PROVED GEOTHERMAL RESERVES – FRAMEWORK AND METHODOLOGY

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ABSTRACT

Globally, oil & gas proved reserves are used for a variety of business purposes. Because their use is governed by standards and regulations, the results are considered to be reasonably credible. In the geothermal business the situation is at a less mature stage of development with less credibility of results. What are the important elements of the framework used in oil & gas that can be brought to bear on the process of determining proved reserves in the geothermal business? This paper presents a framework for a standardized approach to determine proved geothermal reserves, and reviews commonly used assessment methods.

The proposed framework for approaching the determination of proved reserves involves six steps. 1) Define proved reserves and the criteria to be satisfied. 2) Define the commercial and project entities for which an assessment is to be made. 3) Define the date of reporting. 4) Define the project profile to be determined. 5) Review all information about the project and apply the appropriate reservoir engineering calculation to determine the output profile that meets the standards of certainty. 6) Demonstrate that the project has a positive net present value based on expense and price projections which meet the required standards of certainty.

Four methods for computing a generation output profile are reviewed. 1) Use power density from an analogue field. 2) Reservoir simulation. 3) Application of Monte Carlo methods to volumetric calculations. 4) Decline curve projections. Each method is briefly reviewed and the appropriate conditions for application are presented.

1. INTRODUCTION

Proven reserves are used in the oil & gas industry to provide a measure of the financial value of a resource-based asset. In the hydrocarbon producing business, the unit of reserves is the commodity which is sold – barrels of oil or standard cubic feet of natural gas. While the details of ownership & contract configuration in the geothermal business vary, ultimately the corresponding commodity sold is electricity.

In the oil & gas business, proved reserves are derived for a variety of commercial purposes, including regulatory requirements for external reporting to a government agency such as the United States Securities and Exchange Commission (SEC), investors, financing from external organizations, and performance management. They are generally governed by standards and regulations, and consequently the results are usually considered to be credible.

In the geothermal business matters are at a less mature state of development, and consequently the results may be less credible. Grant (2000) has provided an overview of geothermal reserves as part of a review of methods for determining the values. Sanyal and Sarmiento (2005) provided an expanded discussion of geothermal reserves as part of presenting proved reserves results for four Philippine fields. Clotworthy et al. (2006) proposed a starting point for the development of geothermal reserves determination based on mining and oil & gas standards. In 2008 the Australian Geothermal Code Committee published a framework (the "Australian Code") for reporting the results of geothermal exploration, testing and development (The Australian Geothermal Code Committee, 2008; Ward et al., 2009.) This Australian Code was updated in 2010 (Australian Geothermal Energy Group, 2012). While use of the Australian Code does not appear to be required by any regulatory agency, members of the Australian Geothermal Energy Association are required to use it when reporting the results of their activities.

This paper focuses narrowly on describing a framework for determining proved geothermal reserves, with the objective of establishing a clear and credible basis. The elements of this class of reserves are first presented, including definitions, steps and other considerations. Then methods for estimating such reserves for hydrothermal systems are discussed. The framework presented is consistent with both the Australian Code as well as the updated Petroleum Resources Management System sponsored by the SPE, AAPG, WPC and SPEE (SPE-PRMS, 2007.)

2 PROPOSED FRAMEWORK

The following describes a proposed framework for developing values of proved geothermal reserves.

2.1 Criteria for proved reserves

Define proven geothermal reserves as the electricity that can be generated and sold with reasonable certainty over the project life. Commonly used units are Mega Watt-hour, [MWh] . The value of proved geothermal reserves reported will have the following underlying elements:

- The quantity is an estimate made with reasonable certainty;
- The quantity is based on:
  - existing technology,
  - expected operating conditions,
  - realistic operating efficiency based on experience,
  - current economic conditions, or those that are projected with reasonable certainty,
  - a valid sales contract,
  - the existence of required approvals from regulatory bodies, and
  - financial commitment from the commercial entity that owns the project;
- Total field net generation corresponding to the time frame of any sales contract at the committed MW capacity, unless this cannot be assured with reasonable certainty. A typical value is 30 years. If such an

amount of total net generation cannot be determined with reasonable certainty, the value is based on a shorter period.

- The value is based on the information available on a specified date, and the generation expected from this "as-of" date forward.

The discussion in this paper is for the case where a resource has been characterized and a commercial entity has not yet begun to generate and sell electricity. Sometimes reserves assessments are made for an operating project – in this case the underlying elements would be adjusted appropriately.

Either of two standards of certainty may be used:

2.1.1 Deterministic

For proved reserves, there is "reasonable certainty" that the value determined can be achieved. For comparison, probable reserves are defined as "as likely as not" to be achieved, and possible reserves as "possible but not likely."

2.1.2 Probabilistic

For proved reserves, based on credible analysis, there is a 90% likelihood that the actual value achieved will be greater than or equal to value determined. This is commonly annotated as the P_{90} value. For comparison, probable reserves are defined as the P_{50} value and possible reserves as the P_{10} value.

The United States SEC has recently allowed for the use of probabilistic methods to oil and gas estimate reserves, in particular if the reserves estimate is project-based (Lee, 2009.)

2.2 Define the project and commercial entity

Proved reserves are determined based on a defined project occurring within the framework of a commercial entity. Both the project and commercial entity need to be clearly defined.

2.3 Define the date of reporting

Proved reserves are based on a defined as-of date and only the information available on that date. While details will depend on the project, a common date corresponds to the end of the accounting reporting date for the commercial entity.

2.4 Define the project output profile

Figure 1 presents an idealized probable project generation profile, during which there is i) rapid ramp-up of generation as the field is brought on-line, ii) constant generation for some period of time, and iii) declining generation which terminates some time later when the plant is decommissioned.

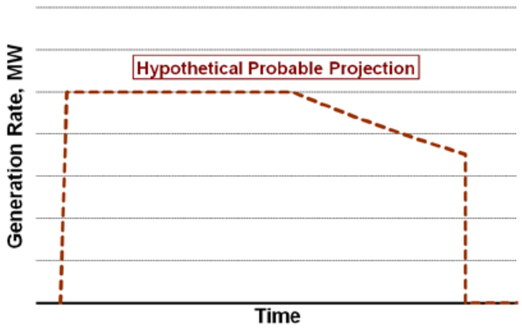

Figure 1: idealized probable generation profile

In Figure 2 an idealized generation profile that can be expected with reasonable certainty is overlain on top of the probable profile. This generation follows the probable profile for a period of time and then drops to zero. If the project has a sales agreement that is based on a specified average generation level for a given period of time, this might be represented by the "reasonable certainty" curve if the field is able to provide the needed geothermal fluid.

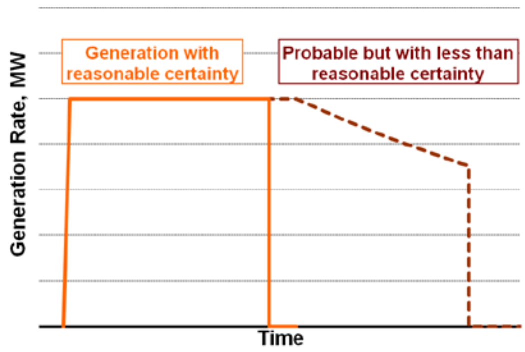

Figure 2: Profile of proven generation overlain on probable

Depending on the sales agreements of the project, it may be possible to have a declining generation profile which can be demonstrated to be economic. In this case, an alternate generation profile with reasonable certainty such as that shown in Figure 3 would be used or acceptable. The alternate profile in Figure 3 has the same total generation as the "reasonable certainty" profile in Figure 2.

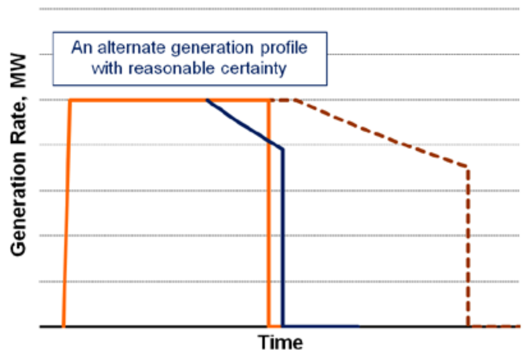

Figure 3: Alternate generation profile with reasonable certainty

As indicated above, the specific project profile to be determined will depend on what stage the project is in.

2.5 Determine and apply the method used to compute project output profile

The next step is to review all of the available data and decide on the method of analysis to be used in determining the cumulative generation of the project profile that meets the standard of certainty on the reserves reporting date. Section 2 provides an overview of methods commonly used to do this.

The information and results used as input into the analysis needs to be sufficiently well documented and organized so that an independent reviewer could, in principle, repeat the analysis. Even though there may be a team involved in developing different elements of a reserves analysis, the results should be attributable to a single individual. This person is called the 'Competent Person' in the Australian Code (Ward et al, 2009) and the 'Reserves Estimator' in the SPE-PRMS (2007).

Four different kinds of information typically make up the inputs to proved reserves values, as reviewed in the following.

2.5.1 Subsurface

Current best practice in geothermal reservoir assessment involves the development of a conceptual model that incorporates a broad range of geoscience and engineering data and analysis. A credible analysis of reserves requires a credible conceptual model. A proved reserves assessment needs to additionally include some level of evaluation of the mechanical integrity of project wells and the degree to which there is risk of well mechanical failure during the life of the project.

2.5.2 Reservoir and land access

For many projects the operator can in principle access the entire reservoir with wells. However, there are some circumstances where this is not practical. For example, this may be as a result of limited access to the needed surface area due to private ownership rights. It may also be a result of development occurring on the edge of a protected area such as a forest or park.

Figure 4 displays the total area, A_t, of a hypothetical geothermal resource that would typically be defined by measured temperatures in the core and perhaps at some edges. The rest of the boundary would be defined by geophysical methods or wells with no temperature or permeability. An access boundary is depicted, separating two areas of the resource - one with access, A_a, and one with no access, A_{na}.

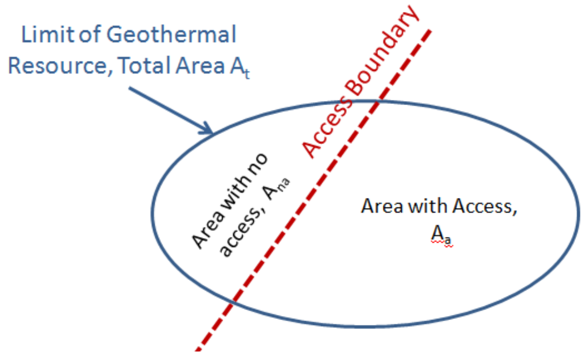

Figure 4 - A hypothetical resource with limited land access

At the simplest level of analysis, if wells could not be drilled across the access boundary, proved reserves for a project with access only to the area A_a would need to factor the total proved reserves for the resource by (A_a/A_t). Adjustments to such a calculation might be made, depending on the details of the conceptual model of the resource.

2.5.3 Surface gathering and conversion process

Project information about the conversion of the geothermal fluid into electricity is needed in order to derive proved reserves. This involves both the design and expected operational efficiency of the surface facilities. Specifically, how much geothermal fluid is expected with reasonable certainty to be needed to generate each MWh of electricity sold over the lifetime of the project?

For example, the Wairakei Field mass, energy and generation history up to 2000 (Clotworthy, 2001) can be used to show that specific steam consumption at Wairakei during the period 1965-2000 averaged 7.0 tonnes of steam for each MWh of electricity generated. A similar analysis can be done for the Bulalo Field using annual steam production and generation rates (Clemente and Villadolid-Abrigo, 1993; Benito et al., 2005) to show that for the period 1980-1992 an average of 9.2 tonnes of steam were produced for each MWh of electricity generated. These values are based on steam produced in the field rather than delivered to the power plant.

By comparison, a modern field with a single owner using triple-flash separation to take advantage of the high pressures associated with a high-temperature reservoir may only require 5.45 tonnes of steam for each MWh of electricity generated. In this case the steam basis is the effective flash to 12 bara separation pressure and the steam is that actually delivered to the power plant operating at design conditions and with no operational losses (Horie, 2009).

2.5.4 Regulatory conditions

An assessment of the risk of curtailed power generation based on noncompliance of field activities and reservoir performance needs to be made, to the extent that the operation of the field is conditionally dependent on regulatory agency approvals. In many countries this might be based on environmental factors.

2.6 Demonstrate positive net present value

Finally, an analysis which demonstrates that the project has at least a positive net present value needs to be made using cost and price projections that meet the required standard of certainty. The details of such an analysis will depend on the business purpose of preparing the proved reserves assessment. In some cases a review of the business case for the project may be sufficient.

2.7 The proved reserve value

A proved reserve value for a project is thus a single value, representing the electrical generation that a project is capable of producing and selling with a high degree of confidence after a specified date using information, technology and economics at the as-of date specified. Such proved reserves may be added to a company's proved reserves ledger, intended to be removed only when they are sold. It is common to add supplemental proven reserves for a field to the ledger - for example, based on field performance, expansion of field limits or other new information. Occasionally it is also necessary to remove proved reserves for reasons other than sale – for example due to a downward revision based on field performance. However, this is to be avoided. The spirit within which the technical assessment of proved reserves is made is to determine the largest value that will assure with reasonable certainty that they will only be removed from the ledger as a result of sale.

3 OVERVIEW OF DETERMINATION METHODS

The objective of this section is to provide an overview of methods that can be used to determine proved reserves, highlighting the important considerations in appropriate application.

3.1 Application of power density metric to analogue fields

In this method an attempt is made to identify a developed field with sufficient history and which has characteristics similar to the field being assessed. If such a field can be identified, an analysis of the power density of development is made, e.g. sustainable MW_e for 30 years per km^2 of thermal resource. This power density is then applied to the field being evaluated, with any appropriate adjustments for different reservoir temperature or plant specific steam consumption. As an example, Grant (1996, 2000) has presented the results of a power density analysis for various fields. Sarmiento and Björnsson (2007, p. 226) present power densities for various fields in Iceland and the Philippines but do not provide the quantitative basis for the Philippines fields.

The concept underlying this method is the idea that hydrothermal systems with similar characteristics will have similar power densities that are only weakly dependent on the area of the thermal system. For example, the Bulalo Field in the Philippines can be characterized as a relatively hot system with average temperature of 280 ^oC that was initially liquid-dominated but with the upper portion of the column at saturation conditions. Natural recharge has been less than net exploitation withdrawals, leading to the creation of a widespread two phase zone throughout most of the upper portion of the reservoir. The boiling which has occurred in the core reservoir in the fractures and matrix has led to a cooling of those rocks, which is a key underlying physical process allowing thermal energy to be extracted from the system. A second process of thermal energy extraction is through the heating of reinjected fluids. This reservoir has been described by Strobel (1993), Clemente and Villadolid-Abrigo, (1993) and Sta. Maria et al (1995), among others.

Another example of a field that may be used as an analogue is the Wairakei Field. The key characteristics of this field with an average initial temperature of perhaps 255 ^oC are that it has a high level of permeability, strong natural recharge and has not evolved a widespread and deep two-phase zone with continuing decreases in pressure. Additionally, the history of the field and its performance has been well documented. The following brief summary has been derived from the discussion in Grant and Bixley (2011.) In contrast to Bulalo, the physics associated with thermal energy recovery at Wairakei are associated with the deep 260 ^oC recharge and the warming up of cooler lateral recharge that is natural and more recently also derives from reinjected fluids. While the field did initially develop two-phase and vapor-dominated zones, these appear to have stabilized. This can be demonstrated by computing the average field enthalpy from the mass and energy profiles published for the field using data from Clotworthy (2001). From 1955 to 2000 the producing enthalpy averaged 1,110 kJ/kg, corresponding to saturated liquid water at 255 ^oC. The standard deviation was only 35 kJ/kg, indicating approximately stable behavior. An additional complicating factor in any evaluation of the power density of Wairakei is the observation that it is linked with the Tauhara Geothermal field, and estimates of the influx from Tauhara need to be made.

Once an appropriate analogue for the field under assessment has been found and evaluated, details of the two fields need to be reviewed and adjustments made to the analogue field power density for physical differences in the field under assessment, such as average reservoir temperature, specific steam consumption and land access issues.

3.2 Reservoir simulation

The construction of a numerical model of a reservoir based on a conceptual model which integrates all available information is a common practice. Such models can be used for the determination of proved reserves if they appropriately incorporate the critical physical processes which will affect the long term performance of the wells feeding a power plant. Examples of such processes include:

- Vaporization of liquid contained in the less-permeable rock removed from the fractures that feed the wells.
- Heating of cooler recharge or injected fluids as they move to production wells.
- Deep hot recharge in response to net mass withdrawals.
- Mass and heat transfer interaction between the highly permeable zones that normally feed geothermal wells and the somewhat lower permeability remaining rock volume.

Confidence in the appropriateness of such physical processes in a model may be obtained by satisfactory calibration of field history for an operating field. Gaining the needed confidence for a field with no full-scale operating history is more challenging and places an increased burden on appropriately designed and executed geoscience and well evaluation studies.

The derivation of a deterministic value for proved reserves using numerical simulation is in principle straightforward – simply develop a numerical model with the appropriate level of confidence in the physical processes and then run it in forecasting mode under a range of operating conditions.

The development of probabilistic proved reserves using numerical simulation is similarly in principle straightforward – develop a sufficient number of equi-probable models which match the initial state and any operating history and incorporate realistic elements of the critical physical factors. And then run these models in forecasting modes. Doing this in practice is not straightforward and there do not appear to be any publications reporting on such work for operating geothermal fields. In the next section a method is described which uses an idealized numerical model of a reservoir in conjunction with the Monte Carlo method and a volumetric calculation to derive proved, probable and possible reserves.

3.3 Application of probabilistic methods to volumetric calculations

Two different kinds of volumetric calculations are used to estimate resource capacity: those based on the heat in-place and those based on mass in-place.

Use of Monte Carlo methods applied to a heat in-place calculation for determination of proved reserves has been reported by Sanyal and Sarmiento (2005). A subsequent review of the method as applied to resource estimation in general emphasizes the need to use actual field data when defining the reservoir parameters (Garg and Combs, 2010.)

This is particularly true of the recovery factor parameter that is used in these calculations.

Various recent estimates of appropriate values of recovery factor have been made. Sanyal et al. (2002) apply a numerical calculation using analytic and Monte Carlo methods to general parameters estimated for geothermal reservoirs associated with volcanic systems to derive recovery factors of 0.05 to 0.10. Sanyal et al. (2004) use a semi-empirical calculation to estimate recovery factors in the kinds of hydrothermal systems assessed in USGS Circular 790 (Muffler, 1979), which included 37 fields in California, Utah and Nevada. They report that the resulting recovery factors are in the range 0.03 to 0.17 and with a mean of 0.11 and standard deviation of 0.08. They additionally report that this mean is close to a recovery factor of 0.131 which would make the original USGS estimates for these fields essentially the same as more recent estimates of their resource base. Finally, Williams (2007) has estimated recovery factors for three operating geothermal fields in the United States and concluded that care is needed in order to use consistent techniques when estimating the volumes and fracture porosities of the reservoirs.

With the exception of the three fields reported by Williams, there do not appear to be any published estimates of recovery factors for fields with a long operating history and based on data specific to a field. Thus, while calculations with the volumetric heat in-place method do generate a range of resource estimates from which a P_{90} value can be extracted, it is difficult to see how they are able to meet the required standard of certainty that this is a highly likely outcome.

Parini and Riedel (2000) have reported on a methodology that uses a mass in-place volumetric method to estimate a range of generating capacities for a field and can be used to estimate proved reserves. In this method an idealized numerical model of the field is constructed which contains the key physical parameters affecting field performance. The model is then run many times, sampling all variables around which there is uncertainty, and from which multiple values of mass recovery are computed. In the example reported ten variables with defined uncertainty properties were used as input to the model runs. This allows for a relationship between the uncertain variables and the mass recovery factor to be defined. This is then used to estimate a probability distribution for electrical generating capacity, from which the P_{90}, P_{50} and P_{10} values can be extracted.

3.4 Decline curve projections

Decline curve analysis is an accepted method for determining proved oil or gas reserves and commonly applied to single wells which are the only take points in a reservoir. This method of analysis is also commonly applied to geothermal wells for purposes of estimating future makeup wells in the field. It has also been applied to major groupings of power plants at The Geysers (Goyal and Box, 2004.) While there do not appear to be any published reports of the use of this method to determine proved reserves, the method may be appropriate if the right circumstances apply. These are primarily that there are no step-changes in the surface or reservoir conditions that impact well performance.

4 SUMMARY

A proved geothermal reserve is a single value of generation that can be sold from a defined project with high confidence as of a specified date and for which the project has a positive net present value.

A framework has been presented for the determination of such a value which is consistent with standards used in the oil and gas industry and also with the Australian Geothermal Code. The steps required for this determination are discussed, with elaboration of various requirements and considerations.

Finally an overview of the four main determination methods was presented, with observations on the requirements for their application so that the computed results meets the required standard of certainty.

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