A REVIEW OF GEOTHERMAL RESOURCE ESTIMATION METHODOLOGY

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ABSTRACT

The reliability of resource estimation methodology has become increasingly important due to the rapid developments in the geothermal industry. Several resource assessment methods are used at different stages of resource development to estimate resource potential. This work reviews the resource estimation methodology with particular focus on the volumetric (stored heat) method.

The most contentious parameter in calculation of stored heat is the recovery factor. There is no agreed upon model in the industry that can be used to estimate this factor; different authors use analogy to existing fields or a preferred range of values. Several existing models were analyzed and a new model was suggested for relating the recovery factor and permeability to the types of geothermal systems based on enthalpy of the system.

The reservoir size and temperature distribution have a very significant role in the calculation of the resource potential. Uncertainty in these parameters increases the inaccuracy of the stored heat estimation. Different values for the cut off temperature have been used in different geothermal fields. The value adopted depends on the type of geothermal resource, power conversion technology and the local electricity price.

Resource sustainability has an effect on resource life. Many geothermal fields (e.g. Wairakei, Larderello and the Geysers) had constant production capacity long after their economic life of 25-30 years.

Reservoir modeling is the most accurate resource estimation method. However, it has limited applicability in green fieldsdue to inadequate information of field parameters. The stored heat method is more suitable for green fields before field production to provide approximations of resource potential. Stored heat calculations was modified to account for the difference between hydrothermal and enhanced geothermal systems behavior by incorporating natural heat input into the reservoir.

1. INTRODUCTION

1.1 Background

A total of 24 countries now generate electricity from geothermal resources. The total installed capacity worldwide is 10,898 MWe, corresponding to about 67,246 GWh of electricity (Bertani 2012). The push towards geothermal energy has been necessitated by the need to move from high dependency on fossil fuels. Geothermal resources are being developed to substitute fossil fuel (Korkmaz Basel, Serpen et al. 2010). The geothermal development update for the period 2005-2010 reports that the expected growth for the period 2010–2015 could reach an installed capacity of up to 18.5 GW (Bertani 2012).

The geothermal industry is facing an increasing need for reliable estimation of geothermal reserves. The growing number of investors participating in the geothermal industry demand that the industry should agree upon a methodology of estimating, assessing, classifying and reporting geothermal resources (Clotworthy, Ussher et al. 2006). The consenting process in most countries is long, expensive and detailed. Therefore, it is important to have a comprehensive knowledge of resource potential, when applying for environmental consents in a new field (SKM 2002). There is also an emerging concern on sustainability of geothermal resources. Many countries with geothermal power are developing policies that are aimed at sustainable production.

The Australian Geothermal Energy Group (AGEA 2010) has formed a geothermal code of practice with the aim of standardising the methodology for estimating, assessing, quantifying and reporting of geothermal resources and reserves. The AGEA (2010) has categorised the commercial viability of geothermal prospects into two classes, resource and reserve. This categorisation provides information to investor and interested parties on the level of confidence attached to the estimated energy potential of a geothermal resource.

1.2. Objectives

The main objectives of this work are:

a. To define the scope and extent of preliminary field assessment and how it combined with reservoir modeling.

b. Develop models for recovery factor from real field examples.

c. Establish cut off parameters depending on development strategy of resources.

d. Address the effect of resource sustainability on the estimation of field potential and redefine project lifetime from sustainability perspective.

The main approach will be to categorize geothermal systems based on the reservoir's temperature and enthalpy. The classifications will be used as the base for assigning probable reservoir parameters such as the porosity, permeability and recovery factor.

2. RESOURCE ESTIMATION METHODS

The methods used for resource assessment vary depending on the available information at different stages of geothermal development. The accuracy of the methods depends on the certainty of available information. These methods are outlined below:

- Power density method
- Surface thermal flux method
- Planar fracture method
- Magmatic heat budget method
- Numerical reservoir modelling
- Stored heat (Volumetric) method

Stored heat estimation and numerical modelling are the two most commonly applied methods in geothermal resource assessment (AGEA 2010). The stored heat method is normally used during field exploration stage, before production. On the other hand numerical modelling gives the most accurate resource evaluation (Sanyal and Sarmiento 2005). During initial stages of the exploration, numerical modelling is limited by insufficient knowledge of the reservoir parameters. Wells have to be drilled and tested, before an appropriate model that truly represents the physical state of the reservoir can be developed (Sarmiento and Björnsson 2007).

Stored heat on the other hand is easily applicable in the early stages of resource development and it can be used in any geologic environment. It uses parameters that can be measured or estimated. The uncertainties in the method are compensated by the use of probability distribution to give reasonable estimates (AGEA 2010).

The stored heat method has been used to assess a number of fields around the world. In USA USGS carried out an assessment of its geothermal fields in 1978 and a review of the same fields was done by GeothermEx in 2004. Both assessments were done using the volumetric method. The results show that the 1978 assessment was too optimistic mainly due to an overestimate of resource size and recovery factor of 0.25 (Sanyal, Klein et al. 2004).

A comparison of stored heat estimates and numerical assessments in the Philippine geothermal fields show that calculations by volumetric method were close to the optimum capacity. Large variations on estimates obtained in 1980 and 1982 for Mahiao-Malitbog were as a result of uncertainties on use of recovery factor (25-50%) and the lack of sufficient knowledge of the reservoir (Sarmiento and Bjornsson (2007).

The major uncertainties in the stored heat method identified from various sources are the correct estimation of reservoir size, recovery factor and temperature distribution (Arkan and Parlaktuna 2005), (Sarmiento and Bjornsson 2007), (Williams 2007). The recovery factor has never been confidently determined (Parini and Riedel 2000). Recovery factor is an empirical parameter used in different fields studies based on expert judgment (AGEA 2010). The cut off parameters vary depending on field and exploration strategy. Calculating resource capacity of different fields from numerical simulation tend to give lower estimates when compared to stored heat method (Grant and Bixley 2011). This is in contrast to the experience in the Philippines reported by Sarmiento and Bjornsson (2007).

3. PROPOSED CHANGES TO RESOURCE ESTIMATION METHODS

3.1 Application of stored heat and numerical modeling to resource estimation

The stored heat method is the best method for assessment of green fields. Numerical modeling/simulation gives reliable accurate estimates of the potential of a geothermal field especially following exploration drilling and production. The main limitation to reservoir modeling at initial stage of development is inadequate information. It is easier to improve stored heat calculations at the initial stages of the development of the resource. Numerical modeling is more accurate when there is exploration and production data of the resource and good spread of wells in the field. It is appropriate to employ reservoir modeling when a reservoir has been confirmed by drilling and reservoir delineation begins. However, it should be kept in mind that; the timeframe for performing numerical modeling and stored heat assessment are vastly different. Much quicker and more benefit from stored heat assessment at earlier stages. With more data, time invested in numerical modeling is well spent.

3.2 Proposed refinements to the volumetric method of resource estimation

The proposed refinements include the following:

a. The power potential in MW_e is estimated by equation 1. This equation is based on stored heat only and does not consider natural heat input by convection in the form of mass flux in hydrothermal systems, hence a modification to equation (1).

$$W_e = \frac{H_{th} R_f \eta_c}{L.F} \tag{1}$$

where W_e Power plant capacity in MW_e

H_{th} Theoretical available heat

R_f Recovery factor

η_c Conversion efficiency

F Power plant load factor/ capacity factor

L Power plant life (in seconds)

The measured natural thermal output from hydrothermal geothermal systems if significant (q > 100 MWth), should be combined with the stored heat as proposed in this work (equation 2) which is a modification of equation 1. Surface thermal flux is the minimum heat input of the revised equation and it is subject to modifications with knowledge of the reservoir model.

$$W_e = \left\{\frac{H_{th}}{L} + n\,q\right\}\frac{R_f \eta_c}{F} \tag{2}$$

where

q is the measured natural thermal output of the system in MW_{th}.

n Multiplier of recovery factor ($n \geq 1$) indicating that there is higher recovery factor for the natural heat output than that for stored heat (n= 2.0 is proposed here).

For hydrothermal systems with a natural output ~ $q \geq 100$ MW_{th} natural heat flow should be considered in equation (2). However, for $q < 100$ MWth and for HDR/EGS systems then q= 0 should be used in equation (2) which will reduce it to equation (1).

This criterion of (q > 100 MW_{th}) is open for debate, but I feel strongly that the natural thermal flow in hydrothermal system should not be ignored if it is significant (q > 100 MW_{th}) such as that of Wairakei, Waimangu, Waiotapu-Waikite, Tongariro (Ketetahi) etc. Whereas having a relatively high heat flux of say 200mW/m^2 charging a geothermal system with an area of 25 km^2 (a reasonable size hydrothermal system) means q=5.0 MW_{th}. When adding to the stored heat in equation (2), it will have no significant effect on the potential power plant capacity for a resource of this size once it is reduced by the recovery factor and conversion efficiency. The above relation is based on the idea that natural thermal flow in hydrothermal systems should not be ignored especially if it's significant i.e.Wairakei, where surface heat flux is ~400MW_{th} (SKM 2002). This argument distinguishes hydrothermal and hot dry rock systems when using the stored heat method.

The additional factor takes into consideration ongoing heat input into the boundaries of the reservoir in the form of mass flux or conductive heat flux. The parameter q is a function of time $q(t)$. The heat input into the reservoir changes with time; it can increase, decrease or remain constant. Numerical reservoir modeling of Wairakei shows that mass flux into the reservoir has increased with time as a result of reservoir stimulation (Yeh, O'Sullivan et al. 2010) and (Allis 1981). (Figure 1 below). This means that the natural heat (through hot mass) input into the reservoir also changes with time in the case of the Wairakei geothermal field that heat flux is a function of time $q(t)$. An arbitrary function was derived from Figure 1 below and plotted to compare stored heat equation against, new model with constant heat flow into the reservoir and new model with heat flow as a function of time (Figure 2).

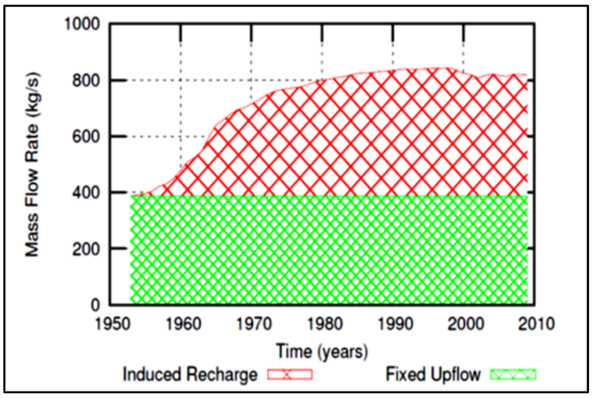

Figure 1: Wairakei mass up flow at the bottom of the model with components of fixed and pressure induced up flow (Yeh, O'Sullivan et al. 2010).

The most accurate way of determining the natural heat input into a reservoir is by reservoir modeling.

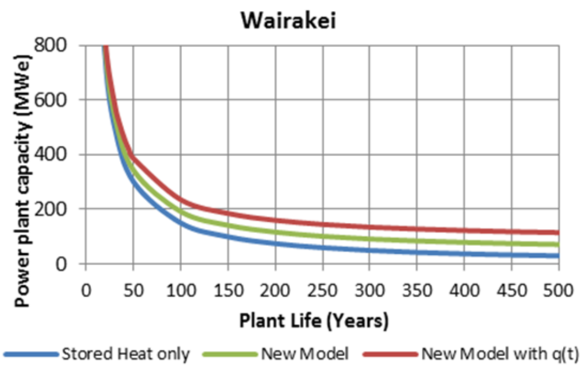

Figure 2: Comparison between stored heat calculation (equation 1) and the new proposed model equation for Wairakei geothermal system with a surface heat flow of 400 MW_{th} (SKM 2002).

Hydrothermal systems with a thermal output of q≥100MW_{th} natural heat flow should be considered in equation (2) (Zarrouk 2013). However, for q<100 MW_{th} then q=0 should be used (e.g. in areas with relatively low heat flux like hot dry rock systems). This is because when applying the factor and conversion efficiency (equation 2) the value added heat becomes very small and hence less significant on estimated power capacity. A comparison between stored heat calculation (equation 1) and the new proposed model (equation 2) for Wairakei (400MW_{th}), Tongariro (200MW_{th}), Te Kopia (100MW_{th}) and Ngataramaki (40MW_{th}) shows that when surface heat flux is less than 100MW_{th} there is no significant contributions to estimate of stored heat by the new model (equation 2) see Figures 2-5.

The proposed new refined model given in equation (2) acknowledges that not all the natural thermal flow is recoverable. In this case the natural heat flow and stored heat have been treated to the same recovery factor even though it is obvious that natural heat flow has a higher contribution in comparison to stored heat.

A graphical representation of the comparison between the power potential of current model (1) and the new proposed model (2) for a range on natural heat flow is given in Figures 3-5 below:

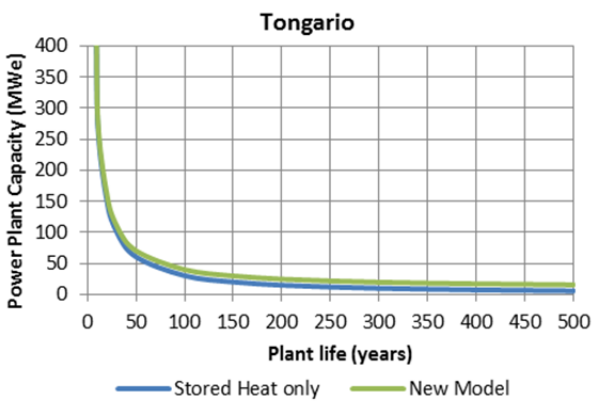

Figure 3: Comparison between stored heat calculation (equation 1) and the new proposed model (equation 2) for a surface heat flow of 200MWth, Tongariro geothermal system (SKM 2002).

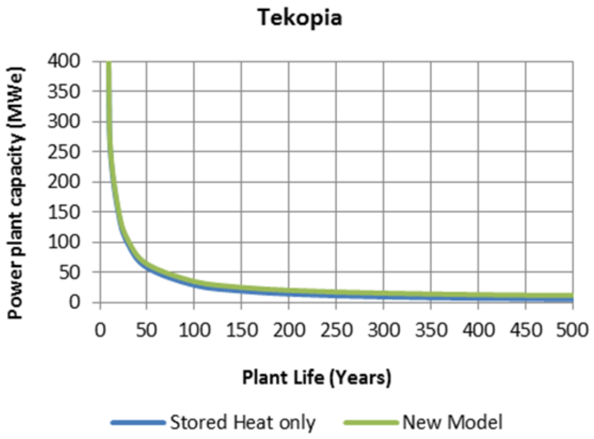

Figure 4: Comparison between stored heat calculation (equation 1) and the new proposed model (equation 2) for the Te Kopia geothermal system with a surface heat flow of 100MW$_{th}$ (SKM 2002).

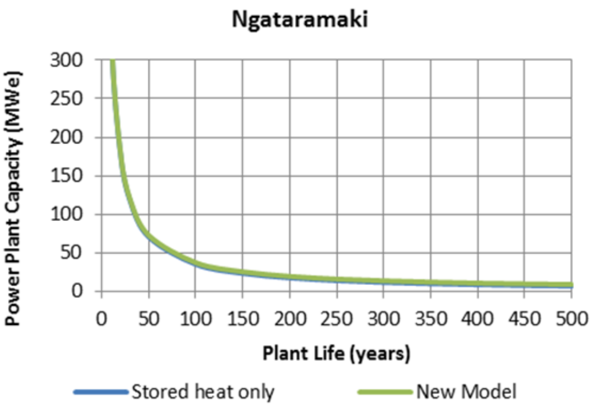

Figure 5: Comparison between stored heat calculation (equation 1) and the new proposed model (equation 2) for the Ngatamariki geothermal system with a surface heat flow of 40MW$_{th}$ (SKM 2002).

b. Recovery Factor

- The recovery factor is a term used in the stored heat method to account for the uncertainty of how much energy can be recovered from a reservoir. It represents how uniformly thermal energy can be exploited close to the exhaustion state of the reservoir economically.
- Williams (2007) used a more theoretical approach to suggest a range of 5 to 20%, intended to be applied to both natural fracture dominated resources and EGS system. The self-similar models developed by Williams represent a complex fracture dominated system that relate fraction of permeable volume to fraction of total flow and eventually recovery factor. The models were matched to existing fields, that is Dixie Valley and Beowave, USA, which matched different fractural dimensions proposed in the self-similar models. The challenge of this model is when it is applied to green fields it become virtually impossible to determine the nature of fractures in the field in the initial stages of field development.
- Typically 15% and 25% (Simiyu, 2013) are used as recovery factor without basis or justification of value chosen (Figure 6). Although the recovery factor is related to reservoir porosity and permeability, the typical choice of values used to calculate stored heat did not base derivations from this relationship. The recovery factor has been based on subjective assumptions by resource persons carrying out the assessment.

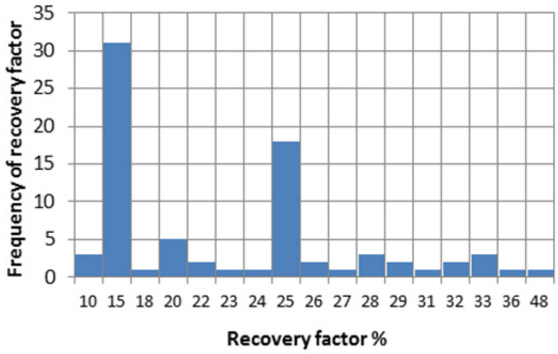

Figure 6: Distribution of recovery factor from 74 geothermal field assessment studies (from Simiyu, 2013).

Range of values for recovery factors have been assigned to different classifications of reservoir systems based on the enthalpy from published data (Tables 1 and 2). The most likely porosity and permeability range has been assigned to each class with a comparative recovery factor.

The value of recovery factor assigned to hot water systems is 10%, derived from the recovery factor from the modeling studies of Beowave field (Williams 2004) .

In two-phase liquid dominated low enthalpy fields the approximate range of field porosity is 15-20%. The following fields were considered Wairakei, Miravalles, and Ahuachapán with recovery factor of 20-30% (Brock and Gudmundsson 1989). Modeling of Wairakei indicates that the reservoir has been stimulated due to production and the recharge has increased. This means that the recovery factor for the Wairakei field could be higher than the 20-30% range estimated for low enthalpy systems (Allis 1981).

Medium enthalpy systems have a range between 6-10% porosity determined from published data of medium enthalpy fields. The fields used to determine suitable range of 10-17% for recovery factor are Mahanagdong (Bayrante 1992), Palimpinon (Maunder, Brodie et al. 1982), Ohaaki, Kawerau (SKM 2002) and Cerro Prieto (Westwood and Castanier 1981).

High enthalpy fields are characterized by low porosity and permeability. Suitable range of porosity values 5-10% and estimated recovery factor of 10-17%. These values were derived from high enthalpy fields such as Olkaria East and West (Ofwona 2005), Bacman, MakBan (Vicedo 2008), Rotokawa, Mokai (SKM 2002) and Mindanao.

Vapor dominated systems exhibit the lowest porosity and permeability. The porosity range is quite low about 3-5% and possible range of recovery factor is 8-10%. These estimates are from published work on resource assessment of the Geysers (Williams 2007), Kamojang, Darajat and Larderello (Allis 2000).

Table 1: Summary of categories of geothermal systems (Kaya et al 2011)

Category		Temperature	Enthalpy
Hot-water		T<220 °C	h<943 kJ/kg
Two-phase, liquid-dominated	Low-enthalpy Medium Enthalpy High Enthalpy	220 °C<T<250 ºC 250ºC<T<300ºC 250ºC<T<330ºC	943 kJ/kg<h<1100 kJ/kg 1100 kJ/kg<h<1500 kJ/kg 1500 kJ/kg<h<2600 kJ/kg
Two-phase, vapour-dominated		250ºC<T<330ºC	2600 kJ/kg<h<2800 kJ/kg

Table 2: Range of recovery factors can also be assigned to the different types of geothermal systems with evidence from field porosity and experiences (Kaya, Zarrouk et al. 2011)

Category		Temperature	Porosity	Recovery Factor	Field Examples	Reference
Hot-water		T<220 °C		10%	Beowave	Williams (2004); Kaya, Zarrouk et al. (2011)
Two-phase, liquid-dominated	Low-enthalpy	220ºC<T<250ºC	15-30%	20-30%	Wairakei, Miravalles, Ahauchapan, Ngawha, Onikobe	Westwood and Castanier (1981); Brock and Gudmundsson (1989); SKM (2002)
	Medium Enthalpy	250ºC<T<300ºC	6-10%	10-25%	Mahanagdong, Nesjavellir, Palimpinon, Cerro Prieto, Berlin, Amatitlan, Sumikawa, Kawerau, Ohaaki, Sibayak Hatchobaru, Las Tres Virgenes	Bayrante (1992); Amistoso, Aquino et al. (1993); SKM (2002)
	High Enthalpy	250ºC<T<330ºC	6-10%	10-17%	Olkaria East and West, Los Humeros, Lihir, Los Azufres, Dieng, Kakkonda, Bacman, Mak-Ban, Gunung Salak, Krafla, Zunil, Rotokawa, Yamagawa, Onuma, Mutnovsky, Namafjall, Mokai, Mindanao	SKM (2002); Ofwona (2005); Pastor, Fronda et al. (2010)
Two-phase, vapour-dominated		250ºC<T<330ºC	3-5%	8-12%	Kamojang, Dajarat, Larderello Geysers, Tongonan	Antúnez, Bodvarsson et al. (1994); Allis (2000); Williams (2004); Williams (2007)

3.2.3 Resource Size

The accuracy of estimation can be improved by using updated conceptual model of the field. Conceptual models give the best estimates of reservoir size and help to delineate outflow zones. The thickness of the reservoir should be determined from measurements of drilled wells. When drilled wells are not available the maximum thickness of reservoir is the maximum drillable depths. Geophysical surveys through: cap signature (i.e. top of reservoir), geothermal indications from 3D MT models and microseismic data can also be used.

Stored heat assessment can be refined by dividing the reservoir into smaller blocks and calculate the stored heat for each block separately. Dividing the reservoir into smaller blocks requires sufficient data to justify the subdivisions from drilled wells. This method does not lend itself well with the Monte Carlo simulation. Monte Carlo simulation iterates over a range of possible values using probability analysis while division of reservoir into small blocks aims at assigning particular values to parameters in each block.

a. The temperature distribution of reservoir should be taken as an average when geothermometers are used to estimate reservoir temperature. Monte Carlo simulation can be used to iterate from a suitable range of values to determine the distribution of temperature in the reservoir. Temperature distribution determined from measured wells is more accurate.

b. Conversion efficiency as a function of reservoir enthalpy as published in a world-wide review of conversion efficiency of geothermal power plants should be considered in equations (2). A generic conversion efficiency of 12% can be used for geothermal power plants based on worldwide average review (Moon and Zarrouk 2012).

3.2.4 Cut off Temperature

The cut off temperature cannot be set at a particular value since it depends on the enthalpy of the system, the water rest level, development technology and prevailing electricity prices. A range of 170 ºC to 190 ºC is reasonable for flashing technology. Lower values of cut of temperature have been used in the USA (10-40 ºC) and 80 ºC in Turkey (Sanyal, Klein et al. 2004). However, these values are used in warm or hot water systems (Kaya, et al, 2011) and the development strategy in these countries must have allowed for lower cut off temperatures (Arkan and Parlaktuna 2005).

DISCUSSION

Stored heat method is the most appropriate for assessment of green fields. The main limitation of the stored heat method is that it does not take into account the dynamic nature response of a reservoir to production. This results in reservoir pressure changes and fluid recharge. It is also difficult to define recharge response of a green field.

Numerical modeling is the most comprehensive resource estimation method but has limited applicability at the initial stage of resource development due to insufficient information.

Reservoir modeling has contributed significantly to improvements in stored heat method in the following ways:

- It has demonstrated that there is a net heat input into the reservoir in the form of mass and heat flow, which is ignored by the stored heat method. This heat (through mass) input changes with time due to reservoir stimulation (Yeh et al. 2010).

The calculations of stored heat are very sensitive to resource size, recovery factor, temperature distribution and specific heat of the rock. These parameters need to be evaluated accurately to give the best estimates of the resource using stored heat method.

Refinements to the calculation of stored heat by Zarrouk (2013) proposed that the mathematical expression for stored heat be amended to include consideration of natural heat flow. The argument is that for hydrothermal systems with a thermal output of $q \geq 100MW_{th}$ natural heat flow should be considered in the equation. The natural thermal flux of high enthalpy and vapour dominated systems is low and hidden. The proposed equation 2 may serve to differentiate hydrothermal systems from EGS systems and high enthalpy hydrothermal systems which have fewer surface thermal manifestations.

Resource sustainability has an effect on resource life in stored-heat calculations. Geothermal energy utilization is strongly linked with the sustainability of the resource and hence longer development lifetimes (50 and 100 years) should be considered. This implies that project life times (20-30 years) based on common business models is not applicable. Many geothermal fields (Wairakei, Larderello the Geysers and others) had a consistent production capacity after their economic life of 25-30 years. By incorporating the sustainability of the resource the difference between the standard power potential equation and the proposed equation which accommodates natural heat input is obvious.

The most contentious parameter in the calculation of stored heat is the recovery factor. Different models have been used to determine its value but they seem inadequate. The self-similar models by Williams (2007) give a good representation of fractured reservoirs. However, its application is limited by the fact that it is virtually impossible to determine the nature of fractures of green field. The proposed model of recovery factor in this work has been based on the characteristics of reservoir a classifications based on enthalpy. There are few publicly available publications on resource assessment of different fields worldwide.

Probability analysis using the Monte Carlo method should be applied to stored heat assessments. Such analyses should be limited to the main resource variables. The Monte Carlo methods does not compensate for significant errors in assumptions concerning resource parameters. The higher the uncertainty of variables in calculation the more sensitive the calculations are to the parameter.

CONCLUSIONS

Stored heat method is the most commonly used method for assessment of green fields. However, once exploration drilling and production begins reservoir modelling (simulation) should be used.

If there is a reliable heat flux surveys of the fields, the proposed refinements to the stored heat method push the method towards being more fundamentally correct and representative.

The most contentious parameters in the calculation of stored heat are the recovery factor and size of the resource. For stored heat updated conceptual model should be used to estimate size of the reservoir. The proposal to use a range of possible values assigned to different classes of reservoirs based on the enthalpy is realistic since it is based on real field examples.

The conversion efficiency and recovery factor models have both been based on enthalpy. The conversion increases with higher enthalpy fields as the recovery factor decreases. There is a balance in parameters between the conversion and recovery factor between low enthalpy to high enthalpy system.

Probability analysis using the Monte Carlo method should be applied to the stored heat assessments. Such analyses should be limited to the main resource variables.

The methodology used in AGEA (2010) is generally reasonable. However, it does not consider the long-term sustainability of the geothermal resources. The proposed refinements to the methodology give distinction between EGS and hydrothermal systems and recommend longer project life lifetime to address the sustainability of the geothermal system. This does not negate the importance of the economic life of a project. However, basing geothermal project on the economic life only is not sufficient for resource assessment.

RECOMMENDATIONS

The accuracy of this model should be tested with future estimation of resource potentials against numerical models of the fields.

More work is needed to better quantify the recovery factor, which needs to be better defined.

Reservoir modelling can be used to evaluate the accuracy of stored heat calculations. The estimates of recovery factor, temperature distribution, permeability, porosity, areal extent and rock properties can be confirmed through numerical modelling.

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