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HOMEWORK ASSIGNMENT
VOLUMETRIC RESOURCE ASSESSMENT

This project involves performing a simple volumetric resource assessment of an imaginary geothermal system with the properties listed below:

Estimated volume V= 5 km$^3$
Reservoir temperature $T_R$= 280 – 300°C
Porosity ϕ~12%
Rock density $\rho_r$=2850 kg/m$^3$
Rock heat capacity $\beta_r$ =850 J/kg°C
Average feed-zone depth D=1500 m

Also assume:

- accessibility **A= 100%** and
- a recovery factor **R=0.12**

*The system is liquid-dominated and the thermal properties of the water in the reservoir can be found in steam-tables.*

We consider a mean reservoir temperature $T_R$ =290°C and we assume that the geothermal reservoir is fully in liquid conditions. According to the steam tables: http://www.thermexcel.com/english/tables/eaubou1.htm

$$h_w(T_R) = 1.289 * 10^6\ J/kg$$

$$\rho_w(T_R) = 731.9\ kg/m^3$$

$$specific\ heat\ capacity\ of\ the\ fluid = \beta w = 4964\ J/kg.K$$

1. ESTIMATE THE RECOVERABLE THERMAL ENERGY FOR THE SYSTEM FOR A REFERENCE TEMPERATURE $T_0 = 30°C$. ALSO ESTIMATE THE THERMAL POWER ASSUMING UTILIZATION FOR 50 YEARS.

$$E_{rock} = V(1-\varphi)\rho_r\beta_r(T_R - T_0) = 5 * 10^9 * (1 - 0.12) * 2850 * 850 * (290 - 30)$$

$$E_{rock} = 2.77 * 10^{18} J$$

$$E_{fluid} = V\varphi\rho_f\beta_f(T_R - T_0) = 5 * 10^9 * 0.12 * 731.91 * 4967 * (290 - 30) = 5.67 * 10^{17} J$$

$$E_{res} = E_{rock} + E_{fluid} = 2{,}77 * 10^{18} + 0{,}567 * 10^{18} = 3.34 * 10^{18}\ J$$

$$E_{recoverable} = ARE_{res} = 1 * 0.12 * 3.33 * 10^{18} = 4{,}0 * 10^{17} J$$

$$P_{thermal} = \frac{E_{recoverable}}{\Delta t} = \frac{4{,}0 * 10^{17}}{50 * 365.25 * 24 * 3600} = 1.43 * 10^8 \frac{J}{s} = 2.54 * 10^8\ W$$

$$P_{thermal} = 253\ MW$$

2. ESTIMATE THE ELECTRICAL GENERATING POTENTIAL (ELECTRICAL POWER CAPACITY) USING THE METHOD OUTLINED IN CLASS, ASSUMING A UTILIZATION FOR 50 YEARS AND A GENERATION EFFICIENCY OF 13.5%

We consider a reference temperature of $T_0 = 30°C$ and a conversion efficiency $n$ (thermal energy to electrical power) of 13,5%.

$$E_e = nE_{recoverable} = 0{,}135 * 4{,}0 * 10^{17} = 5.4 * 10^{16} J$$
$$P_e = \frac{E_e}{\Delta t} = \frac{5.4 * 10^{16}}{50 * 365.25 * 24 * 3600} = 3.42 * 10^7 W = 34\ MW$$

3. *ALSO ESTIMATE THE ELECTRICAL GENERATING POTENTIAL USING THE ALTERNATE METHOD OUTLINED BELOW. ASSUME A SEPARATION PRESSURE FOR THE POWER GENERATION OF 8 BAR-G.*

For a separation pressure of 9 bar-a (=8 bar-g + 1bar atm), the boiling temperature is

$$T_{sat} = 175{,}36°C$$

- $h_w(T_{sep}) = 7.427 * 10^5\ J/kg$
- $\rho_w(T_{sep}) = 891{,}91\ kg/m^3$
- $h_s(T_{sep}) = 2.773 * 10^6\ J/kg$
- $\rho_s(T_{sep}) = 4{,}655\ kg/m^3$

We assume liquid conditions in the reservoir, so the total fluid enthalpy at reservoir temperature (290°C) is $h_t = 1.289 * 10^6 J/kg$. The energy flow estimated in the first question is $E_{recoverable} = 4{,}0 * 10^{17} J$, which corresponds to a total power of 253 MW over a period of 50 years.

Knowing that $P = Qh$, we can use the energy flow to obtain the total expected mass flow rate:

$$Q = \frac{P\ (\frac{J}{s})}{h\ (\frac{J}{kg})} = \frac{2.53 * 10^8}{1.289 * 10^6} = 196\ kg/s$$

Knowing the total enthalpy of a reservoir fluid $h_{t(T_{res})} = Xh_s + (1 - X)h_w = 1289$ kJ/kg that is separated at a surface pressure of 9 bar-a, we can calculate the steam fraction:

$$X = \frac{h_t - h_w(P)}{h_s(P) - h_w(P)} = \frac{1.289 * 10^6 - 7.427 * 10^5}{2.773 * 10^6 - 7.427 * 10^5} = \frac{1289 - 743}{2773 - 743} = 0.27 = 27\%$$

With the expected mass flow rate Q, the total reservoir fluid enthalpy $H_t$and the steam and water enthalpy at inlet pressure $H_s$, $H_w$, the electrical generating potential using the alternate method is:

$$P_e \sim 0.5Q\frac{H_t - H_w}{H_s - H_w} * 10^6$$
$$P_e \sim 0.5 * 196 * 0.27 * 10^6 = 2.655 * 10^7 W = 26MW$$

4. Compare the results of the three methods employed in (2) and (3).

The first method is revealed to be the most optimistic of the two; it is based on an estimated conversion efficiency and a reference temperature of 30°C, and gives a total output of 34 MW. This conversion efficiency depends on the power plant type and on the whole geothermal system. It therefore cannot be totally and exactly defined before having long-term production data that provide better information and knowledge on the reservoir. The method in (3), based on an estimation of the steam fraction at the wellhead, gives an electrical power capacity equal to 26 MW for a production period of 50 years. It is the most pessimistic estimated value that mainly depends on the estimated mass flow rate, assumed to be here 196 kg/s. A constant extraction rate is in reality rarely the case in geothermal reservoir production (annually and long-term variations over the lifetime of the reservoir), that is why this value is a real approximation. This flow rate can however be only determined after a detailed study of the permeability and other hydraulic/thermal properties of the reservoir. Finally, this method is based on a rule of thumbs that assume that 2kg/s of steam are necessary to generate 1MW of electricity. Based on these two values, we can therefore assess the upper and lower electrical potential of the studied system for a pre-defined production time of 50 years. This exercise reveals the complexity of estimating the volumetric potential of a geothermal resource and the necessity to use several methods to get an insight on its uncertainty.