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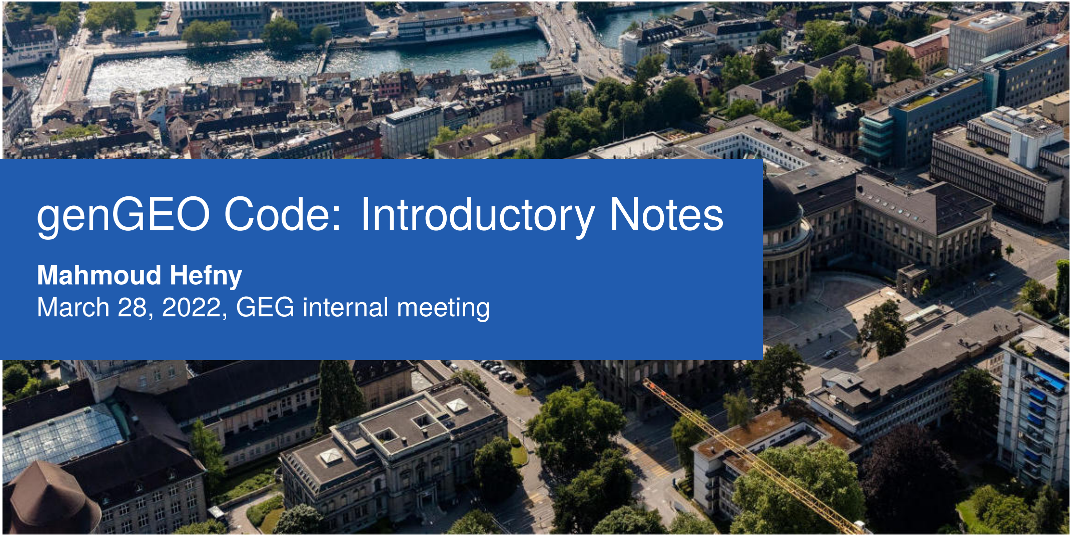
ETH – Earth Science Department
Geothetmal Energy and Geofluids



genGEO Code: Introductory Notes

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Outline

Outline

genGEO: motivation

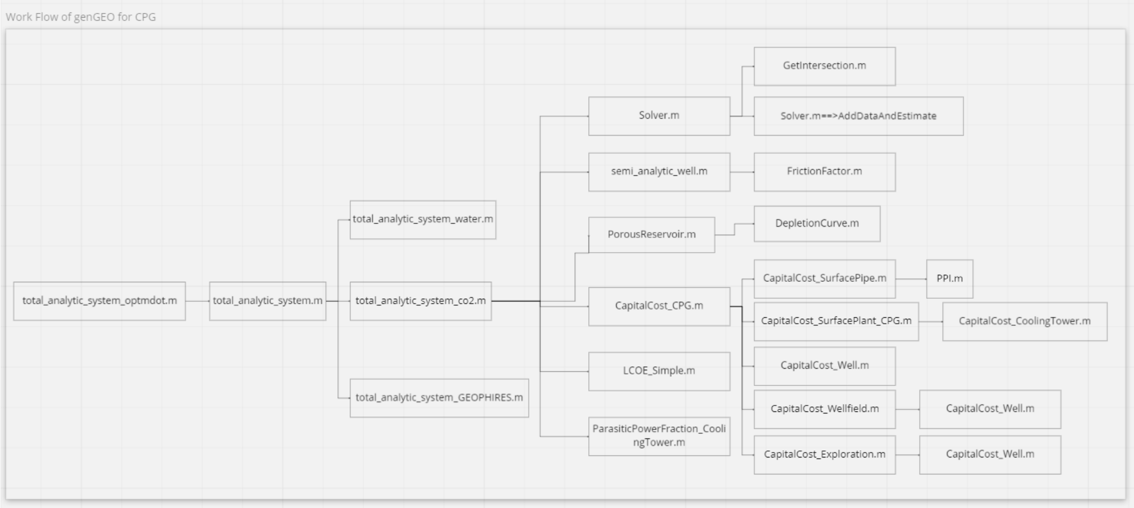
genGEO is an open-source package for the **gen**eralizable **GEO**thermal techno-economic simulator from sedimentary basins. genGEO (`version 0.0.1`) couple the following modules:

- Levelized Cost of Electricity
- Capital cost
- Surface power plant
- Well model
- Reservoir model

genGEO: Links

- This presentation is hosted in the overleaf project under this **Link**
- The Overleaf project for the genGEO draft for future submission to SoftwareX, **Link**
- The Miroboard planning project **Link**

genGEO: workflow for CPG



Outline

Module 01: Levelized Cost of Electricity

Simplified LCOE model

The simplified LCOE `[$/W-h]` for any geothermal project can be estimated using Equation 1

$$\mathrm{LCOE} = \frac{\mathrm{C_{geothermal}}}{\bar{\mathrm{W}}} \times \frac{\mathrm{CRF} + \mathrm{F_{O\&M}}}{\mathrm{CF} \times 8760} \tag{1}$$

where, $\mathrm{C_{geothermal}}$: captial cost model `[Watts]`, $\bar{\mathrm{W}}$: Average plant capacity `[MWe]`, $\mathrm{F_{O\&M}}$: O&M Cost Fraction `[MWe]`, CF: Capacity Factor `[-]`. The CRF is the capacity recovery factor (Equation 2)

$$\mathrm{CRF} = \frac{\mathrm{A}}{\mathrm{P}} = \frac{\mathrm{d} \times (1+\mathrm{d})^{\mathrm{FP}}}{(1+\mathrm{d})^{\mathrm{FP}} - 1} \tag{2}$$

where, d: discount rate `[-]`, and FP: Finanical Period `[year]`

Code repo.

The Matlab code repo. is `LCOE_Simple.m`

Outline

Capital Cost Model

$$C_{\text{Geothermal}} = C_{\text{Plant}} + C_{\text{Wells}} + C_{\text{SurfacePiping}} + C_{\text{Wellfield}} + C_{\text{Exploration}} + C_{\text{Stimulation}} \quad (3)$$

Code repo.

For a CPG, the Matlab code repo. is `CapitalCost_CPG.m` Link

Module 02: Capital Cost Model

Multipliers for Indirect Costs and Contingency

[A] Indirect Costs multiplier, X_{IC}

X_{IC} calls Engineering, Procurement, and Construction Management (EPCM) costs, which are necessary costs for administration, planning, and design that are separate from the plant material and labor costs

[B] Contingency Costs multiplier, X_{PC}

X_{PC} accounts for unknown costs that are omitted or unforeseen due to a lack of complete project definition and engineering, even though contingencies cannot be explicitly determined at the time the estimate is prepared."

Module 02: Capital Cost Model
Multipliers for Indirect Costs and Contingency

Component	$\mathbf{X_{IC}}$	$\mathbf{X_{PC}}$
Surface plant	$X_{IC\text{-}p}$: 1.12	$X_{PC\text{-}p}$: 1.15
Wells	$X_{IC\text{-}well}$: 1.05	$X_{PC\text{-}well}$: 1.15
Surface piping	$X_{IC\text{-}pipe}$: 1.12	$X_{PC\text{-}pipe}$: 1.15
Wellfield	$X_{IC\text{-}wf}$: 1.05	$X_{PC\text{-}wf}$: 1.15
Exploration	$X_{IC\text{-}expl}$: 1.05	$X_{PC\text{-}expl}$: 1.15
Stimulation	$X_{IC\text{-}stim}$: 1.05	$X_{PC\text{-}stim}$: 1.15

Module 02: Capital Cost Model

2.1: Surface Power Plant, C_{Plant}

$$C_{\text{Plant}} = X_{\text{PC-p}} \times X_{\text{IC-p}} \times C_{\text{Plant-BEC}} \tag{4}$$

where,

$$C_{\text{Plant-BEC}} = C_{\text{Plant-TEC}} \times (1 + X_{\text{CL}} + X_{\text{CM}} + X_{\text{ST}} + X_{\text{F}}) \tag{5}$$

$$C_{\text{Plant-TEC}} = C_{\text{Plant-PEC}} \times X_{\text{SE}} \tag{6}$$

$$C_{\text{Plant-PEC}} = C_{\text{T-G}} + C_{\text{Pump}} + C_{\text{C-Tower}} + C_{\text{HeatExchanger}} + \dots \tag{7}$$

Module 02: Capital Cost Model

2.1: Surface Power Plant, C_{Plant}

Cost Multiplier	**Value**	**Description**
$X_{IC\text{-}p}$	1.12	Indirect cost multiplier
$X_{PC\text{-}p}$	1.15	Project contingency multiplier
X_{CL}	0.58	Construction Labor Cost (building and assembling, including fringe)
X_{CM}	0.11	Construction Material Cost (concrete, pipe, wire, rentals, etc.)
X_{ST}	0.00	Sales Tax
X_{F}	0.04	Equipment Freight
X_{SE}	1.39	Secondary Equipment Cost (control system, pumps, valves, building, etc.)

2.1.1: Turbine-Generator Cost, $C_{T\text{-}G}$

In genGEO, the specific turbine-generator cost is the GETEM flash turbine-generator cost, with an added coefficient (i.e. 0.67) so the genGEO curve passes through the average NETL coal plant steam turbine cost (Equation 8).

$$C_{\text{T-G}} = 0.67 \times PPI_{\text{T-G}} \left[S_{\text{T-fluid}} \times 2830 \times \left(\dot{W}_{\text{Turbine}}\right)^{0.745} + 3680 \times \left(\dot{W}_{\text{Turbine}}\right)^{0.617} \right] \tag{8}$$

where, $\dot{W}_{\text{Turbine}}$ is the turbine-generator gross power $[kW_e]$. $S_{\text{T-fluid=CO2}}$ = 1.20 and for other fluids $S_{\text{T-fluid=other}}$ = 1.00

2.1.2: Pump Cost, C_{Pump}

Pumps (injection, production, circulation,...) in geothermal induce a pressure gradient and causing movement. Two type of production well pumps (located several hundred meters below the surface in the production well) are used in geothermal power plant: (1) Lineshaft (considered in genGEO), and (2) Submersible (not considered in genGEO). In genGEO, the total pump cost, C_{Pump}, is given in Equation 9 and is a function of the type of pump (surface or lineshaft) and the pump material.

$$C_{Pump} = PPI_{Pump} \times S_{Pump} \times C_{Pump\text{-(Surface, Lineshaft)}} \tag{9}$$

where, the pump material multiplier, S_{Pump}, is of 1.00 or 2.09, for Water-based or CO_2-based geothermal power plant, respectively. All sources are given in the table next slide.

$$C_{Pump\text{-Surface}} = 1750 \times \left(1.34 \times \dot{W}_{Pump}\right)^{0.7} \tag{10}$$

$$C_{Pump\text{-Lineshaft}} = 1750 \times \left(1.34 \times \dot{W}_{Pump}\right)^{0.7} + 5750 \times \left(1.34 \times \dot{W}_{Pump}\right)^{0.2} \tag{11}$$

2.1.3: Cooling/Condensing Tower Cost, $C_{\text{C-Tower}}$

In genGEO, the total cost of a cooling or condensing tower, $C_{\text{C-Tower}}$, is determined by a two-step process (Equations): 1) finding the cost of a Baltimore Aircoil Company (BAC) cooling tower with a nominal cooling capacity of 1 MW_{th}, and 2) up-scaling the cost to the cooling capacity required.

$$C_{\text{C-Tower}} = C_{\text{Ref-BAC}} \times \left(\frac{\dot{Q}_{\text{Cooling}} + \dot{Q}_{\text{Condensing}}}{\dot{Q}_{\text{Ref-BAC}}} \right)^{0.8} \tag{12}$$

where,

$$C_{\text{Ref-BAC}} = \text{PPI}_{\text{PE}} \times \dot{Q}_{\text{Ref-BAC}} \times \text{TDC} \times (F_{\text{Cooling}} \times c_{\text{Cooling}} + (1 - F_{\text{Cooling}}) \times c_{\text{Condensing}}) \tag{13}$$

$$F_{\text{Cooling}} = \frac{\dot{Q}_{\text{Cooling}}}{\dot{Q}_{\text{cooling}} + \dot{Q}_{\text{Condensing}}} \tag{14}$$

2.1.4: Heat Exchanger cost, $C_{HeatExchanger}$

Heat exchangers are used within a geothermal power cycle to transfer heat from one fluid to another, for instance, within evaporators or condensers. The cost of the heat exchanger is the product of the heat exchanger type cost and the heat exchanger cost index, PPI_{HX}. There are four types of heat exchanger costs in genGEO: shell&tube ($C_{S\&T}$), gasketed plate ($C_{GasketedPlate}$), welded plate ($C_{WeldedPlate}$), and bonded plate ($C_{BondedPlate}$) (as shown in Equation 15)

$$C_{HeatExchanger} = PPI_{HX} \times C_{S\&T,\ GasketedPlate,\ WeldedPlate,\ BondedPlate} \tag{15}$$

where,

$$C_{S\&T} = 239 \times A_{HX} + 13400 \tag{16}$$

$$C_{GasketedPlate} = 29 \times A_{HX} + 1560 \tag{17}$$

$$C_{WeldedPlate} = 69 \times A_{HX} + 4670 \tag{18}$$

$$C_{BondedPlate} = 2.6 \times (69 \times A_{HX} + 4670) \tag{19}$$

Module 02: Capital Cost Model

2.1: Surface Power Plant, C_{Plant} – Heat Exchanger Cont.

Assuming that the heat transferred through the exchanger, $\dot{Q}$, is known, then Equation 20 is used to calculate the Heat Transfer Area, A_{HX}.

$$\dot{Q} = U \times A_{HX} \times \Delta T_{LMTD} \tag{20}$$

where, ΔT_{LMTD} is the Log Mean Temperature Difference, and U is the overall Heat Transfer Coefficient,

$$\Delta T_{LMTD} = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} \tag{21}$$

It is a function of the temperature differences at arbitrarily assigned ends “A”, ΔT_B, and “B”, ΔT_B

Module 02: Capital Cost Model

2.2: Well Cost, C_{Wells}

The total cost of the wells in genGEO is the sum of the cost of each of the total number of wells drilled, C_{Wells}, as provided in Equations 22.

$$C_{\text{Wells}} = \sum_{i=1}^{G_{\text{wells}}} \left(C_{\text{Well-drilling,i}} + \Delta C_{\text{CO2-Well,i}}\right) \tag{22}$$

In the following slide, all equations costs are based on 2002$. Therefore, costs are adjusted by year using the pipe cost index, $PPI_{O\&G}$

Module 02: Capital Cost Model

2.2: Well Cost, C_{Wells}

2.2.1: Geothermal Drilling Success Rate, $C_{\text{Well-drilling}}$

$$C_{\text{Well-drilling}} = \frac{C_{\text{Well}}}{S_{\text{Well}}} \tag{23}$$

The values of the well success rate in genGEO, S_{Well}, is given as 95%, 75%, and 90% for oil-gas (sedimentary), traditional geothermal (fractured), and EGS (basement), respectively.

2.2.2: Geothermal Well Cost, C_{Well}: Cost in 2002$

$$C_{\text{Well}}(\text{Baseline}) = X_{\text{IC-well}} \times X_{\text{PC-well}} \times PPI_{\text{O\&G}} \times \left(0.105 \times L_{\text{Well}}^2 + 1776 \times L_{\text{Well}} \times D_{\text{Well}} + 275300\right) \tag{24}$$

$$C_{\text{Well}}(\text{Ideal}) = X_{\text{IC-well}} \times X_{\text{PC-well}} \times PPI_{\text{O\&G}} \times (1288 \times L_{\text{Well}} \times D_{\text{Well}} - 62 \times L_{\text{Well}} + 275300) \tag{25}$$

2.2.3: Well Cost Adjustment for CO_2, $\Delta C_{\text{CO2-Well}}$

$$\Delta C_{\text{CO2-Well}} = X_{\text{IC-well}} \times X_{\text{PC-well}} \times PPI_{\text{O\&G}} \times \left(265 \frac{\$}{m^2} \times L_{\text{Well}} \times D_{\text{Well}} + 133 \frac{\$}{m} \times L_{\text{Well}}\right) \tag{26}$$

Module 02: Capital Cost Model

2.3: Surface Piping System Cost, $C_{\text{SurfacePiping}}$

Surface Piping System Cost (or field gathering system) is predominantly the pipe cost to connect the wellheads to the central generating plant (Equations).

$$C_{\text{SurfacePiping}} = X_{\text{IC-Pipe}} \times X_{\text{PC-Pipe}} \times PPI_{\text{Pipe}} \times (c_{\text{SpecfSurfacePiping}} \times L_{\text{Pipe}}) \tag{27}$$

where,

$$c_{\text{SpecfSurfacePiping}} = 2205 \frac{\$}{m^3} \times D^2_{\text{Pipe}} + 134 \frac{\$}{m} \tag{28}$$

The above equations are given based on 2002$ cost.

Wellfield development costs include the cost to permit and develop a geothermal power plant site. For CO_2-based geothermal system, additional permit and monitoring wells and equipment must be included (Equation 29).

$$C_{\text{Wellfield}} = C_{\text{Permitting}} + \Delta C_{\text{Permitting-CO}_2} + \Delta C_{\text{Monitoring-CO}_2} \tag{29}$$

For CO_2 monitoring well, the wellfield costs are normalized by the Active Monitoring Area (AMA), $A_{\text{CO2-AMA}}$, of the CCS development. The AMA is the Area of Review (AOR), $A_{\text{CO2-,AOR}}$, plus a 0.5 mile (800 m) buffer on all sides.

$$\begin{aligned} A_{\text{CO2-AOR}} &= \left(L_{\text{Wellzone}}\right)^2 \\ A_{\text{CO2-AMA}} &= \left(L_{\text{Wellzone}} + 1600\text{m}\right)^2 \end{aligned} \tag{30}$$

Module 02: Capital Cost Model

2.4: Wellfield Development Costs, $C_{Wellfield}$

2.4.1: Base Wellfield Development Costs, $C_{Permitting}$

$$C_{\text{Permitting}} = X_{\text{IC-wf}} \times X_{P\text{C-wf}} \times \text{PPI}_{\text{Permit}} \times \left(665700 \frac{\$}{\text{site}}\right) \tag{31}$$

2.4.2: Wellfield Cost Adjustment for CO_2 permitting, $\Delta C_{Permitting\text{-}CO_2}$

$$\Delta C_{\text{Permitting-CO}_2} = X_{\text{IC-wf}} \times X_{\text{PC-wf}} \times \text{PPI}_{\text{Permit}} \times \left(45000 \frac{\$}{\text{km}^2}\right) \times \frac{1\ \text{km}^2}{10^6\ \text{m}^2} \times A_{\text{CO}_2\text{,AMA}} \tag{32}$$

2.4.3: Wellfield Cost Adjustment for CO_2 monitoring, $\Delta C_{Monitoring\text{-}CO_2}$

$$\Delta C_{\text{Monitoring-CO}_2} = C_{\text{MonitoringWells-CO}_2} + C_{\text{SurfaceMonitoring-CO}_2} \tag{33}$$

where,

$$C_{\text{MonitoringWells-CO}_2} = G_{\text{MonitoringWells-CO}_2} \times C_{\text{Well,D=21.6 cm}} \tag{34}$$

$$C_{\text{SurfaceMonitoring-CO}_2} = X_{\text{IC-wf}} \times X_{\text{PC-wf}} \times \text{PPI}_{\text{O\&G-s}} \times \left(138000 \frac{\$}{\text{km}^2}\right) \times \frac{1\ \text{km}^2}{10^6\ \text{m}^2} \times A_{\text{CO2,AMA}} \tag{35}$$

Module 02: Capital Cost Model

2.5: Exploration Costs, $C_{\text{Exploration}}$

The exploration cost, consists of two primary tasks: drilling exploration wells and reservoir modeling.

$$C_{\text{Exploration}} = C_{\text{Modeling}} + \Delta C_{\text{CharaterizationWells}} + \Delta C_{\text{Modeling,CO}_2} \tag{36}$$

where,

$$C_{\text{Modeling}} = X_{\text{IC-expl}} \times X_{\text{PC-expl}} \times PPI_{\text{O\&G-s}} \times \left(508000 \frac{\$}{\text{site}}\right) \tag{37}$$

$$\Delta C_{\text{CharacterizationWells}} = 0.2 \times C_{\text{Well}} \times \frac{G_{\text{CharacterizationWells}}}{S_{\text{Well}}} \tag{38}$$

$$\Delta C_{\text{Modeling, CO}_2} = X_{\text{IC-expl}} \times X_{\text{PC-expl}} \times PPI_{\text{O\&G-s}} \times \left(44800 \frac{\$}{\text{km}^2}\right) \times \frac{1\ \text{km}^2}{10^6\ \text{m}^2} \times A_{\text{CO}_2\text{,AMA}} \tag{39}$$

Module 02: Capital Cost Model

2.6: Well Stimulation Costs, $C_{\text{Stimulation}}$

$$C_{\text{Stimulation}} = \begin{cases} 0, & (\text{Hydrothermal}) \\ X_{\text{IC-stim}} \times X_{\text{PC-stim}} \times G_{\text{Wells}} \times 715000, & (\text{EGS}) \end{cases} \tag{40}$$

Outline

Module 03: Operation and Maintenance (O&M) Costs

Operation and maintenance (O&M) costs, $C_{\text{O\&M}}$, are needed to calculate the Levelized Cost of Electricity (LCOE) of any electricity generator. genGEO reports O&M cost in this analysis with respect to three commonly reported sub-costs: 1) Labor, 2) Material, and 3) Taxes and Insurance. genGEO suggests the O&M cost fraction, $F_{\text{O\&M}}$, may be approximated as 5.5%.

$$C_{\text{O\&M}} = 0.055 \times C_{\text{Geothermal}} \tag{41}$$

where, $C_{\text{Geothermal}}$ can be estimated using Equation 3.

Outline

Module 04: Surface Power Plant

4.1: Surface Power Plant Type

Module 04: Surface Power Plant
4.2: Organic Rankine Cycle (ORC)

4.3.1: Maximize Specific Electric Power

4.3.2: Minimize Specific Electric Cost

4.3.3: Optimization Results

Outline

Module 05: Wellbore Model

The heat conduction through the wellbore is found by applying a 1-D analytical solution of radial heat conduction in a semi-infinite solid from Carslaw & Jaeger (1959) to each element. The wellbore is numerically solved for pressure, P, (Equation 42) and enthalpy, h, (Equation 43) for each element, *i*.

$$\mathrm{P_{i+1}} = \mathrm{P_i} - (\rho \times \mathrm{g} \times \Delta \mathrm{z}) - \Delta \mathrm{P_{Loss,i}} \tag{42}$$

$$\mathrm{h_{i+1}} = \mathrm{h_i} - \mathrm{g} \times \Delta \mathrm{z} - \frac{\dot{\mathrm{Q}}_{\mathrm{Loss,i}}}{\dot{\mathrm{m}}} \tag{43}$$

where,

$$\dot{Q}_{\mathrm{Loss,i}} = \Delta \mathrm{z} \times 2 \times \pi \times \mathrm{k_{Rock}} \times \beta \times (\mathrm{T_{w,\,i}} - \mathrm{T_{e,i}}) \tag{44}$$

$$\beta = \begin{cases} (\pi \times \mathrm{t_d})^{-0.5} + \frac{1}{2} - \frac{1}{4}\left(\frac{\mathrm{t_d}}{\pi}\right)^{0.5} + \frac{1}{8}\mathrm{t_d}, & \mathrm{t_d} \leq 2.8 \\ \frac{2}{\ln(4 \times \mathrm{t_d}) - 1.16} - \frac{1.16}{(\ln(4 \times \mathrm{t_d}) - 1.16)^2}, & \mathrm{t_d} > 2.8 \end{cases} \tag{45}$$

$$\mathrm{t_d} = \frac{\mathrm{k_{Rock}}}{\rho_{\mathrm{Rock}} \times \mathrm{c'_{Rock}}} \frac{4 \times \mathrm{t}}{\mathrm{D^2_{Well}}} \tag{46}$$

Outline

The reservoir impedance is the ratio of the pressure difference between the injection well downhole and production well downhole to the mass flowrate through the reservoir. This value is essential to determine (I) the circulation flowrate of a geofluid, (II) how much pumping is required, (III) the ease at which geothermal heat can be extracted from a reservoir, (Iv) and ultimately the profitability of doing so.

- For 5-spot well pattern: (Equation 47)

$$\frac{\Delta \mathrm{P}}{\dot{\mathrm{m}}} = \frac{\bar{\mu}}{\bar{\rho}} \times \frac{1}{\kappa \mathrm{b}} \times \frac{1}{4} \times \ln\left(\frac{4\mathrm{L}}{\pi D}\right) \tag{47}$$

- For a well-doublet: (Equation 48)

$$\frac{\Delta \mathrm{P}}{\dot{\mathrm{m}}} = \frac{\bar{\mu}}{\bar{\rho}} \times \frac{1}{\kappa \mathrm{b}} \times \frac{1}{\pi} \times \ln\left(\frac{\mathrm{L}}{e\mathrm{D}}\right) \tag{48}$$

where *e* is Euler's number.

Code repo.

The Matlab code repo. is `PorousReservoir.m`

Two types of geothermal reservoirs:

- Thermally replenishing reservoirs are connected to deep, high-temperature heat sources via fractures, and thus the production temperature of geofluid removed from them tends to be relatively constant through fluid advection.
- Thermally isolated reservoirs have no connections to deep heat sources and have only a finite amount of heat to extract, which may be augmented by heat conduction from surrounding geologic layers. In this case, the non-dimensional temperature (Equation 49) is the ratio of reservoir production temperature less the reservoir injection temperature to the initial reservoir production temperature, less the reservoir injection temperature.

$$\Gamma = \frac{\mathrm{T} - \mathrm{T}_{\mathrm{inj}}}{\mathrm{T}_{\mathrm{initial}} - \mathrm{T}_{\mathrm{inj}}} \tag{49}$$

Outline

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