Stored Heat Calculations – Time for Review

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Keywords: *Stored heat calculations, power density calculations, geothermal development.*

ABSTRACT

This paper reviews some preliminary methods of assessing power potential of geothermal fields (particularly stored heat and power density), while (re)introducing an additional stored mass calculation.

Equating stored heat estimates with two different reference temperatures (e.g. USGS's original ambient temperature versus a 180°C abandonment temperature) shows that recovery factor is a function of reference temperature and reservoir temperature (Ra = Rb x (Tres - Tb)/(Tres - Ta)). This is not always recognised, such that differing recovery factors from different reference temperatures have been mixed in calculation schemes and ascribed to formation type or effects of reservoir temperature. Alternatively, reference temperatures have been changed without adjustment of recovery factors from the original reference temperature.

The paper brings the various methodologies into a single power density graph to show how they may relate particularly to accessible depth of reservoir, porosity and temperature. The family of curves suggests that Wilmarth's "Main Sequence" and "Hot Arc" lines may require re-examination. The convergence of various quick capacity assessments about real world data either speaks to the usefulness of these methods, or to the dominance of the stored heat paradigm in ultimate sizing of geothermal developments.

Nearly twenty years ago, the USGS revised its stored heat calculation methodology which included stochastic modelling and led to a recalibration of recovery factor for condenser reference temperature using a limited database of US operating geothermal power stations. In the last twenty years many stations have been added globally such that a significant database of real-world operating plant could be created for recalibration of the recovery factors in stored heat calculations. If the associated numerical reservoir simulations for these plants are also considered in the recalibration, then a clear view on sustainable capacity for each field would be available for this recalibration purpose.

The paper calls for a review of stored heat methodology and especially recovery factor, ideally using a single reference temperature as a means of calibrating effects of formation type and reservoir temperature as examples. It then goes on to question who could lead such an initiative.

1. INTRODUCTION

One of the origins for this paper was in a due diligence exercise undertaken in 2007 in which the assets of PNOC-EDC were being offered on the market. This offering included the geothermal fields that PNOC-EDC had developed and all their potential. As such the potential capacity of these fields was important for which various models were provided including stored heat calculations and numerical reservoir simulations.

As part of good process, independent verification was provided and this included a review of stored heat field capacity assessment by GeothermEx (in practice, GeothermEx had undertaken the comparative study earlier in 2004 at PNOC-EDC's request (GeothermEx 2004)). GeothermEx provided their stored heat calculations for various sectors of fields using the same inputs as PNOC-EDC. Marginal differences can be expected for two similar methodologies with different reference temperatures, but the field and sector capacities by the two companies differed by a factor of around 2.2 for every sector with GeothermEx calculating the higher capacity. Both PNOC-EDC and GeothermEx are highly respected and well known for their competence and had internal checks to ensure thoroughness of their calculations. GeothermEx compared the results, made some observations such as high recovery factors used by PNOC-EDC despite having the lower estimate, but did not resolve the differences. This particular Philippines comparison has also been referred to by Malcolm Grant (Grant, 2014)

This leaves questions like "why were the stored heat capacities different?" and "what are the implications?" – a subject of this paper.

Resource capacity estimates commonly use stored heat (volumetric) calculations, power density, or natural heat loss (also referred to as surface thermal flux) at preliminary stages of development, and lumped parameter or numerical simulation modelling once there is substantial drilling, testing and operational data (Ciriaco 2020). Recently, some have argued for a new machine learning approach (Holmes, 2024). Several of these are discussed in the paper but the focus is on early-stage estimates using stored heat and power density calculation.

2. STORED HEAT CALCULATIONS

There is a strong case for increased reliance on numerical reservoir simulation models, especially once the information for model calibrations comes through drilling and some level of operation. However, first principles approaches should not be overlooked, especially in the initial exploration phase. These tell us that the potential of one field compared with another similar field could be greater if the volume (area and depth) of a reservoir is greater, or if the temperature is higher as examples. Experience tells us that whatever theory may tell us, this needs to be tempered by comparison with real life examples, with some scaling factor being necessary. Simple formulations that use these first principles are available through stored heat and power density calculations.

Stored heat calculations are based around the assumption that some fraction of the total heat in place in a reservoir should be available for development. That calculation includes an assessment of the total heat in rock and fluid within the accessible reservoir. This heat is assessed against a base temperature (below which any heat is deemed useless).

The basic formulae are as follows but there have been more recent refinements to this:

$$Q = A \cdot h \cdot C \cdot \rho \cdot (T_i - T_f) \qquad \text{Equation 1}$$

Where:

Q = Stored Heat

A = Areal extent of the reservoir

h = Average reservoir thickness

C = Specific heat of the rock water mix

ρ = Density of rock water mix (a function of porosity)

T_i = Initial average reservoir temperature[1]

T_f = Base/reference/abandonment/rejection temperature – these various terms are used to describe this temperature depending on source.

The equation would normally be expanded out to give the heat in the rock, heat in the liquid and heat in the steam separately, but this simplified form is useful for discussion.

There are two dominant camps in terms of base or reference temperature. The United States Geological Survey (USGS) has been a leader in formalizing and propagating this methodology and initially set a reference temperature as ambient temperature (15^{o}C default value). In terms of the Philippines resource calculations mentioned in the Introduction, GeothermEx was in this camp, although they modified ambient temperature to 30^{o}C for Philippine conditions (and arguably should have used 50^{o}C to match rough condenser temperatures).

A counter view was that much of the heat was of no use for electricity generation, so it was better to use a base temperature more related to the available technology or to available energy. Back in the 1960's and 1970's the dominant technology was flash steam turbine technology supported by artesian wells, so a base temperature of 180^{o}C was chosen. This was sometimes referred to as an abandonment temperature. This allowed for separation and further loss of pressure through the Fluid Collection and Disposal System (FCDS) piping and pressure vessels before the station, and allowed for common station operating pressures. An alternative justification for this reference temperature was that wells would cease to flow at temperatures below 180-200^{o}C (Grant 2014). The value of this base temperature will be discussed later in the paper. PNOC-EDC (and much of the World including New Zealand, Japan and Iceland consultants) was in this 180^{o}C camp. Even more variability has been introduced for the reference temperature in recent years.

The assessed available heat is then converted to electricity:

$$E = Q \cdot R \cdot \eta_c / (F \cdot L) \qquad \text{Equation 2}$$

Where:

E = estimate of installable power station capacity

Q = stored heat as defined in equation 1

R = recovery factor – subject to a range of factors

η_c = energy conversion factor showing the efficiency of converting heat into electricity (commonly a simple utilisation efficiency but sometimes based only on the First Law of Thermodynamics) – typically about 10% but actually a function of temperature/enthalpy

F = plant factor/availability factor (ratio of actual GWhs generated to theoretical maximum) – commonly 90-95%

L = Economic life of the plant, normally taken to be 30 years, though there may be reasons for shorter or longer (intergenerational) lives.

Energy conversion rate varies with temperature such that there is clearly a linear relationship at least with enthalpy as shown by Moon (Moon and Zarrouk, 2012) and extended by White to allow for sub-atmospheric flash (White, 2021) (see Figure 1). In practice, Moon had modelled energy conversion efficiency against enthalpy with equations for each type of technology (e.g. single flash or binary cycle plant), but this has been converted to a rough temperature assuming fluids were at saturated conditions. From Figure 1, efficiency can be related to reservoir temperature by the equation:

$$\text{Utilisation Efficiency (\%)} = 0.0439T_{res} - 1.87 \qquad \text{Equation 3}$$

Note that this efficiency is not the same as "First Law" efficiency which will net off heat rejected to the environment, or "Second Law" efficiency which will also subtract off thermodynamic unavailability. Instead this represents the simple ratio of net electricity out versus heat extracted from the field (all common enthalpy tables are referenced relative to 0^{o}C), so will include thermodynamic and economic constraints forced by practical design of the stations this is indexed to.

Recovery factors had been determined somewhat by trial and error rather than any thorough experimentation or calibration (with recent exception for USGS). Subir Sanyal (Sanyal et al, 2004) outlined the initial evolution of recovery factors. From experience in the petroleum industry, it was observed that the recovery factor for petroleum for an ideal sedimentary formation should be about 50%. Some very early stored heat calculations used this 50% value, but it clearly oversized the power plant. (But note a misapplication of experience here: the petroleum industry assumed 50% of stored mass and therefore energy within pores could be recovered, while stored heat calculations added in the substantial component of heat stored in rock.)

[1] Note that all references to temperature in this paper are in degrees Celsius

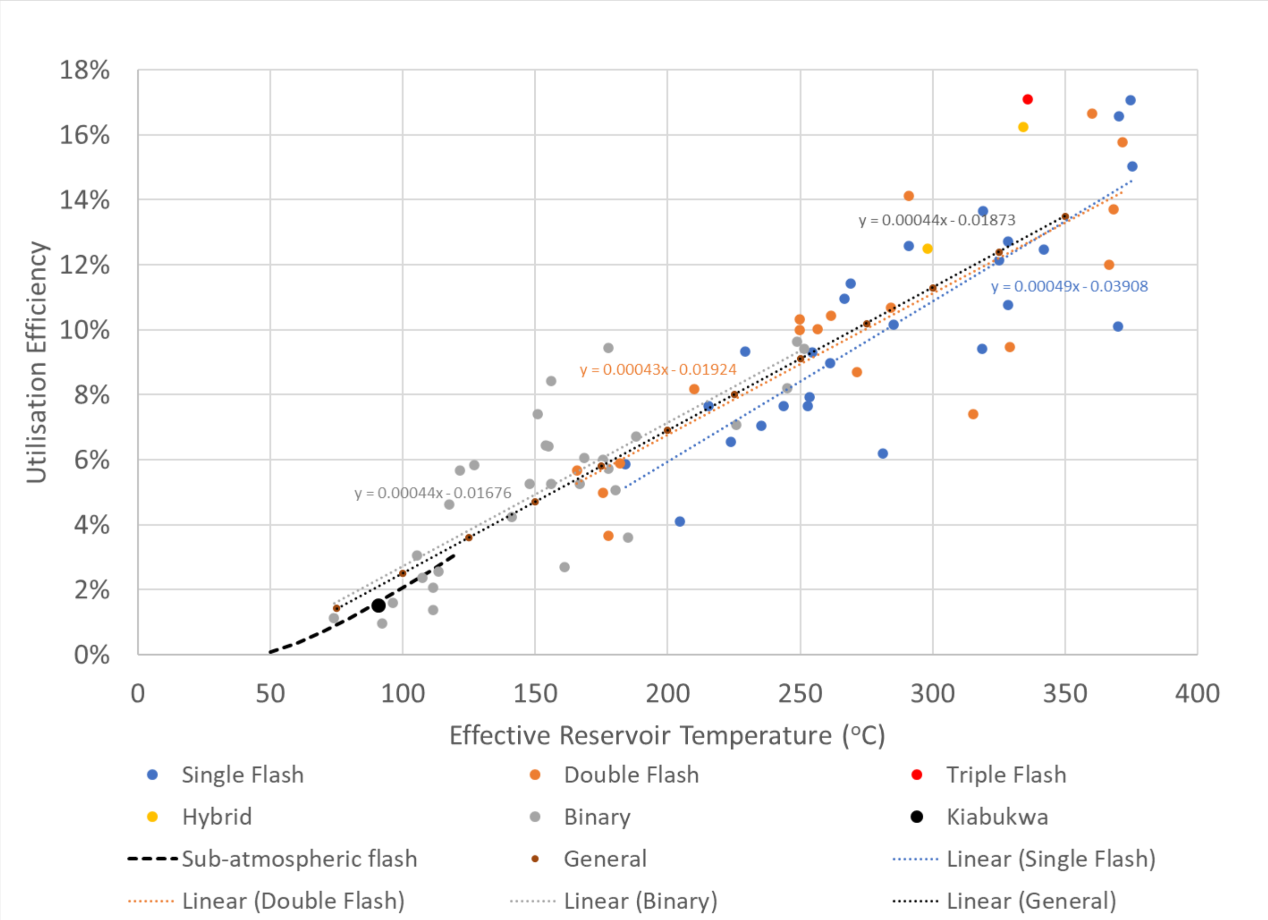

Figure 1: Observed utilisation (power conversion) efficiencies for a range of technologies including sub-atmospheric flash (based on Kiabukwa and an associated theoretical sub-atmospheric flash curve) and reservoir temperatures [Source: modified from White, 2021 and previously based on data in Moon and Zarrouk, 2012]

A history of the development of the stored heat technique is interesting. Most papers outlining the history go back to a 1977 paper by Patrick Muffler (USGS) and Raffaele Cataldi. However, this paper and an earlier 1965 USGS paper by Donald White point to pioneering work by John Banwell in New Zealand (papers in 1963 and 1964) and Gunnar Bodvarsson in Iceland. Banwell's work was later applied by Peter Macdonald to fields like Kawerau and Broadlands.

The earliest New Zealand example of the technique so far found is in a cooperative paper between Peter Macdonald (NZ DSIR) and Patrick Muffler (USGS) in which a capacity was calculated for Kawerau in 1972 (Macdonald and Muffler 1972). Muffler had been seconded to the DSIR Geophysics Division in 1970 for geothermal experience before taking on the coordinator role for the USGS Geothermal Research Program between 1971 and 1976, and brought his stored heat experience back to the US. Features of this calculation were a 50% recovery factor and a 100ºC reference temperature (previously used by Banwell), an energy conversion efficiency of 16% (very high) leading to a capacity when converted to 30-year life at 90% load factor of 60-100MWe for Kawerau depending on appropriate field area (6-10km^2). Note that Kawerau will soon have installed generation exceeding 210MW and area is now thought to be about 35km^2.

However, assuming that 50% of the volume of a geothermal reservoir was porous and interconnected, a recovery factor of 0.5 x 0.5 or 25% was deduced (Sanyal et al, 2004). This 25% recovery factor was formalised by the USGS in a 1978 paper (Circular 790). It was assumed that recovery factor should be a function of porosity. A common porosity in fields was 10% so this was equated to 25% recovery factor with a linear relationship assumed, so recovery factor became 2.5 times the porosity. Those using the USGS methodology with this recovery factor and ambient reference temperature still found this 25% recovery factor led to significant oversizing of station capacity (Sanyal et al, 2004). This led to a further recalibration by USGS after 2004 with recovery factor essentially halved again, now using stochastic analysis (i.e. calculations that used randomly selected values in a distribution curve for each input value across thousands of calculations to determine a probability distribution curve) to compare calculations with actual performance of US operating plant. At this point, because USGS calculations were indexed to about 20 real world (US-based) plant performances (see Table 1), recovery factor using that system would have included allowance for a range of factors inherent in operating plant including: influence of reinjection, condenser temperature/pressure, influence of field recharge and natural throughflow, non-availability of heat, etc. (Half of these developed fields had reservoir temperatures less than 180ºC so would have been assessed as of zero potential with a 180°C reference temperature). The reference temperature was also adjusted recognising an approach temperature was required in the design of the cooling tower, such that ambient temperature could never be reached – the reference temperature becoming the condenser inlet temperature (about 40°C).

Table 1: Fields used in GeothermEx 2004 review (Note that the Geysers was omitted from GeothermEx analysis because data was supplied by operators rather than independently assessed) [Source: Sanyal et al 2004]

Field	Mean Temperature (°C)	Mean Resource Base (MWe)	Sustainable Capacity (MWe)
Beowawe	210	58	30
Brady's HS	182	22	20
Desert Peak	196	79	50
Empire	153	11.6	5
Honey Lake	116	13	3
Rye Patch	182	94	15
Soda Lake	181	62	15
Steamboat	188	78	50
Stillwater	160	52	30
Wabuska	123	17	1
Coso	278	490	300
East Mesa	154	167	90
Heber	173	158	80
Long Valley	183	148	70
Salton Sea	302	1881	800
Cove Fort	177	105	30
Roosevelt HS	204	120	75
	Av = 186°C		

Those using the 180°C reference temperature followed a similar evolutionary path. The 25% recovery factor was arrived at from USGS, and those using this combined with likely input values found this only rarely oversized a station to the resource (Ohaaki was a possible exception). For a 180°C reference point, likely input values led to apparently safe sizing of stations. Though not properly calibrated, it could be said that P50 inputs provided a P90 (conservative) capacity estimate. Subsequently, 180°C proponents noted the use of stochastic modelling by USGS, so introduced this stochastic approach without change of recovery factor from around 0.25. At this point it was assumed that P50 inputs would give an apparently logical P50 capacity output, when in fact they would still have been giving a P90 output.

This error in non-recalibration of recovery factor with introduction of stochastic modelling is highlighted in the PNOC-EDC/GeothermEx comparison. The PNOC-EDC P50 capacity estimates were a very close match to the GeothermEx P90 estimates, supporting the hypothesis that P50 inputs for the 180°C reference point give P90 estimates. It was also noted that the GeothermEx P90 and PNOC P50 estimates were good approximations to the observed sustainable capacity for the fields.

Note that the error in using P90 estimates with a 180°C reference temperature will lead to significant underestimation in national resources in countries like New Zealand or Indonesia as examples.

3. RECOVERY FACTORS ARE SPECIFIC TO REFERENCE TEMPERATURES

In the Philippines comparison, GeothermEx was surprised about how high the recovery factor used by PNOC-EDC was compared with their own, and this despite the PNOC-EDC estimate being the lower estimate. In practice, it is obvious that the recovery factors for the two calculation schemes should be different. Recovery factors must be a function of the calculation methodology.

Assuming estimates for any reference temperature should still give the same capacity estimates, combining Equations 1 and 2 above, and eliminating all common factors gives the following simple relationship:

$$R_a \,.\, (T_i - T_a) = R_b \,.\, (T_i - T_b) \qquad \text{Equation 4}$$

or

$$R_a = R_b \,.\, (T_i - T_b)/(T_i - T_a) \qquad \text{Equation 5}$$

Where

R_a or $_b$ = recovery factor at condition a or b

T_i = initial reservoir temperature

T_a or $_b$ = reference temperature a or b

This requires putting aside the notion that recovery factor is an inherent property of a resource type or formation, though this may have an influence.

The following figure shows how these recovery factors may be related to each other, comparing values of required recovery factor with those associated with ambient 15°C conditions i.e. assumptions within the original USGS methodology. From Figure 2, as a gauge of effects if converting a USGS recovery factor with 15°C ambient reference temperature to a 180°C reference temperature then the new recovery factor would be between 2 and 3 times the USGS value across a reservoir temperature range of 250-300°C. This is the order of magnitude of the ratio of recovery rates normally observed for the two dominant camps.

Equation 5 and Figure 2 show that recovery factors are a strong function of their respective reference temperature and at least need the reservoir temperature to enable conversion, if not indicating that recovery factors are a function of reservoir temperature. It is rarely recognized that recovery

ISSN 2703-4275

factors are specific to reference and reservoir temperatures (see Table 2 below for one example). Interestingly, the Sanyal et al 2004 paper did include a correction to recovery factor partly based on the difference between using reference temperatures of 15 and 21°C. However, very often the major difference between 15°C and 180°C references temperatures are ignored and people have searched for an explanation of different recovery factors in terms of a reservoir temperature effect (Zarrouk and Simiyu 2013) or assigning them to different reservoir types (AGEG 2010). What should be obvious is that recovery factors sourced at one reference temperature should not be used at another reference temperature without suitable recalculation.

It is normally assumed that recovery factors are constant with temperature. However, this could only be true for one reference temperature because of Equation 5. The author suspects that this reference temperature is zero °C, but in terms of dominant paradigms, the nearest are recovery factors set for 15°C reference temperature (for which Sanyal et al calculated a value of 0.11). If it is assumed that recovery factors are constant relative to a reference temperature of 15°C, and a value R_1 is found at T_{res1} with reference T_{ref1}, then a new recovery factor R_2 can be found at T_{res2} with reference T_{ref2}

$$R_2 = R_1 \,.\, (T_{res1} - T_{ref1}) / (T_{res1} - 15) \,.\, (T_{res2} - 15) / (T_{res2} - T_{ref2})$$
Equation 6

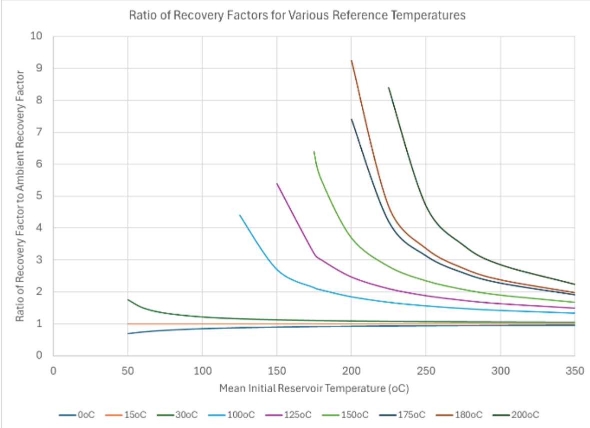

Figure 2: Relationships between recovery factors for various reference temperatures and reservoir temperatures (using Equation 5)

In terms of the PNOC-EDC and GeothermEx comparison, both companies used generally accepted recovery factors for their reference temperatures in their calculations, but neither used recovery factor corrections.

Table 2: Extracts from Version 2 of the Australian Geothermal Lexicon showing misapplication of recovery factors [Source: AGEG, 2010]

Lexicon - Summarised Description	Possible Reference	Commentary
Base/reference temperature to be a realistic plant rejection temperature for climatic conditions. (Note: effects of varying reference temperatures on recovery factors were recognised in text but not quantified).	Could be calling on USGS condenser temperature	Apparently aligns with USGS practice but recovery factor is not recalculated with change in rejection/reference temperature.
For EGS and fracture-dominated reservoirs with information on fracture spacings - use a uniform fracture model for recovery factor	Williams 2007	Aligns with USGS practice post recalibration
For fracture-dominated reservoirs (including EGS) without fracture spacing information - use mean USGS recovery factor value of 14% or uniform probability of 8-20%	USGS	Aligns with USGS practice post recalibration
In sedimentary or porous volcanic-hosted reservoirs with porosity less than 7% - use a mean USGS recovery factor value of 17.5% or uniform probability between 10-25%	USGS	Mixes pre- and post-recalibration values and assumes all could be valid.
In sedimentary or porous volcanic-hosted reservoirs with porosity greater than 7% - use recovery factor of 2.5 x porosity up to 50%	Text refers to New Zealand experience (Lawless and Lovelock, 2002)	Mixes 180°C camp assumptions and pre-1978 limit with inappropriate reference temperatures

4. APPROPRIATENESS OF THE 180°C REFERENCE TEMPERATURE

Given the 180°C reference temperature methodology has never been calibrated, a question should be asked about its retention.

The 180°C reference temperature was suggested when the only technology that appeared available was flash steam or dry steam turbines. The original proponents had forgotten that an earlier technology (sub-atmospheric flash with steam turbine) used at Kiabukwa in what was Belgian Congo had allowed use of hot spring water at 91°C (White, 2021). It was an article on this plant that had alerted New Zealand Government departments that the English company Merz and

McLellan had competency in geothermal development and led to their selection for Wairakei development. Today the globally pervasive binary cycle technology commonly uses brine temperatures around 140°C with Chena operating in the 74-99°C range. These days there is increasing attention on geothermal energy for direct use, including many applications in Europe for district heating (sometimes with electricity generation in the off season). These direct uses can use temperatures of 90°C or lower but will have markedly different conversion efficiencies from input heat to process heat. In this context retention of a system that ignores heat below 180°C seems unhelpful.

The old USGS ambient reference temperature methodology held no such limitations but, as seen in the Philippines case or at Chena, there may be some variance in ambient temperatures in different parts of the world. An allowance for condensing temperature potentially adds more variability depending on technology, but makes sense for the type of plant more commonly found in the USA. For steam-dominated fields such as the Geysers or for the many binary cycle plants all fluid extracted from the field is brought to the station, so use of condenser temperature effectively incorporates a First Law efficiency into the equation. Not so for flash steam plants where brine and steam follow different paths and rejection temperatures.

An alternative approach is to assume a zero °C reference temperature (Ciriaco et al 2020) when it comes to recalibration (provided energy conversion efficiency is defined in a compatible way), then the recovery factor can be adjusted to whatever reference is desired using Equations 5 and 6.

5. ALTERNATIVE PERSPECTIVES

One of the rebel minds in the geothermal industry belonged to Russell James, often able to address complex issues with simple practical equations. To see how his mind worked refer to his 1984 NZ Geothermal Workshop paper "Power Potential of Geothermal Fields" (James, 1984).

While not immediately obvious, this paper included a stored heat calculation, essentially taking heat stored in the fluid (also known as "mass-in-place") and applying a factor κ (equal to the fraction of fluid removed in time t years "whether as throughput or as a proportion of the original interstitial water" or a mixture, assuming t/κ was constant). There was no reference temperature in the calculation implying a reference temperature of 0°C. James equated what he assessed as the sustainable capacity of Wairakei at 150MWe with a reservoir volume (defined by area A ($15km^2$), depth L (typical drilled depth below the cap of 1km) and porosity ξ (of 30%)), reservoir liquid density ρ (which he then converted to a simple function of temperature that he had fitted between temperatures of 225 and 325°C), divided by operating life (30 years) and multiplied by the power potential of each t/h of fluid produced (this figure also being reduced to a simple function of initial "base" reservoir temperature and had been derived in a cooperative paper with Tsvi Meidav (James and Meidav, 1977)). After substituting in his assumed values for Wairakei (including a reservoir temperature of 254°C) he was able to obtain a ratio of t/κ of 78 (i.e. 78 years to drain Wairakei if there was no recharge or reinjection while assumed life of the plant was 30 years) then using his generalised properties as functions of temperature, James was able to show that the potential of a field utilising single flash could be expressed as:

$$MWe/km^2 = (T/86.9)^2 \qquad \text{Equation 7}$$

Much work has gone into Wairakei since 1984 including: Te Mihi makeup well connection (1983); drilling of first makeup wells (from 1985) (up until 1982 efforts to maintain station output had been limited to derating the station high pressure which had the double benefit of lowering wellhead pressure to increase mass flow and lowering separation pressure which increased steam fraction); efficiency measures in the 1990s; 55MWe Poihipi station was commissioned in 1996 initially supplied by steam wells but purchased by Contact Energy in 2000 and converted to 2-phase supply; reinjection became a strong feature from the late 1990s; 15MWe binary cycle bottoming plant was commissioned in 2005 using existing brine otherwise directed to direct use and reinjection; the 166MWe Te Mihi station was commissioned in 2014. Numerical reservoir models have been developed/refined and long-term evidence-based strategies developed/implemented.

On latest information (area potentially up to $31.8km^2$, depth still around 1km (based on weighted depth of wells in three sectors), porosity around 15%, mean natural state temperature in the drilled area of 236°C - for the initial years when 150MWe seemed the sustainable level) then t/κ becomes 72 – but it could be argued that Wairakei was not exploited to its full potential in the initial years (there were no makeup wells until the mid-80s). Alternatively, a sector breakdown (using O'Sullivan et al 2021) can show interstitial pore volume is about $4.8km^3$, while historic and projected take across 120 years of operation will be about $10km^3$ such that t/κ = 120 x 4.8/10 = 58 i.e. approximately 60 years. In this case 60 years is assumed as the correct value and the proposition can be re-expressed as: over the commercial life of 30 years for a geothermal station, 50% of the original interstitial fluid can be removed in sustainable production. Recall the early basis for the stored heat calculation: that for the petroleum industry recovery factor for petroleum for an ideal formation was about 50%. There is, at least approximately, an equivalence in terms of this mass withdrawal.

While James' formula is simple in terms of field potential being directly proportional to the square of temperature, the preference here is to leave in additional factors that make up the stored heat calculation

$$E = A \,.\, D \,.\, \xi \,.\, \rho \,.\, H.\eta_c /(2 \,.\, F \,.\, L) \qquad \text{Equation 8}$$

Where most symbols are as previously defined

D= drilled depth of reservoir below cap

ρ = density of water in this region

H = enthalpy of water in this region

In practice, there would be a family of curves setting out likely values with temperature. If expressed as power density E/A, then the rough limits would be set by low values of D of 1km and of porosity of 0.1 and high values of D of 2.5km and porosity of 0.2. These limiting lines have been plotted on Max Wilmarth's power density graph as shown in Figure 3.

Figure 3 also includes an equivalent plot of stored heat values with the same assumptions for well depth and porosity. This assumes constant recovery factor of 0.11 (from Sanyal et al) at 15°C reference temperature for which there were a basket of reservoir temperatures around 186°C from which recovery factors are calculated for a 40°C reference temperature line, while recovery factors for a 180°C reference temperature line were assumed based on a recovery factor of 0.25 assumed at a basket of reservoir temperatures around 250°C. Recovery factors scale up with porosity. Specific heat of rock is assumed at 0.9 kJ/kgK and rock density is assumed at 2700 kg/m^3. For clarification purposes, sample recovery factor corrections are shown in Table 3.

For the stored heat P50 value at 40°C reference temperature a further line has been drawn equal to the P50 value divided by 1.5. This is to approximate the P90 value at which power stations would normally be sized, since the ratio of P50:P90 values on a national basis has been observed by the author to vary between 1.3 and 2.2. All these values need some recalibration.

To an extent, the Wilmarth power density graph is comparing oranges with mandarins, since Wilmarth has used an area based on the locus of a 500m radius around production well clusters versus an area here equal to that covering all of the reservoir. However, for many fields, well coverage will be across the field leading to rough equivalence. There will be other peculiarities based on the specific confidential advice from parties associated with specific fields.

It is useful to look at outliers on the graph. On the high side, stations like Don A Campbell, Hatchobaru and Silangkitang are characterized by exceptionally productive wells relative to station capacity leading to highly concentrated production. In practice the whole field is likely to be affected, such that if field area (from resistivity or similar) is used then these fields drop down into the expected family range. This may indicate that Wilmarth's power density values would be better to use reservoir area rather than the locus of wells (then all schemes would be compared on the same basis). On the low side, some of these developments can be thought of as first stages in larger developments e.g. Oguni, Bjarnaflag, Mataloko, Pico Alto, and are sometimes demand-limited due to location on small islands e.g. Hachijo-jima.

Superposition of the various graphs leads to the question of how real Wilmarth's Main Sequence and Hot Arcs lines are (particularly the uptick in the high temperature "Rifts" zone), or is there just a random scatter between the family of curves? In any case, all of these theoretical lines are converging around real field data. This either indicates the usefulness of these methods, or that the stored heat paradigm is still dominating the ultimate sizing of geothermal developments.

Table 3: Sample calculations of corrected recovery factor for stored heat capacity using Equations 5 and 6

	Reservoir Temperature = 200°C	**Reservoir Temperature = 300°C**
Reference T = 180°C	0.25*(250-180)/(250-15)*(200-15)/(200-180) = 0.689	0.25*(250-180)/(250-15)*(300-15)/(300-180) = 0.177
Reference T = 40°C	0.11*(200-15)/(200-40) = 0.127	0.11*(300-15)/(300-40) = 0.121

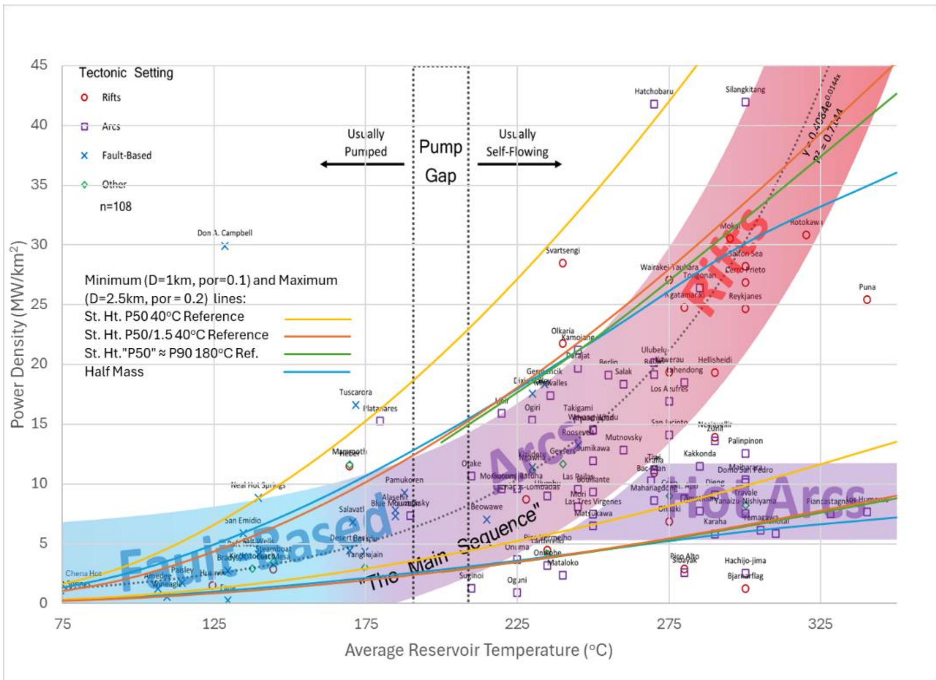

Figure 3: Plot of Curves from this work on the Wilmarth et al Power Density Curve [Source: modified from Wilmarth et al 2021]

6. A QUICK LOOK AT NUMERICAL RESERVOIR SIMULATIONS

One response to apparent weaknesses and blind spots in stored heat (or power density) calculations is to suggest that numerical reservoir simulations should be used.

Numerical Reservoir Simulation models are invaluable once fields have been developed and calibration is possible against real reservoir response to known measurable operations. At that time, the crudeness of stored heat calculations next to the specificity of the simulation does make the stored heat calculation for the developed field redundant and unwanted.

The value of these numerical models may have been underestimated when it comes to calibrating stored heat or energy/power density calculations. Russell James had good reasons to assess that the sustainable capacity of Wairakei was 150 MWe, whereas a numerical reservoir simulation could have indicated greater potential. Both (at the time) may have missed the full potential of Te Mihi area and neither would have been ready for the Poihipi extension proven for Alastair McLachlan. However, a model could have established that a more aggressive sustainable development strategy from deeper production including makeup drilling is possible. Wairakei is now projected to be able to maintain the current almost 310MW for the next 50 years (dropping off a little towards the end). It is recommended that these models be used in determining sustainable capacity for fields in future when recalibrating stored heat and power density calculations.

Going back to the exploration stage, efforts have gone in to establishing techniques for using numerical reservoir simulation with all of the initial unknowns – this work being led by the University of Auckland. A combination of geoscience exploration data, fast model setup with the help of Leapfrog, fast but coarse resolution simulations (using Waiwera based on the Leapfrog model, together with thousands of varying geoscience parameters within reasonable ranges), and tools like data space inversion and ABC-ccandu help to quantify uncertainties leading to a resource assessment. Approximate Bayesian Computation (ABC) filters out models which are unlikely to be consistent with the exploration data. Production scenarios including individual wellbore simulations, are then generated to maximise energy extraction. This then leads to statistical results including P90, P50 and P10 estimates (Dekkers et al, 2022). This sort of work can be undertaken in a month or possibly less. The author still has concerns that such high-powered computation could give an illusion of accuracy above that achieved, whereas stored heat and power density honestly display their crudeness.

7. A REVIEW OF WAIRAKEI FOR PERSPECTIVES ON RECALIBRATION

Use of numerical reservoir models is recommended to calibrate these calculation schemes. To gain insight into potential issues, a recently published report for Wairakei reconsenting (O'Sullivan et al, 2021) was reviewed.

The report set out the natural state condition of the field which would be the basis for stored heat or "half mass" calculations. There is a hot upflow in the Te Mihi sector with outflow especially SE of this. Under exploitation, the field was allowed to drop in pressure by about 28 bar (by about the late-1970's) with quite a wide area in the Te Mihi and Western Borefield areas affected, beyond the locus of production wells. This led to significant flow increases especially from the sides, including an inflow from the Tauhara field, leading to mass balance from the 1980s. Tauhara inflow continued until reinjection along the Tauhara boundary stopped this in a net sense. Reinjection will be an ongoing feature of operation for fluid beyond that required for direct use applications or hot stream maintenance. Modeling indicates that current levels of development (equivalent to about 310MWe) can be maintained for another 50 years, though some mass flow decline will be noticeable in the last 15 years.

The report had sufficient information to enable views on thickness of cap, and temperature profiles below the cap in certain sectors. There was no specific information on effective porosity in the report, though modelers were prepared to give a general guide. However, to set out fully characterized sectors, cooperation with modelers with approval of the commercial developers would be required. All this information would be within the models, but that would require Non-Disclosure Agreements and direct involvement of the modelers presumably at developer expense.

Modelers asked how area should be defined for any of these calculations given the leaky nature of the boundaries. However they had effectively used the resistivity boundary themselves and then measured flows across this.

The report included much information about mass and heat flows, including projections. In terms of detail, it was hard to find reinjection details (some production was given as net production after reinjected fluid was subtracted), though a type of formula set out projected reinjection quantities. Other reports such as Dean et al 2014 helped with this information.

No information was given on historical generation levels or utilisation efficiency in the report, but early generation could be derived from Thain and White 1993 combined with given mass and heat flows, and graphs of average discharge enthalpy. Later spot measurements were possible using combined station outputs from World Geothermal Congress New Zealand updates. Actual generation could have been obtained directly from the developer through a separate request. This could then have been used with mass flow and enthalpy data to derive utilisation efficiency. Fields like Wairakei will end up with some hybrid efficiency because of the multiple stations, including bottoming plant, changing with time.

A check on utilisation efficiency highlighted a weakness with the current stored heat and "half mass" models. These use the mean temperature of the fluid in the top of the reservoir up to the cap (equivalent to 236ºC for Wairakei) in calculating utilisation efficiency. However, the wells are not tapping mean temperature but peak temperature in the outflow (about 250ºC) while some wells tapped shallow steam zones. Some uplift in feed temperature is required to better estimate this efficiency. Alternatively the approach may be to simply correlate the mean temperature and associated heat with the actual generation to recalibrate Equation 3 and Figure 1.

Despite complexity the final utilisation efficiency for Wairakei is about 10%, based on actual heat supplied, but this will lift if the lower 236ºC temperature is assumed for stored heat calibration.

The model shows that in the last 15 years out to 2070 or beyond, the mass flow will start to drop off by a total of 7% while enthalpy should stay at 1050 kJ/kg. This is meant to imply the field is under stress and near its limit. However by many standards this is still a commercially attractive flow and enthalpy. What is very likely is that existing stations and even stations to be built in the next decade or so will have been retired by then and new stations would have been built designed for the expected future conditions. With that in mind, it is not clear what constitutes the commercial limit of operation. For now, it can be assumed that incumbent developers know this best, and currently planned development levels leave no room for competition or additional generation.

As mentioned above, Wairakei exploitation led to major flow changes within the reservoir with a variety of inflows from the base and sides, and decreasing loss to the surface, in turn causing mass balance from the 1980s. These major flows (see Figure 4) bear no obvious relationship to the initially accessible fluid or heat in the reservoir on which stored heat, power density and "half mass" calculations are based. This undermines the credibility of these schemes in the minds of the reservoir modelers, since rates are based on assumptions of fixed quantities. It seems that these schemes help to set a limit on rate of take, while inflows and reinjection help to determine longevity. Thus, Wairakei field operating life looks to extend beyond 120 years, and far beyond a normal commercial life of 30 years.

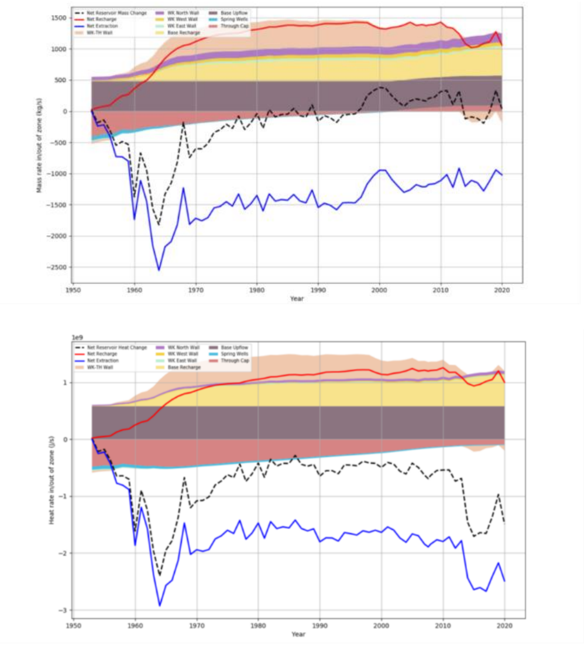

Figure 4: Wairakei mass and energy flows showing major flows across any boundary. [Source: O'Sullivan et al 2021)

8. PARTIES THAT COULD ASSIST A REVIEW PROCESS

There are weaknesses with the stored heat methodologies, while at the same time this type of scheme represents a powerful means of assessing potential of fields at an early stage of investigation. The fundamental need is to repeat the process of recalibration that the USGS went through nearly twenty years ago. A quick review of geothermal developments in the top 10 countries by installed capacity shows around 100 developed fields outside the United States (Huttrer, Darma, Omenda, Daysh, Yasukawa, 2021) most of which will be supported by numerical reservoir simulations for accurate indexing.

Who are some of the parties that could potentially play a role in such a recalibration? USGS could undertake further review of US data. There are twenty years of new developments and a further twenty years of operational experience on existing plants for additional calibration. Many of these fields will have their own numerical reservoir simulations, which can then be used to better gauge the sustainable carrying capacity of each field (rather than assuming existing capacity equals maximum capacity or beyond if full capacity cannot be maintained with reasonable effort). The much wider database should allow better conclusions on say the influence of temperature or formation type on recovery factor.

Could USAID then help global uptake of renewable energy through extending the USGS methodology to bring in a global database of geothermal developments?

The United Nations has developed a framework classification for resources and has a special geothermal expert group to direct attention at appropriate expression of resource classification (e.g. UNECE 2017, Ussher et al 2023). This group is a joint UNECE/International Geothermal Association group. This group is known to have an interest in quantification as well as format (personal communication Graeme Beardsmore).

Other international organisations could have a role in the review. These could include the International Energy Agency – Geothermal, or though less targeted the International Renewable Energy Agency headquartered in Abu Dhabi (a country trying to diversify in renewable energy direction from its oil and gas background).

9. CONCLUSIONS

This work has brought a range of preliminary reservoir assessment methods to a common basis.

Stored heat calculations and energy density curves can play a valuable role in field capacity assessment at early dates. This can be used ahead of numerical reservoir simulation at the exploration stage for relative assessment of fields.

Until recalibration is done, station sizing using 15°C reference temperature should use P90 inputs while sizing using 180°C reference temperature should use P50 inputs (each using generally accepted recovery factors for those reference temperatures, ideally adjusted as per this paper).

A recalibration of recovery factors and of energy density data can be made using the hundreds of globally developed fields. This calibration can be improved if numerical reservoir simulations of the developed fields are used to determine how well loaded or overloaded these existing developments are, though some care may be needed around area assessment. Useful calibration information will be available in public facing summary reports but best practice would require modelers direct involvement to properly interpret their model.

Such work should give greater confidence to developers and investors.

A leader is now required for this recalibration.

ACKNOWLEDGEMENTS

Thanks are extended to Graeme Beardsmore, Mike O'Sullivan, John O'Sullivan, and Max Wilmarth for advice on this paper. Also, thanks are given to Jim Lawless and Greg Ussher for related discussions over the years.

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ISSN 2703-4275