Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Methods of Early Geothermal Energy Resource Assessment – A Modern Conceptual and Mathematical Model

Hugo Fernando Navas; Michele Pipan

Universita Degli Study di Trieste, Department of Mathematics and Earth Sciences, via Weiss 1, I-34127 Trieste, Italy

hfnavas_lion@yahoo.com; pipan@units.it

Keywords: Geothermal development stages, early assessment, natural exponential decay, Volumetric method, Monte Carlo Simulation, Corona Exponential Decay Method, Real natural field capacity.

ABSTRACT

Early in a geothermal field development the owners and financiers want to know the number of MWe capacity of the plant that can be sustained by the new field although very limited information about the field has been gathered. In the past 50 years 3 methods of early assessment have been developed, each based on different concepts, mathematics, and statistics. Models are based on a conceptual model of the field.

The "**Volumetric method"** was implemented more than 40 years ago, when no history or data from many fields and thousands of boreholes were available. It is basically a static energy calculation and the method can provide an early estimate of MWe capacity, normally greater than the natural real one.

The "**Monte Carlo Simulation**" method produces a wide range of possible solutions, and then a statistical probabilistic value can estimate the final geothermal field estimate of MWe. The application to real cases (e.g. Iceland) proved that the resulting estimates are still above the true value, possibly because it is based on the same linear static formula of the volumetric method.

We propose a novel concept and method of early capacity estimate based on a more realistic **exponential decay formulation**, adjusted using the true statistical dynamic sampling from different real fields developed during the last 50 years, and statistical decay data from over 5,000 wells drilled. The first tests on real cases provide more realistic estimates of the MWe capacity compared to the traditional ones.

On one hand owners and managers want to know the estimated capacity MWe as close as possible to the sustainable reality, while on the other hand managers and financiers} tend to favor the estimated potential MWe with "Big Numbers", provided by the earlier methods – to have a larger project and more room for adjustments.

1. INTRODUCTION

A revision with historical details of 2 traditional and 1 new early assessment methods is undertaken to show and compare the different results, in a particular case studied, and how they aim to determine the elusive "real natural field capacity" to produce electric energy MWe, in a sustainable manner.

Volumetric method, Monte Carlos Simulation, Corona Exponential Decay Model, compared to "Natural Reality", [**MWe**]. Exponential decay model is closer to nature or reality than random numbers; several charts are included to show examples. The conclusion is that developers have to make a choice of what model suits their intended audience. 2 models and methods yield big numbers, and the other is closer to reality, but again its selection depends on preference and audience.

2. VOLUMETRIC MODEL REVIEW – SOME INTERESTING HISTORIC DETAILS

It is a simple mathematical model of static energy calculations, designed for the early exploratory stage of geothermal development that satisfactorily provides a basic comparison among other geothermal fields, and later can be used to support results from other models. It calculates the formation rocks energy and the reservoir fluid energy, while excludes all dynamic changes during production, mass balance, permeability, reinjection, injection, pressure change, enthalpy increase or other dynamic conditions

The Volumetric Method to assess the MWe capacity of a new geothermal field was conceptualized and developed by Mr. Raffaele Cataldi et al., Italy, in the slide rule analog era, previous to powerful personal computers of today. Circa mid 70s. The same mathematical model is still in use today by modern computerized evaluations. The work was quite remarkable and valid since at the time there were only few geothermal fields developed and few wells drilled compared to thousands of wells today.

The scientific merit of the 50 years old exploration stage volumetric assessment method is that at the time there was no long history of geothermal power plant operations, and in the analog times there were no available powerful hardware and software tools so common today, plus today the experience of about 500,000 MWe years and about 5,000 drilled wells today, provide a wealth of known data to base a revised modern exploratory method of estimation.

In brief, the **volumetric** method developed in the late 1970s, prior to the computer and software world of today, is a method to produce a first estimate of the generating capacity of a geothermal system. It is a **rough estimate** used for comparative purposes among different fields using the same method.

Authors: Navas and Pipan.

In essence it estimates the **static energy** content in the volume of reservoirs, and tries to give a first straight linear indication of how much of it can be extracted and available at the surface and converted to electricity. It excludes all energy flow dynamic changes of conditions and realities of a geothermal system under exploitation.

2.1 Volumetric Method Mathematical Model

The volumetric model method calculates the **total energy** [MWh], stored in the **static volume** (Area x Thickness) of the reservoir = {**rocks + fluid**}. Static parameters like resistivity, temperature, porosity and others are based on the [geophysical + geological + geochemical] data available during exploration stage. It is understood this is a non-rigorous review of all steps and calculations:

$$E_{total} = E_{water} + E_{rocks} \quad (1)$$

Table A.

Parameter	Unit	Description of static parameter used in the calculation of (1)
Er	MWh	**Energy** stored in rocks formation
Ew	MWh	**Energy** stored in geothermal fluid **liquid**, or **2 phase** (see caption**)**
V	m3	Total estimated **volume** of the geothermal reservoir
T	°C	**Temperature** at the bottom of reservoir
Tref	°C	**Temperature** at the surface for conversion process, ambient
Φ		**Porosity** of the rocks formation
X	*%*	Steam **mass fraction**, or Steam **Quality**
hs, hw	Kwh/t	**Enthalpy** of steam, and brine
ρs, ρw, ρw-ref	*Kg/m3*	**Densities** steam, brine, brine at surface reference
βr, βw		**Heat capacity rock and water**

As a general observation, the volumetric static method for calculating the energy of water uses in its calculation the delta energy between bottom reservoir conditions and surface conditions. Such delta of the 2 conditions is the net loss, or gain, on the path from reservoir to surface, further this model makes the classical mistake of assuming adiabatic flow over the 2 km path from reservoir to surface on its resulting estimate of MWe. This is not agreed.

$$E_{surface} = E_{total} \cdot (A) \cdot (R) \qquad \text{both factors A R are fractional reducers} \quad (2)$$

Table B.

	Unit	Surface linear assumptions for reduction used for calculation of (2)
A	0.0 – 1.0	Fraction of energy Available at surface from drillings (see caption)
R	0.05 – 0.25	Recovery factor: **difficult to estimate** fraction of how much is technologically recovered
	HFN	**E total** is a rough estimate **E recoverable** is rougher

This factor is more than >1.0 from decades of experience and observation, instead of less than < 1.0 therefore is not agreed.

The resulting electric capacity [MWe] is calculated by the volumetric model as energy recoverable on the surface, times a surface technology efficiency, over a time period.

$$E_e = \eta \cdot E_{surface} \quad (3)$$

$$P_e = E_e / \Delta t \quad (4)$$

Table C.

	Unit	Surface energy conversion assumptions for calculation (3) and (4)
Ee	MWh	the electric energy produced Over the total exploitation period
ŋ	0 – 1	Electric energy conversion as a fraction of energy recoverable (8% to 16%) Over the total exploitation period. 10 % to 20 % is true **experience (**see caption**)**
Pe	MWe	Power capacity derived from electric energy produced over the total period of exploitation
Δt	Years	Total Period of exploitation
Pe	MWe	Power capacity of the field To estimate the plant dimension

To calculate these efficiency values the table uses a correlation efficiency table that reflects the technologies of the 70s but does not reflect the developed technologies of today. Further the design and concern of a turbine manufacturer is only of the steam quality, and flow reaching the turbine, and how to control it – not its previous or historic changes in its path. Efficiency is technology dependent for overall total field energy conversion.

12% –14% [condensing turbines] **Up to 18% [well head system]** **8% [back pressure turbines]**

In short: Volumetric Method Capacity Calculation in 2 reducing processes

$$\mathbf{MWe = [Ew + Er]*(A * R)*\{\eta / \Delta t\}} \quad (5)$$

The 4 multiplier reducing factors represent 2 different processes:

(Process of energy change from reservoir to reach the surface) {Process of energy conversion at the surface}

Bottom conditions yield the energy available at bottom that will suffer changes [**gains + loses**] on its path to the surface. The ΔT from bottom to surface ambient is an over simplification of said energy change from bottom to surface in addition to the energy changes on the surface {loses from: separation + transportation + leaks + venting + conversion}.

Experience of over 100 geothermal fields developments with 5,000 drilled wells and operations show that flat linear parameters are not how nature processes behaves in reality of geothermal developments and operations. The Volumetric **Method is 40+ YO, from the analog time before the computer age, and is not expected to be accurate**. However in time this tool has gained acceptance by managers and financiers. The volumetric method invariably will result in big numbers compared to a sustainable reality.

3. STATISTICAL SAMPLING AND MONTE CARLOS SIMULATION REVIEW – SOME HISTORIC DETAILS

In statistics and survey methodologies, **sampling** is concerned with the selection of a subset from within a statistical population to estimate characteristics of the whole. Acceptance sampling is used to determine if a production lot of material meets the governing specifications. Advantages of **statistical sampling** are that the cost is lower and data collection is faster than measuring the whole population. Results from probability theory and statistical theory are used to guide practice in industry, businesses and research in general, sampling is widely used for gathering information about a large population, region, or zone.

A **random sampling** or "representative" subset of a population is produced for computer simulation, **pseudo-random number sampling**.

Much of probability and mathematical statistics deals with random variables constructed from random samples – the sample mean, sample variance, sample covariance, and order statistics are particularly important examples.

Methods of pseudo-random number sampling were first published by John von Neumann in the early 1950s. These were developed for Monte-Carlo simulations in the Manhattan Project (A research and development project that produced the first atomic bombs during World War II. It was led by the United States with the support of the United Kingdom and Canada); pseudo-random number sampling or non-uniform pseudo-random variable generation is the numerical practice of generating pseudo-random numbers that are distributed according to a given probability distribution. The US Department of Energy, DOE, traces its roots to WWII and this Manhattan Project.

3.1 The Monte Carlo Simulation

Monte Carlo refers to a commonly used approach for solving problems using computer algorithms to **simulate the variables** in a problem. Typically an algorithm is developed to "model" the problem, and then the algorithm is run many times (from a few hundred, or thousands) in order to develop a statistical data set for how the model behaves. No actual data is used.

- Geothermal developments also use the Monte Carlo simulation as another tool for first estimation of **plant capacity of energy production MWe**, based on total energy contained in static volume.
- The algorithm is the same as the volumetric method: $\mathbf{MWe = [Ew + Er]*(A * R)*\{\eta / \Delta t\}}$ **(5)**
- The range of the variables produces a wide range of possible output, MWe.
- Probability refinement focused on a **90% confidence interval** yields the simulation result. Yet it is still is a big number since it is derived from the volumetric estimation formula.

A quite useful imbedded mathematical concept is that the TRUE and REAL reservoir capacity is an unknown, but it exists; the Monte Carlo simulation and volumetric method are efforts to estimate it.

4. EXAMPLE OF TRADITIONAL METHODS [VOLUMETRIC METHOD + MONTE CARLO SIMULATION].

The main 2 static parameters for the volumetric assessment are the estimated **temperature of the reservoir, T** and the estimated volume, **V**.

The reservoir volume has an historic natural initial state, "before", and then after exploitation starts it will have dynamic "changing conditions" – especially pressure drawdown, enthalpy increase, and steam quality of production X increase.

The observed objection to this method of estimating the MWe capacity of the field, is that in principle it uses only the same mathematical model that was developed in the 70s for the volumetric method.

The Monte Carlo simulation is a modernized version of the volumetric method, inheriting its shortcomings or overestimated results. The Monte Carlo simulation method will also produce estimated numbers larger than a sustainable reality.

Authors: Navas and Pipan.

Ultimately these methods are early estimates that do not have to be taken as a clear and definite solution or answer to the question of what is the sustainable plant capacity, even if are produced by late software and hardware, since the underlying mathematical formula is the one causing the overestimate.

Below the main parameters, and assumed frequency distribution used for Monte Carlo simulation and its corresponding pseudo random number sampling. A computerized large number of outcomes are generated, and then statistically analyzed.

Table D.

Parameter	Unit	Range Min	Max	Distribution	Notes For Corona
Reservoir Surface area	Km2	40	45	Triangular	OK 6.5 km^2
Reservoir Thickness	Km	2.0	2.5	Constant	OK
Reservoir Volume	**Km3**	**80**	**112.5**		40 % range, 84.5 Km3
Bottom Temperature	°C	250	300	From chart	h 1325KJ/Kg=368 KWh/t
X fraction % (See caption)		0.75	1.0	Triangular	
Reinjection temperature	°C	30		Single value	Surface T_{ref} ambient
Porosity, ϕ		0.05	0.15	Triangular	OK
Rock density, δr	Kg/m3	2,500	2,900	Triangular	OK
Rock heat capacity, βr	KJ/kg °C	800	1,000	Triangular	
Geothermal unit, βr	KWh/t °C	222	278	Triangular	25 % range difference
Water density, δw	Kg/m3	700	800	Constant	OK
Water heat capacity, βw	KJ/kg °C	4.800	6.200	Constant	OK
geothermal unit, βw	KWh/t °C	1.333	1.722	Constant	30 % range difference
Recovery factor, R	%	10	20	Triangular	Challenged to be e^(Xt)
Efficiency of energy conversion thermal to electric, η	%	11	15	Triangular	***challenged to use data of operations 12%
Period of utilization Δt Distortion if 30 – 100 years	Years	50	50	Single value	

One of the main challenges to the volumetric method, being static, with the bottom conditions in a water dominated field is usually all compressed liquid, X = 0% reaching saturation during the ascent, while at the surface X = 50% – 60 % initially, and further increasing to 70 – 90 + % over time, and this change cannot be reflected with its simple mathematical model.

5. GEOTHERMAL CORONA ENERGY EXPONENTIAL DECAY MODEL AND METHOD

Corona Exponential Decay Energy model is a more accurate concept and method, yielding a smaller number, and closer to reality, by definition exponential is a number that changes in time with respect to itself.

However it must be noted that there is an identified trend that the Monte Carlo simulation method is the one that many managers / consultants / financiers like and prefer to get larger estimation numbers, larger loans, larger fees, etc.

Management / Owners should understand and acknowledge the "reality numbers", even if choose to work with the "big numbers".

Corona mathematical model to estimate uses the same initial conceptual model of the field, self-discharging wells, assumes mass balance to sustain pressure to a minimum decay and achieve constant production flow.

Single phase compressed super cooled water energy estimation in the reservoir.

$$\mathbf{Ew = V\ \varphi\ \delta w\ [enthalpy_{\ bottom}]} \tag{6}$$

MWe = Ew * f(Corona field parameters Cf) Corona factor is of exponential decay form in time: $Cf = B * (e)^{-\alpha t}$

$$= \mathbf{E}_{\ water} * \{1.45 * e^{(0.789)}\} * [0.14\ e^{(-13)}]. \tag{7}$$

This mathematical form conserves the energy processes of water flow from reservoir to surface and conversion on the surface

Corona Exponential Decay Energy model parameters Cf:

Enthalpy h (1.00 – 1.45), Efficiency η (10 – 20 %)

Exponential factor [from statistical geothermal fields data] * e^ (0.789 - 13).

Corona Exponential Decay Energy Model for Hypothetical Hydrothermal Reservoir

Calculations for a hypothetical bounded hydrothermal reservoir: shape a circular cylinder. Declare a reservoir volume, V, and thickness is arbitrary and hypothetical, but acceptable for showing the initial estimate process. The reservoir **diameter 7.2 Km**, radius 3.70 Km, area 43 km2, and its vertical thickness is 2.0 km. Porosity = 10%.

Total water volume in the reservoir is therefore 86,016.8 million m3 *0.1 = **8,601.7 million m3**.
The reservoir initially has compressed water at P_{bottom} = 150 bars and T = 275°C, Saturation < 60 bar.
Initial bottom enthalpy 1210 KJ / Kg = **336 KWh/t, density 771.91 Kg/m3**, entropy 3.0 KJ / (Kg °K).
Energy water bottom: $E_{water\ bottom}$ = **2,230.82 million MWh**.

Pressure drawdown in reservoir to P < **60** bars will result in ***in*** situ flashing of liquid water to vapor.
Water ascent processes during well production will result in reduced P in well borehole that will flash when reaching its corresponding saturation Psat before reaching the surface conditions.

MWe = E w * (Corona field parameters, Cf): Ew * (1.45 * e^-0.7989)*(0.14 * e^ - 13).

= 2,230.82 million * (1.45 * e^ - 0.7989) * (0.14 * e^-13).

= **465 MWe.**

- **Corona Exponential Decay Energy model** uses known **factors** based on millions of hours of operations.

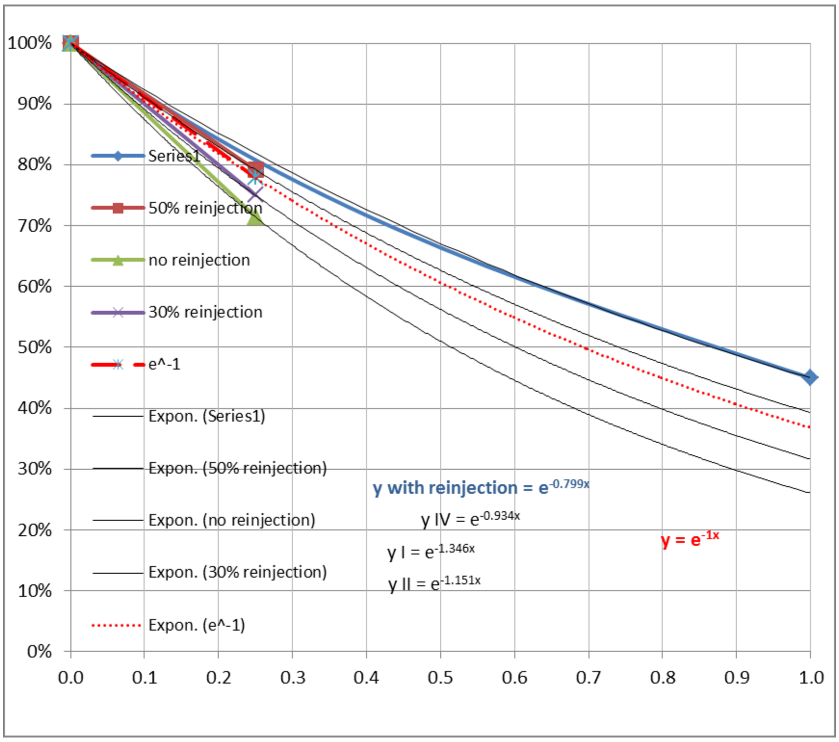

Figure 1: Exponential Decay is the natural way by definition. X = time in centuries, Y = decay.

Table E. Models for different stages of development to estimate real capacity

Static = **early assessment models** With limited initial data	Dynamic = continuous assessment models with data from Operations / calibration
Target = Sustainable Reality MWe {unknown variable} for installed capacity {Fixed MWe}	
Volumetric model [overestimate] = ++ MWe **Monte Carlo simulation** [overestimate] = + MWe **Corona exponential decay model** [closest to reality] = MWe	Lumped parameter Numerical modeling □ Single-phase water systems □ Single-phase steam systems □ 2 - phase (water and steam) systems □ 2 - phase systems with CO2 or other gas □ Hyper-saline brine systems □ Systems with magmatic heat transfer □ Single porosity / dual porosity systems □ Etcetera.

The following 2 tables present all the results in 2 different forms of the same geothermal area studied, as columns or rows.

Table F. Example of XYZ Geothermal Field. Information presented for comparison of methods by columns.

Reality	**Corona Energy**[7]	**Monte Carlo** Simulation[8]	**Volumetric**[9]
Maximum exponential decay	Modern Model Revised **e** decay 4 YO	**90%** confidence interval **[Wide range]** [450-910] 10 YO	Static Energy Model Mean Value Rough 45 YO
~ **465** MWe	**466** MWe	**520** MWe	**670** MWe
Owners / Managers		**Managers / Financiers**[10] **"Big Numbers"**	

[7] Pipan Forte Navas, Italy 2010 -2014
[8] Manhattan Project 1950s; revised for geothermal conditions application, Iceland 2006.
[9] Raffaele Cataldi et al. Italy, circa late 1970s
[10] Often and commonly managers and financiers like to develop based on "Big Numbers"… however we consider that owners need to know the facts and Reality.

[Volumetric Assessment + Monte Carlo Simulation + Lumped Parameter + Numerical Models + Corona]

Table G. Information presented for comparison of methods by rows.

<Big Numbers>	**Unit**	**Result**	**Notes**
C1 Volumetric mean value	MWe	**670**	**First guess > high estimate of capacity**
C2 Numerical Model 2012	MWe	**580**	**204 Km2 concession area;** 2.843 MWe-per km2
C3 Lumped Parameter Model	MWe	**520**	90% limit from cumulative distribution
Monte Carlo Minimum / Maximum	MWe	**450 / 910**	**Uncertainties** reflected in the very wide range
Monte Carlo 90 % Confidence Limit	MWe	**520**	**Expected outcome > overestimated plant capacity**
Reality / Sustainable w 100% reinjection	MWe	**465**	
field demand / Installed capacity		**~ 568**	provision for inefficiency {205 + 115 + 80 + 8 + 160}
<Exceeds the estimated resources?>	MWe	**~ 534 net**	for {**45 + 140 + 105 + 70 + 4 + 140**} = **534 net MWe**
Corona Energy Estimate	MWe	**466**	Better method for initial estimate <HFN method>
WJ numerical model 2009	MWe	**430**	Smaller concession area study.

6. CONCLUSIONS

- There are several developed methods to estimate the real potential capacity of the field capacity since early development; there are traditional methods that yield <big numbers estimates>, there is reality, and there are methods that can yield estimates being closer to reality.
- The geothermal field developer has to make a choice about which / why / when / where to use one or more of these methods, for strategic, business, or scientific purposes.
- Volumetric method yields greater estimates compared to reality.
- Monte Carlo Simulation yields a wide range of computed generated outputs.
- Confidence interval 90% yields a larger estimate than reality, since in essence it is using the same mathematical algorithm as the volumetric model.
- Exponential decay energy model yields a lower and closer to reality estimation. This is our claim.

REFERENCES

Kenya Electricity Generating Company, KenGen, Consultation Services Report 4 from Mannvit, ISOR, Vatnaskil, Verkis, (2012); Volumetric Resource Assessment and Lumped Parameter Pressure Response Modeling for the Greater Olkaria Geothermal System. 43 pages.

Muffler, LPJ, R. Cataldi; Methods for Regional Assessment of Geothermal Resources. (1978).

US Department of Energy, DOE, http://energy.gov/management/office-management/operational-management/history/manhattan-project.