A REVIEW OF THE VOLUMETRIC STORED-HEAT RESOURCE ASSESSMENT: ONE METHOD, DIFFERENT RESULTS

Jaime Jose Quinao* and Sadiq J. Zarrouk

Department of Engineering Science, University of Auckland, New Zealand

*jaime.quinao@mightyriver.co.nz

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ABSTRACT

The volumetric stored-heat assessment method developed by the United States Geological Society (USGS) in the 1970's has become one of the standard resource assessment methods for geothermal systems. This method has been updated and modified by various groups and authors to account for new information and honour the existing uncertainties of the parameters both in the subsurface and conversion technologies. These updates and modifications have made the assessments from volumetric methods ambiguous. This paper provides a review of the existing volumetric methods and attempts to bring the various assumptions together to provide like-for-like comparison of geothermal resource estimates.

1. INTRODUCTION

The volumetric stored-heat method was developed by the USGS in the 1970's to assess the production potential of geothermal systems in the United States (Nathenson, 1975; White and Williams, 1975; Muffler and Cataldi, 1978; Muffler, 1979). The calculated production potential represents the fraction of recoverable thermal energy from the total thermal energy stored in a volume of porous and permeable geothermal reservoir, converted into electrical energy through an energy conversion efficiency factor.

The method is straightforward and easy to implement, providing capacity estimates of identified geothermal systems albeit with large simplifying assumptions e.g. recovery factor, conversion efficiency, etc. Updates to the methodology were focused on providing better estimates of these assumed factors based on long-term geothermal production experience (Sanyal et al., 2004; Williams, 2007; Williams et al., 2008). Other authors focused on the uncertainty of the parameters in the volumetric method equation and how these uncertain parameters are used as inputs in probabilistic resource evaluation (Parini and Riedel, 2000; Garg and Combs, 2010; Onur et al., 2010).

These updates generated several versions of the basic volumetric method. The results from these different versions of volumetric resource assessments became ambiguous, prompting several authors to publish guidelines on how to navigate the various assumptions in the method (Garg and Combs, 2010; Garg and Combs, 2011; Lawless for AGRCC, 2010).

This paper is written in a similar attempt to provide an illustrative comparison of the main versions of the volumetric method, the common assumptions, and the main differences.

2. VOLUMETRIC METHOD VERSIONS

2.1 USGS volumetric stored-heat method

The original method developed by the USGS estimates the production potential of a geothermal system from the total thermal energy available in the reservoir, the fraction of that total energy that can be recovered at the wellhead, and the portion of that recovered thermal energy that is converted to electrical energy/power capacity.

The following set of equations is from the latest USGS method update (Williams et al., 2008). The total thermal energy in the reservoir, q_R, is shown as:

$$q_R = \rho CV(T_R - T_0) \quad (1)$$

where ρC is the volumetric specific heat (thermal capacity) of the reservoir rock, V is the volume of the reservoir, T_R is the average reservoir temperature, and T_0 is a reservoir reference or a dead state temperature. The original USGS version evaluated all the thermal energy in the reservoir volume above a dead state temperature at ambient conditions (15°C). The latest USGS method update appears to have modified this to 75°C for Alaska and 90°C for most of the USA as a higher temperature cut-off for electricity generation (Williams et al., 2008). This reservoir reference temperature limits the total recoverable energy in the reservoir and should not be confused with the power cycle reference temperature (set here at an average ambient temperature of 15°C) that limits the wellhead energy available for electricity conversion.

The recoverable thermal energy available at the wellhead q_{WH}, is estimated using a recovery factor, R_g

$$q_{WH} = R_g q_R \quad (2)$$

The original USGS method suggested using 25% (range is from 0 to 50% with a triangular distribution) updated by Williams (2007) and Williams et al. (2008) to 8-20% for fracture-dominated reservoirs and higher (10-25%) for sediment-hosted reservoirs. Both of these updated recovery factor ranges have uniform probability distributions.

The thermal energy at wellhead may also be expressed in terms of the fluid mass, m_{WH}, the saturated liquid enthalpy of the produced fluid at wellhead, h_{WH}, and the enthalpy at the power cycle reference temperature, h_0, as

$$q_{WH} = m_{WH}(h_{WH} - h_0) \quad (3)$$

The maximum available thermodynamic work of the fluid at the wellhead, W_A, is only a fraction of q_{WH} and is given by:

$$W_A = m_{WH}[h_{WH} - h_0 - T_0(s_{WH} - s_0)] \quad (4)$$

where T_0 is the power cycle reference temperature in absolute temperature units (Kelvin), s_{WH} and s_0 are the entropy of the fluid at the wellhead conditions and at the reference temperature, respectively.

The W_A and the production potential of a system are evaluated over a period of time (usually 30 years) that represents the power plant life or the economic life of the geothermal development. Equation (4) is then stated in terms of rates as

$$\dot{W}_A = \dot{E} = \dot{m}_{WH}[h_{WH} - h_0 - T_0(s_{WH} - s_0)] \quad (5)$$

where $\dot{E}$ is known as exergy (DiPippo, 2012).

This maximum available work is then converted into electric energy, $\dot{W}_e$, using a utilization efficiency, η_u, usually at around 0.4 to 0.5 The plant capacity factor is assumed to be 100%.

$$\dot{W}_e = \eta_u \dot{E} \quad (6)$$

2.2 Australian Geothermal Reporting Code Committee (AGRCC) method

The succeeding set of equations is from the second edition of the Geothermal Lexicon for Resources and Reserves Definition and Reporting compiled by Lawless (AGRCC, 2010) for the Australian Geothermal Reporting Code Committee (AGRCC). The document defined the total thermal energy, Q or H_{th}, of a reservoir more extensively by including the thermal energy content of the fluid part of the reservoir volume and is shown as

$$Q = H_{th} = Ah \left\{ \begin{array}{c} [C_r\rho_r(1-\phi)(T_i - T_f)] + \\ [\rho_{si}\phi(1-S_w)(h_{si} - h_{wi})] + \\ [\rho_{wi}\phi S_w(h_{wi} - h_{wf})] \end{array} \right\} \quad (7)$$

where the first bracketed terms represent the thermal energy in the rock, the second group of terms represents the energy in the steam, and the third group represents the energy in the water/liquid.

The volume of the reservoir is described by the areal extent of the reservoir, A, and the average reservoir thickness, h. $C_r\rho_r$ is the volumetric heat capacity of the rock at initial reservoir conditions, ϕ is the average porosity or the fluid-filled void spaces of the reservoir volume, T_i is the average initial reservoir temperature and T_f is the rejection temperature, similar to the reservoir reference temperature in equation (1). The density of steam and water at initial reservoir conditions are represented by ρ_{si} and ρ_{wi}, respectively. The steam and water enthalpies at reservoir temperature are represented by h_{si} and h_{wi}. The water enthalpy at the rejection temperature is h_{wf}, S_w is the relative water saturation of the reservoir.

Similar to the USGS version, a recovery factor, R_f, is used to determine the portion of the total thermal energy in the reservoir that can be extracted. Instead of prescribing a recovery factor to be used, the AGRCC allows for a range of factors previously used, e.g., 2.5 times the porosity, provided there is appropriate justification for using a particular recovery factor (AGRCC, 2010). A conversion efficiency, η_c, is used to convert the recovered thermal energy into electric energy, and a project life or power plant life, L, is used (also usually at 30 years). A power plant capacity factor or load factor, F, is factored in and is usually at 90-95%. The estimate for electric production potential is given as:

$$\dot{W}_e = \frac{H_{th}R_f\eta_c}{L\,F} \quad (8)$$

3. SAMPLE CALCULATIONS

The same general principles apply to all versions of the volumetric method. However, the definition of the reservoir volume, the total thermal energy content, the recoverable energy, the efficiency of conversion and other factors were interpreted and implemented differently by different groups.

To illustrate these interpretations, we will apply the volumetric stored-heat method to an idealized geothermal system with reservoir parameters listed in Table 1.

Table 1. Parameters for an idealized geothermal system.

Parameter	Value	Units
Area	9	km^2
Height (thickness)	1.14	km
Density (rock)	2600	kg/m^3
Heat Capacity (rock)	1000	J/kg-K
Reservoir Temp	265	°C
Porosity	8%	
Water sat, S_w	1.0	

The conversion technology used in this example is a single flash power plant with a separation pressure of 9 bar abs. Using this flash plant, the rejection temperature is the liquid saturated temperature at 9 bars, 175.35°C. This is our assumed reservoir reference or cut-off temperature. The wellhead pressure is at 11 bar abs.

3.1 Total thermal energy (stored-heat or heat in place)

3.1.1 USGS Method

Using equation (1), the total thermal energy in the volume is:

$$q_R = 2600 \times 1000 \times (9 \times 10^6 \times 1140) \times (89.65) \quad (9)$$

$$q_R = 2.39 \times 10^{18}\,J$$

Garg and Combs (2011) described a "volumetric heat capacity of fluid-saturated rock" to account for the energy contained in the fluid as

$$\overline{\rho c} = \phi\rho_w c_w + (1-\phi)\rho_r c_r \quad (10)$$

where the density of water, ρ_w, and the heat capacity of water, c_w, are evaluated at the reservoir temperature. This increased the total volumetric thermal energy by around 4%.

$$q_R = V\overline{\rho c}(T_R - T_0) = 2.49 \times 10^{18}\,J \quad (11)$$

While the overall increase is not large, the distribution of thermal energy between the reservoir rock and reservoir fluid is worth noting.

$$q_{rock} = V(1-\phi)\rho_r c_r(T_R - T_0) = 2.20x10^{18}\,J \quad (12)$$

$$q_{water} = V(\phi\rho_w c_w)(T_R - T_0) = 2.88x10^{17}\,J \quad (13)$$

The thermal energy stored in the rock volume is around 88% while the energy stored in the fluid-filled pore volume is around 12%.

3.1.2 AGRCC Method

Equation (7) is also used to estimate the total thermal energy in the same volume.

$$Q = H_{th} = 2.47 \times 10^{18}\,Joules$$

where the energy in the rock volume is similar to equation (12) and is about 89% of total.

$$Q_{rock} = AhC_r\rho_r(1-\phi)\left(T_i - T_f\right) = 2.20 \times 10^{18}\,J \qquad (14)$$

The thermal energy in the fluid volume evaluated using liquid saturated enthalpies at the initial reservoir temperature and at the reservoir reference temperature is comparable to equation (13) and is about 11% of total.

$$Q_{fluid} = Ah\rho_{wi}\phi S_w(h_{wi} - h_{wf}) = 2.66 \times 10^{17}\,J \qquad (15)$$

In both methods, the fraction of energy contained in the *in situ* fluid supports the possible correlation between the effective porosity and recovery factors. A higher effective porosity means there is a large volume of energy-carrying fluid that may be extracted and a large surface area is available to heat transfer from cooler fluid recharge. If all the fluid is extracted, the recovery factor is already at 11-12% for this test reservoir, without any heat recovery from the rock component. Simiyu (2013) observed a similar correlation between reservoir enthalpy, effective porosity, and recovery factors.

3.2 Recovered thermal energy (energy at wellhead)

The recovered thermal energy, determined by a recovery factor suggested at 25% by the original USGS method, is a large uncertainty in the volumetric stored-heat estimate. Various authors have updated the recovery factor as fields were developed and long-term production histories became more available. GeothermEx recommended that USGS consider a lower range of recovery factors at 3-17% with 11% as the mean value (Sanyal et al., 2004). Simiyu's review of recovery factors used in 74 fields worldwide resulted in typical values of 15% and 25% (2013).

3.2.1 USGS Method

For the USGS method, this was originally set at 25% updated by Williams et al. (2008) to 8-20% (fracture-dominated) or 10-25% (sedimentary/porous volcanic-hosted reservoirs) based on the behavior of heterogeneous fracture-dominated reservoirs (Williams, 2007). To maximize the recovery, it is assumed that this idealized reservoir is of the porous volcanic-hosted type. The USGS recovery factor used is 17.5%, the mean of the 10-25% distribution. Applying this to equation (9):

$$q_{WH} = R_g q_R = 0.175 \times 2.39x10^{18} = 4.18x10^{17}J \qquad (16)$$

3.2.2 AGRCC Method

In the AGRCC, a recommendation is made to use a recovery factor equal to 2.5× ϕ if the reservoir volume has a high average porosity (over 7%). For this reservoir, the recovery factor is 20% and applied to the AGRCC (2010) equation, results in:

$$QR_f = 2.47 \times 10^{18} \times 2.5 \times 0.08 = 4.93 \times 10^{17}J \qquad (17)$$

3.3 Converting recovered thermal energy into electricity

3.3.1 USGS Method

In the USGS method, it is noted that not all of the recovered energy at wellhead is thermodynamically available to do work, hence the use of equations (3-4). The equivalent mass of fluid at the surface required to carry all the recovered thermal energy is given by equation (3).

$$m_{WH} = \frac{q_{WH}}{(h_{WH} - h_0)} = \frac{4.18 \times 10^{14}kJ}{(1160 - 63)} \qquad (18)$$

$$= 3.81 \times 10^{11}kg$$

While the fluid at wellhead is generally a two-phase mixture, the h_{WH} is evaluated as saturated liquid (at the wellhead pressure, 11 bar) because liquid has smaller entropy, s_{WH}, to ensure a higher W_A (Muffler, 1979). The energy lost due to raising the water against gravity is very small. The enthalpy at the power cycle reference temperature, 15°C, is also evaluated at saturated liquid conditions, h_0.

Equation (4) gives us the maximum work available as:

$$W_A = m_{WH}[h_{WH} - h_0 - T_0(s_{WH} - s_0)] \qquad (19)$$

$$W_A = 3.81 \times 10^{11}[1160 - 63 - 288.15(2.19 - 0.22)] \times 1000$$

$$W_A = 2.04 \times 10^{17}J$$

The available work from the recovered thermal energy, at a 15°C reference temperature, is only about 50% of the q_{WH}.

Evaluating this for a project life of 30 years, and a utilization efficiency of 0.4, the electric energy, $\dot{W}_e$, is given by equation (6).

$$\dot{W}_e = 0.4 \times \frac{2.04 \times 10^{17}}{30 \times 365.25 \times 24 \times 3600} \times 1x10^{-6} \qquad (20)$$

$$\dot{W}_e = 86.2\,MW_e$$

Garg and Combs (2011) provided examples to illustrate that the W_A should be evaluated based on the specific power cycle used to generate electrical energy. They argued that for single flash systems, as is our case, the mass considered for equation (4) should only be the steam that enters the turbine and that the enthalpy and the entropy terms should be evaluated at the turbine inlet conditions or at separated steam conditions (9 bar).

$$W_{Aturbine} = m_{turbine}\left[h_{sepS} - h_0 - T_0(s_{sepS} - s_0)\right] \qquad (21)$$

$$W_{Aturbine} = 0.206 \times m_{WH}[2772 - 63 - 288.15(6.62 - 0.22)]$$

$$W_{Aturbine} = 6.80x10^{16}J$$

Equation (20) is similar to equation (4) with the wellhead condition replaced by turbine inlet/separated steam.

In this example, the available work from the recovered thermal energy, at a 15°C reference temperature, is only about 16% of the q_{WH}. Evaluating this at a similar project life of 30 years with a higher turbine utilization efficiency of 0.7 (Garg and Combs, 2011)

$$\dot{W}_e = 0.7 \times \frac{6.80\times10^{16}}{30\times365.25\times24\times3600} \times 1 \times 10^{-6}$$

$\dot{W}_e = 50.25 MW_e$

3.3.2 AGRCC Method

Using the result from equation (17) into equation (8), the electric capacity is estimated using a 100% load factor, 30 years of project life, and a conversion efficiency of 12% (Zarrouk and Moon, 2014).

$$\dot{W}_e = \frac{4.93\text{x}10^{17} \times 0.12}{30 \times 365.25 \times 24 \times 3600} \times 1 \times 10^{-6}$$

$$\dot{W}_e = 62.5\ MW_e \qquad (22)$$

4. COMPARISON

The volumetric thermal energy of the reservoir is practically the same for both methods. Note that the USGS method had a slightly lower q_{WH} because it ignores the energy contained in the *in situ* fluid. While it is obvious that majority of the energy in the reservoir volume is contained in the rock, the fraction of energy contained in the fluid is large enough (11-12%) that the recovered thermal energy, q_{WH}, may be supplied mainly from the *in situ* fluid.

The recovery factors used were not too different, 17.5% and 20% for the USGS and the AGRCC methods, respectively. The difference in recovery factors used influenced the estimated production potential but normalizing these to a single value is easy.

The utilization and conversion efficiencies are where the main differences lie. If we define an effective efficiency such that it only represents the amount of useful converted energy from the total recovered energy, we can compare the methods directly.

$$\eta_{eff} = \frac{\dot{W}_e \times L}{Q_R \times R_f} \qquad (23)$$

The results are listed in Table 2.

Table 2. Effective efficiencies of the methods.

Method	η_{eff}
USGS	19.5%
USGS (Garg and Combs, 2011)	11.4%
AGRCC	12%

The USGS estimate had to be evaluated for the particular power cycle (single flash plant) to be near the production potential estimate and the conversion efficiency of the AGRCC equation. This conversion efficiency is from Zarrouk and Moon's conversion efficiency review (2014). The similarity between the effective efficiency of the USGS method (modified by Garg and Combs (2011)) and the review results is possibly due to the popularity of flash plants in geothermal.

Without modifying the USGS method, the USGS utilization efficiency, η_u, has to be at 25% or the AGRCC conversion efficiency, η_c, has to be at 18% to arrive at the same production potential.

5. SUMMARY

The volumetric stored-heat concept is straightforward and is useful in providing fast estimates of production potential for geothermal prospects. A general method developed by the USGS in the 1970s has evolved into different versions, making volumetric resource estimates ambiguous.

The method to estimate the total thermal energy in a reservoir volume is consistent among the different versions, with the recent additional detail of counting the energy of the *in situ* fluid. In the example shown above, the total stored-heat energy is not largely affected by this addition (an increase of about 4%) but the clearer distribution of the total energy between the fluid and rocks provides insight into the components of the recovered thermal energy.

As suggested by the AGRCC, using a conversion efficiency of around 10-12% to estimate the electric capacity from the recovered thermal energy should be sufficient for estimating geothermal resource potential, especially during the early stages of development. The maximum work and the exergy approach is theoretically more robust but is unnecessarily complicated when a more generic approach is required, such as doing a country-wide assessment of undeveloped geothermal potential.

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