Estimating Wairakei's 50 Years and 100 Years MWe Potential Capacity from a Calibrated Natural State Model using Experimental Design (ED) and Response Surface Methodology (RSM)

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ABSTRACT

Wairakei geothermal field has been operating since 1958, which is years beyond the initial expected production life. There is still significant hot geothermal fluid available for electricity generation that can sustain production for many more years. It is interesting to estimate the theoretical capacity (MWe) of the field assuming it runs for another 40 years, a total production life of 100 years since commissioning.

Two different resource assessment methods were investigated: the volumetric (stored heat) method, and also Experimental Design (ED) and Response Surface Methodology (RSM). In particular, the use of the Plackett-Burman design for building a polynomial model using a calibrated natural state reservoir model with minimum number of required simulation runs was investigated.

Results obtained from Plackett-Burman suggest that Wairakei could sustain a P50 of 294 MWe for 50 years and 219 MWe for 100 years since commissioning. Findings also reveal that permeability and injection parameters are critical to sustain operation for the first 50 years while sufficient permeability and porosity are crucial to support the operation up to 100 years.

1. INTRODUCTION

The Wairakei geothermal field has been operating for over 62 years generating electricity, and even longer for direct use applications (Bromley and Carey, 2018). At present, it has an installed capacity of about 353 MWe: 132 MWe from the Wairakei Power Station and binary plant, 55 MWe from the Poihipi Power Station, and 166 MWe from the Te Mihi Power Station (Sepulveda *et al.*, 2016). Planned initially as a power and heavy water distillation plant, the original Wairakei Power Project ended up as a geothermal power-only facility with an initial installed capacity of 193 MWe (Thain and Carey, 2009).

Production from the Wairakei geothermal resource was initially estimated to last for only 20 years (Morris, 2018). SKM (2002) estimated the potential capacity of Wairakei to be 600 MWe P50, 450 MWe (P90) and 850 MWe (P10) for 30 years using the volumetric method and 510 MWe (30 years), 153 MWe (100 years), 77 MWe (200 years) and 51 MWe (300 years) using the heat flow method. On the other hand, results of earlier reservoir modelling studies suggest that Wairakei can continue producing electricity at the 2003 level of approximately 170 MWe (O'Sullivan and Mannington, 2005) for at least another 50 years (O'sullivan, Yeh and Mannington, 2009).

Wairakei's ability to sustain its nominated generation capacity for over 60 years (at the original station) and still have excess capacity to support additional MWe (such as Poihipi and Te Mihi power stations) is unique to this geothermal field. There was a rapid decline in reservoir pressure during the early 1960s, but the resource reached a quasi-stable state in the 1970s primarily because of induced (production stimulated) recharge (O'Sullivan and Mannington, 2005). The significant pressure drawdown has induced boiling of the shallow reservoir and resulted in an increased in steam available for Wairakei to capitalise. There is still a substantial amount of energy available within the field as there was no further significant reservoir pressure decline beyond the 1970s. This paper attempts to quantify how many MWe the Wairakei reservoir can provide if it runs for another 40 years (a total production life span of 100 years).

1.1. Resource Estimation Methods

Quantifying the MWe capacity of a geothermal field can be done in several ways but the most widely used techniques are the volumetric (stored heat) method, and numerical reservoir modelling (Ciriaco *et al.*, 2020). Recently, the use of Experimental Design (ED) and Response Surface Methodology (RSM) to develop a predictive polynomial model has been gaining popularity (Ciriaco *et al.*, 2020). This resource assessment technique was first tried in the petroleum industry as it allows incorporating uncertainty in the model predictions. Several studies have already implemented the ED-RSM workflow in a geothermal field. The most recent one compared the results from a three-level Full Factorial, two-level Full Factorial and Box Behnken designs and suggests that a two-level full factorial may be sufficient to describe the relationships between MWe and the significant reservoir parameters (Ciriaco *et al.*, 2020).

A two-level Full Factorial design is an experimental setup that allows evaluation of all possible parameter combinations that can be modelled by a first order regression model. The most commonly used two-level Full Factorial design for screening parameters is the Plackett-Burman. It is particularly useful for reducing the number of experimental runs required to investigate the relationship of an output parameter with the factors that are known to affect it (Ciriaco *et al.*, 2020).

1.2 Plackett-Burman Design

The Plackett-Burman design has been demonstrated to be useful in identifying the parameters that have a significant influence on the output of interest with a minimum number of design points. It is also the most widely used in geothermal applications (Hoang, Alamsyah and Roberts, 2005; Quinao and Zarrouk, 2014, 2018). It is a two-level fractional ED design that can be used as a substitute for the two-level Full Factorial in the improved ED-RSM workflow as shown in Figure 1 (Ciriaco *et al.*, 2020).

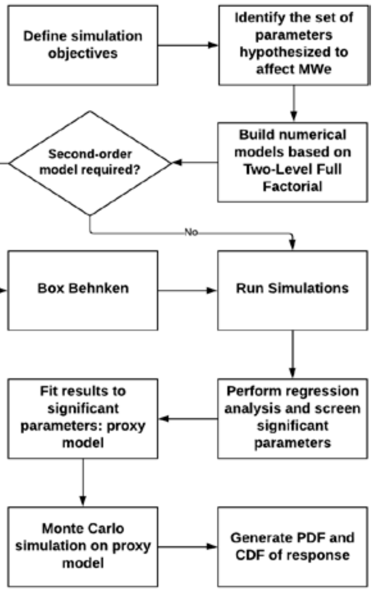


Fig. 1: The improved ED-RSM workflow for geothermal probabilistic resource assessment (after Ciriaco et al., 2020).

2. THE WAIRAKEI GEOTHERMAL FIELD

The Wairakei geothermal field is located about 7 km north of the Taupo Township in the Taupo Volcanic Zone (TVZ), situated at the centre of the North Island of New Zealand (Figure 2). It is separate from - but connected to - the Tauhara geothermal field to the south-east. Wairakei is a two-phase low enthalpy system with a high permeability, contained within almost impermeable boundaries separating it from the surrounding cold regions. The reservoir is dominated by the saturation temperature/pressure relationship, modified by the withdrawal of steam from the upper levels, and by an increasing inflow of hot water at depth (Bolton, 1970).

2.1 The Wairakei-Tauhara Numerical Reservoir Model

Several versions of the numerical model of the Wairakei-Tauhara system have been developed over the years. The 2014 version of the model will be used in this study (Yeh et al., 2014). The 2014 model has 41,458 blocks consisting of 1002 columns, each divided into 56 layers. In terms of model resolution, this 2014 version has finer grid blocks with more-uniform block structure that avoids having large blocks connected to smaller ones. Detailed discussion about the model grid design can be found in the paper of Yeh et al. (2014).

Figure 3 shows the pre-exploitation temperature distribution of the calibrated model at 187.5 MASL (Fig. 3a) and -275 MASL (Fig. 3a). There is a bigger and wider area with at least 220 °C in Wairakei compared to Tauhara at the shallow reservoir, but the latter is hotter at the deeper region. On the other hand, the model permeability distribution as shown in Figure 4 suggests that there is a higher permeability at the shallow reservoir of Wairakei (Fig. 4a) than Tauhara. At -275 MASL (Fig. 4b), there exists a high permeability region in both fields and in the area between them, suggesting that they are possibly hydrologically connected.

3. IMPLEMENTATION

The present research attempts to calculate the power potential of Wairakei for 50 years and 100 years, assuming year zero is 1958 – the year the original power station was commissioned. Two different methods will be used and compared: the volumetric method and the Plackett-Burman design (ED-RSM). The Monte Carlo simulation will be used to generate a probabilistic distribution of the estimated MWe.

A calibrated natural state model of Wairakei is used to build a polynomial model. This natural state model has also been calibrated against the production data of the field. The parameters and parameter values chosen are based on the parameters used by Ciriaco et al. (2020) when they used ED-RSM to estimate the MWe capacity of the Rotorua and Ohaaki geothermal fields. Each parameter was assigned a minimum (low) setting and a maximum (high) setting according to the requirement of the Plackett-Burman design. This range of values accounts for possible uncertainty. Table 1 shows a summary of all the parameters used in this study and their values. The low and high ranges were initially based on expert knowledge, with a very wide range considered. It is important to mention that the location and number of production and injection wells in a field are the most difficult settings when designing an experiment. This is where subject matter expertise and also the unique field setting play an important role.

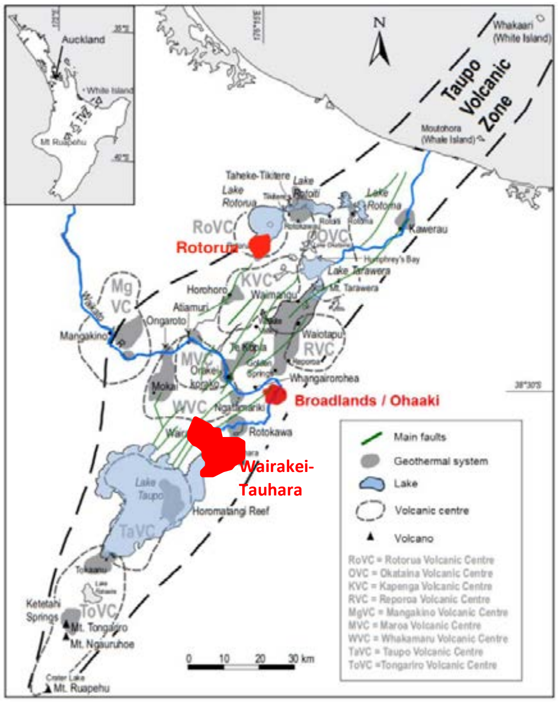
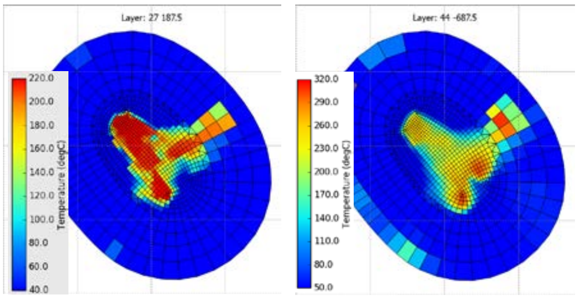


Fig. 2: Map of the Taupo Volcanic Zone (TVZ) and the location of the Wairakei-Tauhara geothermal field.

Table 1. Input parameters (variables) and values used to build the proxy model of Ohaaki and Rotorua geothermal fields (after Ciriaco *et al.*, 2020).

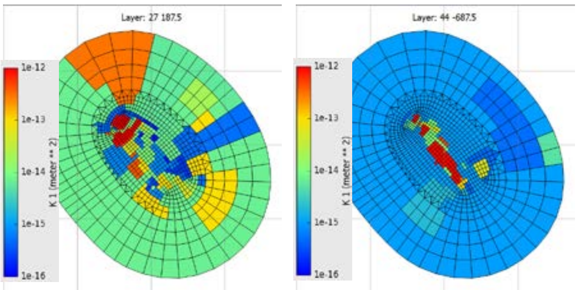
Parameter / Variable	Unit	Low (-1)	High (+1)
Permeability (x, y and z directions)	$10^{-15}m^2$	1	1000
Porosity		0.01	0.3
Injection fluid enthalpy	kJ/kg	334.9 (80 °C)	675.6 (160 °C)
Fraction of extracted mass flow reinjected into the reservoir	(%)	50	90



a) Simulated temperature at layer 27 (187.5 MASL)

b) Simulated temperature at layer 44 (-687.5 MASL)

Fig. 3: The natural state temperature distribution of Wairakei-Tauhara geothermal field at: a) layer 27 (187.5 MASL) and b) layer 44 (687.5 MASL)



a) Permeability (kx) at layer 27 (187.5 MASL)

b) Permeability (kx) at layer 44 (-687.5 MASL)

Fig. 4: The permeability distribution at the x-direction of Wairakei-Tauhara geothermal numerical model at: a) layer 27 (187.5 MASL) and b) layer 44 (687.5 MASL)

3.1 Experimental Design (ED) and Response Surface Methodology (RSM)

The equation for calculating the MWe from the results obtained from the numerical simulation is provided below:

$$MW_e = \left[\sum_{i=0}^{i=n} \dot{m}\,(t_{i+1} - t_0) \times h\,(t_{i+1} - t_0) \right] \times \eta_c \qquad (1)$$

where:

$\dot{m}$ = mass flow rate (kg/s)
h = enthalpy (kJ/kg)
t_i = time step (seconds)
η_c = conversion efficiency (%)

Conversion efficiency of η_c = 0.12 was used in the calculation, as suggested by Zarrouk and Moon (2014).

The calculated MWe together with the values of the chosen reservoir parameters were used in the regression analysis. The process of building an empirical model involves determining a functional relationship between an output variable y to a set of input variables having a polynomial function, $f(x)$, and a random error, ε, which is assumed to be normally distributed with mean $(\mu,)$ zero and variance $(\sigma 2)$ this being called response surface modelling (Simpson, 1998):

$$y(x) = f(x, \beta) + \varepsilon \qquad (2)$$

The polynomial function (x) is a low order polynomial which can either be linear or quadratic and can be written in a matrix form:

$$Y = X\beta + \epsilon \qquad (3)$$

where:

Y	response vector
X	design matrix
β	vector of parameters
ε	error vector

3.2 Volumetric stored heat method

The volumetric stored heat method introduced by the United States Geological Survey (Muffler and Cataldi, 1978; Ciriaco, et al, 2020) for calculating the theoretical thermal energy q stored in the reservoir is performed by dividing the reservoir into n different regions of volume V_i and temperature T_i, i = 1, 2, .., n, using the equation below:

$$q = \sum_{i=1}^{n} \rho_i c_i V_i (T_i - T_f) \qquad (4)$$

where:

$\rho_i c_i$	Volumetric heat capacity of a saturated rock, J/°C m3
V_i	Volume of i^{th} region of n numbers of lithology. The product of area A and thickness h of the reservoir ($V = A \times h$), m3
T_i	Initial temperature of i^{th} lithology, °C and
T_f	Cut-off or final abandoned reservoir temperature, °C

By multiplying the calculated thermal energy by the fraction of recoverable energy and conversion efficiency, the MWe can be computed as shown below:

$$MW_e = \frac{q \times R_f \times \eta_{conv}}{F \times L} \qquad (5)$$

where:

MW_e power potential, MWe

q	thermal energy stored in the reservoir (MJ)
R_f	recovery factor
η_{conv}	conversion efficiency (%)
L	plant life (seconds)
F	capacity or load factor (%)

A range of possible values are assigned to the uncertain reservoir parameters such as reservoir volume ($V = A \times h$), initial reservoir temperature (T_i), reference temperature (T_f), conversion efficiency (η_{conv}), power plant factor (F) and recovery factor (R_f) to calculate a probabilistic MWe prediction using a Monte Carlo simulation.

Calculating the MWe potential using the volumetric stored heat method is straight forward. A simple triangular distribution was assigned to each parameter. By substituting the collected values SKM (2002) for the parameters in the equation and running a Monte Carlo simulation, a probabilistic distribution of MWe was generated. The parameter values used are summarized in Table 2.

Table 2. Values for the parameters in the stored heat calculation for the Wairakei field.

Parameter	Parameter Value		
	minimum	most likely	maximum
Resource area (km^2)	15	20	30
Resource thickness (km)	2.0	2.15	2.65
Temperature (°C)	250	255	265
Conversion Efficiency	0.07	0.12	0.17
Recovery Factor	0.1	0.125	0.15
Reference Temperature (°C)	20	100	180

4. RESULTS AND DISCUSSION

Eight (8) simulation runs were carried out for each experimental run. This means that for each experimental run, eight (8) different versions of the calibrated Wairakei numerical model were created to capture all possible combinations of the chosen variables. Determining the maximum number of production blocks that could sustain production for 50 years and 100 years was not easy. Several iterations were performed by selecting the production blocks from the main production area bounded by at least 220 °C intersection at layer 27 (187.5 MASL) down to layer 44 (-687.5 MASL), where there is still enough permeability based on the model.

The results of the experiment suggest that the calibrated Wairakei numerical model can sustain production for 50 years and 100 years at a fixed rate of production from three different layers: layer 27 (187.5 MASL), layer 39 (-225 MASL) and layer 44 (-687.5 MASL). Due to pressure drawdown, the fluid produced from Layer 27 changed from initially low enthalpy to high enthalpy. However, only a small production area can sustain high-enthalpy production until 50 years and 100 years.

Ciriaco et al. (2020) have shown that while a second-order polynomial model best describes results from computer simulation, a first-order polynomial derived from a two-level fractional design gives comparable estimates. Hence, we did not carry out any second-order experimental runs and proceeded to building a first-order polynomial model of the simulation results from the Plackett-Burman design.

The final polynomial model of the Wairakei production model for 50 years using the Plackett-Burman design is given below:

$$MW_e(50\ years) = 311.60 + 7.38e12 * kx + 6.94e12 * kz - 2.77e - 5 * RI\ Enthalpy - 15.04 * \%RI \quad (6)$$

The p-values of the significant variables are summarized in Table 3. A p-value of less than 0.05 implies that the chosen parameter is a significant predictor of MWe. The results reveal that permeability (kx and kz), injection enthalpy and fraction of injected water (%RI) are significant predictors of MWe. This indicates the importance of permeability and injection fluid in sustaining production for 50 years. Monte Carlo simulation implemented on Equation 6 suggest that Wairakei has an estimated capacity of 294 MWe (P50). The probabilistic plot is shown in Figure 5.

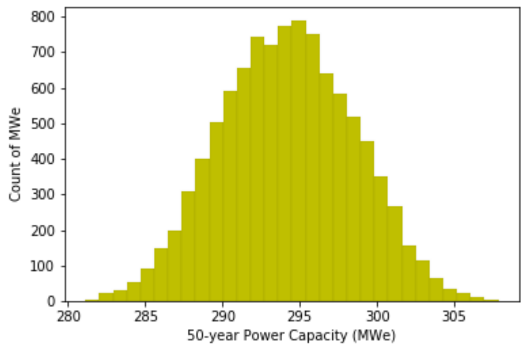


Fig. 5: Plackett-Burman 50-year probabilistic resource assessment of the Wairakei Geothermal Field.

Table 3. The p-values of the first order Plackett-Burman regression model of main effects with significant parameter based on the 50-year production run of Wairakei model.

	p-value
kx	0.01566
kz	0.01851
RI Enthalpy	0.00785
%RI	0.02706
R-squared	*0.9718*
Adjusted R-squared	*0.9342*

If Wairakei produced electricity for 100 years, the results of the simulation suggest that it could sustain production of 219 MWe (P50). This estimate was obtained after applying Monte Carlo simulation on the final polynomial model of the Wairakei numerical model for a 100-year plant life given below:

$$MW_e(100\ years) = 198.60 + 4.91e12 * kx + 1.50e13 * ky + 2.59e13 * kz - 17.79 * porosity \quad (7)$$

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The p-values of the variables of the polynomial model of Equation 7 is summarized in Table 4 while the plot of the simulation results is shown in Figure 6. Only kx and ky turned out to be significant predictors of MWe for the 100-year experimental runs. The results suggest that sufficient permeability is critical to support production up to 100 years. Moreover, the difference between the sustained production for 50 years (294 MWe) and 100 years (219 MWe) is very small. This indicates that there is sufficient pressure support in the Wairakei reservoir that allows a manageable decline in MWe for another 50 years.

Table 4. The p-values of the first order Plackett-Burman regression model of main effects based on the 100-year production run of Wairakei model.

	p-value
kx	0.00883
ky	0.00184
kz	0.12675
porosity	0.14003
R-squared	*0.9811*
Adjusted R-squared	*0.956*

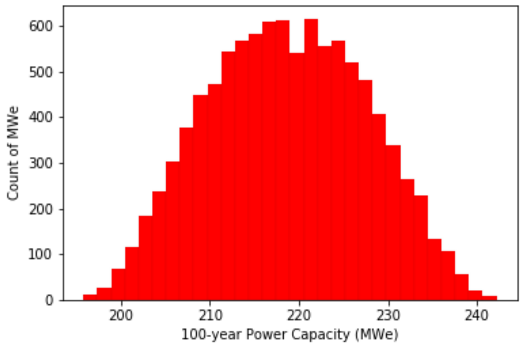

Fig. 6: Plackett-Burman 100-year probabilistic resource assessment of the Wairakei Geothermal Field.

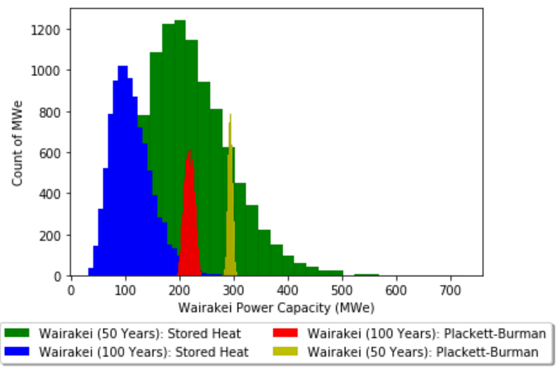

Fig. 7: 50-year and 100-year probabilistic resource assessment of the Wairakei Geothermal Field using the volumetric method and Plackett-Burman.

The MWe estimates obtained using the Plackett-Burman and stored heat volumetric method are summarized in Table 5 and Figure 7. Results from Plackett-Burman for both 50 years and 100 years are within the 50-year estimate of the volumetric stored heat while the 100-year estimate of stored heat is lower compared to ED-RSM.

The uncertainty band of the MWe calculated from the stored heat method is wider than the Plackett-Burman. It appears that the ED-RSM workflow reduces the uncertainty associated with the prediction. This is not fully understood yet and requires further investigation. It is highly likely that the uncertainty band is underestimated. But it is also possible that predictions from ED-RSM and calibrated numerical model have lower uncertainty than those obtained from the analytical volumetric method.

Table 5. Summary of estimated potential MWe of the Wairakei Geothermal Field using Plackett-Burman and the volumetric stored heat method.

	P90 (MWe)	P50 (MWe)	P10 (MWe)
Plackett-Burman (50 years)	289	294	300
Plackett-Burman (100 years)	207	219	230
Stored Heat (50 years)	133	212	323
Stored Heat (100 years)	68.0	106.50	161.98

5. CONCLUSION

Estimating the MWe potential of Wairakei for 50 years and 100 years using Experimental Design (ED) and Response Surface Methodology suggests that:

- Only a small area of the Wairakei field can sustain high enthalpy production for 50 years and 100 years.
- The relatively small difference between the MWe sustained for 50 years and 100 years production life indicates presence of sufficient pressure support in the Wairakei reservoir.
- Permeability and injection are crucial to sustain production for 50 years while permeability and porosity are key in maintaining production for 100 years.
- Plackett-Burman can be a useful two-level fractional Experimental Design for developing a first-order polynomial model of a numerical model.

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