Istituto di Geoscienze e Georisorse
Consiglio Nazionale delle Ricerche

Geothermal Assessment and Potential Calculation

Standards, Tools and Gaps for a Global Harmonised Evaluation

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Geothermal energy resource estimate

Why: it play a crucial role in the decision-making, financing, development, and operation of geothermal projects (business decision, government and public reporting, project finance,...)

Why: it requires a deep understanding of geological processes, and provides an opportunity for integrating geological, geophysical, geochemical data

Why: it is the most asked question from journalists when talking about geothermal energy, to underline the importance of developing geothermal projects (energy source to solve our huge energy demand, economic driver, a piece of solution for climate change issues, ...)

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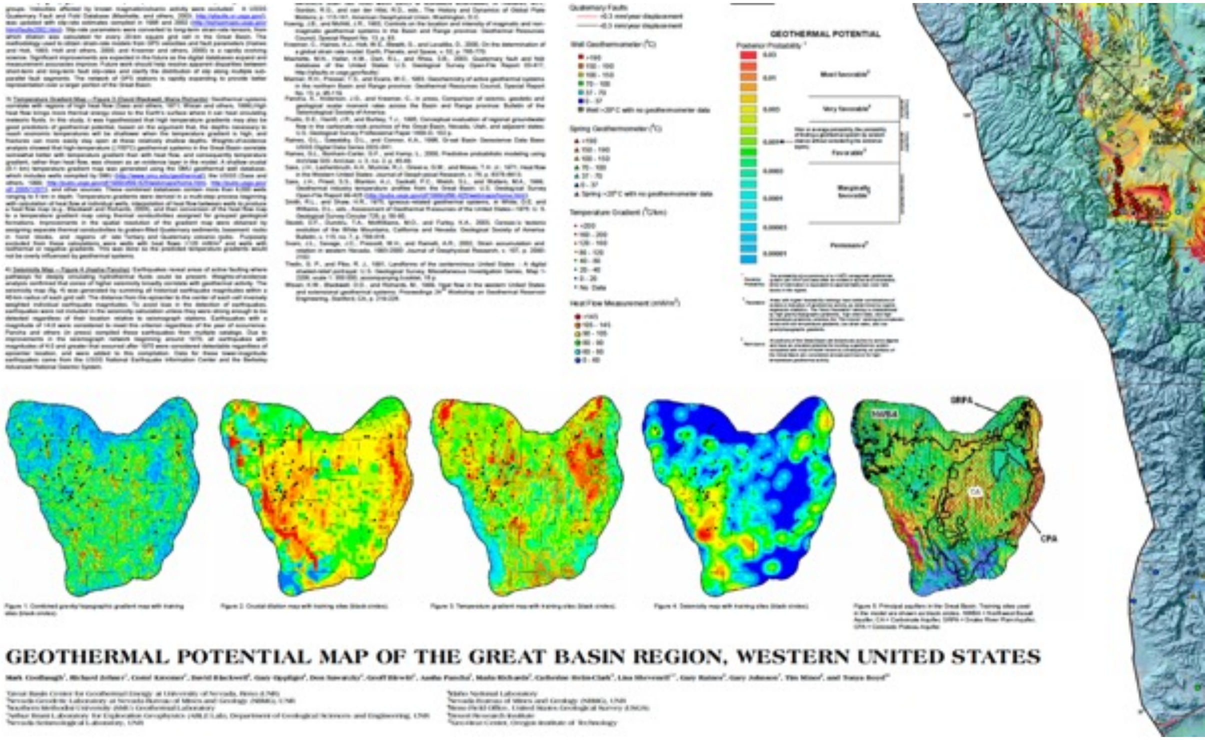
Geothermal energy resource estimate

What?

Geothermal energy resource estimate

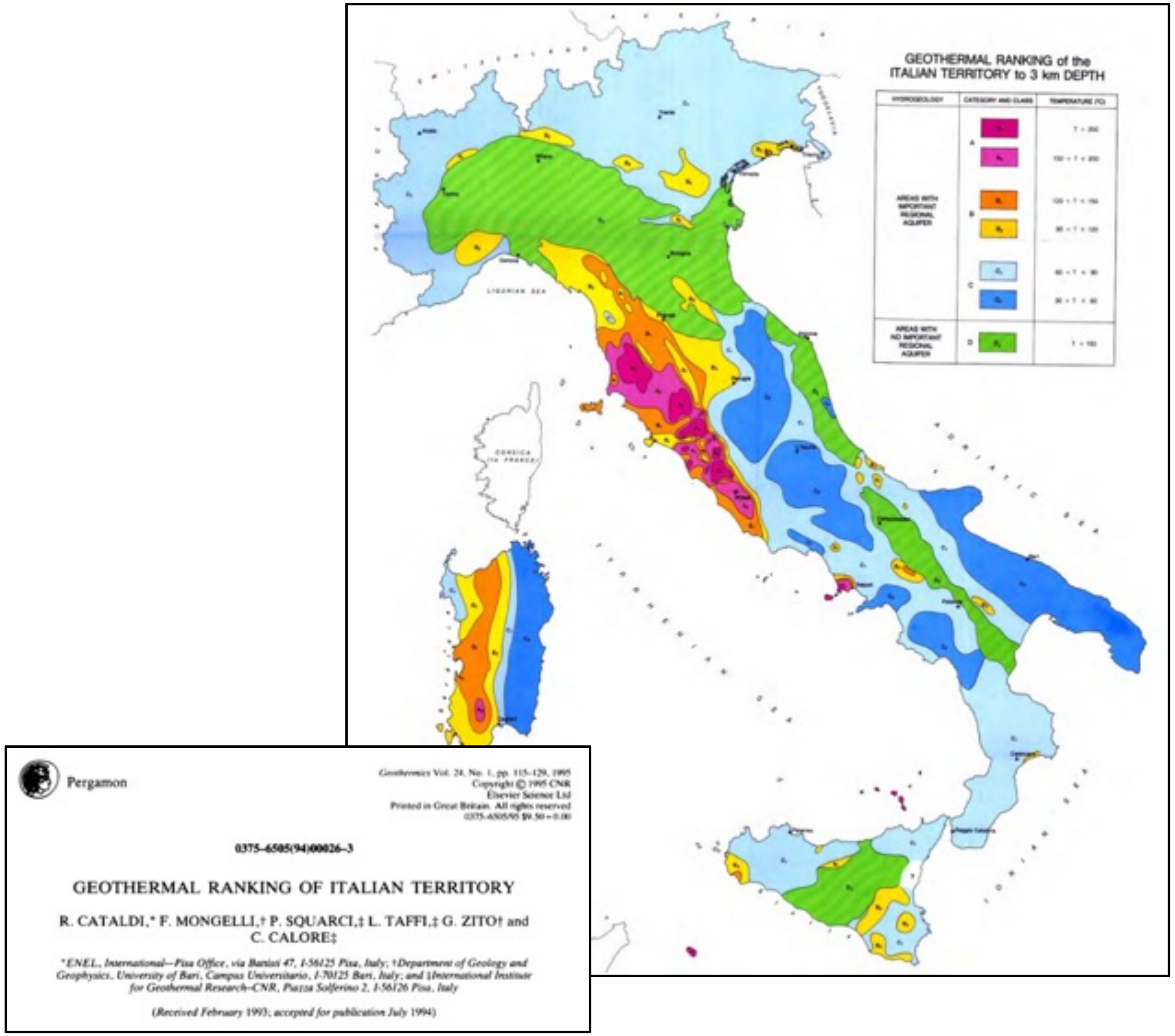
What?

The most promising places for siting a project



GEOTHERMAL POTENTIAL MAP OF THE GREAT BASIN REGION, WESTERN UNITED STATES

Geothermal potential assessment of Italy



Pergamon

Geothermics Vol. 24, No. 1, pp. 115–129, 1995

0375-6505/95 $9.50 + 0.00

0375–6505(94)00026–3

GEOTHERMAL RANKING OF ITALIAN TERRITORY

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Inventario delle Risorse Geotermiche Nazionali
CNR, ENEA, ENEL, ENI - Legge N. 896-1986.

Ranking based on:

- Geothermal fluid temperature
- Depth of the regional geothermal reservoir

A1: Regional reservoir, Z < 3 km, T > 200°C
A2: Regional reservoir, Z < 3 km, 150°C < T < 200°C

B1: Regional reservoir, Z < 3 km, 120°C < T < 150°C
B2: Regional reservoir, Z < 3 km, 90°C < T < 120°C

C1: Regional reservoir, Z < 3 km, 60°C < T < 90°C
C2: Regional reservoir, Z < 3 km, 30°C < T < 60°C

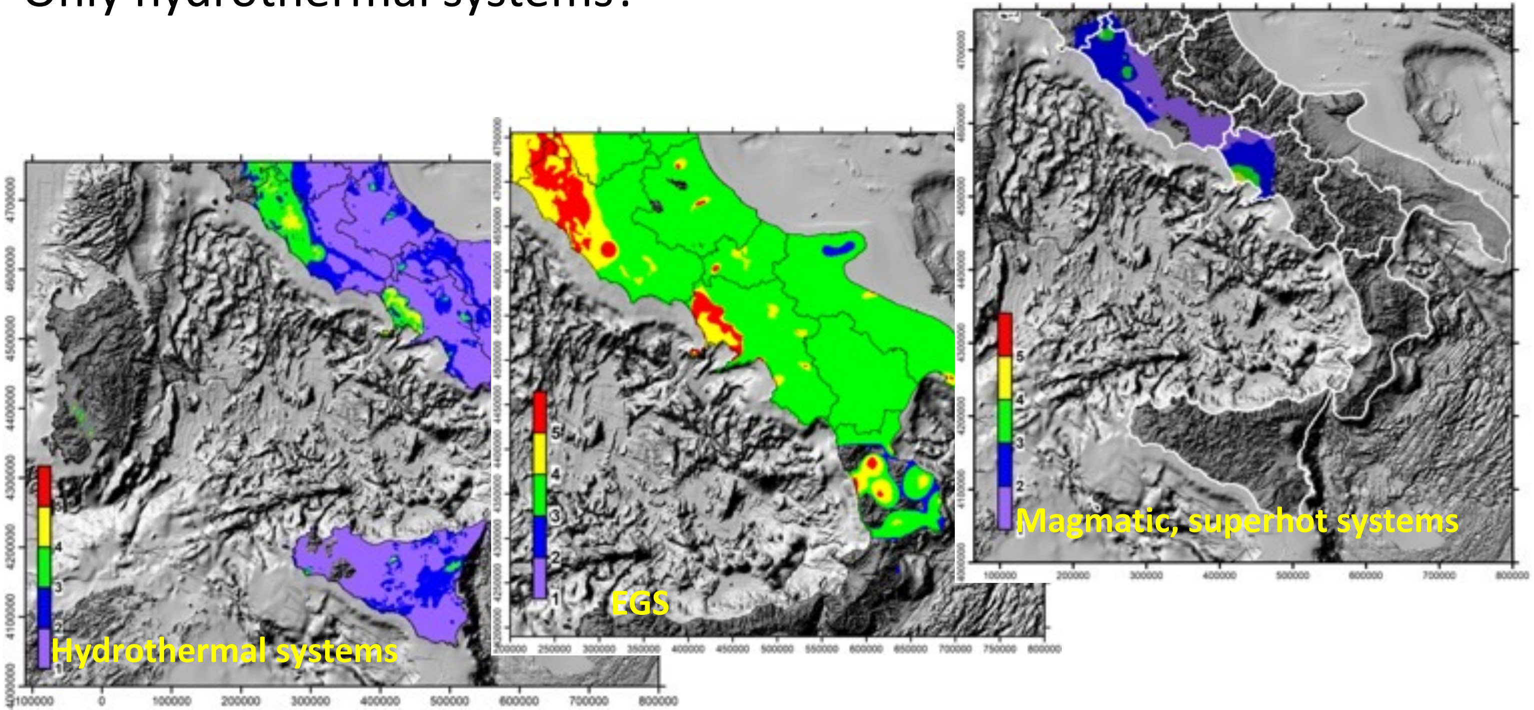
D1: Local reservoir, Z < 3 km, T < 150°C

Geothermal energy resource estimate

What?

The most promising places for siting a project

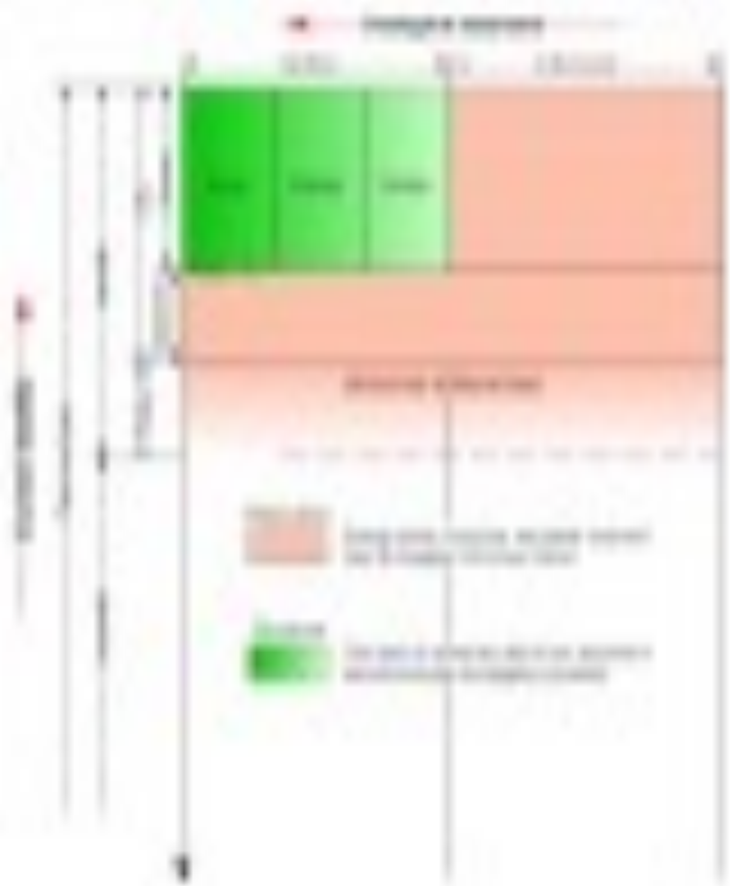
Only hydrothermal systems?



Geothermal energy resource estimate

What?

What is a resource?

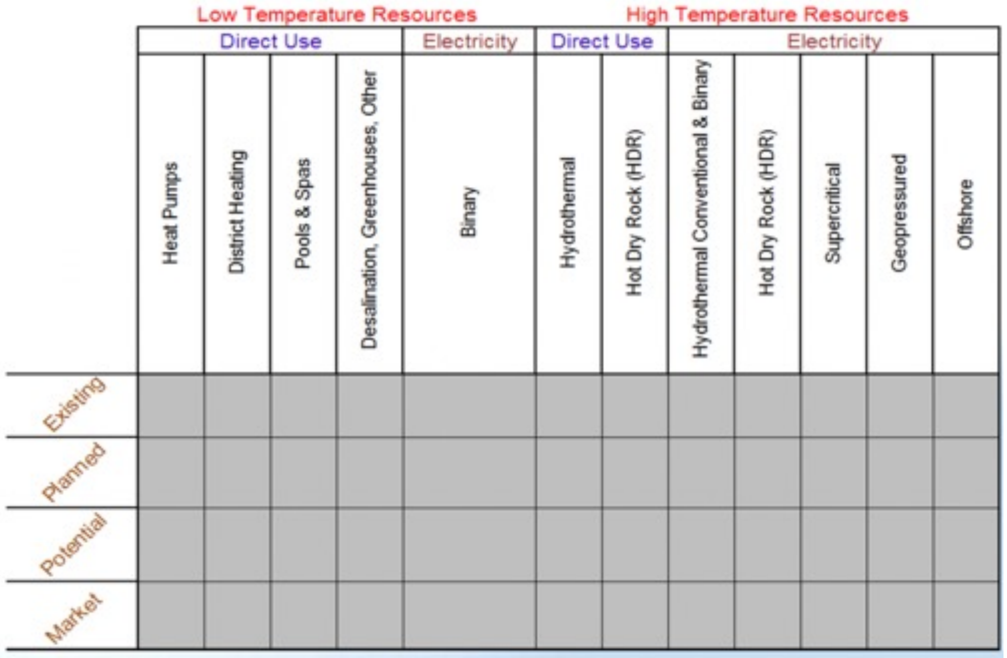


Muffler and Cataldi, 1978

Geothermal energy resource estimate

What?

What is a resource?



	Low Temperature Resources					High Temperature Resources						
	Direct Use				Electricity	Direct Use		Electricity				
	Heat Pumps	District Heating	Pools & Spas	Desalination, Greenhouses, Other	Binary	Hydrothermal	Hot Dry Rock (HDR)	Hydrothermal Conventional & Binary	Hot Dry Rock (HDR)	Supercritical	Geopressured	Offshore
Existing												
Planned												
Potential												
Market												

Bromley 2009

Geothermal energy resource estimate

What?

The sector never arrived to standard terms

Geothermal reporting codes in Australia and Canada were developed for their specific stock exchange markets.

Such codes lack the necessary element for the consistent comparison of geothermal resources with respect to other energy sectors

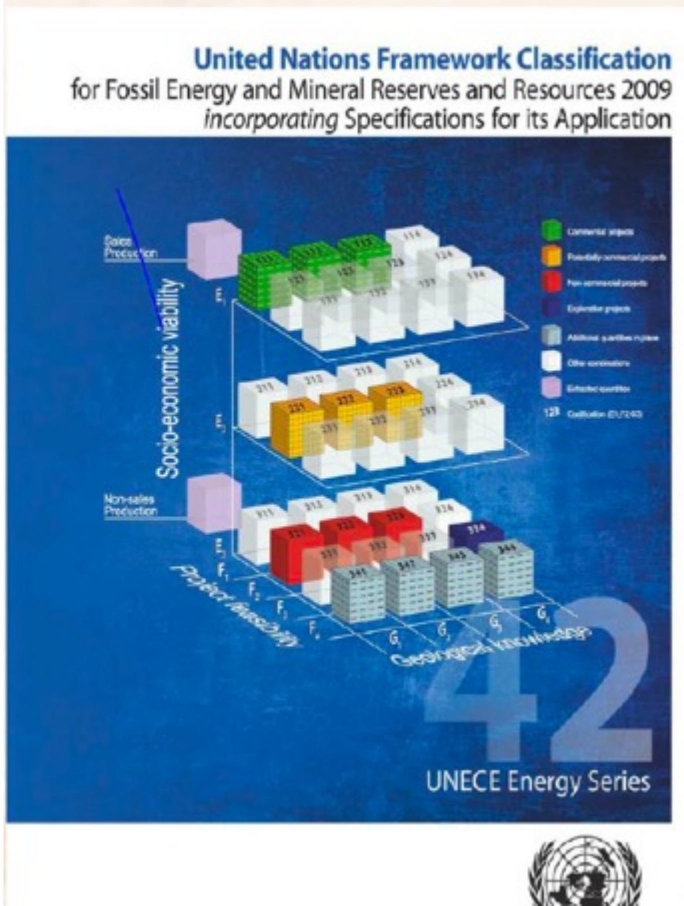
Geothermal energy resource estimate

What?

What is a resource?

United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009)

A project-based classification framework to represent, in a uniform way, the maturity and uncertainty of the (future) “extraction” project, reporting the related resource/energy quantities



United Nations Framework Classification
for Fossil Energy and Mineral Reserves and Resources 2009
incorporating Specifications for its Application

42

UNECE Energy Series

Geothermal energy resource estimate

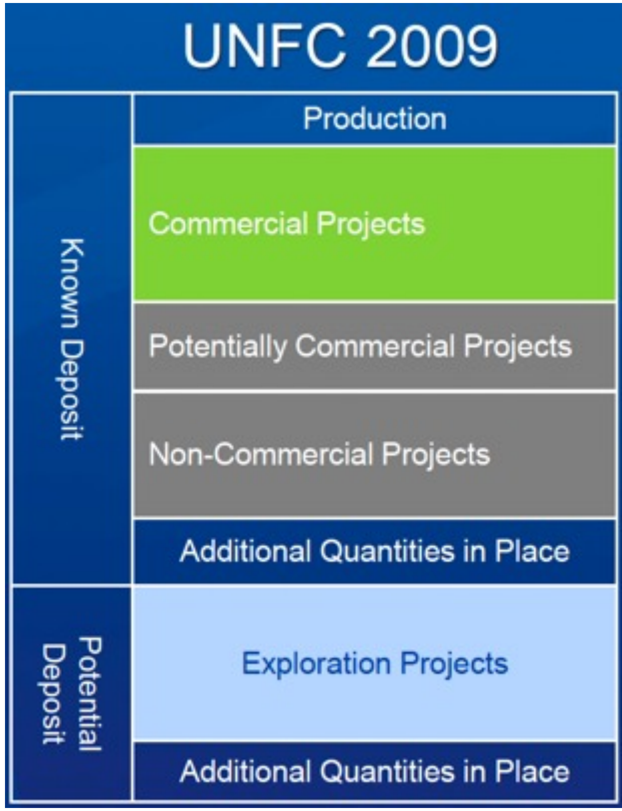
What?

What is a resource?

Geothermal Energy Source (= deposit = accumulation) is the thermal energy contained in a body of rock, sediment and/or soil, including any contained fluids, which is available for extraction and conversion into energy products

Geothermal Energy Product is an energy commodity that is saleable in an established market

Geothermal Energy Resources are the cumulative quantities of Geothermal Energy Products that will be extracted from the Geothermal Energy Source



Geothermal energy resource estimate

UNFC for Geothermal energy

Generic, principles-based classification system

- Now applicable to solid minerals, fossil energy, renewables (geothermal energy) and injection projects
- NOT a **quantification** system!

Based on three criteria

- ‘**E axis**’ *(degree of favorability of social and economic conditions for establishing commercial viability of project)*
- ‘**F axis**’ *(maturity of studies and commitments necessary to implement project)*
- ‘**G axis**’ *(level of confidence in the estimate of reported quantities and potentially recoverable quantities)*

Geothermal energy resource estimate

What is a geothermal resource?

What is the standard for estimating its potential?

There is still a need for a comprehensive and common assessment and comparison framework serving as a foundation for a comprehensive overview of current and future energy sustainability **scenarios** at project, company, national, regional and/or global levels to be used by investors, regulators, governments and consumers

Methods to compute the geothermal potential

They can be divided into two main groups, based on the type of input data required by the method:

- A single point or **static – methods** that do not need production history data

- Historical or **dynamic – methods** that require production history data.

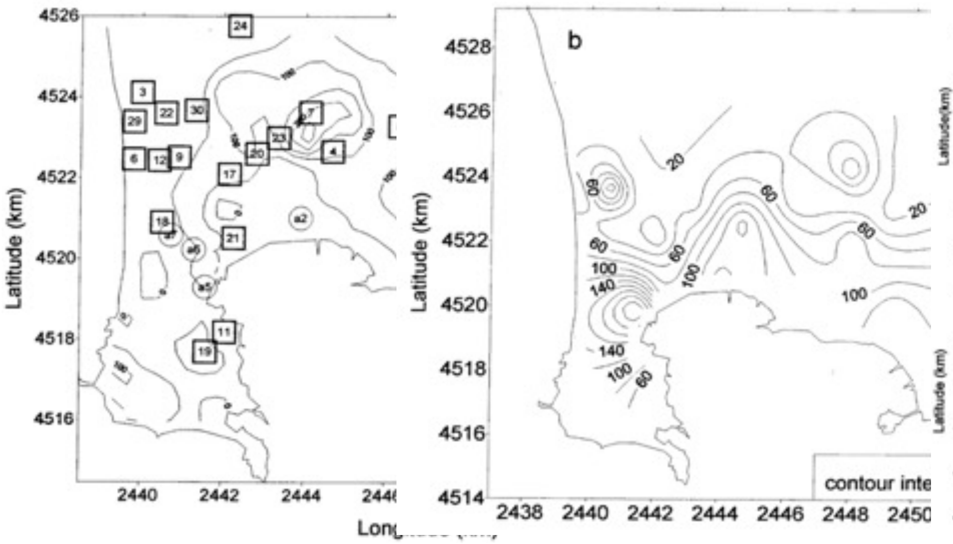
The methods requiring a static dataset as input are:
1) Method of surface heat flux
2) Planar fracture
3) Magmatic heat budget
4) Total well flow
5) Volumetric
6) Mass-in-Place
7) Power density

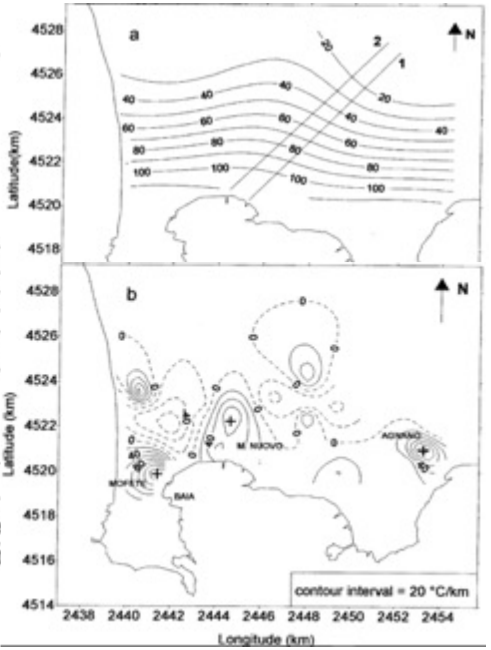
The methods requiring a dynamic dataset as input are:
1) Decline analysis
2) Lumped parameter
3) Numerical reservoir simulation

Ciriaco et al., 2020

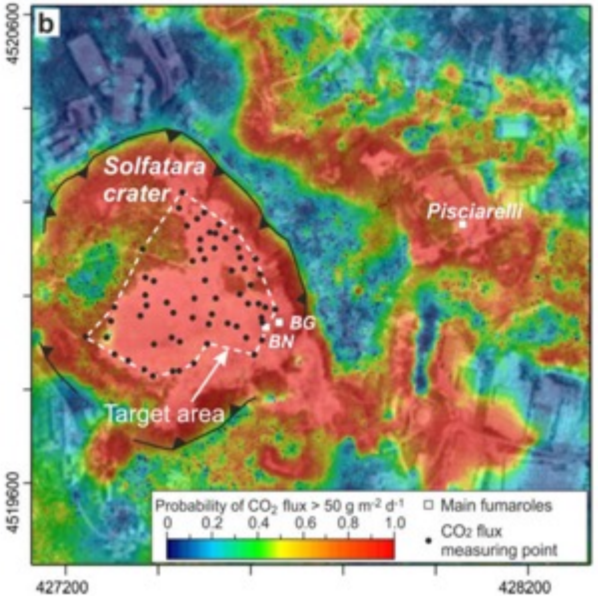
Static methods

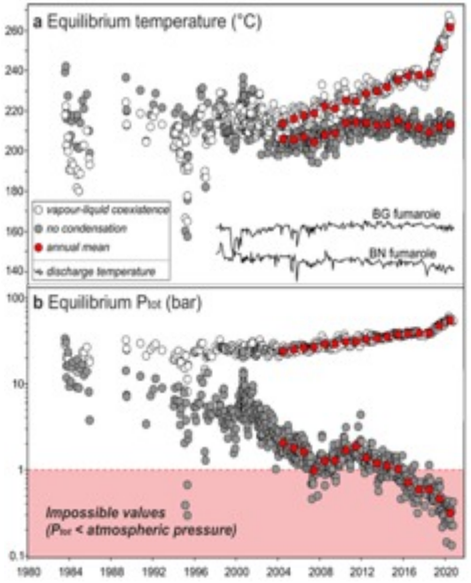
Corrado et al. (1998)





Chiodini et al. (2021)





Surface heat flux method

This method approximates the total theoretical minimum amount of heat that can be withdraw from a geothermal resource through measuring the heat loss at the ground surface from:

- Hot springs, geysers, fumaroles, mud pools
- Thermal grounds

The total amount of heat can be expressed as the sum of the convective and conductive components:

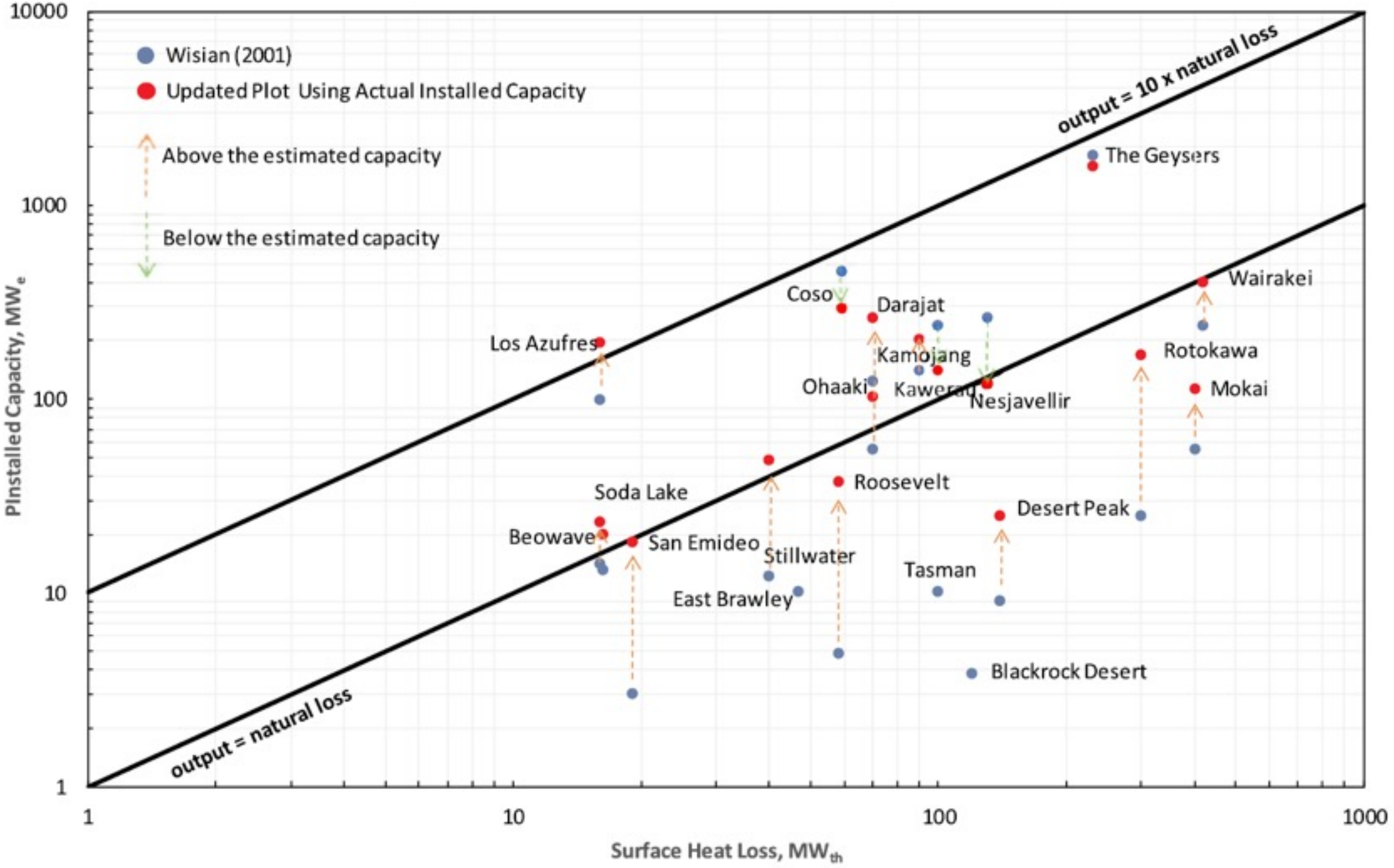
$$q_{tot} = \sum_{i}^{n} q_{si} + q_c$$

Where:

- q_{tot} is the total amount of heat
- q_{si} is the total thermal energy estimated from the individual surface manifestations, and accounts for the convective term
- q_c is the conductive heat flow.

Static methods

Surface heat flux method



From Ciriaco et al. (2020)

Static methods

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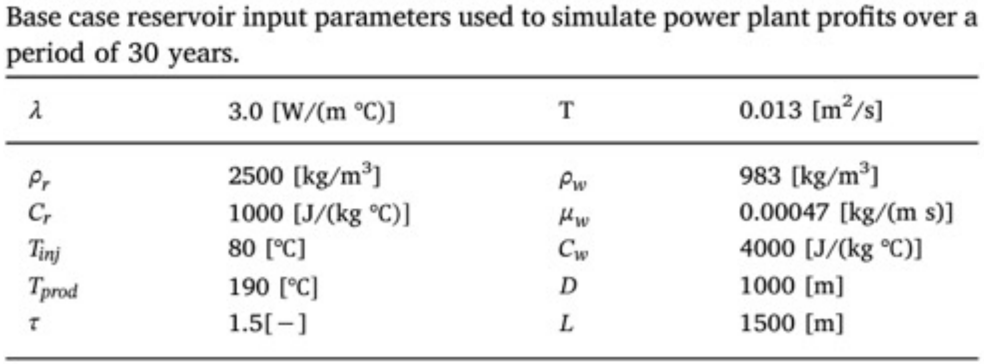
Patterson et al. (2020)



Base case reservoir input parameters used to simulate power plant profits over a period of 30 years.

λ	3.0 [W/(m °C)]	T	0.013 [m^2/s]
ρ_r	2500 [kg/m^3]	ρ_w	983 [kg/m^3]
C_r	1000 [J/(kg °C)]	μ_w	0.00047 [kg/(m s)]
T_{inj}	80 [°C]	C_w	4000 [J/(kg °C)]
T_{prod}	190 [°C]	D	1000 [m]
τ	1.5[−]	L	1500 [m]

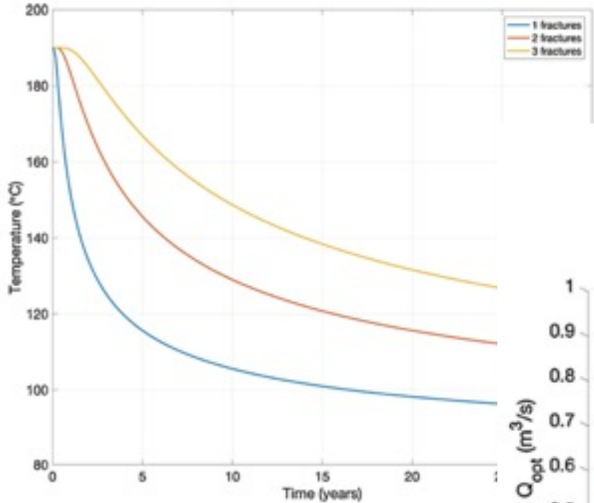
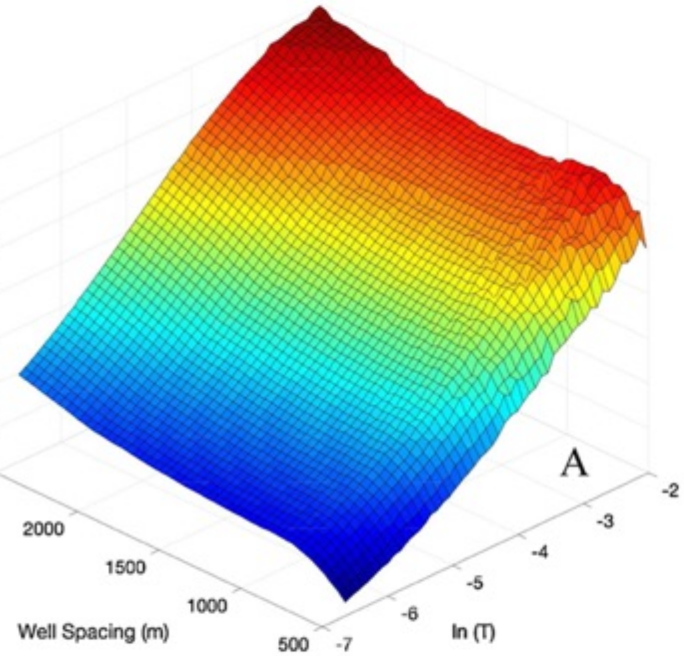


Fig. 5. Production well water temperature profiles through the
lation period for realizations up to 3 hydraulically active fractu



Sensitivity analysis finds that changes to well spacing (L) and reservoir effective transmissivity (T) exert the largest effect on the expected net present value (ENPV)

Planar fracture method

In this method the fluid is heated up passing through the fractures in the rocks. The theoretical extractable heat per unit fracture area can be estimated from the end temperature ratio as proposed by Bodvarsson (1974), which is expressed as:

$$T_D(t) = \frac{T_{prod}(t) - T_o}{T_{inj} - T_o}$$

Where:

- T_D is the dimensionless temperature at the production well
- T_{prod} is the production water temperature $[°C]$
- T_o is the initial rock temperature $[°C]$
- T_{inj} is the injection water temperature $[°C]$

This model can be applied also in case of multiple fractures, but only if there is a minimum distance between them expressed as follows:

$$\frac{d}{2} = 3 * \sqrt{\alpha * t_0}$$

Where:

- α is the thermal diffusivity $\left[\frac{m^2}{s}\right]$
- t_0 is the production period $[s]$

Static methods

Magmatic heat budget method

This method is a qualitative assessment of relative potential, it estimates the volumes of silicic magma chambers to predict their age of emplacement and to calculate the amount of geothermal energy remaining in the intrusion and adjacent country rock.

Power density method

The power density method assumes that power capacity per unit area $\left[\frac{MW_e}{km^2}\right]$ of the productive resource is a function of reservoir temperature T_i:

$$\frac{MW_e}{km^2} = \left(\frac{T}{86.9}\right)^2$$

The power density method requires very few assumptions compared to the other methods for estimating resource potential. However, its usability and reliability are as good as the data that was used to generate the plot and the empirical correlation. The method described for delineating the reservoir area is not applicable for projects at the exploration phase and may not be appropriate when there are only a few wells drilled. Furthermore, the available capacity of geothermal fields changes with time.

Mass-in-place method

This method mimics the volumetric method which uses the total mass in-place (MIP) instead of heat in-place (HIP).

Example (Romagnoli et al. 2010). Since the Larderello–Travale system has an area of about 400km^2 and an average thickness of about 2 km, the total reservoir volume (V_{res}) is 800 km^3. Assuming a porosity (Φ) of about 2%, the available volume for the steam storage in the reservoir (V_{steam}) is:

$V_{steam} = V_{res} \cdot \Phi = 16$ km^3.

Thus, the maximum steam amount (M_{steam}) which could be contained in the Larderello–Travale geothermal system is:

$M_{steam} = V_{steam} \cdot \rho_{steam}$ (300 degC & 50 bar) = 16 km^3 · 22.075 kg/m^3 = **0.35×10^9 t**

Total well flow

This method is a simple approach of summing up the measured output of the well after performing intensive discharge test.

Grant (2000) argues that the total well flow demonstrates the ability of the field to deliver fluid but not the total potential capacity of the field, which could be higher if more wells are drilled.

Static methods

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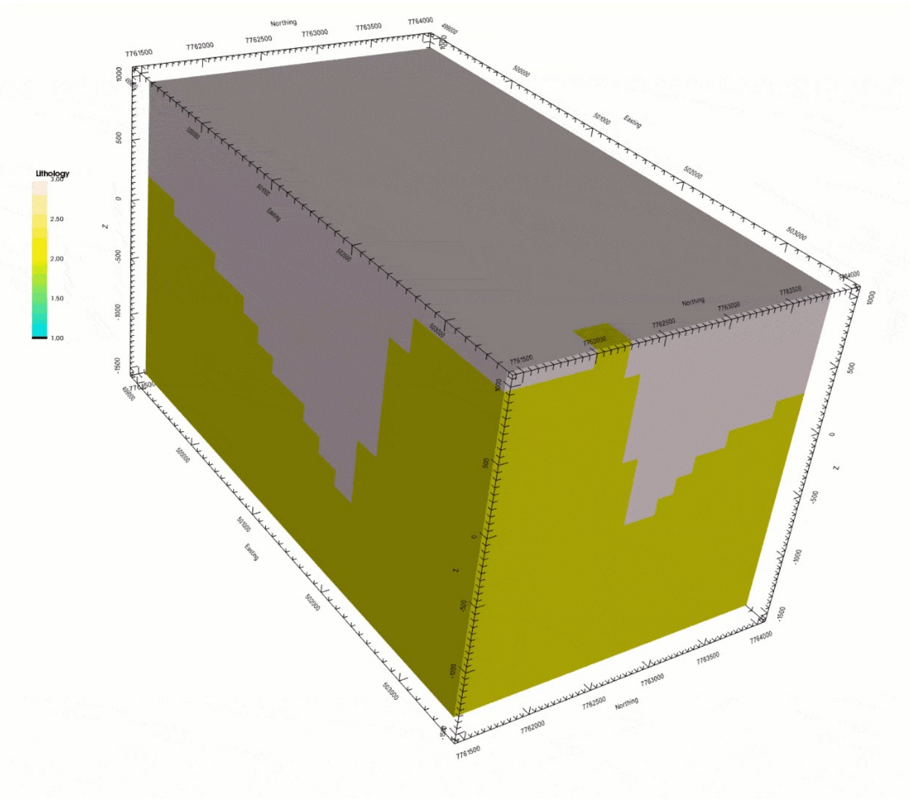
Volume method



This method is one of the most used for the evaluation of the geothermal potential. The power potential can be estimated with the following formula:

$$MW_e = \frac{q \times R_f \times \eta_{conv}}{F \times L}$$

Where:

- MW_e is the power potential $[MW_e]$
- q is the thermal energy stored in the reservoir $[MJ]$
- R_f is the recovery factor $[-]$
- η_{conv} is the conversion efficiency $[\%]$
- L is the plant life $[s]$
- F is the capacity or load factor $[\%]$

The thermal energy q stored in the reservoir can be calculated by dividing the reservoir into n different regions of volume V_i and temperature T_i.

$$q = \sum_{i=1}^{n} \rho_i c_i V_i (T_i - T_f)$$

Where:

- $\rho_i c_i$ is the volumetric heat capacity of a saturated rock $\left[\frac{J}{m^3 °C}\right]$
- V_i is the volume of i^{th} region of n numbers of lithology. The product of area A and thickness h of the reservoir ($V = A \times h\ [m^3]$)
- T_i is the initial temperature of i^{th} lithology $[°C]$
- T_f is the cut-off or final abandoned reservoir temperature $[°C]$

Dynamic methods

Decline analysis

Decline analysis is a simple method for estimating the resource potential over a short period. It involves fitting a known production history data, and the fitted equation is then used to forecast future production capacity. The production data declines with time and the decline is usually assumed to follow an harmonic or exponential trend:

$$\left(\frac{1}{Q}\right)\frac{dQ}{dt} = -D * Q^b$$

Where:

- Q is the production rate
- b=0 (exponential) or b=1 (harmonic)
- D is the decline rate.

Decline analysis is mostly used as an assessment tool during the production stage. However, the method is considered not suitable for long-term reserves estimation and is inferior to a well calibrated 3D numerical reservoir model.

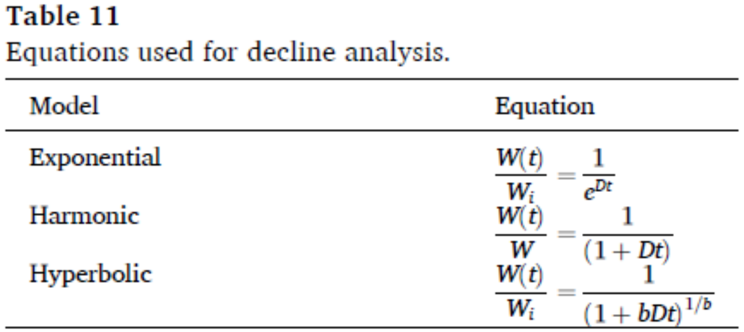


Table 11
Equations used for decline analysis.

Model	Equation
Exponential	$\frac{W(t)}{W_i} = \frac{1}{e^{Dt}}$
Harmonic	$\frac{W(t)}{W} = \frac{1}{(1+Dt)}$
Hyperbolic	$\frac{W(t)}{W_i} = \frac{1}{(1+bDt)^{1/b}}$

Lumped-parameter

In a simple lumped-parameter model the reservoir is treated as a single box or closed reservoir. The pressure decline as a result of fluid withdrawal can be described as a linear function of the cumulative production and the mass and energy equations are often reduced to ordinary differential equation:

$$m\frac{dP}{dt} + W_{prod} - W_{mech} = 0$$

Where:

- m is the mass of geothermal fluid $[kg]$
- $\frac{dP}{dt}$ is the variation of the pressure over the time $\left[\frac{Pa}{s}\right]$
- W_{prod} is the energy produced $[kJ]$
- W_{mech} is the mechanical energy produced $[kJ]$

Similar to decline analysis, the predictive capability of lumped-parameter models is still limited, and inferior compared to numerical reservoir models.

Dynamic methods

Numerical reservoir simulation

The numerical reservoir simulation has been proven as the most reliable option for geothermal resource assessment. It is a more advanced tool that numerically models the physics of fluid flow and heat transfer and the complex nature of reservoir geometry.

The three important stages in numerical development are as follow:

1. Development and Conceptual model: it serves as a guide to set up the numerical model, understanding the important aspects of the reservoir and the physical process affecting it
2. Numerical Calibration Model:
   - Natural state matching: It involves matching the pre-exploitation temperature and pressure profiles and surface manifestation data (natural thermal power output)
   - Production history matching: With the natural state as initial condition, production history matching involves simulating field responses to fluid withdrawal and injection
3. Forecasting: The final model calibrated against pre-exploitation and production history data is used to test various future production scenarios being considered going forward in time

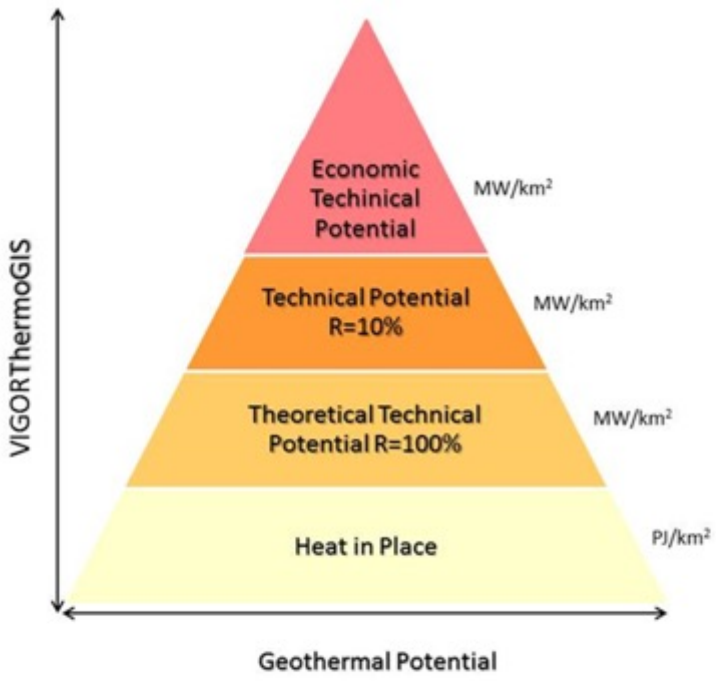
Geothermal potential assessment

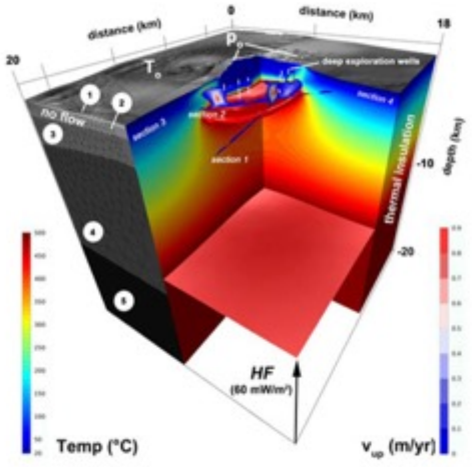
Why: Resource assessment and reserve estimation play a crucial role in the decision-making, financing, development, and operation of geothermal projects.

How: Several methods exist having variable accuracy in evaluating the output potential. The Volume Method is the most applied approach.

What: Quantifying power potential (MW_e) of geothermal fields at their early stage of development, where there is limited information about the resource.

VIGOR THERMOGIS



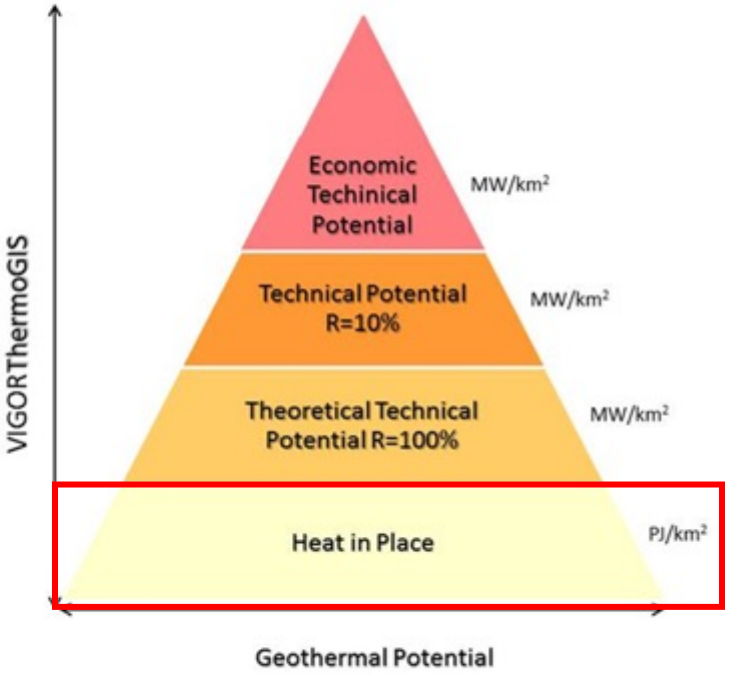


Based on the Volume Method

- The code uses 3D subsurface models and temperature distribution
- The volume element (VOXET) has specific dimensions and in the pre-processing phase the input data must be sampled using the same grid
- The geological units are characterized by average petrophysical values (density, specific heat) considered uniform in the whole volume without taking into account the variation of thermal properties with temperature
- Consider a technology based on the geothermal doublet (1 production and 1 injection well)
- Consider a binary plant for power production (with a constant average cycle relative efficiency value) or a DH

Input data: 3D geological and 3D thermal models

Heat in Place (HIP)



It represents the quantity of Energy (Joule) stored in each Volume Element of the geothermal reservoir.

It is a function of the density and specific heat of the rock and the temperature at which the volume element is found.

For each volume element, the HIP grid is given by:

$$HIP\ [PJ] = V \times \left(\rho c_p\right)_{rock} \times \left(T_x - T_o\right) 10^{-15}$$

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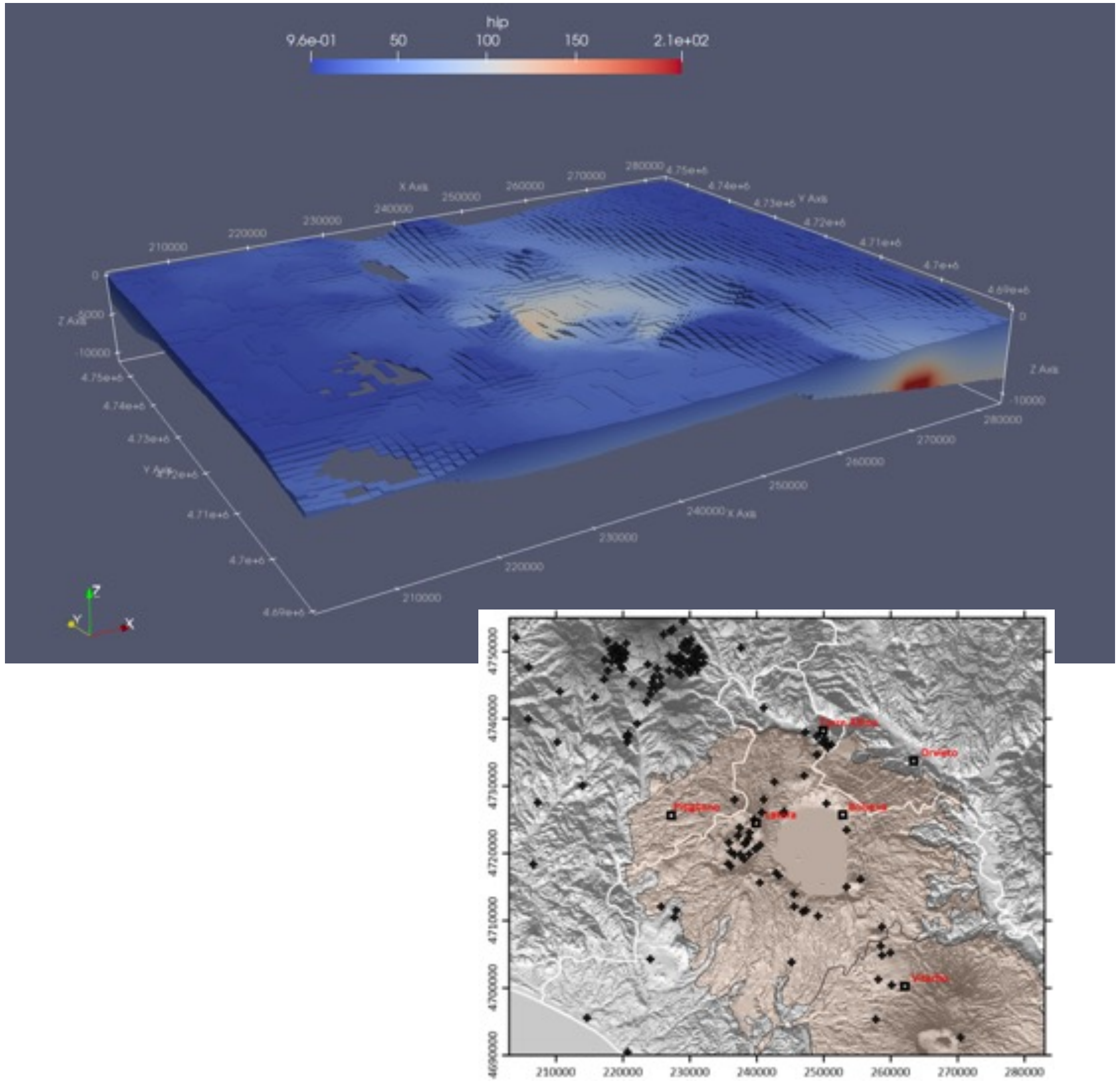
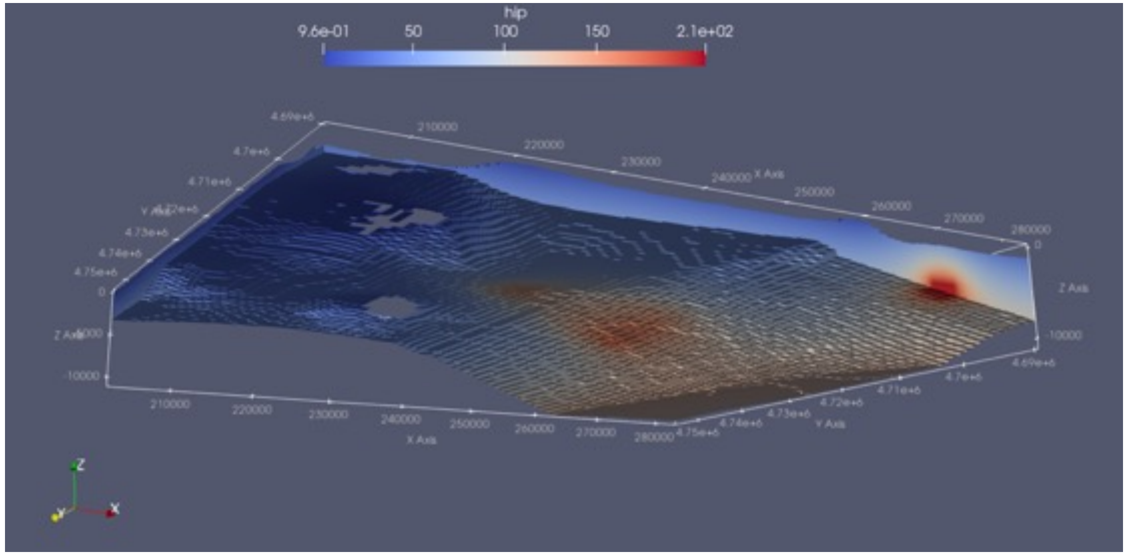
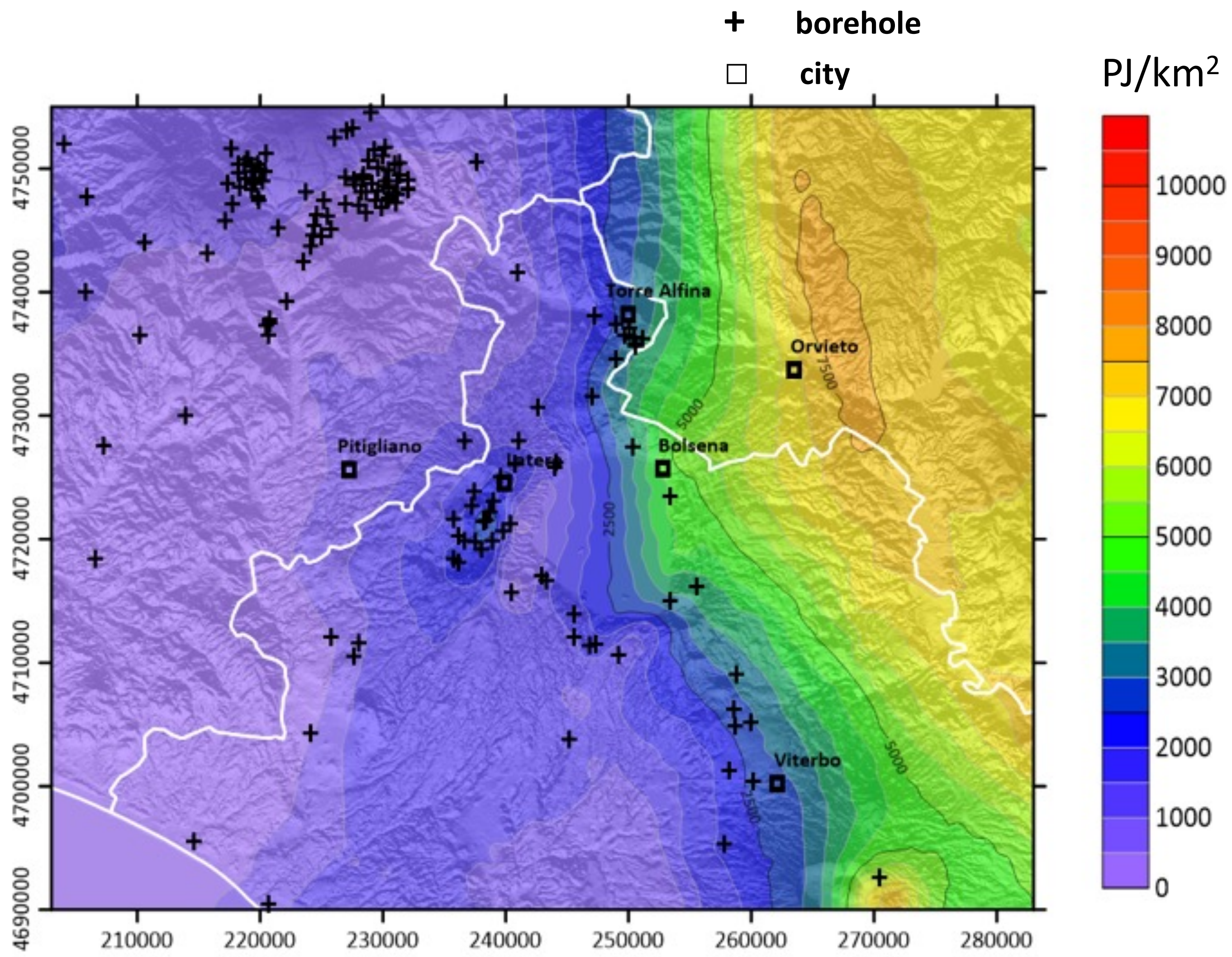
Heat in Place (HIP)



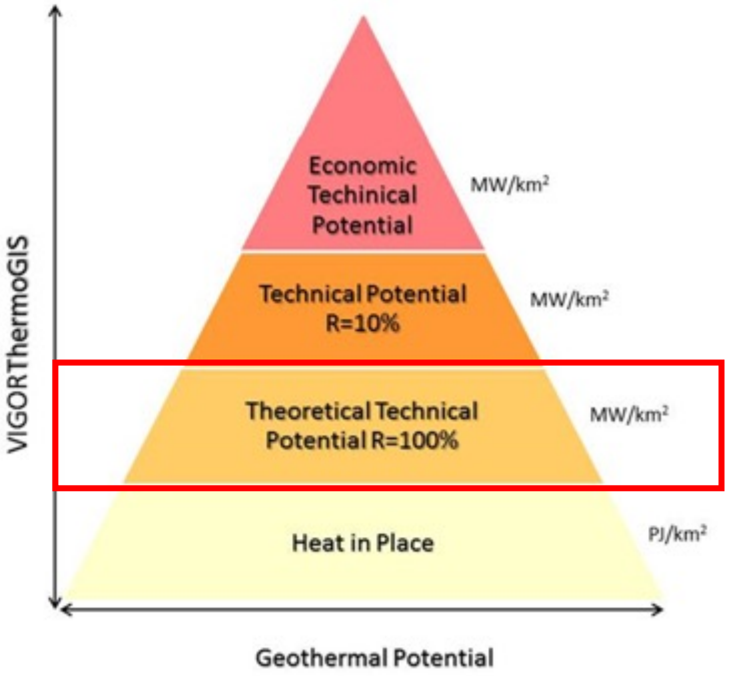


Heat in Place (HIP)



The code output is a Heat In Place MAP resulting from the VERTICAL SUM of the values of each volume element of the reservoir divided by the area of the volume element (J/km^2).

Theoretical Technical Potential (TTP)



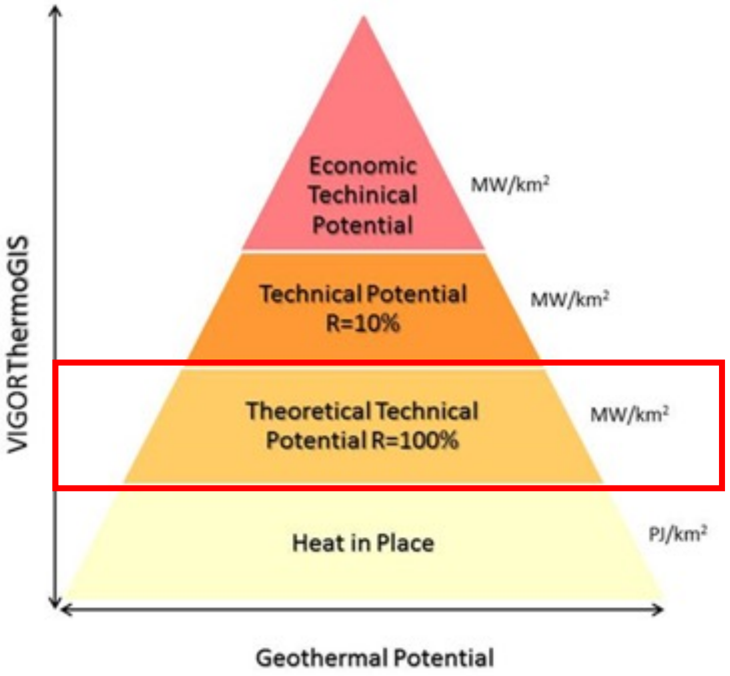
It represents the Power (Joule/second = W) that can be produced by each Volume Element of the reservoir having T ≥ MINIMUM temperature (T_{MIN}) required by the specific technology (e.g. 120 °C for electricity production).

This calculation occurs in two steps:

1. **THEORETICAL CAPACITY (TC):** it is the quantity of thermal energy (Joule) theoretically (100%) extractable from the underground depending on the technology. It depends on the production temperature (Tx = temperature of the volume element ≥ TMIN), on the RE-INJECTION temperature and on the volumetric heat capacity of the rock.

$$TC\ [PJ] = V \times (\rho c)_{rock} \times \left(T_x - T_{injection}\right) 10^{-15}$$

Theoretical Technical Potential (TTP)



It represents the Power (Joule/second = W) that can be produced by each Volume Element of the reservoir having T ≥ MINIMUM temperature (T_{MIN}) required by the specific technology (e.g. 120 °C for electricity production).

This calculation occurs in two steps:

2. **THEORETICAL TECHNICAL POTENTIAL (TTP):** it is the Power (Watt) theoretically (R=100%) producible in a time interval (30 years). It depends on the theoretical capacity, on the efficiency of the system (η) and on the efficiency of the heat exchange in the subsoil between fluid and rock (R).

$$TTP\,[MW] = TC \cdot \frac{\eta \times R}{(30 \cdot 365 \cdot 24 \cdot 60 \cdot 60)} 10^{-6}$$

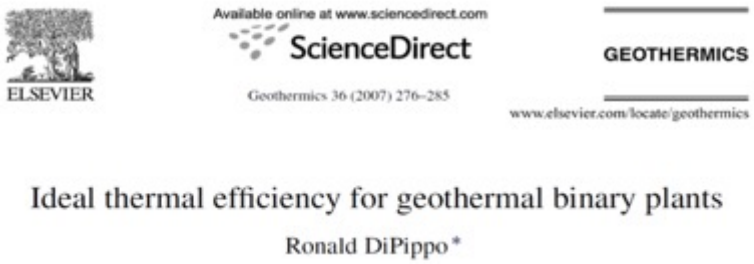
Theoretical Technical Potential (TTP)

Binary cycle efficiency

$$\eta = \eta_{ideal} \cdot \eta_{rel}$$

$$\eta_{ideal} = \frac{T_{prod} - T_{injection}}{T_{prod} + T_{injection}}$$

Average value
η_{rel} = 58±4%
(44%-67%)



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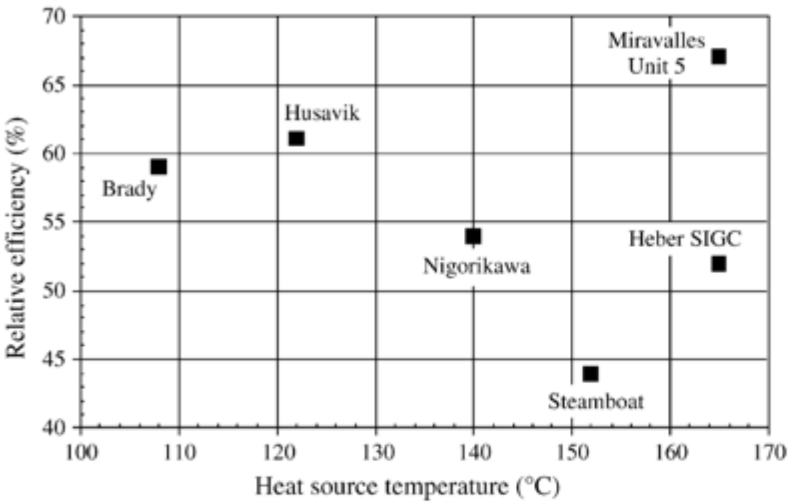
Ideal thermal efficiency for geothermal binary plants

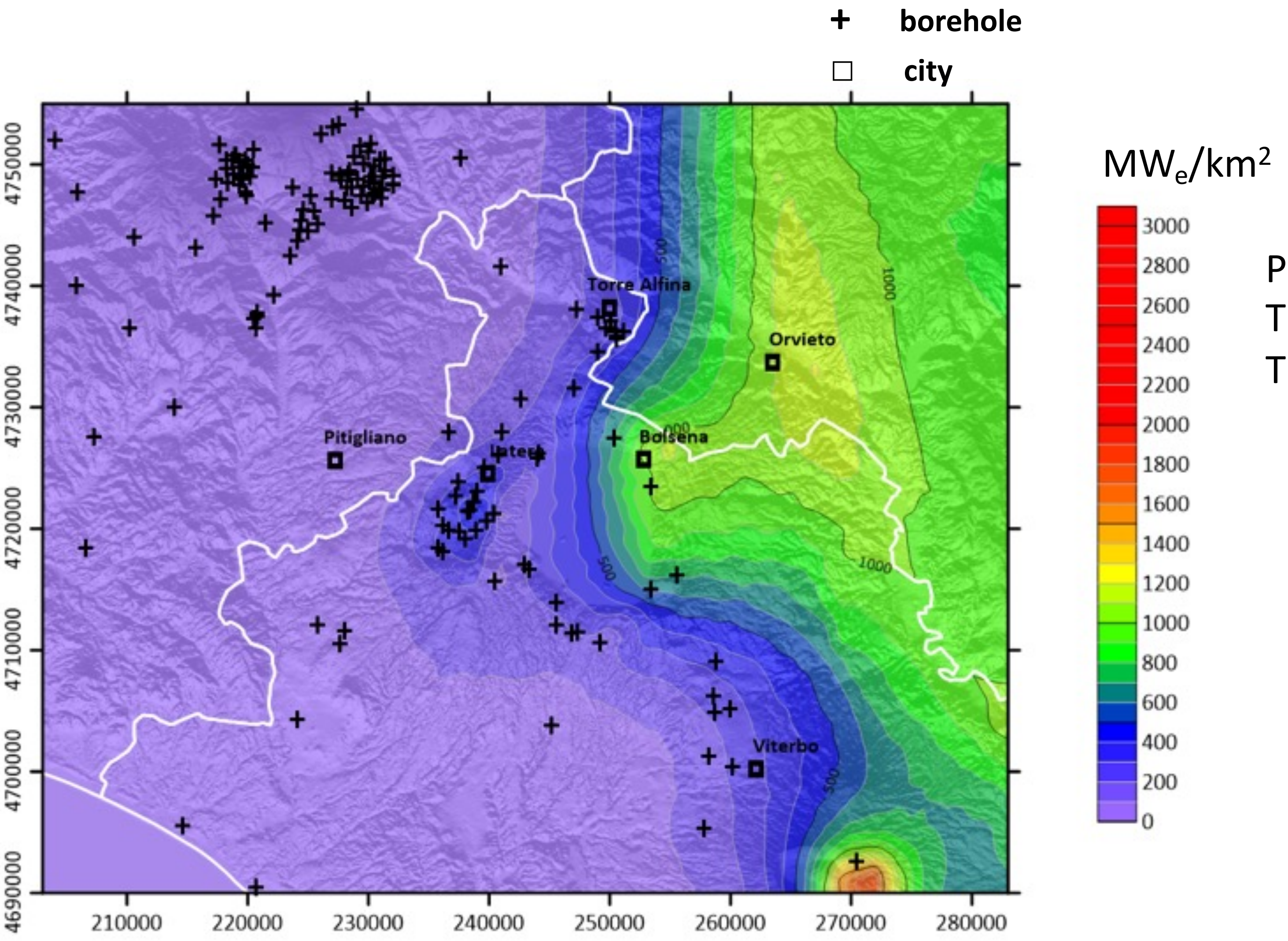
Ronald DiPippo *



$$TTP\,[MW] = TC \cdot \frac{\boxed{\eta} \times R}{(30 \cdot 365 \cdot 24 \cdot 60 \cdot 60)} 10^{-6}$$

For a DH systems the efficiency is set at 90%

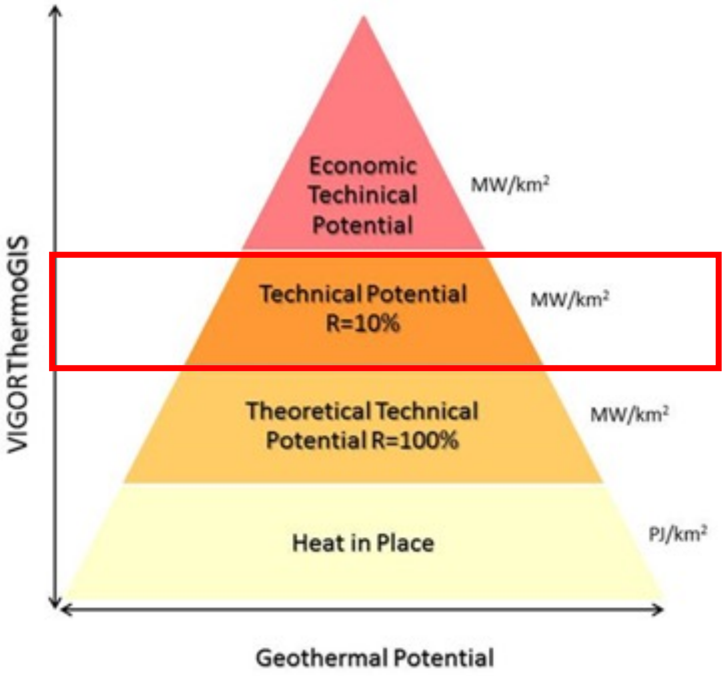
Theoretical Technical Potential (TTP)



Power
T_{MIN} = 120 °C
T_{INJ} = 107 °C

The code output is a MAP of the Theoretical Technical Potential obtained from the SUM on the VERTICAL of the values of each volume element of the reservoir divided by the area of the volume element (MW/km^2).

Technical Potential (TP)



It represents the Power (Joule/second = W) that can be produced by each Volume Element of the reservoir having T ≥ MINIMUM temperature (T_{MIN}) required by the specific technology (e.g. 120 °C for electricity production) for a recovery factor ≠ 0

$$TTP\,[MW] = TC \cdot \frac{\eta \times \boxed{R}}{(30 \cdot 365 \cdot 24 \cdot 60 \cdot 60)} 10^{-6}$$

The value of R depends on:

- fractured volume of the rock
- heat exchange surface
- hydraulic permeability
- rock temperature.

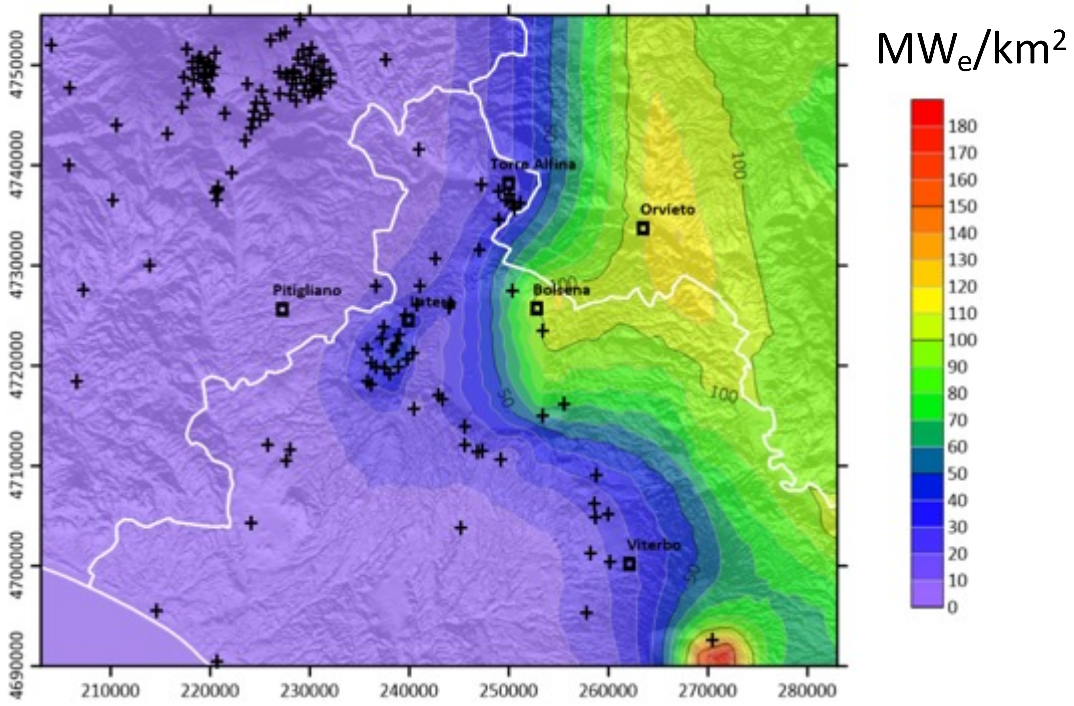
R varies from 0.01 for an EGS (Enhanced Geothermal System) to a maximum of 0.5 for a high permeable hydrothermal reservoir. Without any direct information, it is recommended to use a value between 0.02 and 0.20 (average value 0.1 or 10%).

Technical Potential (TP)

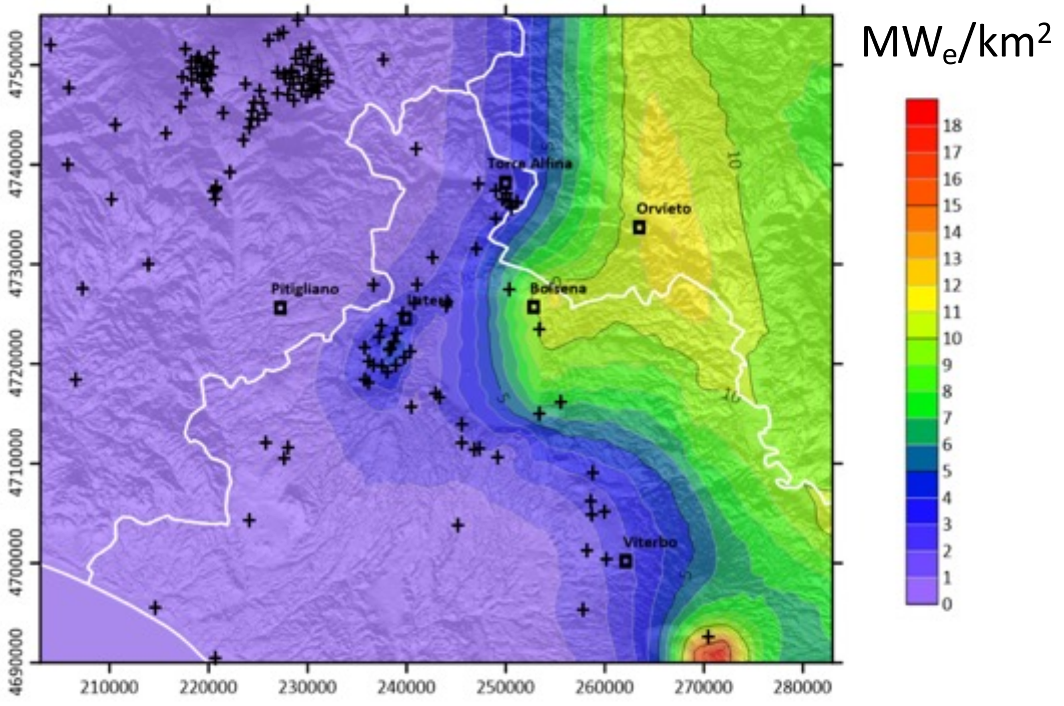
Power
T_{MIN} = 120 °C
T_{INJ} = 107 °C

+ **borehole**
□ **city**

R = 10%

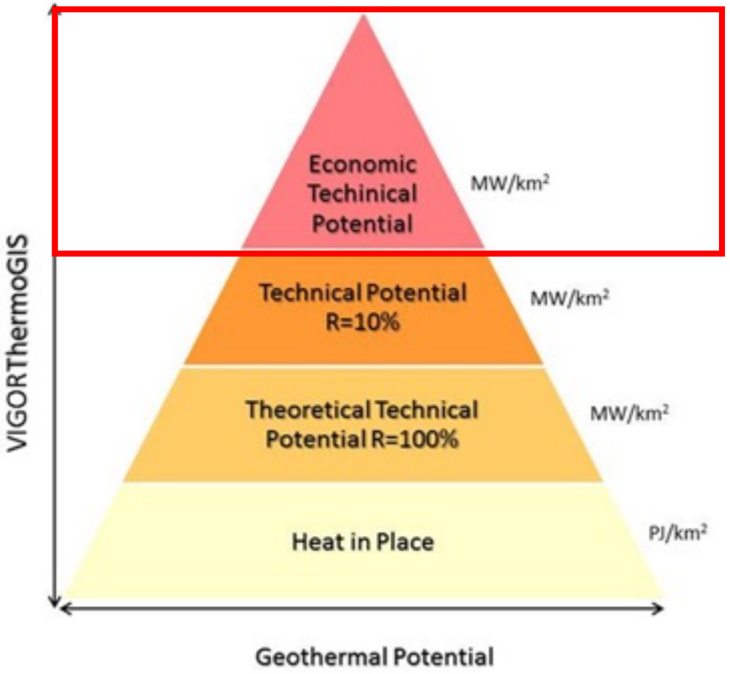


R = 1%



Technical-Economical Potential (ETPlcoe)

The Technical-Economic Potential is calculated starting from the Technical Potential (R = 10%) accepting only those cells of the 3D grid where the Levelized Cost of Energy (LCoE) is lower than a given threshold (< 200 €/MWe for electricity).



LCoE is calculated as the ratio between:

- the cash flow during the operational life of the plant (costs incurred for drilling, power plant, maintenance + earnings)
- the quantity of electricity (MWe) produced over 30 years.

Hydraulic transmissivity

$$q_v \; [m^3/s] = \Delta p \cdot \left[\frac{2\pi \boxed{K\,H}}{\boxed{\mu_{prod}} \ln\left(\boxed{L}/\boxed{r_w}\right)} + \frac{2\pi K\,H}{\mu_{inj} \ln\left(L/r_w\right)} \right]$$

Fluid viscosity

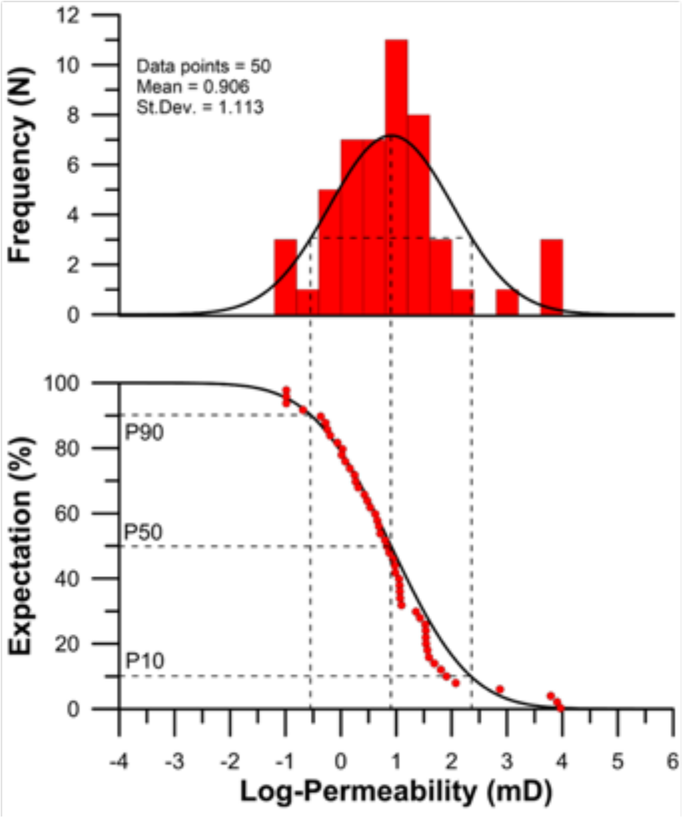
Borehole distance

Borehole radius

$$P_{th} = q_v \left(\rho c_p\right)_f \cdot \left(T_{prod} - T_{in}\right)$$

$$P_e = P_{th} \cdot \eta_{ideal} \cdot \eta_{rel}$$

Technical-Economical Potential (ETPlcoe)



HYDRAULIC PERMEABILITY (K) is the parameter with the largest uncertainty. It has a great influence on the performance of the geothermal doublet.

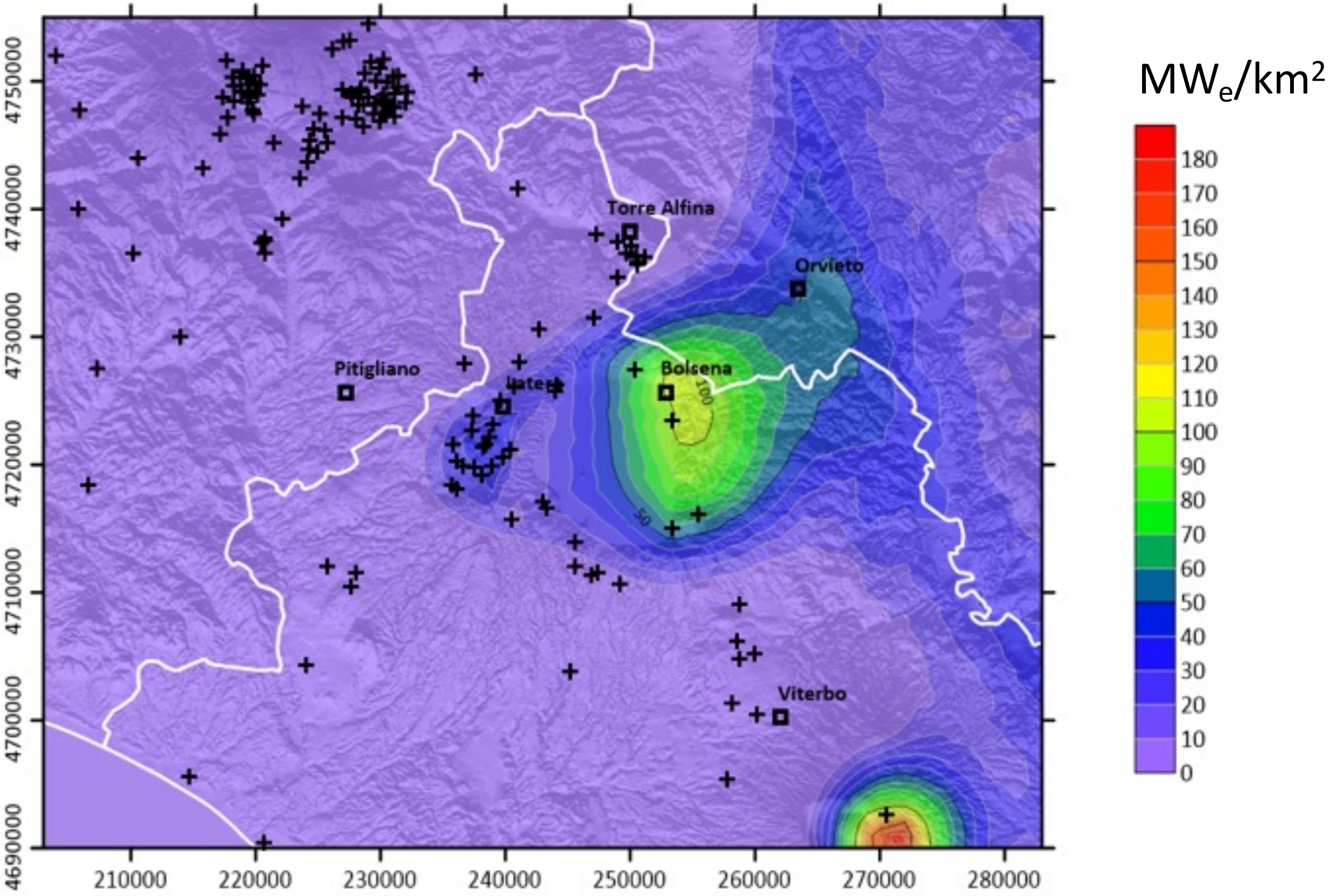
For this reason, a MONTE CARLO statistical approach was developed to assign expected hydraulic transmissivity values with a probability of 10%, 50% and 90%.

H = 250 m
K = 0.8 ± 0.2 mD

Technical-Economical Potential (ETPlcoe)

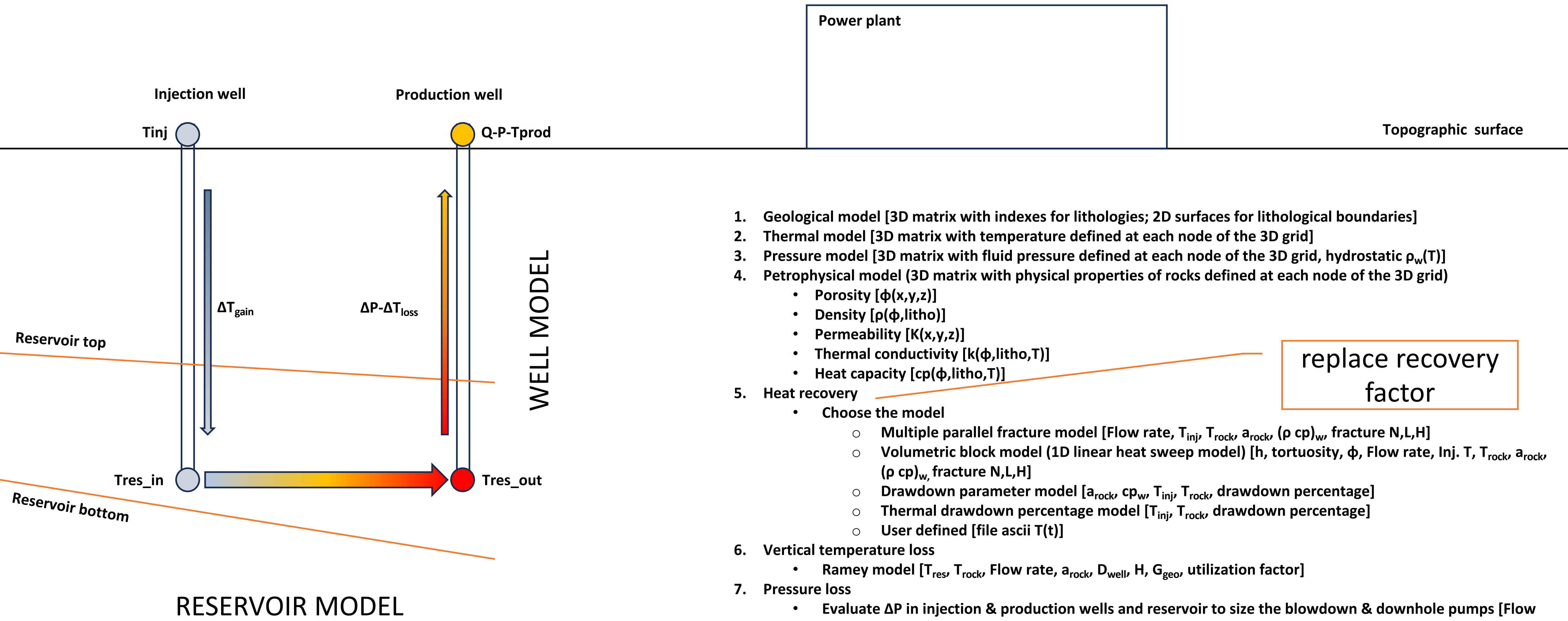
Power
T_{MIN} = 120 °C
T_{INJ} = 107 °C

P=50%



The code output is a MAP of the Technical-Economic Potential (P10-P50-P90) obtained from the VERTICAL SUM of the values of each volume element of the reservoir divided by the area of the volume element (MWe/km^2).

New perspectives



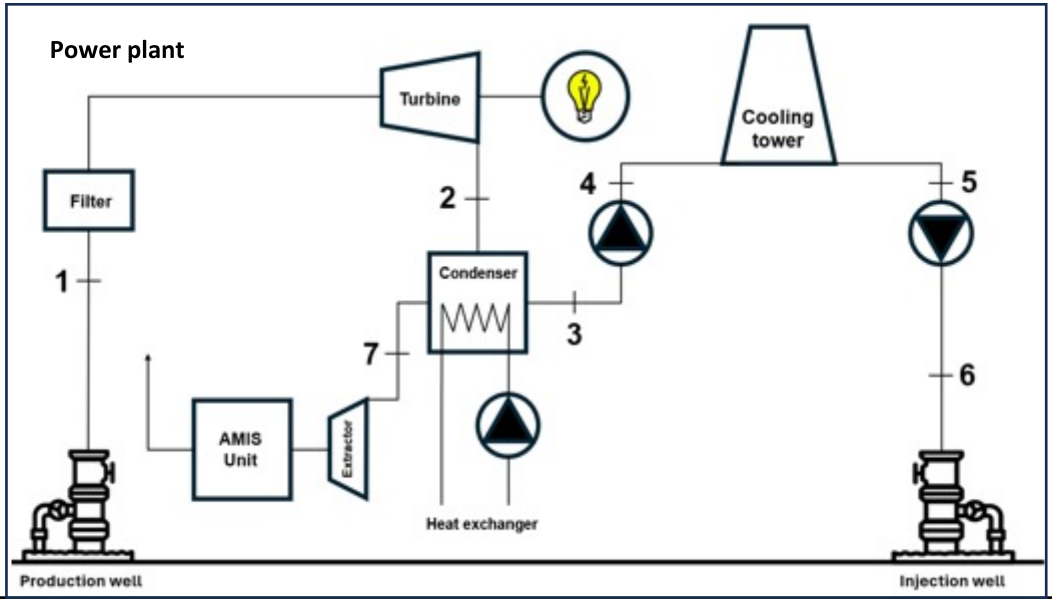
1. Geological model [3D matrix with indexes for lithologies; 2D surfaces for lithological boundaries]
2. Thermal model [3D matrix with temperature defined at each node of the 3D grid]
3. Pressure model [3D matrix with fluid pressure defined at each node of the 3D grid, hydrostatic $\rho_w(T)$]
4. Petrophysical model (3D matrix with physical properties of rocks defined at each node of the 3D grid)
    - Porosity [$\phi(x,y,z)$]
    - Density [$\rho(\phi,\text{litho})$]
    - Permeability [$K(x,y,z)$]
    - Thermal conductivity [$k(\phi,\text{litho},T)$]
    - Heat capacity [$cp(\phi,\text{litho},T)$]
5. Heat recovery
    - Choose the model
        - ○ Multiple parallel fracture model [Flow rate, T_{inj}, T_{rock}, a_{rock}, $(\rho\ cp)_w$, fracture N,L,H]
        - ○ Volumetric block model (1D linear heat sweep model) [h, tortuosity, ϕ, Flow rate, Inj. T, T_{rock}, a_{rock}, $(\rho\ cp)_w$, fracture N,L,H]
        - ○ Drawdown parameter model [a_{rock}, cp_w, T_{inj}, T_{rock}, drawdown percentage]
        - ○ Thermal drawdown percentage model [T_{inj}, T_{rock}, drawdown percentage]
        - ○ User defined [file ascii T(t)]
6. Vertical temperature loss
    - Ramey model [T_{res}, T_{rock}, Flow rate, a_{rock}, D_{well}, H, G_{geo}, utilization factor]
7. Pressure loss
    - Evaluate ΔP in injection & production wells and reservoir to size the blowdown & downhole pumps [Flow rate, Dwell, ρw, friction factor]

replace recovery factor

New perspectives

OUTPUT Subsurface model:

- FLOW RATE [kg/s]
- PRESSURE [bar]
- TEMPERATURE [degC]



1. INPUT data: FLOW RATE [kg/s] – PRESSURE [bar] – TEMPERATURE [degC]
2. USER input data:
   - **power plant type**
   - *component efficiencies*
   - *capacity factor*
3. Modelling of thermodynamic cycle for different power plant technologies (Dry steam, Single Flash, Binary, Cogeneration) accounting for efficiency of each component (thermal and kinetic energy losses)
4. Monitoring thermodynamic properties of the fluid (pressure, temperature, enthalpy) at the entry and exit of each component.
5. The code finds for the optimal turbine output
6. The code computes:
   - Net electricity production (accounting for the total energy produced and the energy consumption of the different components)
   - Utilization efficiency (W_{net} / Exergy_{fluid})
   - Specific steam consumption (kg / kWh)

New perspectives

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Review

Efficiency of geothermal power plants: A worldwide review

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Power production: validation thermodynamic model against worldwide operating power plants

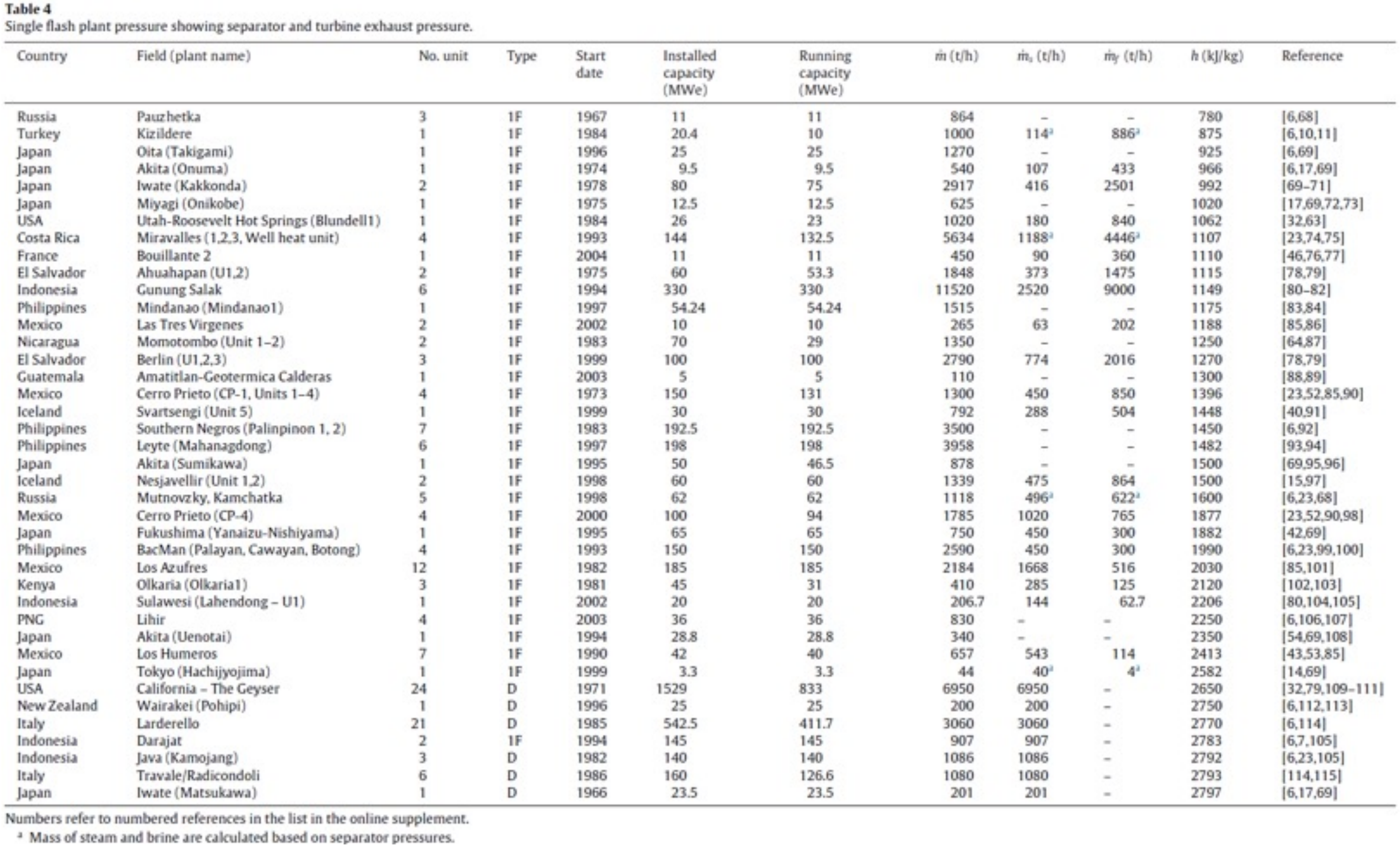


Table 4
Single flash plant pressure showing separator and turbine exhaust pressure.

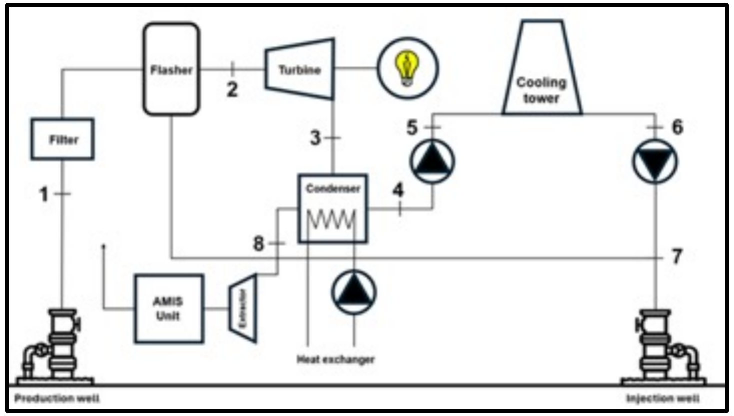
Country	Field (plant name)	No. unit	Type	Start date	Installed capacity (MWe)	Running capacity (MWe)	$\dot{m}$ (t/h)	$\dot{m}_s$ (t/h)	$\dot{m}_f$ (t/h)	h (kJ/kg)	Reference
Russia	Pauzhetka	3	1F	1967	11	11	864	–	–	780	[6,68]
Turkey	Kizildere	1	1F	1984	20.4	10	1000	114[a]	886[a]	875	[6,10,11]
Japan	Oita (Takigami)	1	1F	1996	25	25	1270	–	–	925	[6,69]
Japan	Akita (Onuma)	1	1F	1974	9.5	9.5	540	107	433	966	[6,17,69]
Japan	Iwate (Kakkonda)	2	1F	1978	80	75	2917	416	2501	992	[69–71]
Japan	Miyagi (Onikobe)	1	1F	1975	12.5	12.5	625	–	–	1020	[17,69,72,73]
USA	Utah-Roosevelt Hot Springs (Blundell1)	1	1F	1984	26	23	1020	180	840	1062	[32,63]
Costa Rica	Miravalles (1,2,3, Well heat unit)	4	1F	1993	144	132.5	5634	1188[a]	4446[a]	1107	[23,74,75]
France	Bouillante 2	1	1F	2004	11	11	450	90	360	1110	[46,76,77]
El Salvador	Ahuahapan (U1,2)	2	1F	1975	60	53.3	1848	373	1475	1115	[78,79]
Indonesia	Gunung Salak	6	1F	1994	330	330	11520	2520	9000	1149	[80–82]
Philippines	Mindanao (Mindanao1)	1	1F	1997	54.24	54.24	1515	–	–	1175	[83,84]
Mexico	Las Tres Virgenes	2	1F	2002	10	10	265	63	202	1188	[85,86]
Nicaragua	Momotombo (Unit 1–2)	2	1F	1983	70	29	1350	–	–	1250	[64,87]
El Salvador	Berlin (U1,2,3)	3	1F	1999	100	100	2790	774	2016	1270	[78,79]
Guatemala	Amatitlan-Geotermica Calderas	1	1F	2003	5	5	110	–	–	1300	[88,89]
Mexico	Cerro Prieto (CP-1, Units 1–4)	4	1F	1973	150	131	1300	450	850	1396	[23,52,85,90]
Iceland	Svartsengi (Unit 5)	1	1F	1999	30	30	792	288	504	1448	[40,91]
Philippines	Southern Negros (Palinpinon 1, 2)	7	1F	1983	192.5	192.5	3500	–	–	1450	[6,92]
Philippines	Leyte (Mahanagdong)	6	1F	1997	198	198	3958	–	–	1482	[93,94]
Japan	Akita (Sumikawa)	1	1F	1995	50	46.5	878	–	–	1500	[69,95,96]
Iceland	Nesjavellir (Unit 1,2)	2	1F	1998	60	60	1339	475	864	1500	[15,97]
Russia	Mutnovzky, Kamchatka	5	1F	1998	62	62	1118	496[a]	622[a]	1600	[6,23,68]
Mexico	Cerro Prieto (CP-4)	4	1F	2000	100	94	1785	1020	765	1877	[23,52,90,98]
Japan	Fukushima (Yanaizu-Nishiyama)	1	1F	1995	65	65	750	450	300	1882	[42,69]
Philippines	BacMan (Palayan, Cawayan, Botong)	4	1F	1993	150	150	2590	450	300	1990	[6,23,99,100]
Mexico	Los Azufres	12	1F	1982	185	185	2184	1668	516	2030	[85,101]
Kenya	Olkaria (Olkaria1)	3	1F	1981	45	31	410	285	125	2120	[102,103]
Indonesia	Sulawesi (Lahendong – U1)	1	1F	2002	20	20	206.7	144	62.7	2206	[80,104,105]
PNG	Lihir	4	1F	2003	36	36	830	–	–	2250	[6,106,107]
Japan	Akita (Uenotai)	1	1F	1994	28.8	28.8	340	–	–	2350	[54,69,108]
Mexico	Los Humeros	7	1F	1990	42	40	657	543	114	2413	[43,53,85]
Japan	Tokyo (Hachijyojima)	1	1F	1999	3.3	3.3	44	40[a]	4[a]	2582	[14,69]
USA	California – The Geyser	24	D	1971	1529	833	6950	6950	–	2650	[32,79,109–111]
New Zealand	Wairakei (Pohipi)	1	D	1996	25	25	200	200	–	2750	[6,112,113]
Italy	Larderello	21	D	1985	542.5	411.7	3060	3060	–	2770	[6,114]
Indonesia	Darajat	2	1F	1994	145	145	907	907	–	2783	[6,7,105]
Indonesia	Java (Kamojang)	3	D	1982	140	140	1086	1086	–	2792	[6,23,105]
Italy	Travale/Radicondoli	6	D	1986	160	126.6	1080	1080	–	2793	[114,115]
Japan	Iwate (Matsukawa)	1	D	1966	23.5	23.5	201	201	–	2797	[6,17,69]

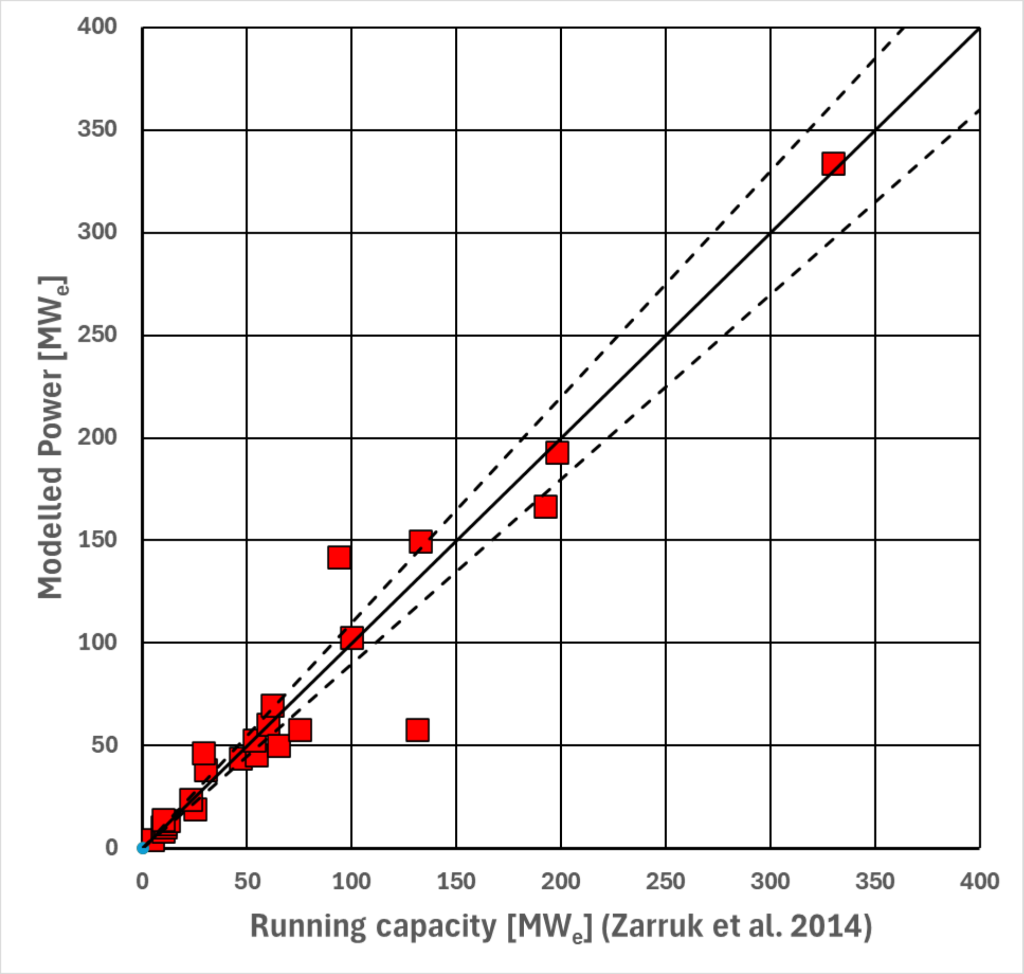
Numbers refer to numbered references in the list in the online supplement.

[a] Mass of steam and brine are calculated based on separator pressures.

New perspectives

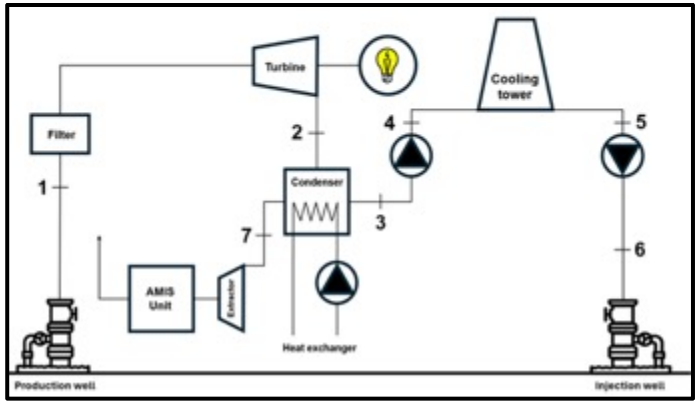
Power production: single flash power plant

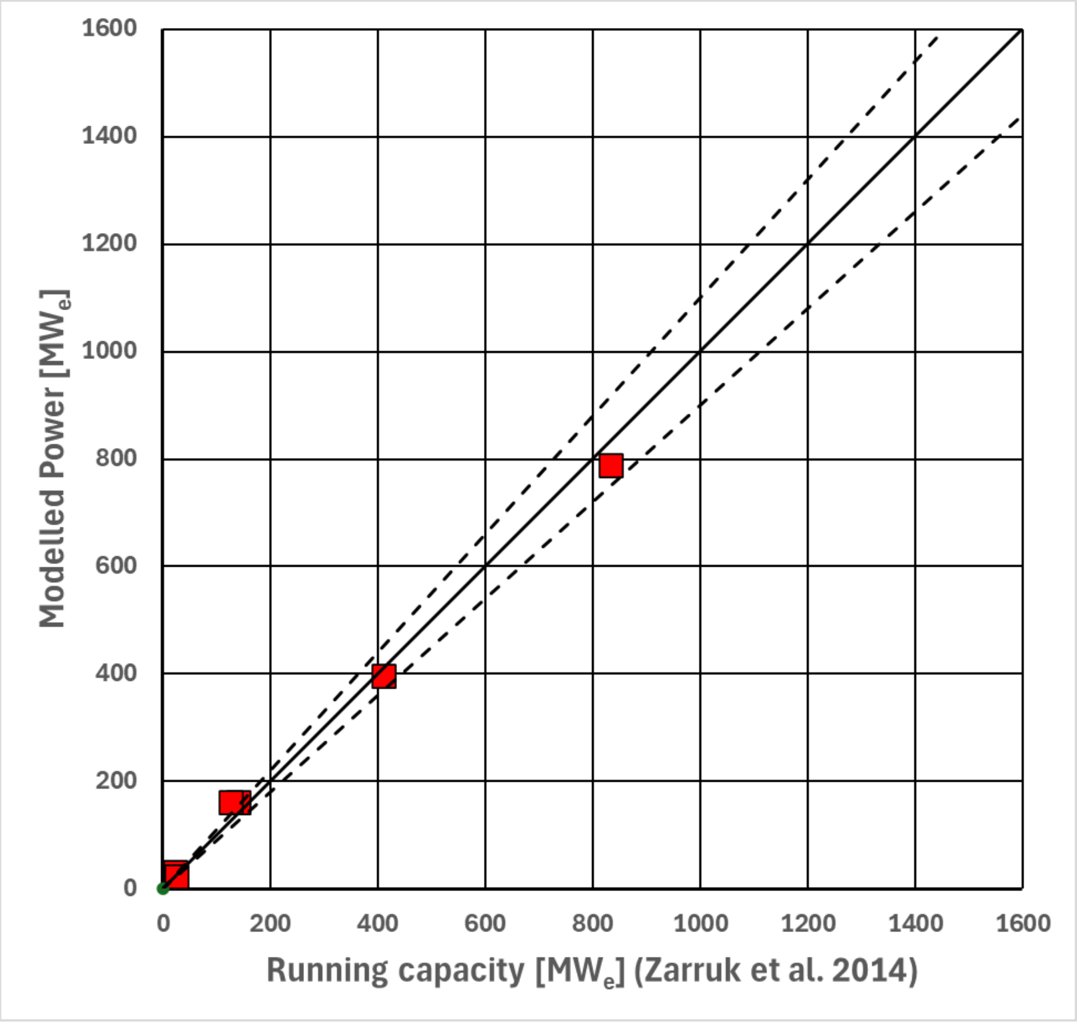




New perspectives

Power production: dry steam power plant





Conclusions

Needs:

- coherent and standard terminology
- harmonized methods for resource reporting for different geological settings, advanced resource development perspectives (EGS, superhot, DBHE, etc.) and extended resource use (e.g. GSHP, storage). it should include the mapping of geothermal reserves and resources as well as communicating the robustness of estimations (at different stages of the project)
- Public and transparent performance analysis tools for evaluating the resource potential and for resource analysis reporting

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