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Comparison of Stochastic Based Volumetric Heat in Place Methods for Predicting Power (Electricity) Generation Potential of Liquid-Dominated Geothermal Systems

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ABSTRACT

This paper focuses on review and comparison of three probability based volumetric heat in place methods which can be used for predicting a power (electricity) generation potential of a liquid-dominated geothermal system. These are the USGS (the United States Geologic Survey) method proposed in 1970, the MIT (Massachusetts Institute of Technology) proposed in 2006 and the Garg-Combs methods proposed in 2015. By considering synthetic and geothermal field data from Turkey, all three methods were evaluated and compared by using both the Monte Carlo Simulation (MC) and the Analytic Uncertainty Propagation (AUP) Methods. The uncertainty in power generation potential estimation due to uncertainties in input parameters such as areal extent, thickness, resource temperature, porosity, density, isobaric, volumetric specific heat capacity of reservoir rock, etc., is assessed by using the statistical markers of P10 (proved), P50 (probable) and P90 (possible). One of the contributions of the paper is that new AUP equations for each of the three methods have been derived and presented. The results predicted by the new AUP equations derived in this work show excellent agreement with the results predicted by the MC method, yet do not require extensive MC simulations or commercial software use. Suggestions were made about the proper usage of USGS and MIT methods that usually give overestimated results by the usage of arbitrarily chosen reservoir input parameters.

For comparison purposes, we consider predicting the electricity generation capacity of the Aydin-Germencik field in Turkey and Turkey's 25 geothermal fields which are interpreted as amenable fields for electricity generation by the MC and AUP methods based on the USGS, MIT, and Garg and Combs (2015). It is shown that the Garg and Combs (2015) method without any usage of arbitrary values and considering the installed power conversion system and thermodynamic properties of the produced water or the secondary fluid of the power conversion system appears to be the most appropriate method to eliminate the subjectivity in selecting the reference (or abandonment) temperature and conversion efficiency and hence to predict the power generation of a geothermal field or country more realistically.

1. INTRODUCTION

In recent years, the use of geothermal energy, particularly for electricity production, has increased globally – today, global geothermal installed capacity has reached 14,369 MWe (http://www.thinkgeoenergy.com/global-geothermal-capacity-reaches-14369-mw-top-10-geothermal-countries-oct-2018/). For example, at the end of 2018, Turkey has reached 1347 MWe installed capacity with 47 power conversion plants (Ulgen and Haizlip 2019) and plans to increase the installed capacity to 2000 MWe by the end of 2020 (Figure 1) (http://www.thinkgeoenergy.com/turkey-targets-2000-mw-geothermal-power-generation-capacity-by-2020/). Today, Turkey is in the top fourth globally with its installed electricity production capacity from geothermal resources, following US, Philippines and Indonesia (http://www.thinkgeoenergy.com/global-geothermal-capacity-reaches-14369-mw-top-10-geothermal-countries-oct-2018/).

As is well-known, being one of the renewable and sustainable alternative energy sources to fossil fuels, geothermal steam and hot water provide earth's heat for district heating and heat pump applications (direct use) and electricity production (indirect use) today. Our focus in this study is on the indirect use of geothermal energy for electricity production or power generation (denoted by PW) from liquid dominated geothermal reservoirs which are amenable to electricity production by either binary or flash system.

During early stage of exploration or development of a geothermal liquid dominated system, which may be amenable to electricity production, it is preferable to use a probabilistic approach rather than a deterministic approach to predict its power generation to mitigate the risks associated with decision making by taking into a consideration of uncertainties about thickness, volume, porosity, permeability, stored heat in rock and the liquid, etc. To propagate such uncertainties into the predictions of power generation, the United States Geological Survey (USGS) method developed in 1970s and the Massachusetts Institute of Technology (MIT) method developed in 2006 are widely used with Monte Carlo Simulation Methods (MCM) giving probabilistic results of reserves such as proved (P10), probable (P50) and possible (P90). Here P10 corresponds to the 10^{th} percentile of the generated CDF (cumulative density probability function) and that means the proved PW value is equal or higher than that value with a probability of 90%. Similarly, P50 corresponds to the 50^{th} percentile of CDF representing for the probable PW value is equal or higher than that value with 50% probability. P90 corresponds to the 90^{th} percentile of CDF meaning that the real PW value of possible reserve is equal or higher than that value with 10% probability.

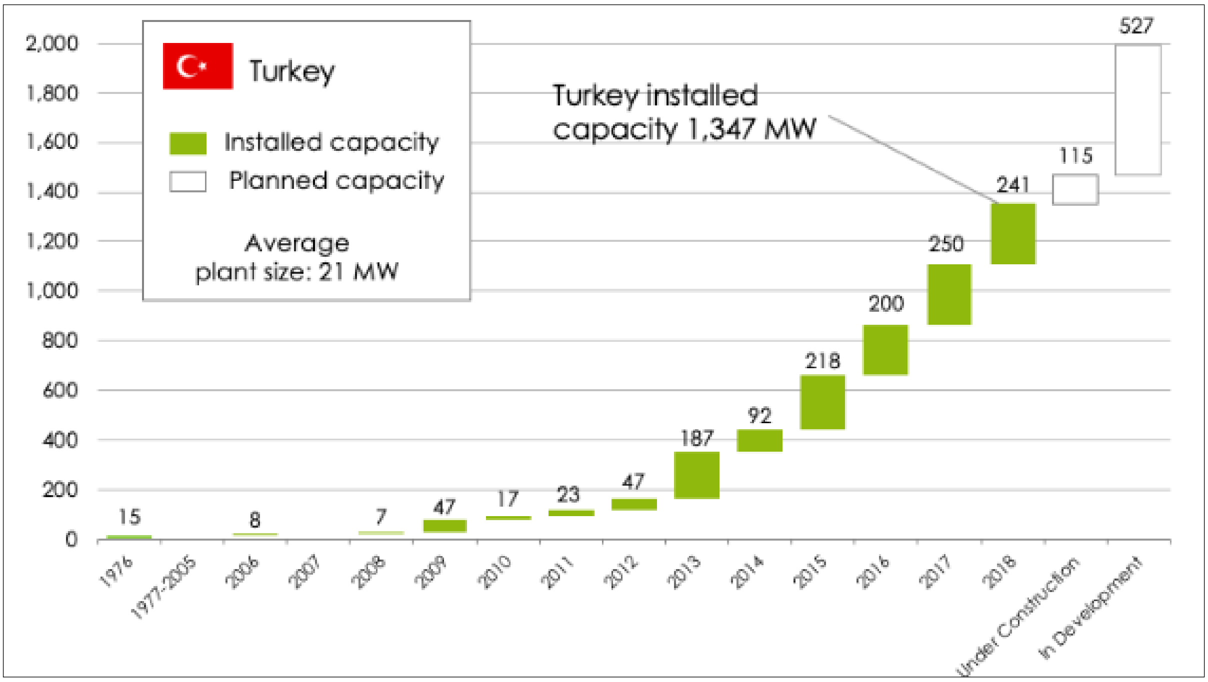

Figure 1: Geothermal power generation installed and planned capacity in Turkey (http://www.thinkgeoenergy.com/turkey-targets-2000-mw-geothermal-power-generation-capacity-by-2020/)

The USGS and MIT methods are based only on the 1st law of thermodynamics neglecting the 2nd law entropy changes and the real operating parameters of a given power conversion system (single flash or binary power plant) and hence yield overestimated predictions of PW. Garg and Combs (2010, 2011, 2015) proposed and provided a new formulation of volumetric probabilistic calculation of geothermal reserves by considering the second law of thermodynamics and the power conversion system dependency of the input parameters. They showed that input parameters such as reference temperature (T_R) and conversion efficiency (η_c) must be chosen according to the basic power conversion system that is appropriate for a geothermal system under consideration, such as, single flash or binary. The secondary fluid thermodynamic properties must be used while working on binary power plants. Garg and Combs (2015) also proposed that the recovery factor must be taken into consideration as "0" for the geothermal fields in very early stage of exploration. So in this paper, we consider the new formulations of Garg and Combs (2015) for binary and flash power plants and evaluate them in different cases where recovery factor is "0" or higher than zero in comparison to the results obtained from the USGS and MIT methods.

In this study, we provide new equations for the analytic uncertainty propagation methods for each of these three methods. The AUP method for the purposes predicting heat in place with uncertainty was first proposed by Sarak et al. (2009) and Onur et al. (2010). It is a very simple, accurate and quick alternative to the MC method in estimation of heat in place or producible electricity potential from a geothermal reservoir. The original contribution of this paper is that new AUP equations for each of the three methods have been derived and presented. Our objectives in this study are **(i)** to present the working equations of AUP method for each of the three methods. The detailed derivations of these equations are given in Altin (2017), **(ii)** to demonstrate the use of the AUP method with each of the USGS, MIT and Garg and Combs (2015) methods and compare the results obtained from the AUP with those from the MC simulation method. For comparison purposes, we consider predicting the electricity generation capacity of the Germencik field in Turkey (Unverdi and Cerci 2013) and Turkey's 25 geothermal fields which are interpreted as amenable fields for electricity generation (as presented in Basel (2010) dissertation). In her PhD, Basel (2010) considered a reference (or abandonment) temperature of 100 ^{0}C for these 25 geothermal fields by using the MIT method. As a result of her study, Basel (2010) estimated the electricity production potential of these 25 fields as 1269 (P10), 1500 (P50) and 1839 MWe (P90) based on probabilistic summation of the field potentials and 840 (P10), 1428 (P50) and 2371 (P90) based on the arithmetic summation of the fields with electricity production potentials. Onur et al. (2010) provide details of the arithmetic and probabilistic summation methods to estimate potential of stored or recoverable heat for a country by aggregating thermal resources involving more than one field.

2. UNCERTAINTY ASSESSMENT

Assessing uncertainty in predictions of stored heat and electric generation capacity of a geothermal system is the most important task for decision makers. The uncertainty in these predictions results from the uncertainties associated with the input parameters used in these predictions. The input parameters with large uncertainties used in these predictions are reservoir temperature (T_R), areas (A), thickness (H), and thermal recovery factor (R_g), as listed in Table 1. Other input parameters with less or no uncertainty are also given in Table 1.

The Monte Carlo (MC) simulation method is widely used to assess the uncertainty while estimating stored heat and electric generation capacity of a geothermal system. In the MC method, probability density functions for temperature, area, thickness, and thermal recovery factor are assumed based on the uncertain estimates to calculate the probability distribution function for the "recoverable heat" (q_{wH}) or the electricity generation capacity (or potential, PW). The probability distribution function for the recoverable heat or electricity is expected to be log-normal based on the central limit theorem (see Onur et al. 2010). So, the MC method is used to sample the resulting probability distribution function for the recoverable heat with randomly to characterize the uncertainty markers such as P10, P50 and P90 by using sufficiently large number of sets of input parameters withdrawn from their defined probability distributions (normal, triangle, etc.) with different seeds. Figure 2 shows the general workflow followed while working with the MC method to predict electricity production potential of a geothermal system with uncertainty.

Table 1 — Parameters used for the calculation of the electric generation capacity (modified from Garg and Combs 2015).

Parameters with large uncertainty	**Parameters with less or no uncertainty**
Reservoir Area (A, m^2)	Reference Temperature (T', ^{0}C)
Reservoir Thickness (H, m)	Conversion efficiency (η_c, fraction)
Reservoir Temperature (T_R, ^{0}C)	Volumetric heat capacity of rock ($(\rho c_p)_R$, kJ/m^3-^{0}C)
Thermal Recovery Factor (R_g, fraction)	Plant load factor (L_F, fraction)
	Plant or project life, (t_p, seconds)

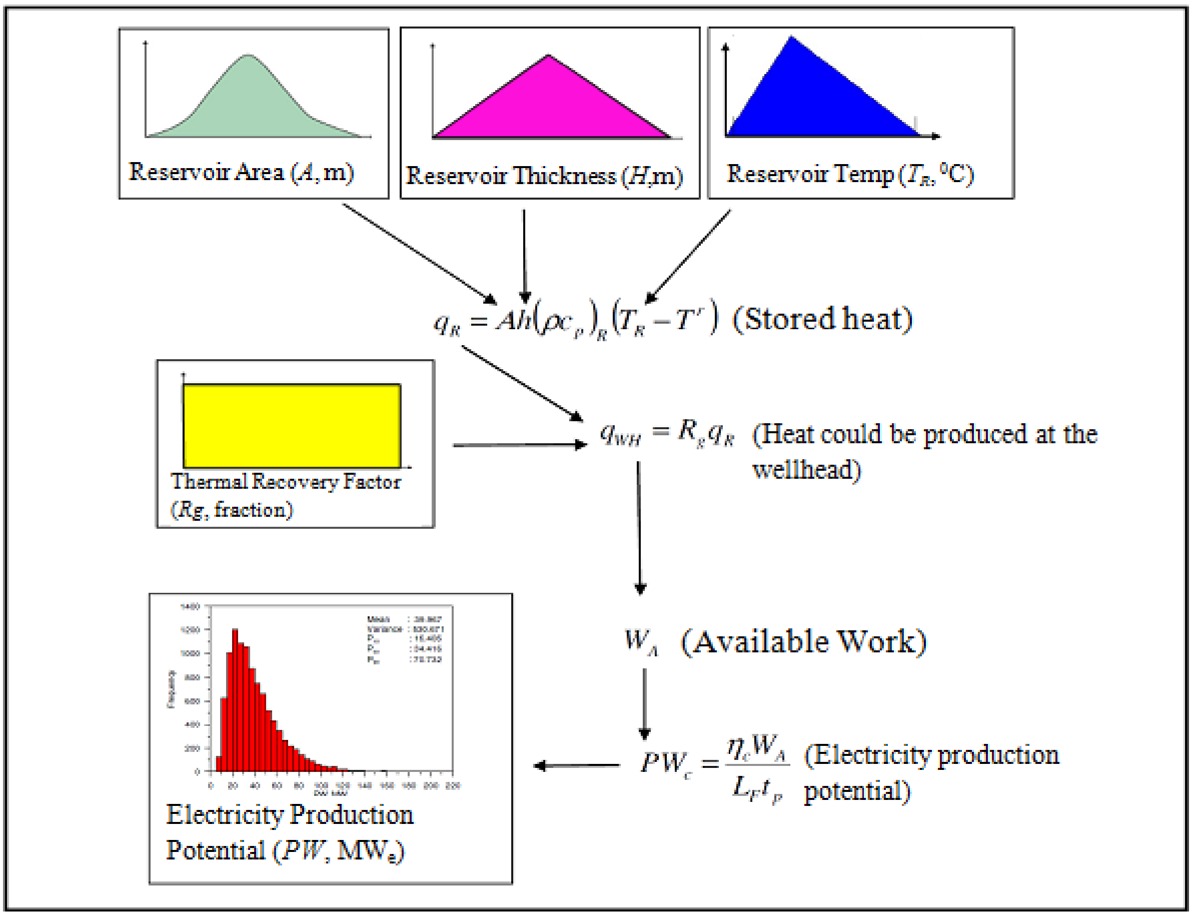

Figure 2: Workflow of the MC method for the predicting the stored heat (q_R), recoverable heat (q_{wH}), and electricity or power generation capacity (PW) with uncertainty

In this study, as mentioned before, we propose the AUP method as an analytical approach to predict electricity potential of a geothermal system with uncertainty. The AUP method is a simple, yet accurate alternative to the MC method, providing nearly perfect match with the predicted values of electricity generation capacities from the MC method, as shown with results presented later.

3. PW

PW refers to how much of heat in place stored is potentially convertible to electricity (or power) and can be approximated by using Eq. 1 below (Muffler 1979, Sanyal 2005, Zarrouk and Moon 2014, Williams 2014, Garg and Combs 2015, Grant 2015);

$$PW = \frac{E_r}{10^3 L_F t_p} = \frac{\eta_c \, W_A}{10^3 \, L_F \, t_p}, \tag{1}$$

where Er, η_c, WA, LF and tp are the recoverable energy at the wellhead (kW), thermal power conversion efficiency, available work, the load factor (referring the percentage of power plant time used for producing electricity) (fraction), the project life (the whole life time of the power plant) (seconds) and 103 is the conversion factor from kWe to MWe, respectively. Eq. 1 denotes Er is approximated by relating the available work (WA) with the power conversion efficiency (ηc). The methods predicting the PW in Eq. 1 differ based on the treatment of ηc and WA. In the following subsections, we review the USGS, MIT, Garg and Combs (2015) methods for treatment of these parameters.

3.1 USGS

In 1970s, the USGS scientists (Nathenson and Muffler 1975; Muffler and Cataldi 1977; Brook et al. 1979) have proposed a volumetric method for calculating the W_A which is given by Eq. 2 below;

$$W_{A,USGS} = R_g AH\left(\rho c_p\right)_R \left(T_R - T^r\right)\left[1 - T_{rK}\frac{\left(s_R - s^r\right)}{\left(h_R - h^r\right)}\right], \tag{2}$$

where R_g, A, H, T_R, T^r, T_{rK}, h_R, s_R and $\left(\rho c_p\right)_R$ are the thermal recovery factor (fraction), area (m^2), thickness (m), resource temperature (°C), reference, dead state or abandonment temperature (°C), the absolute reference temperature (T_{rK} = 15+273.15=288.15 K (Brook et al., 1979), (in the case of the reference temperature is chosen as 15 °C which is the case mostly used in USGS method)), the specific enthalpy of the liquid at reservoir temperature (kJ/kg), the specific entropy of the liquid at the reservoir temperature (kJ/kg-°C) and the volumetric, isobaric specific heat capacity of the liquid saturated rock where assuming that our system is a liquid dominated system with no steam phase, defined by Eq. 3 as

$$\left(\rho c_p\right)_R = \phi \, \rho_l \, c_{pl} + \left(1-\phi\right)\rho_s c_{ps}, \tag{3}$$

where ϕ, ρ_l, ρ_s, c_{ps} and c_{pl} are porosity (fraction), liquid density, solid rock density (kg/m^3), liquid and solid rock matrix specific heat capacity (kJ/kg-°C) respectively. Also stored heat in place and recovery at the wellhead is defined by Eqs. 4 and 5, respectively, as

$$q_R = AH(\rho c_p)_R (T_R - T^r), \tag{4}$$

and

$$q_W = R_g AH \left(\rho c_p\right)_R \left(T_R - T^r\right), \tag{5}$$

where R_g, q_w, and q_R are the recovery factor (fraction), recovered heat at the wellhead (kJ) (Eq. 4) and the stored heat in-place (kJ) (Eq. 5) (Muffler, 1979).

In the applications of the USGS method, all input parameters are combined with their uncertainties and categorized by different data distribution types such as triangular, uniform, normal, log-normal, etc., and assessed by using the MC simulation method. The inconvenience of the USGS method is in the usage or determination of the T^r and η_c. Researchers or interpreters usually use arbitrarily the values of 15 or 40 °C for T^r and the values of 0.11, 0.18, 0.4, etc. for η_c. They may choose these values without considering the type of the power conversion system to be used for generating electricity. It is well known that T^r and η_c have a very strong effect on the results of producible power from the geothermal system (Garg and Combs, 2010, 2011, 2015). The value of T^r should be determined by examining the real thermodynamic system properties and the value of η_c should be determined as a function of reference temperature and power conversion system type of the plant both such as flash or binary. One cannot just believe of the propriety of a value of T^r and η_c and use it for *PW* approximation. Thus, this method may result in very much overly-estimated results for *PW* and mislead the investors in this energy sector by creating geothermal potential ideas that are so much far away from the reality. Garg and Combs (2015) and Altin (2017) have re-examined the re-formulation of the USGS methodology to get an idea about which values of T^r and η_c gives closer results to *PW* values that are estimated by considering the real working condition of the power plant. But again the most realistic way of estimating realistic *PW* approximations is to examine the real condition of the power conversion system and accordingly use the required reference temperature and utilization factor values in our estimations.

3.2 MIT

The volumetric heat in place estimation method of MIT (2006) does not consider any enthalpy or entropy change neither in resource temperature nor in reference temperature by estimating the available work by using the 1st law of thermodynamics as presented in Eq. 6 below;

$$W_{A,MIT} = R_g AH\left(\rho c_p\right)_R\left(T_R - T^r\right) \quad (6)$$

The MIT (2006) method suggests an empirical relationship for η_c to be used only in binary power conversion systems as presented in Eq. 7 below;

$$\eta_c = 0.093457_R - 2.32657 \quad (7)$$

Basel (2010), in her PhD study, used the MIT method for 25 geothermal fields in Turkey. She used T^r =100 °C for all fields and the relationship given in Eq. 7 for calculating the η_c without taking into consideration the type of the power conversion system installed and operating in the field. This is reflected into her cumulative *PW* results obtained by the MC method as 27% over-estimation of P10, 22.5% over-estimation of P50 and 24% over-estimation of P90 in comparison to the Garg and Combs (2015) flash and binary *PW* results (Altin 2017). In a later work, Basel et al. (2013) considered 38 geothermal fields which are accepted as amenable to electricity production, but they didn't give any reservoir characteristics information about the examined geothermal fields such as thickness, porosity, recovery factor, area, resource temperature, reference temperature, thermal power conversion efficiency and even the names of the fields they studied and updated the original values of Basel (2010) based on 25 fields. They claimed that Turkey's updated power generation potential are 1673 (P10), 2263 (P50) and 3140 (P90) MWe, based on the arithmetic averages of arithmetic summation and probabilistic summation methods (Onur et al. 2010).

3.3 Garg and Combs (2015)

Instead of arbitrarily chosen T^r values, Garg and Combs (2015) proposed T_{abn} (abandonment temperature) to be used which is the temperature value below which a geothermal power plant could not be operated efficiently. They stated that the value of T_{abn} is related to the type of the power conversion system operating or decided to be installed in the field such as flash or binary.

Garg and Combs (2015) also proposed that η_c should be used as a function of T_{abn} and the operating real power conversion system as a result of exergy analysis made considering the 2nd law of thermodynamics instead of arbitrarily chosen η_c values. They reported that the η_c values should be taken in the range of 0.7-0.85 according to the power conversion cycle such as flash, binary, combined or hybrid complex conversion systems as the efficiency gets higher with combination of power cycles.

3.3.1 Garg and Combs, Flash (2015)

Flash power cycles have been used power conversion systems installed for geothermal reservoirs having resource temperature values higher than 180 °C (*https://en.wikipedia.org/wiki/Geothermal_power,http://en.openei.org/wiki/Binary_Cycle_Power_Plant*). In flash cycles the produced geothermal water and steam is separated by a separator and the steam is sent to the turbine for electricity generation while the separated water is cooled by a condenser and re-injected to the reservoir by re-injection wells to sustain the production of the reservoir. Garg and Combs (2015) have proposed to take the condenser temperature as 40 °C constant.

Turbine inlet pressure is set equal to the separator pressure (bars) and saturation temperature corresponding to that pressure value should be used for the reference temperature in the volumetric assessment of geothermal reserve ($T_{abn} = T^r = T_{sep}$) (Garg and Combs, 2015).

In Garg and Combs methodology, W_A is approximated by using Eq. 8 below;

$$W_{A,FLASH} = \frac{R_g AH\left(\rho c_p\right)_R\left(T_R - T_{sep}\right)}{h_{gl}(T_{sep})}\left\{h_{stm}\left(T_{sep}\right) - h_w\left(T_c\right) - T_{cK}\left[s_{stm}\left(T_{sep}\right) - s_w\left(T_c\right)\right]\right\} \quad (8)$$

where $h_{gl}(T_{sep})$, h_{stm}, s_{stm}, T_{sep}, h_w, s_w, T_c and T_{cK} are the heat of vaporization (kJ), the enthalpy (kJ/kg), the entropy values (kJ/kg-°C) of the steam, separator temperature, the enthalpy (kJ/kg), the entropy (kJ/kg-°C) values of geothermal liquid, condenser temperature, the absolute condenser temperature (K) respectively. Water properties in Eq. 8 are evaluated along the saturation line. The values given by the International Association for the properties of Water and Steam (IAPWS, 1996) are used for this purpose.

3.3.2 Garg and Combs, Binary (2015)

Geothermal reservoirs having resource temperature values between 57-180 °C are proper for effective electricity production by installation of binary system power plants (*https://en.wikipedia.org/wiki/Geothermal_power, http://en.openei.org/wiki/Binary_Cycle_Power_Plant*). The original geothermal hot water is not directly used for electricity production in binary power conversion systems but it is used to heat the secondary fluid, which has lower saturation temperature and pressure values, used in the system by heat exchangers. The original geothermal water then is re-injected into the reservoir level by injection wells for sustainability of the reservoir.

T_{abn} (abandonment temperature is equal to T_p (pinch point temperature) in binary power conversion systems where T_p denotes the summation of the differential temperature value corresponding to a location in the heat exchanger as the least temperature difference, ΔT , between the primary fluid (geothermal water) and the secondary (usually iso-butane) fluid with the bubble point temperature, T_b, of the secondary fluid as shown in Eq. 9 below (Garg and Combs, 2015). T_b can be determined from thermodynamic data for the fluid (NIST, 2010).

$$T_p = T_b + \Delta T \tag{9}$$

For binary power plants, W_A is approximated by using the relationship as shown in Eq. 10 below (Garg and Combs, 2015).

$$W_{A,BINARY} = \frac{R_g AH(\rho c_p)_R (T_R - T_p)}{h_{sfgl}(T_b)} \left\{ \begin{array}{l} h_{sfg}(T_b) - h_{sfl}(T_c) - T_{cK}\left[s_{sfg}(T_b) - s_{sfl}(T_c)\right] \\ -V_{sf}(T_c, p_{sfb})\left[p_{in} - p_{sfb}(T_c)\right] \end{array} \right\}, \tag{10}$$

where $h_{sfgl}(T_b)$, $h_{sfl}(T_c)$, $s_{sfl}(T_c)$, $h_{sfg}(T_b)$, $s_{sfg}(T_b)$, $V_{sf}(T_c, p_{sfb})$, p_{in}, $p_{sfb}(T_c)$ denote the heat of vaporization for the secondary fluid at its bubble point temperature, the enthalpy and entropy values of the secondary fluid in liquid phase at condenser temperature respectively (kJ/kg), (kJ/kg-^{o}C), the enthalpy and entropy values of the secondary fluid in gas phase at bubble point temperature respectively (kJ/kg), (kJ/kg-^{o}C), the specific volume of the secondary fluid at the condenser temperature at liquid phase and the bubble point pressure (m^3/kg), the turbine inlet pressure (bar), and the bubble point pressure of the secondary fluid at condenser temperature (bar), respectively. The subscripts g and l denote gas and liquid phases, respectively. Given the turbine inlet pressure, the secondary fluid properties or saturation temperature can be evaluated by using NIST tables (NIST, 2010).

4. AUPM

The AUP method (Sarak et al. 2009 and Onur et al. 2010) is a simple alternative analytical application method to the MC method in predicting the stored heat and producible power potential of a geothermal field. The validity of the AUP method for characterizing uncertainty results from the fact that the distributions of stored heat and power generation potential to be computed from the volumetric method tend to be log-normal (see Figure 1). This is a result of the well-known theorem of central limit (CLT) in statistics (Barlow, 1989). Hence the estimated PW will tend to be log-normal because the CLT indicates that natural logarithm of PW (lnPW) be normally distributed in both cases where the input parameters are independent. Besides, Sarak et al. (2009) also shows that the premise of the CLT holds even if the some of the input variables are correlated. In our study, we assumed that all input parameters are independent for simplicity.

The AUP method uses the analytically calculated μ (mean) and σ^2 (variance) of the input parameters and provides an exact result for the mean and variance of a random function f to be predicted if it is linear with respect to the input random variables. Otherwise, if f is nonlinear, then the AUPM provides approximate estimates of the mean and variance of the function f. The approximation becomes better if the nonlinear f can be well approximated by a linear function near the means of the input random variables (Onur et al, 2010).

The AUP method is based on Taylor series expansion of lnPW around the mean values of the natural logarithm of input variables ($\mu_{\ln X_i}s$) (Sarak et al. 2009 and Onur et al. 2010). The AUP method of Onur et al. (2010) considers the natural logarithm of a random function f of M variables, lnX_i, i=1,2,…,M, ln$f$ = ln$f$(lnX_1, lnX_2, lnX_3,…, lnX_M). Then, expanding ln$f$ around the mean (or true) values of lnX_is (denoted by $\mu_{\ln x_i}$, i=1,2,..,M by using a Taylor series up to first derivatives as in Eq. 11 below (Onur et al, 2010):

$$\ln f(\ln X_1, \ln X_2,..., \ln X_M) = f(\mu \ln X_1, \mu \ln X_2,..., \mu \ln X_M) + \sum_{i=1}^{M} (\ln X_i - \mu \ln X_1) \left(\frac{\partial \ln f}{\partial \ln X_i} \right) \Bigg|_{\ln X_i = \mu_{\ln Xi}, i=1,...,M} . \tag{11}$$

The μ and σ^2 of lnPW ($\mu_{\ln PW}$ and $\sigma^2{}_{\ln PW}$) is approximated by Eq. 12 and Eq. 13 below;

$$\mu_{\ln PW} = \ln PW(\mu_{\ln X_1}, \mu_{\ln X_2},..., \mu_{\ln X_M}), \tag{12}$$

and

$$\sigma^2{}_{\ln PW} = \sum_{i=1}^{M} \theta_i^2 \sigma^2_{\ln X_i} + 2\sum_{i=1}^{M-1} \sum_{j=i+1}^{M} \theta_i \theta_j \rho_{\ln X_i, \ln X_j} \sigma_{\ln X_i} \sigma_{\ln X_j}, \tag{13}$$

where θ represents the sensitivity of ln*f* to the variable lnX_i evaluated at the mean values of all the variables as in Eq. 14 below;

$$\theta = \left(\frac{\partial \ln PW}{\partial \ln X_i} \right) \Bigg|_{\ln X_i = \mu_{\ln Xi}, i=1,...,M} , \tag{14}$$

where ρ represents the correlation coefficient of the natural logarithm of the random input pairs and σ is the standard deviation from the mean value. Assuming no correlation between input data pairs of lnXi , Eq. 13 reduces to Eq. 15 below;

$$\sigma^2_{\ln PW} = \sum_{i=1}^{M} \theta_i^2 \sigma^2_{\ln X_i} . \tag{15}$$

So, the AUP method is based on taking the natural logarithm of the parameters used while calculating *PW* from Eq. 16;

$$\ln PW = \ln \eta_c + \ln W_A + \ln \left(\frac{1}{10^3 L_F t_p} \right) \tag{16}$$

After determining $\mu_{\ln PW}$ and $\sigma^2_{\ln PW}$, the probabilistic statistical markers of *PW* could be estimated by using the probability Eqs. 17, 18, and 19 below,

$$P10 = \exp \left(\mu_{\ln PW} - 1.28\sqrt{\sigma^2_{\ln PW}} \right) \tag{17}$$

$$P50 = \exp \left(\mu_{\ln PW} \right) \tag{18}$$

$$P90 = \exp \left(\mu_{\ln PW} + 1.28\sqrt{\sigma^2_{\ln PW}} \right) \tag{19}$$

The AUP method can be applied to the Garg and Combs, USGS, and MIT methods for estimating power generation potential of a geothermal field as shown in the following sub-sections below. The sensitivity of ln*PW* with respect to natural logarithm of a given input parameters that may be treated as uncertain for single-flash and binary power cycles are presented at Table 2. It should be noted that the parameter $(\rho c_p)_R$ can be assumed constant or certain (see Table 1) because its value does not change significantly with the rock and fluid properties in the same reservoir rock. It should be noted that the formula for the sensitivity with respect to resource temperature T_R to be used in computing variance of ln*PW* from Eq. 15 depends on the method to be used and it is given in the following subsections.

4.1 AUP Method for the USGS Method

In the application of the AUPM to the USGS method, the natural logarithm of W_A is given by

$$\ln W_{A,USGS} = \ln R_g + \ln A + \ln H + \ln \left(\rho c_p \right)_R + \ln \left(T_R - T^r \right) + \ln \left[1 - T_{rK} \frac{\left(s_R - s^r \right)}{\left(h_R - h^r \right)} \right] . \tag{20}$$

Note that the last term in the right-hand side of Eq. 20 is also dependent on the TR through the enthalpy [hR = h(TR,pR)] and entropy [sR = s(TR,pR)] of the geothermal reservoir. In this study, we consider reservoir pressure pR is constant and known (or certain), but treat the TR as uncertain, then hR and sR are also uncertain. Hence when we compute the variance of lnPW with respect to TR for the USGS method, we account for the uncertainty in hR and sR by computing the variance of lnPW with respect to TR. So, the sensitivity of lnPW with respect to the natural logarithm of TR is given by

$$\frac{\partial \ln PW}{\partial \ln T_R} = \frac{T_R}{T_R - T^r} - \frac{T_R T_{rK}}{1 - T_{rK} \frac{\left(s_R - s^r \right)}{\left(h_R - h^r \right)}} \left[\frac{s'_R \left(h_R - h^r \right) - h'_R \left(s_R - s^r \right)}{\left(h_R - h^r \right)^2} \right] , \tag{21}$$

where

$$h'_R = \left(\frac{\partial h_R}{\partial T_R} \right)_{p_R} = c_{pl} , \tag{22}$$

and

$$s'_R = \left(\frac{\partial s_R}{\partial T_R}\right)_{p_R} = \frac{c_{pl}}{T_R}. \tag{23}$$

Eqs. 25 and 26 represent the derivatives of the enthalpy and entropy with respect to reservoir temperature (https://en.wikipedia.org/wiki/Relations_between_heat_capacities).

Table 2 — Sensitivity of ln*PW* with respect to natural logarithm of input parameters.

Variable X_i	$\theta_i = \partial \ln PW / \partial \ln X_i^*$
ϕ	$\dfrac{\mu_\phi\left(\mu_{\rho_l}\mu_{c_{pl}} - \mu_{\rho_s}\mu_{c_{ps}}\right)}{\left[\mu_\phi\mu_{\rho_l}\mu_{c_{pl}} + (1-\mu_\phi)\mu_{\rho_s}\mu_{c_{ps}}\right]}$
c_{ps}	$\dfrac{\mu_{c_{ps}}\mu_{\rho_s}(1-\mu_\phi)}{\left[\mu_\phi\mu_{\rho_l}\mu_{c_{pl}} + (1-\mu_\phi)\mu_{\rho_s}\mu_{c_{ps}}\right]}$
ρ_s	$\dfrac{\mu_{c_{ps}}\mu_{\rho_s}(1-\mu_\phi)}{\left[\mu_\phi\mu_{\rho_l}\mu_{c_{pl}} + (1-\mu_\phi)\mu_{\rho_s}\mu_{c_{ps}}\right]}$
c_{pl}	$\dfrac{\mu_{c_{pl}}\mu_{\rho_l}\mu_\phi}{\left[\mu_\phi\mu_{\rho_l}\mu_{c_{pl}} + (1-\mu_\phi)\mu_{\rho_s}\mu_{c_{ps}}\right]}$
ρ_l	$\dfrac{\mu_{c_{pl}}\mu_{\rho_l}\mu_\phi}{\left[\mu_\phi\mu_{\rho_l}\mu_{c_{pl}} + (1-\mu_\phi)\mu_{\rho_s}\mu_{c_{ps}}\right]}$
A	1
H	1
T_R	*Depends on the method used*
R_g	1
t_p	-1
L_F	-1
*evaluated at the mean values of the variables X_is	

4.2 AUP Method for the MIT Method

In the application of the AUPM to the MIT method, the natural logarithm of W_A is given by;

$$\ln W_{A,MIT} = \ln R_g + \ln A + \ln H + \ln\left(\rho c_p\right)_R + \ln\left(T_R - T^r\right) \tag{24}$$

The sensitivity of the sensitivity of ln*PW* with respect to the natural logarithm of T_R, based on Eq. 24, is computed from

$$\frac{\partial \ln PW}{\partial \ln T_R} = \frac{\partial \ln W_{A,MIT}}{\partial \ln T_R} = \frac{T_R}{(T_R - T^r)}. \tag{25}$$

4.3 AUP Method for the Garg and Combs method

As mentioned earlier, the producible amount of power or electricity is calculated by Eq. 8 for flash power cycles. In the application of the AUP method the Garg and Combs flash method, the natural logarithm of W_A for a single-flash power cycle is computed from;

$$\ln W_{A,FLASH} = \ln R_g + \ln A + \ln H + \ln\left[(\rho c_p)_R\right] + \ln(T_R - T_{sep}) + \ln\frac{\left\{h_{stm}\left(T_{sep}\right) - h_w\left(T_c\right) - T_{cK}\left[s_{stm}\left(T_{sep}\right) - s_w\left(T_c\right)\right]\right\}}{h_{gl}(T_{sep})}, \tag{26}$$

whereas in the application of the AUPmethod to the Garg and Combs binary method, the natural logarithm of W_A for a binary power cycle is computed from

$$\ln W_{A,BINARY} = \ln R_g + \ln A + \ln H + \ln\left[(\rho c_p)_R\right] + \ln(T_R - T_p) + \ln \frac{\left\{\begin{matrix} h_{sfg}(T_b) - h_{sfl}(T_c) - T_{cK}\left[s_{sfg}(T_b) - s_{sfl}(T_c)\right] \\ -V_{sf}(T_c, p_{sfb})\left[p_{in} - p_{sfb}(T_c)\right] \end{matrix}\right\}}{h_{sfgl}(T_b)} . \quad (27)$$

It should be noted that the last logarithm terms in the right-hand sides of Eq. 20 and Eq. 21 are just constants and certain. These values determined depending on the proper or installed power cycle are computed from International Association for the properties of Water and Steam (IAPWS, 1996) and The National Institute of Standards and Technology (NIST, 2010).

The sensitivity of the sensitivity of lnPW with respect to the natural logarithm of T_R, based on Eqs. 26 and 27, is computed from

$$\frac{\partial \ln PW}{\partial \ln T_R} = \frac{\partial \ln W_{A,FLASH}}{\partial \ln T_R} = \frac{\partial \ln W_{A,BINARY}}{\partial \ln T_R} \frac{T_R}{(T_R - T^r)}. \quad (28)$$

5. EXAMPLE APPLICATION TO THE AYDİN-GERMENCIK GEOTHERMAL FIELD

Here, we consider Germencik geothermal field in Turkey to compare the results of its power generation potential estimated by the three methods; Garg and Combs, USGS and MIT, by using both the AUP and MC methods. As to brief history of the field, in 2009, the operator of the field constructed a 47.4 MWe double-flash power plant based on 6 production and 7 re-injection wells (Unverdi and Cerci 2013). Today the operator has already extended the installed capacity up to 232.3 MWe.

In our calculation, we take A, H, and $(\rho c_p)_R$ data from Basel (2010) PhD dissertation. Basel considered a maximum T_R of 235 °C, but we consider a maximum T_R of 239.5 °C instead as this is the maximum temperature recorded in the wells drilled in the field (Akkus, 2016). We used a conversion efficiency of 87.4% for the Grags-Comb method, as reported by Unverdi and Cerci (2013) since Germencik field is operated by a double-flash power conversion system. For the reservoir area Basel (2010) used 7 km^2 as maximum. Basel (2010) estimated the reservoir area information from field resistivity measurements and geological cross sections prior 2010. This value of area seems small as compared to the reported values of 50 km^2 by Unverdi and Cerci (2013) and 36 km^2 by Tureyen et al. (2014). The reported values of 50 km^2 and 36 km^2 presumably include new concession areas. We define a triangular area distribution with 25 km^2 minimum, 30 km^2 mode and 50 km^2 as the maximum value.

In Germencik double-flash power cycle, the produced fluid entering the high pressure steam system is separated at 5.972 bars at the turbine inlet (Unverdi and Cerci 2013). Ignoring any pressure drop between the high-pressure separator and the turbine inlet, T_{sep} is 158.644 °C. The turbine inlet pressure is set equal to the separator pressure. T_c is 40 °C (Unverdi and Cerci 2013). Table 3 and Table 4 presents the values and distributions of the input parameters to estimate the power potential of Germencik geothermal field by using the volumetric heat in place methods of Garg and Combs (2015) and USGS and MIT, respectively. For each of these volumetric heat in place methods, we apply both the AUP method (AUPM) and MC method (MCM) to compare the accuracy of the AUPM approximation to the MCM. The results obtained are summarized in Table 5. As seen from Table 5, for each of the five cases considered, the AUPM provides estimates of statistical markers of P10, P50, and P90 very close to the values of those predicted by the MCM. For the MCM method, we simulated 25,000 outcomes of the PW by random sampling of the input parameters having distributions. The USGS method applied in Case 2 (C2 in Table 5) overestimates the statistical markers about 20%, while the MIT method applied in Case 4 (C4 in Table 5) overestimates the statistical markers about 25%, as compared to those statistical markers predicted from Garg and Combs based on flash power cycle. The results for the USGS and MIT methods applied in Cases 3 and 5 (see C3 and C5) are presented in Table 5 to show that by arbitrarily changing the values of reference temperature (T^r) and conversion efficiency (η_c), we can decrease the difference between the statistical markers computed from the USGS (or MIT) method and the Garg and Comb method which does not require arbitrary use of these parameters. One can use a trial and error procedure to determine the appropriate (or optimal) values of T^r and η_c to be used in the USGS and MIT methods to obtain the closest values of statistical markers obtained by the Garg and Combs method. We note that the values of PW predicted by Garg and Combs method seems to be consistent with the real condition of Germencik double-flash power plant installed capacity, which has been increased to 232.3 MWe recently. It is interesting to note that this value is very close to our P10 (proved) value of the PW.

Table 3 ─ Input parameters used for the Garg and Combs method for Aydin-Germencik field.

Parameter	Dist. Type	Min.	Mode	Max.
Reservoir Area (A, m^2)	Triangular	25000000	30000000	50000000
Reservoir Thickness (H, m)	Triangular	750	1500	2000
Resource Temperature (T_R, °C)	Triangular	205	220	239.5
Porosity (ϕ , fraction)	Triangular	0.01	0.075	0.125
Specific heat capacity of brine $(c_p)_L$, kJ/kg-°C)	Constant	4.18		
Density of brine (ρ_f , kg/m^3)	Constant	845.01		
Specific heat capacity of rock $(c_p)_R$, kJ/kg-°C	Triangular	0.85	0.9	0.95
Density of rock (ρ_R , kg/m3)	Triangular	2400	2700	2900
Volumetric specific heat capacity of rock $(\rho c_p)_R$, (kg/m^3-°C)	Triangular	2055	2513	2852
Recovery factor (R_g, fraction)	Triangular	0.07	0.18	0.24
Seperator pressure (p_{sep}, bar)	Constant	5.972		
Plant seperator temperature (T_{sep}, °C)	Constant	158.644		
$T_R - T_{sep}$ (°C)	Triangular	46.356	61.356	80.856
Plant condenser temperature (T_c, °C)	Constant	40		
Power conversion efficiency (η_c , fraction)	Constant	0.874		
Project life (t_0, 30x31557600, sec)	Constant	946728000		
Load factor (L_F, fraction)	Constant	0.95		
h_{stm} (T_{sep}=158.644 °C) (kJ/kg)	Constant	2755.94		
s_{stm}(T_{sep}= 158.644°C) (kJ/kg-°C)	Constant	6.76083		
h_{wl} (T_c=40 °C) (kJ/kg)	Constant	167.533		
s_{wl}(T_c=40 °C) (kJ/kg-°C)	Constant	0.572402		
h_{gl} (T_{sep}= 158.644 °C) =(h_{stm}-h_{wl})	Constant	2086.356		
T_{cK}, K @ (T_c=40 °C)	Constant	313.15		

Table 4 ─ Input parameters used for the USGS and MIT methods for Aydin-Germencik geothermal field.

Parameter	Dist. Type	Min.	Mode	Max.
Reservoir Area (A, m^2)	Triangular	25000000	30000000	50000000
Reservoir Thickness (H, m)	Triangular	750	1500	2000
Resource Temperature (T_R, °C)	Triangular	205	220	239.5
Resource Pressure (p_R, bar)	Constant	52		
Porosity (ϕ , fraction)	Triangular	0.01	0.075	0.125
Specific heat capacity of brine $(c_p)_f$, kJ/kg-°C)	Constant	4.18		
Density of brine (ρ_f , kg/m^3)	Constant	845.01		
Specific heat capacity of rock $(c_p)_R$, kJ/kg-°C	Triangular	0.85	0.9	0.95
Density of rock (ρ_R , kg/m3)	Triangular	2400	2700	2900
Volumetric specific heat capacity of rock $(\rho c_p)_R$ kg/m^3-°C)	Triangular	2055	2513	2852
Recovery factor (R_g, fraction)	Triangular	0.07	0.18	0.24
Specific Enthalpy of the reservoir (h_R, kJ/kg) @ T_R	Triangular	876.201	944.378	1035.36
Specific entropy of the reservoir (s_R, kJ/kg-°C) @ T_R	Triangular	2.37197	2.51235	2.69326
Reference temperature (T^r, °C)	Constant	For USGS: 15, 40 °C For MIT: 15,40 °C		
Thermal conversion factor (fraction)	Constant	For USGS: 0.4 For MIT: 0.11		
Project life (t_p, 30x31557600, sec)	Constant	946,728,000		
Load factor (L_F, fraction)	Constant	0.95		
T_{rK} (T^r=15 °C)	Constant	288.15		
T_{rK} (T^r=40 °C)	Constant	313.15		
h_r (T^r=15 °C) (kJ/kg)	Constant	62.9815		
h_r (T^r=40 °C) (kJ/kg)	Constant	167.533		
s_r (T^r=15 °C) (kJ/kg-°C)	Constant	0.224463		

Table 5 ─ Summary of the results for the power generation potential of the Germencik field by using the Garg and Combs (2015), USGS (1970), and MIT (2006) methods with the AUP and MC methods.

Case	Volumetric Heat in Place Method	Probabilistic Approach	MWe Potential Predicted with Probability			% Difference between AUPM & MCM (relative to MCM)			% Difference in Volumetric Heat in Place Methods (relative to Garg & Combs based on AUPM of C1)		
			P10	P50	P90	P10	P50	P90	P10	P50	P90
C1	Garg & Combs Flash	AUPM	229	358	561	-3.6	2.2	0.88			
		MCM	221	366	566						
C2	USGS (T^r=15 °C	AUPM	278	441	700	-4.1	0.9	-1.2	18	19	20
		MCM	267	445	692						
C3	USGS (T^r=40 °C & η	AUPM	203	336	555	-5.2	-0.6	-3.2	13	7	1
		MCM	193	334	538						
C4	MIT (T^r=15 °C & η	AUPM	312	478	732	-3.7	2.5	0.5	27	25	23
		MCM	301	490	736						
C5	MIT (T^r=40 °C & η	AUPM	273	420	644	-3.0	2.3	1.1	16	15	13
		MCM	265	430	651						

6. EXAMPLE APPLICATION TO 25 GEOTHERMAL FIELDS OF TURKEY

In this application, the data from 25 geothermal fields which were previously considered by Basel in her PhD thesis are examined by using Garg and Combs (2015) method with both the AUP and MC methods. All 25 geothermal fields have resource temperatures greater than 100 ^oC. The results obtained are compared with Basel's (2010) results. All reservoir information such as A, H, R_g, T_R, etc., is given in her PhD dissertation. Basel evaluated these geothermal fields by using the MIT method, assuming a reference temperature of T^r =100 ^oC for all these 25 geothermal fields and calculating the value of η_c by using the MIT empirical equation (Eq. 7) which has been proposed to be used for binary power plants.

In our study, geothermal fields having resource temperatures (T_R) higher than 180 ^oC are assumed to be appropriate for the single-flash power conversion system, whereas geothermal fields having resource temperatures less than 180 ^oC are assumed to be appropriate for the binary system. For all the fields, the turbine inlet and separator pressures are assumed to be 4 bars. For the geothermal power plants which are decided to be amenable for a binary power, the secondary fluid is assumed to be pentane. The assumed differential temperature value between the secondary fluid and the original geothermal fluid is 5 ^oC. The value of η_c is assumed to be 0.75 for both the flash and binary power conversion systems, as suggested by Garg and Combs (2015). The project life and load factor are assumed to be assumed to be 25 years and 0.9. Volumetric isobaric specific heat capacity of the reservoirs is calculated by using constant values of porosity, density of rock and fluid and specific heat capacities of rock and fluid for minimum, most likely, and maximum cases given by Basel (2010). The resultant probabilistic values are evaluated by using a triangular distribution concept. The results are presented at Table 6 below.

Clearly, the MIT method significantly overestimates the electricity production potential of the 25 geothermal fields as compared to that estimated by the Garg and Combs method. Specifically, for these 25 geothermal fields under consideration, the MIT method overestimates the P10 value as 179 MWe higher, the P50 value 263 MWe higher, and the P90 value as 462 MWe higher than those computed from the Garg and Combs (2015). This result corresponds to 27% overestimation of P10, 22.5% overestimation of P50 and 24% overestimation of P90 reserves for the 25 fields under consideration for their producible electricity potential. Finally, we note that the Garg and Combs method with the AUPM predicts very similar results to the Garg and Combs method with the MCM.

7. SUMMARY AND CONCLUSIONS

In this paper, we compared three probability based volumetric heat in place methods; the USGS, the MIT and the Garg-Combs methods which can be used for predicting a power (electricity) generation potential of a liquid-dominated geothermal system. To associate uncertainty into power generation potential predictions by these methods, we developed and presented an alternative, yet simple analytic uncertainty propagation equations to the Monte Carlo (MC) method.

The USGS and MIT methods use arbitrarily chosen reference temperature (15, 30, 40, 100 ^oC) and thermal conversion efficiency values (0.15, 0.3, 0.4, etc.). In the USGS and MIT methods, we found that there is no scientific foundation to choose the reference temperature and conversion efficiency values realistically. That is why these methods often can overestimate or even underestimate the geothermal reserves and power potential of these resources. In the MIT method, some people seem to use the thermal conversion efficiency based on an empirical relationship given for only binary power conversion systems even for the flash power conversion systems. It is not clear that how to choose the conversion efficiency value to be used in the MIT method for the single-flash system. If the empirical equation developed based on the binary systems (see Eq. 7) is used for flash power conversion systems, the MIT method largely overestimates the producible power potential of the geothermal field as shown with the applications to the Aydin-Germencik geothermal in Turkey and to the 25 geothermal fields amenable to electricity production in Turkey. The usage of reference temperature in both methods also seems to be arbitrary, which is another big source of error.

The Garg and Combs (2015) volumetric probabilistic calculation method is applied by considering the 2nd law of thermodynamics and the power conversion system depending to the resource temperature of the reservoir. As this method which considers the real operating power conversion system with its thermodynamic condition based on the 2nd law of thermodynamics being far away from any arbitrary usage of input parameters, it provides more realistic estimates of power generation of a geothermal field or country.

Finally, we conclude that the AUP method is a perfect alternative to the MC method with only 1-5% difference in resultant values with any of the three volumetric heat in place method considered in this study. In this study, we propose an AUP method for the Garg and Combs method which is a very good alternative and simple technique as being not time consuming and does not require the use of a commercial software unlike the MC method for the Garg and Combs method to assess the uncertainty in power generation potentials of geothermal systems.

Table 6 ─ Summary of results for the 25 geothermal fields in Turkey obtained by Garg and Combs method with the AUPM and MCM in comparison with the results of Basel (2010) by using the same reservoir parameters.

Results of Garg and Combs (2015) method based on the AUPM or MCM								Basel's PhD (2010) Results (Method: MIT based on the MCM, T^r=100 °C)			
Field	**Assumed power conversion system**	**Method**	$\mu_{\ln PW}$	$\sigma^2_{\ln PW}$	**P10 MWe**	**P50 MWe**	**P90 MWe**	η_c	**P10 MWe**	**P50 MWe**	**P90 MWe**
Alaşehir, Sarıkız-Manisa	Binary	AUPM	1.894	0.174	3.89	6.65	11.35	0.13	3.3	6.8	12.8
		MCM	1.895	0.187	3.76	6.77	11.49				
Atça-Aydın	Binary	AUPM	0.805	0.086	1.53	2.24	3.26	0.11	1.0	1.7	2.7
		MCM	0.805	0.093	1.49	2.28	3.27				
Balçova-İzmir	Binary	AUPM	0.491	0.265	0.84	1.63	3.15	0.10	0.5	1.1	2.3
		MCM	0.491	0.286	0.82	1.64	3.24				
Dikili-İzmir	Binary	AUPM	2.697	0.244	7.88	14.83	27.91	0.12	4.6	13.0	33.1
		MCM	2.697	0.264	7.51	15.06	28.69				
Germencik-Aydın	Single Flash	AUPM	4.060	0.122	37.05	57.98	90.71	0.18	48.9	82.1	128.4
		MCM	4.061	0.131	35.76	59.23	91.20				
Gümüşköy-Aydın	Binary	AUPM	4.333	0.366	35.10	76.17	165.32	0.10	12.3	48.8	134.1
		MCM	4.333	0.409	32.62	77.56	175.51				
Kızıldere 1-Denizli	Single Flash	AUPM	3.148	0.063	16.89	23.28	32.09	0.17	109.1	139.4	180.4
		MCM	3.149	0.069	16.14	24.06	31.89				
Kızıldere 2-Denizli	Single Flash	AUPM	4.301	0.056	54.57	73.80	99.81	0.20			
		MCM	4.302	0.063	51.80	76.71	99.01				
Nazilli-Aydın	Binary	AUPM	2.535	0.089	8.62	12.62	18.47	0.14	8.3	14.2	22.4
		MCM	2.535	0.097	8.35	12.94	18.55				
Pamukören 1-Aydın	Binary	AUPM	2.218	0.056	6.78	9.19	12.45	0.15	26.4	33.5	42.4
		MCM	2.218	0.063	6.43	9.54	12.31				
Pamukören 2-Aydın	Single Flash	AUPM	2.720	0.061	11.08	15.18	20.80	0.17			
		MCM	2.725	0.067	10.60	15.79	20.74				

Table 6 (continued) ─ Summary of results for the 25 geothermal fields in Turkey obtained by Garg and Combs method with the AUPM and MCM in comparison with the results of Basel (2010) by using the same reservoir parameters.

Results of Garg and Combs (2015) method (AUPM, MCM)								Basel's PhD (2010) Results (Method: MIT based on the MCM, T′=100 °C)			
Field	**Assumed power conversion system**	**Method**	$\mu_{\ln PW}$	$\sigma^2_{\ln PW}$	**P10 MWe**	**P50 MWe**	**P90 MWe**	η_c	**P10 MWe**	**P50 MWe**	**P90 MWe**
Caferbeyli 1 -Manisa	Binary	AUPM	1.783	0.075	4.19	5.95	8.45	0.11	54.6	80.2	121.4
		MCM	1.783	0.081	4.04	6.13	8.40				
Caferbeyli 2-Manisa	Single Flash	AUPM	3.938	0.114	33.31	51.32	79.06	0.15			
		MCM	3.938	0.124	32.01	52.27	80.00				
Umurlu-Aydın	Binary	AUPM	3.722	0.146	25.35	41.35	67.45	0.13	22.8	41.6	69.2
		MCM	3.722	0.165	23.65	42.99	68.70				
Salavatlı-Aydın	Binary	AUPM	4.950	0.228	76.65	141.20	260.11	0.15	78.2	165.1	343.6
		MCM	4.950	0.242	73.20	142.26	268.39				
Seferihisar 1-İzmir	Binary	AUPM	2.134	0.068	6.05	8.69	11.82	0.11	13.8	19.9	28.5
		MCM	2.134	0.076	5.81	8.69	11.82				
Seferihisar 2-İzmir	Binary	AUPM	3.201	0.084	16.93	24.55	35.60	0.09			
		MCM	3.201	0.093	16.27	25.19	35.81				
Simav-Kütahya	Single Flash	AUPM	3.684	0.163	23.77	39.82	66.71	0.16	34.7	59.6	94.9
		MCM	3.682	0.183	22.36	41.14	66.98				
Tekkehamam 1-Denizli	Binary	AUPM	1.640	0.077	3.62	5.15	7.34	0.11	15.2	20.1	26.6
		MCM	1.640	0.085	3.46	5.32	7.34				
Tekkehamam 2-Denizli	Binary	AUPM	1.442	0.073	2.99	4.23	5.98	0.14			
		MCM	1.442	0.082	2.85	4.38	5.97				
Tekkehamam 3-Denizli	Binary	AUPM	2.319	0.074	7.18	10.16	14.40	0.14			
		MCM	2.319	0.080	6.90	10.49	14.30				
Tuzla-Çanakkale	Single Flash	AUPM	2.055	0.206	4.36	7.80	13.96	0.16	6.1	11.4	20.0
		MCM	2.052	0.229	4.14	7.97	14.14				
Salihli Doğu-Manisa	Binary	AUPM	3.145	0.150	14.13	23.21	38.11	0.13	12.6	23.1	39.4
		MCM	3.145	0.164	13.48	23.80	38.71				

Table 6 (continued) ─ Summary of results for the 25 geothermal fields in Turkey obtained by Garg and Combs method with the AUPM and MCM in comparison with the resul ts of Basel (2010) by using the same reservoir parameters.

Results of Garg and Combs (2015) method (AUPM, MCM)								Basel's PhD (2010) Results (Method: MIT based on the MCM, T′=100 °C)			
Field	**Assumed power conversion system**	**Method**	$\mu_{\ln PW}$	$\sigma^2_{\ln PW}$	**P10 MWe**	**P50 MWe**	**P90 MWe**	η_c	**P10 MWe**	**P50 MWe**	**P90 MWe**
Hıdırbeyli Kuzey-Aydın	Binary	AUPM	3.043	0.128	13.27	20.97	33.13	0.11	9.0	16.9	29.8
		MCM	3.043	0.136	12.97	21.32	33.56				
Hıdırbeyli Güney-Aydın	Binary	AUPM	3.477	0.095	21.80	32.36	48.03	0.14	20.5	35.2	56.6
		MCM	3.477	0.103	21.07	33.15	48.03				
İmamköy, Yılmazköy-Aydın	Single Flash	AUPM	4.454	0.265	44.49	85.97	166.12	0.15	79.6	143.4	245.8
		MCM	4.446	0.357	38.53	92.85	168.34				
Kavaklıdere-Manisa	Single Flash	AUPM	5.743	0.127	197.87	312.15	492.43	0.17	264.3	446.4	695.6
		MCM	5.747	0.140	189.38	319.01	501.31				
Ortakçı-Aydın	Binary	AUPM	1.677	0.155	3.23	5.35	8.85	0.12	2.6	4.7	8.4
		MCM	1.677	0.165	3.12	5.46	8.89				
Salihli Kuzeydoğu-Manisa	Binary	AUPM	1.878	0.067	4.70	6.54	9.11	0.14	4.8	7.2	9.9
		MCM	1.878	0.074	4.50	6.73	9.05				
Umurlu Güney-Aydın	Binary	AUPM	2.309	0.176	5.89	10.07	17.21	0.13	5.3	10.1	17.7
		MCM	2.309	0.199	5.42	10.49	17.42				
Erciş, Zilan-Van	Binary	AUPM	1.306	0.154	2.23	3.69	6.10	0.16	1.5	2.9	5.4
		MCM	1.306	0.166	2.14	3.76	6.16				
			AUPM Total:		696	1134	1875				
			MCM Total:		661	1165	1909		840	1428	2371

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