). Pritchett does not provide the average fluid enthalpy, but if we use a typical value from Wairakei of 1150 kJ/kg then the total mass flow is 708 kg/s and the energy flow is 814 MW_{th}, yielding a PR value of 6.1.

After production ceased at 50 years, Pritchett ran his model for a further 1000 years and calculated a 90% energy recovery at this time. He also gave figures at other times, for example, 57.9% energy recovery at 250 years. Thus, the estimate obtained using Eq. (9) of a recovery time of 255 years is of the right order of magnitude.

Pritchett concludes that "Accordingly, it seems reasonable to conclude that geothermal systems which have been thermally depleted in this way will not recover after abandonment on time-scales comparable to lifetimes of typical electrical power development projects. They will, however, recover on time-scales typical of lifetimes of civilizations".

Rybach et al. (2000), Megel and Rybach (2000), and Rybach (2003) also considered the question of the time-scale of the renewability of geothermal resources. They used a modeling study to show that for a doublet system operated cyclically in production-recovery modes a 10-year cycle produced more energy than 20-year or 40-year cycles over a 160-year period. They also used modeling to investigate the thermal recovery of a warm water system following the cessation of the operation of a down-hole heat exchanger operation. They deduced that "*the recuperation period equals nearly the operation period*". They also stated the general

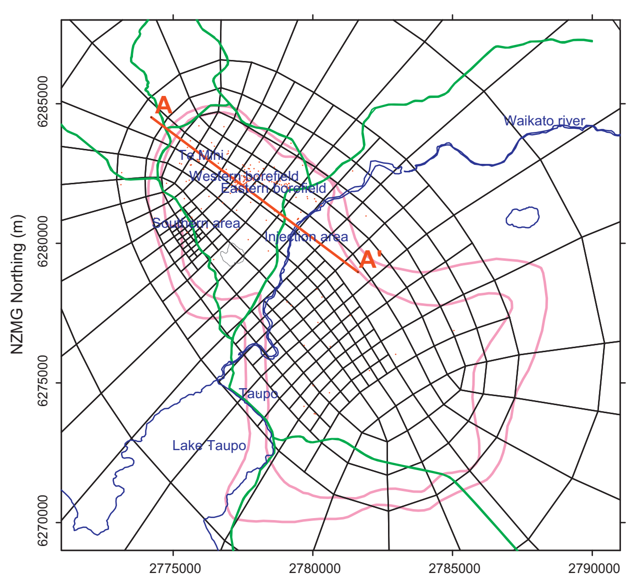

Fig. 3. Plan view of the model structure.

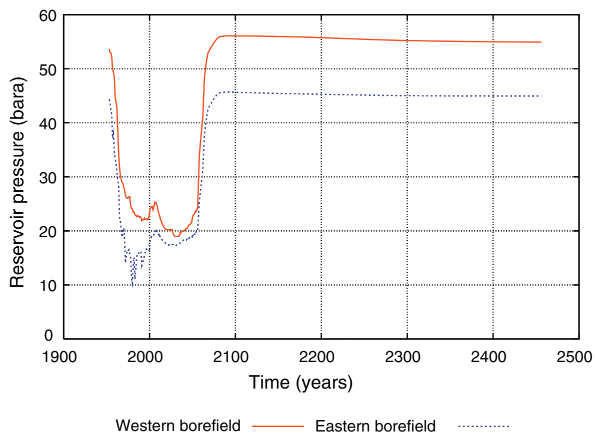

Fig. 4. Pressure decline and recovery.

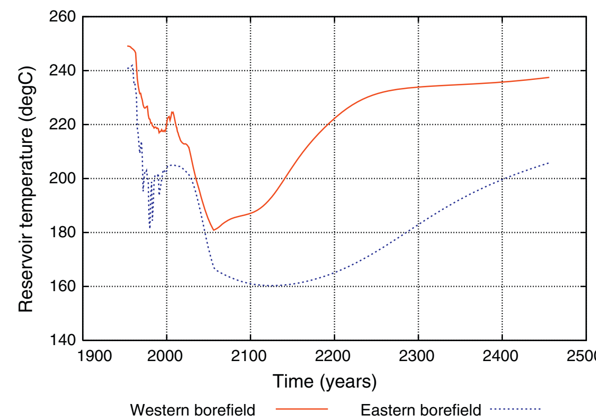

Fig. 5. Temperature recovery.

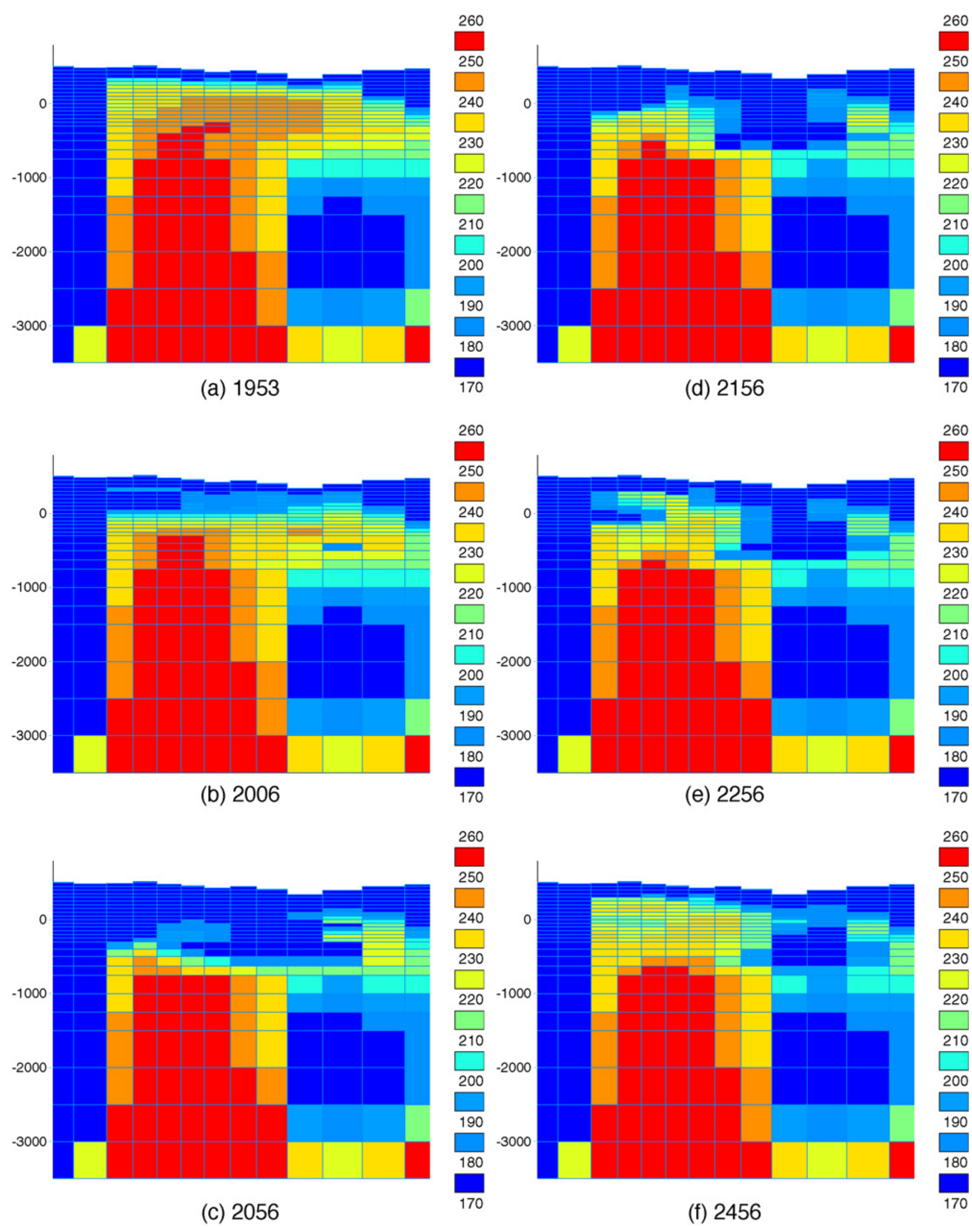

Fig. 6. Temperatures on a vertical slice through the Wairakei model.

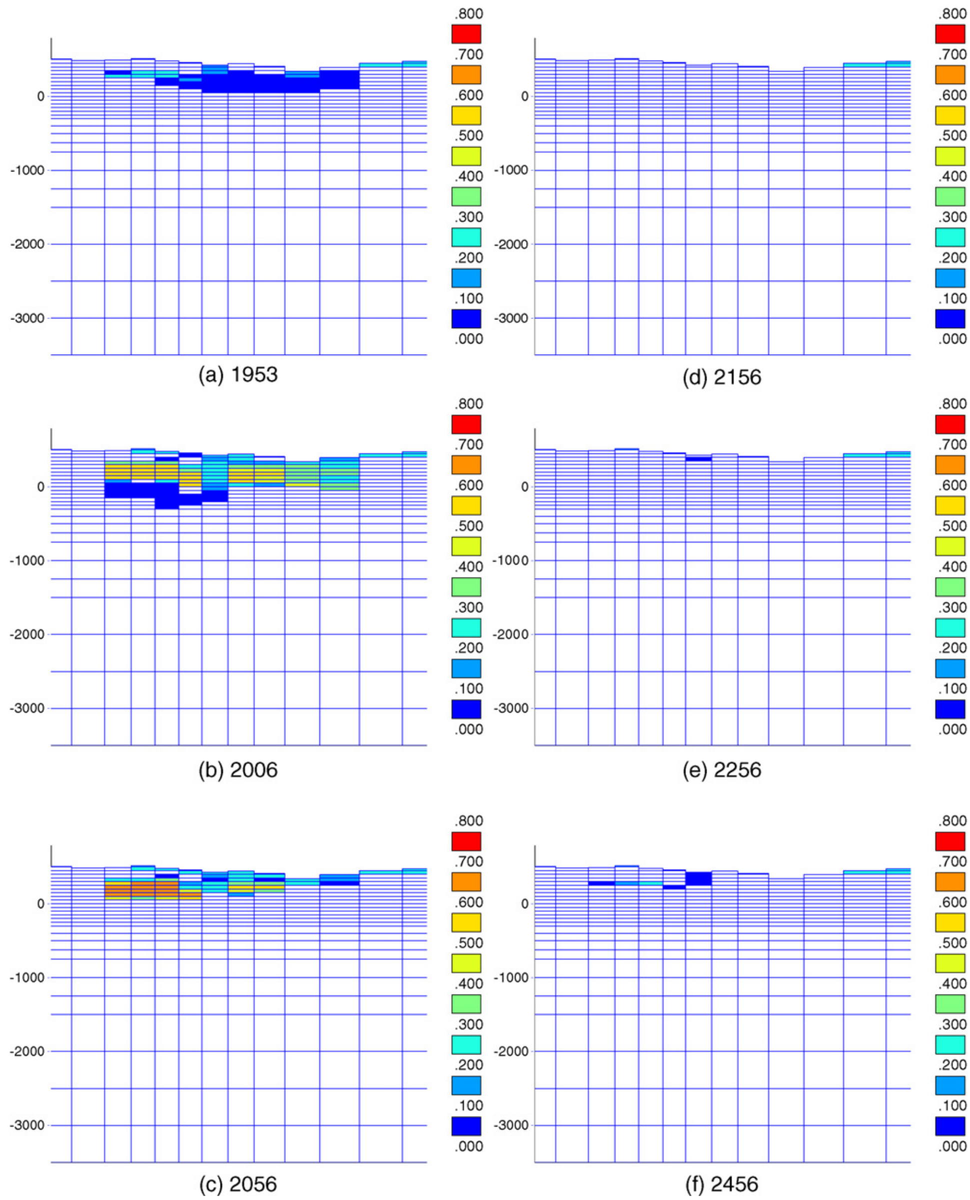

Fig. 7. Vapor Saturations on a vertical slice through the Wairakei model.

conclusion "(*T*)*hus, geothermal resources can be considered renewable on time-scales of technological/societal systems and do not need geological times as fossil fuel reserves do* (*coal, oil, gas*)"

Stefansson (2000) discussed the renewability issue in qualitative terms and stated a similar conclusion "...that the natural recharge of energy to most natural geothermal systems takes place on a similar time-scale as the exploitation of these resources...".

4. Wairakei–Tauhara

The Wairakei–Tauhara system has been under production for just over 50 years (Clotworthy et al., 1999; Bixley et al., 2009). As discussed above, the production ratio for Wairakei is 4.75 [i.e. (produced energy flow)/(natural energy flow) = 4.75], and therefore the current operation at Wairakei is not sustainable on a continuous basis.

In the past, a number of interesting phases have occurred at Wairakei. Early on (late 1950s to early 1960s), the pressure in the borefield declined rapidly (see Fig. 4). By 1970, the pressure stabilized as a quasi-equilibrium state had been established with the combination of induced recharge (cold from the sides and above, and hot from the sides and below) and induced boiling matching production. The boiling induced by the pressure decline resulted in the development of a large boiling zone. As the boiling has progressed, heat has been extracted from the rock matrix and the reservoir temperatures and pressures within the boiling zone have continued to slowly decline. Thus, during the 50 years of production at Wairakei, the mass change effects have occurred on a shorter time scale than the energy change effects.

One of the purposes of the present paper is to investigate the behavior of the Wairakei–Tauhara system after it is shut down at some time in the future. From our analysis above, we anticipate that it will take three to four times the total duration of the production phase to recover, but it is interesting to find out the exact form of the recovery. Experience from the past production history, and the difference in time-scales of mass and thermal effects indicate that the pressure recovery will be much faster than the temperature recovery.

5. Computer modeling

The authors have developed a computer model of Wairakei–Tauhara (O'Sullivan et al., 1998; Mannington et al., 2000, 2004; O'Sullivan and Yeh, 2007, 2010) on behalf of Contact Energy Limited (the field operators). Because of the extensive database for Wairakei–Tauhara and the relatively long production history, it has been possible to develop a well-calibrated model. For the present study, a scenario is considered where production is continued at Wairakei–Tauhara for another 50 years and then the field is shut down for 400 years. This gives a total of 100 years of production followed by 400 years of recovery.

A plan view of the model structure is shown in Fig. 3. The main production areas are labeled: Eastern borefield, Western borefield, and Te Mihi.

6. Results

In Fig. 4, the pressures in the Western and Eastern borefields are plotted for 1953–2456. The rapid decline in pressure after production began in 1953 is clearly shown, and a rapid pressure recovery is predicted after shut-down in 2053. Most of the current production is from the Western borefield and Te Mihi, but after shut-down the pressure recovery is very rapid in both the Western and Eastern borefields. This is a consequence of the high permeabilities in the Wairakei–Tauhara system.

The corresponding plot of temperature versus time is given in Fig. 5. It shows a slower decline followed by the expected slower recovery. The recovery is slower in the Eastern borefield, which is further away from the deep recharge.

Temperatures on a vertical slice through part of the Wairakei model are shown in Fig. 6. The location of the slice is indicated by the line AA' in Fig. 3. Fig. 6(a) shows the pre-exploitation situation in 1953. The upflow of hot water under the Te Mihi borefield and the Western borefield is clear. Similarly, the outflow through the Eastern borefield towards Geyser Valley is visible.

The 2006 temperatures shown in Fig. 6(b) show the effects of the gradual "mining" of heat during the production phase. The temperatures in the Eastern borefield area have declined significantly between Fig. 6(a) and (b). This effect is confirmed by field data. Similarly, the temperatures in the Western borefield and Te Mihi have declined. Fig. 6(c) shows that further mining of heat from the top of the upflow plume will occur by 2056.

After shut-down the slow recovery begins; and by 2156 [see Fig. 6(d)] the hot plume has started to rise in the Western borefield and Te Mihi. This process has proceeded further by 2256 [see Fig. 6(e)] when some recovery in the Eastern borefield can be seen. After an additional 200 years, by 2456, the system has almost recovered to its pre-production state [compare Fig. 6(a) and (f)].

Plots of vapor saturation on the vertical slice are given in Fig. 7. As shown in Fig. 7(a) there was only a low level of boiling in the pre-production state in 1953, but there was a large expansion of the boiling zone during production up to 2006 [see Fig. 7(b)]. The slow cooling of the system between 2006 and 2056 causes the boiling zone to contract slightly [see Fig. 7(c)], although pressures continue to fall slowly. The pressure build-up after shut-down causes the rapid collapse of the steam zone. By 2156, there is very little boiling [see Fig. 7(d)]. However, a very slow return of a very low level of shallow boiling occurs by 2256 and increases further by 2456 [see Fig. 7(e) and (f)]. The boiling zone has still not returned to the natural state conditions by 2456.

The disappearance of the steam zone is also shown by the plots of vapor saturation vs. time for two typical steam zone blocks given in Fig. 8. In these blocks, the boiling ceases very soon after the field shut-down in 2053 and has not returned by 2500.

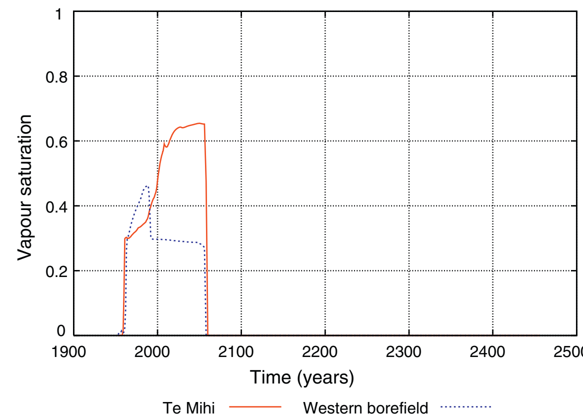

Fig. 8. Vapor saturations vs. time for the Te Mihi steam zone and Western borefield.

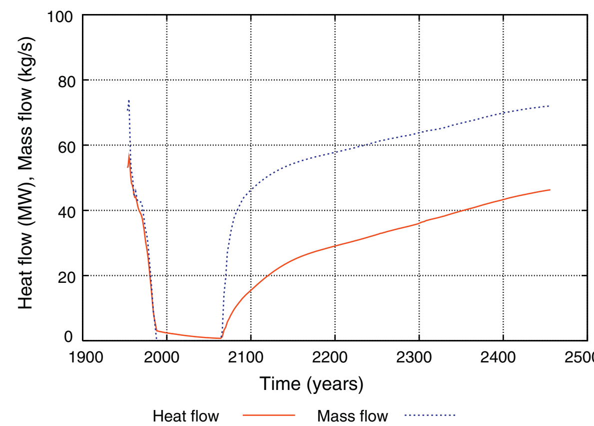

Fig. 9. Heat and mass flows at Geyser valley.

The surface mass and heat flows at Geyser valley are shown in Fig. 9. These plots show the rapid decline of activity at Geyser valley resulting from production (as was observed) and the rapid return of surface flows after field shut-down. However, as is shown in Fig. 9, the surface flows at Geyser Valley after 2053 will be initially cool and it will take a long time for the original thermal activity to redevelop.

Although production at Wairakei caused the thermal activity at Geyser Valley to decrease rapidly, and to eventually cease altogether after a few years, it caused an increase in the steam heated features at Karapiti. The heat flux at Karapiti is shown in Fig. 10.

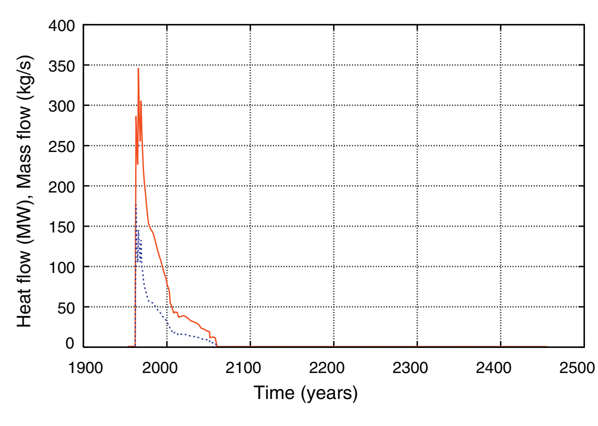

Fig. 10. Heat and mass flows at Karapiti.

This plot shows the thermal activity at Karapiti will continue to slowly decline until 2053, when it will have almost disappeared. After field shut-down, activity at Karapiti will take a long time to re-establish.

7. Conclusions

A reservoir simulation study for Wairakei–Tauhara shows that if steam production for electricity generation is continued at Wairakei–Tauhara until 2053 and then steam production is shut down, the field will recover to almost its pre-production state in 400 years. This is four times the total period of production. The factor of four agrees well with the value of 3.75 obtained from our approximate formula (Eq. (9)). The model results show that the drawn-down pressure at Wairakei will recover very fast, on a time scale of years (see Fig. 4) but the temperature recovery will be much slower, occurring on a time scale of centuries. Thus, Wairakei is indefinitely sustainable on a cycle of 100 years of production (at 170 MW_e) followed by 400 years of recovery. Whether this strategy is optimal is an interesting question that is left to a future study.

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