Geothermics 76 (2018) 164–176

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

A Python-based stochastic library for assessing geothermal power potential using the volumetric method in a liquid-dominated reservoir

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ARTICLE INFO

Keywords:
El Salvador
Volumetric method
Python
Open-source
Monte Carlo
Geothermal power potential

ABSTRACT

We present a Python-based stochastic library for assessing geothermal power potential using the volumetric method in a liquid-dominated reservoir. The specific aims of this study are to use the volumetric method, "heat in place," to estimate electrical energy production ability from a geothermal liquid-dominated reservoir, and to build a Python-based stochastic library with useful methods for running such simulations. Although licensed software is available, we selected the open-source programming language Python for this task. The Geothermal Power Potential Evaluation stochastic library (GPPeval) is structured as three essential objects including a geothermal power plant module, a Monte Carlo simulation module, and a tools module. In this study, we use hot spring data from the municipality of Nombre de Jesus, El Salvador, to demonstrate how the GPPeval can be used to assess geothermal power potential. Frequency distribution results from the stochastic simulation shows that this area could initially support a 9.16-MWe power plant for 25 years, with a possible expansion to 17.1 MWe. Further investigations into the geothermal power potential will be conducted to validate the new data.

1. Introduction

The geothermal resource assessment is an estimation of the amount of thermal energy ("heat in place") that can be transformed from a geothermal reservoir for economic use in a variety of applications. However, such data are often limited or missing during initial geothermal exploration, and a basic assessment method is needed (Saibi, 2018). In the 1970s, researchers at the United States Geological Survey (USGS) developed a method to quantify geothermal resource estimate uncertainties associated with a given hydrothermal area. This simple technique, called the USGS volumetric "heat in place" method, (Cataldi et al., 1978; Garg and Combs, 2015; Muffler and Cataldi, 1978), is therefore also employed in the present study.

The primary purposes of this study are to use the volumetric method to estimate electrical energy production ability from a geothermal liquid-dominated reservoir, and to develop a Python-based stochastic library, called the Geothermal Power Potential Evaluation (GPPeval), with suitable methods for running the simulations. The calculation of geothermal energy stored in a given volume is based on a range of reservoir parameters, carried out using a stochastic Monte Carlo simulation, and applies a probabilistic method for evaluating reserves or resources and the associated estimation uncertainties. Given the geological complexity and heterogeneity of most geothermal reservoirs, this method is more appropriate than the usual deterministic approach that assumes a single value for each parameter to represent the entire reservoir. Instead of assigning a fixed value to a reservoir parameter, numbers within a range of the distribution model are randomly selected and drawn for each calculation cycle over a thousand iterations (Sarmiento and Steingrímsson, 2011; Wakeyama and Ehara, 2009).

Licensed software is available for carrying out this simulation, however the algorithm was programmed using the open-source programming language Python (Python Software Foundation, 2016). Python is a platform-independent, full-feature, object-oriented programming language that has grown in popularity over the last decade due to its versatility and explicit syntax. Furthermore, Python is widely used throughout the geophysics community (Krieger and Peacock, 2014). The stochastic library developed in this study is distributed as is without charge. The Numpy and Scipy modules allow handling of large numerical data sets, and the built-in file handling and flexibility of string manipulations allow for confident processing of files in arbitrary

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https://doi.org/10.1016/j.geothermics.2018.07.009
Received 10 April 2018; Received in revised form 12 July 2018; Accepted 15 July 2018
0375-6505/

formats, e.g., CSV. In addition to the standard modules within Python, GPPeval utilizes the Matplotlib module for graphical visualization, the Beautifultable module for easily printing tabular data in a visually appealing ASCII format to a terminal, and the Mcerp module for performing non-order specific error propagation[1] or uncertainty analysis (Lee, 2014).

The GPPeval is structured as three essential objects including a geothermal power plant module, a Monte Carlo simulation module, and a tools module. The geothermal power plant abstraction or object contains the necessary properties and methods employed in the Monte Carlo simulation. The Monte Carlo abstraction or object has the essential properties and methods for running the Monte Carlo simulation and obtaining the geothermal power potential. The tools abstraction or object has the necessary properties and methods for showing the simulation results. We use hot spring data from the municipality of Nombre de Jesus, El Salvador (Campos, 1988) to demonstrate how the GPPeval can be used to assess geothermal power potential.

2. Thermal Energy Calculations

A typical geothermal reservoir and the required model parameters are shown in Fig. 1. Two distinct purposes are identified in this task:

1 To address the question of geothermal energy, the study area should have specific attributes including a geothermal aquifer or reservoir, cap rock, bedrock, either a fractured-rock environment or permeable rock, convection-driven movement of hot fluid, and a heat source such as an intrusive magma chamber, fossilized dike, or relevant regional activity (DiPippo, 2012).
2 To assess reservoir power generation, the geothermal area should have defined parameters such as the reservoir area (A), thickness (h), and temperature (Tr), the abandon temperature (Ta), average rock porosity (ϕ), rock specific heat (Cr) and density (ρr), fluid specific heat (Cf) and density (ρf), a heat recovery factor (RF), electrical conversion efficiency (ηe), plant net capacity factor (PF), and lifespan (t).

The volumetric method refers to the calculation of thermal energy in a rock and fluid that can be extracted based on a specified reservoir volume, temperature, and reference or final temperature. This approach is based on methods applied by the USGS to assess geothermal resources of the United States (Muffler and Guffanti, 1978). The final or reference temperature using those methods is based on an ambient temperature of 15 °C (or a condensing temperature of 40 °C) that was commonly used in previous USGS applications. However, the use of an arbitrary low reference temperature (i.e., ambient or condensing temperature) often results in an overestimate of the available thermal energy. The abandon temperature, or temperature below which a geothermal reservoir is not producible, should therefore be used as the reference temperature to obtain realistic estimates of the available thermal energy.

Abandon temperature values depend on the power cycle. Thus, for a flash-type power plant, the lower limit of the abandon temperature is given by the saturation temperature, which corresponds to the separator pressure, and the so-called pinch point temperature for a binary power plant. Under appropriate space heating conditions, the abandon temperature is usually 30–40 °C, while a typical high-temperature geothermal resource has an average reservoir temperature of 250 °C. Assuming that a single flash cycle has a separator pressure of 5 bar (saturation temperature of 151.831 °C), the abandon temperature would equal 151.831 °C. Similarly, a conventional low-enthalpy fluid with an average temperature of 150 °C is used to heat a secondary working fluid (isobutane) with an assumed pressure of 20 bar and saturation temperature of 100.36 °C. Therefore, considering a temperature difference of 5 °C at the pinch point, the abandon temperature is 105.36 °C (Garg and Combs, 2015; National Institute of Standards and Technology NIST, 2017). The equation used in thermal energy calculations for a liquid-dominated reservoir is as follows:

$$Q_T = Q_r + Q_w \tag{1}$$

where

$$Q_r = A \bullet h \bullet [\rho_r \bullet C_r \bullet (1-\phi) \bullet (T_r - T_a)] \tag{2}$$

and

$$Q_w = A \bullet h \bullet [\rho_w \bullet C_w \bullet \phi \bullet (T_r - T_a)] \tag{3}$$

with parameters defined in Table 1.

3. Power Plant Sizing

Solutions to Eq. 1 provide only the total thermal energy in the reservoir, while the size of the power plant that could be supported by the resource is calculated by combining the previous into Eq. 5 as follows:

$$P = \frac{Q_T \bullet RF \bullet C_e}{PF \bullet t} \tag{4}$$

$$P = A \bullet h \bullet (T_r - T_a) \bullet [\rho_r C_r (1-\phi) + \rho_w C_w \phi] \bullet \frac{RF \bullet C_e}{PF \bullet t} \tag{5}$$

Parameters are listed in Table 2.

3.1. Recovery factor, conversion efficiency, economic life, and plant factor

The recovery factor refers to the fraction of heat stored in the reservoir that could be extracted to the surface (Sanyal and Sarmiento, 2005). This term depends on the reservoir fraction that is considered permeable and the efficiency by which heat can be withdrawn from such permeable channels. The conversion efficiency accounts for the conversion of recoverable thermal energy into electricity. The economic life of the project is the period required for the full investment to be recovered within its target internal rate of return, which is usually 25 to 30 years. The plant factor refers to the plant availability throughout the year, taking into consideration the period when the plant is scheduled for maintenance, or whether the plant is operated as a base-load or peaking plant. A good performance for many geothermal plants around the world is about 90 to 97% (DiPippo, 2015; Zarrouk and Moon, 2014).

4. Guidelines for the determination of reservoir parameters

Recent developments in the geothermal industry require the establishment of guidelines on how reserve estimation is to be approached and reported in corporate annual reporting or financial statements. Sanyal and Sarmiento (2005) proposed three categories for reserve classification: proven, probable and possible, all of which are more appropriately estimated using volumetric methods. The need for an industry standard is now imminent to create consistency in declarations of estimated reserves for a given project.

Sanyal and Sarmiento (2005) used results from Monte Carlo simulations to determine the proven, probable, and possible or inferred reserves based on the resulting percentiles obtained from the cumulative frequency distribution. The percentile value indicates the probability that the reserve quantities to be recovered will equal or exceed estimates. The following terms are defined in this study such that the proven reserves will have a 90% probability, and 5% for the

[1] The "Non-order specific error propagation" means that Mcerp does not make any assumptions or approximations in how uncertainty in the input variables is converted into uncertainty in the output functions. This Python library, being a random sampling based approach, takes the result as it is. It is possible to perform various statistical analyses on the data to find out information about the resultant distribution (Lee, 2014).