Agenda

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

03 Geothermal reserve estimation and unconventional geothermal systems

04 Oil and gas well conversions, future trends

Recap of Day 3

- Geothermal resource identification involves geological, geophysical, and geochemical surveys to locate promising sites.
- Conceptual models provide a basis for 3D geological models.
- Well logging (temperature and pressure measurements) is essential for monitoring reservoir performance.
- Reserve estimation uses methods like stored heat and volumetric approaches, factoring in recovery and efficiency.
- Steam reservoir performance is tracked using material balance and real-gas law to understand resource changes over time.
- Numerical reservoir simulations provide estimates of geothermal resources, guide optimal well placement and strategies, and forecast field behavior.
- EGS and AGS technologies expand geothermal access to locations with heat but no working fluid or permeability.

Day 4

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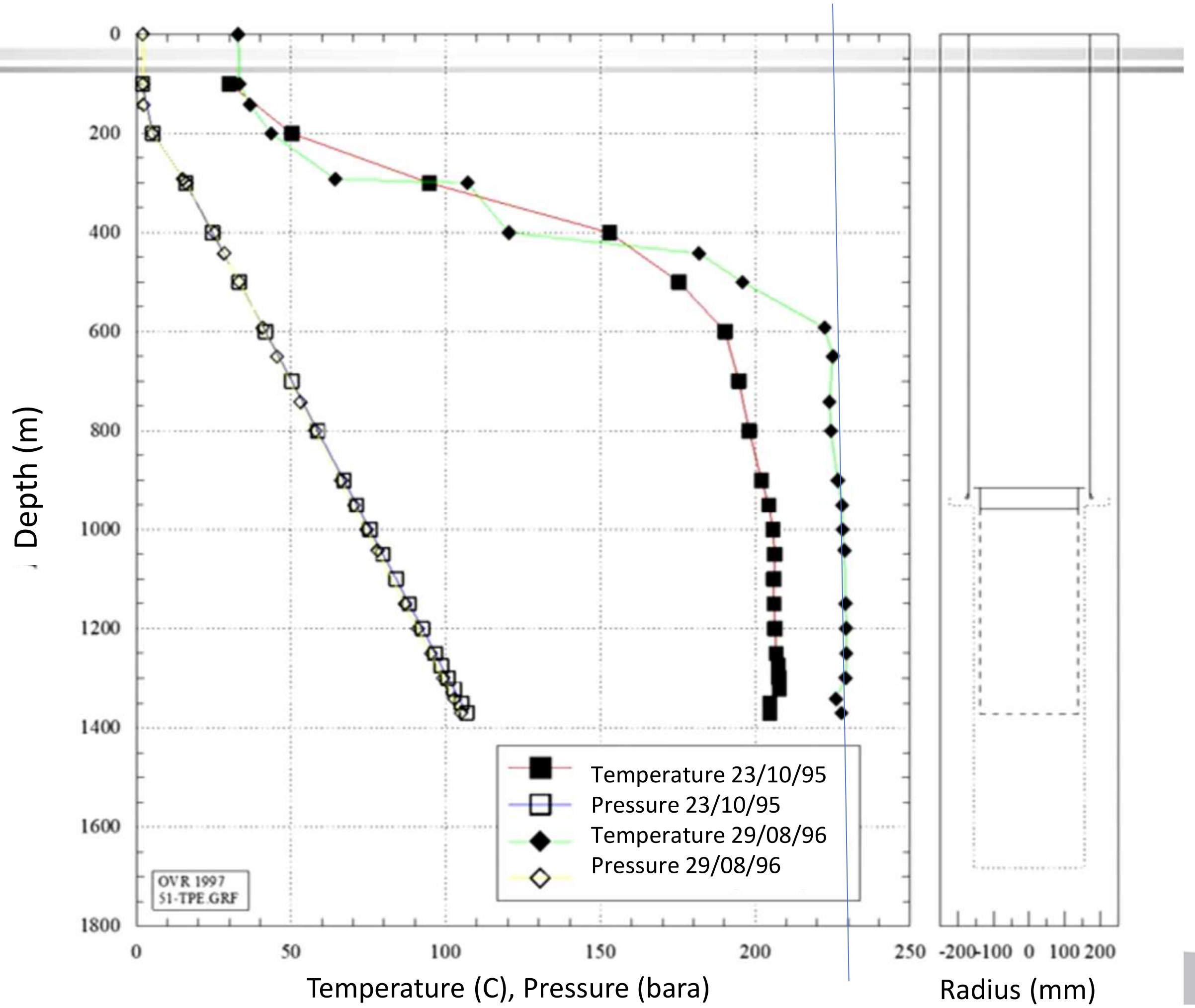
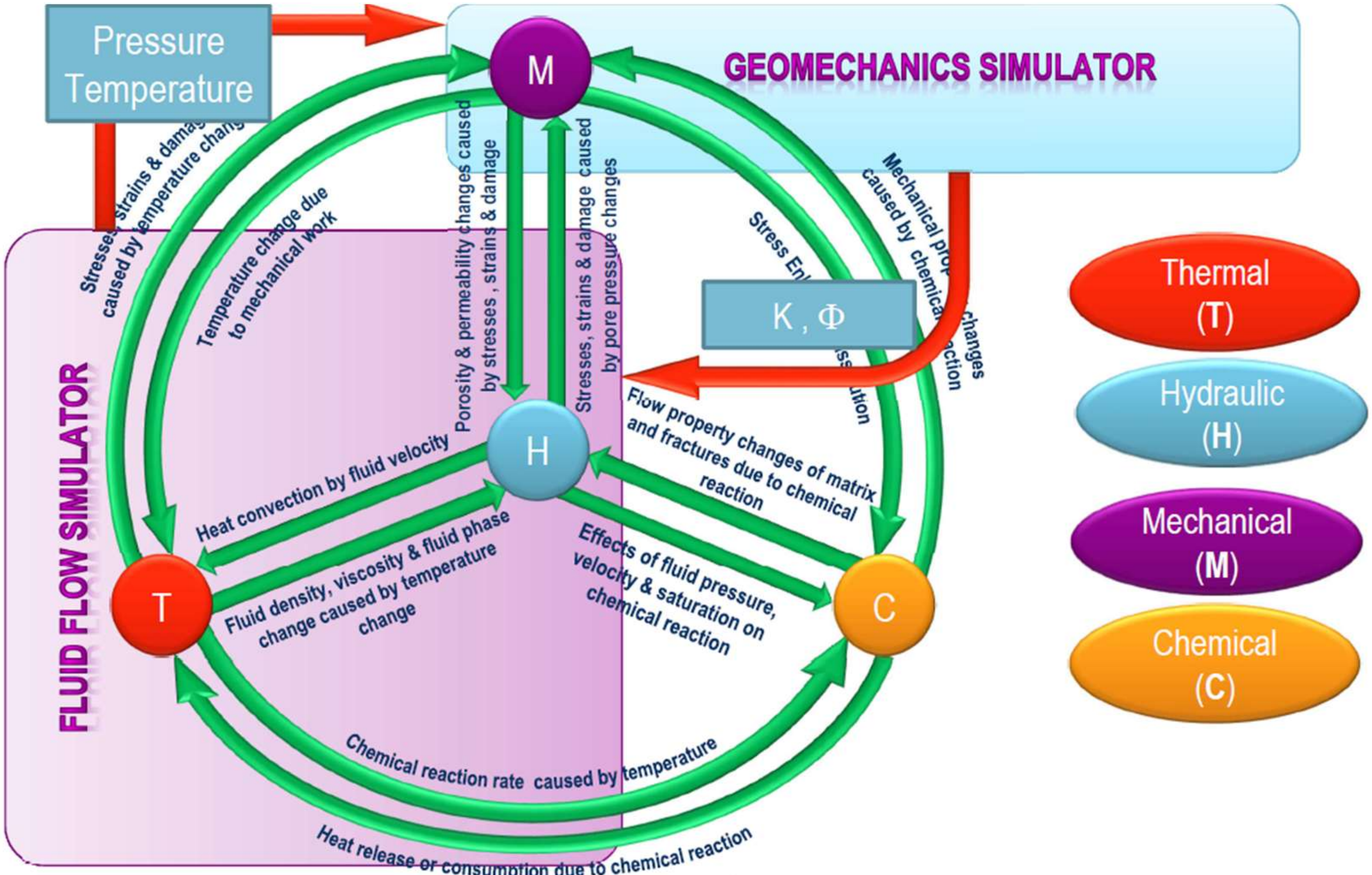
Temperature and Pressure Log



Geomechanics in Geothermal Reservoir Engineering



Geomechanics in Geothermal Reservoir Engineering

- Thermo-poro-elastic constitutive equations:

$$\begin{cases} d\underline{\underline{\sigma}} = \left(K_b - \frac{2}{3}G\right) : d\varepsilon_v^e \underline{\underline{\delta}} + 2G d\underline{\underline{\varepsilon}}^e - b dp \underline{\underline{\delta}} - 3K_b \alpha_b dT \underline{\underline{\delta}} \\ dp = M\left[-b\, tr(\varepsilon_v^e) + \frac{dm}{\rho_f}\right] + 3\alpha_m M dT \\ ds_b = dms_m^0 + \alpha_b d\sigma_{kk} - (3\alpha_m - 3\alpha_b b)dp + \frac{\rho_m C_\sigma^s}{T_0} dT \end{cases}$$

- Coupling parameters:

$$b = 1 - \frac{K_b}{K_m} \qquad \frac{1}{M} = \frac{b - \phi}{K_m} - \frac{\phi}{K_f} \qquad \alpha_m = (b - \phi)\,\alpha_b + \phi\alpha_f$$

Thermo-Hydro-Mechanical Coupling – Governing Equations

▪ Darcy's Law: $\dfrac{\vec{w}_{\mathrm{f}}}{\rho_{\mathrm{f}}} = \dfrac{k}{\mu_{\mathrm{f}}}(-\vec{\nabla} p + \rho_{\mathrm{f}} \vec{g})$	▪ Fourier's Law: $\vec{Q} = -\lambda \vec{\nabla} T$

- Momentum balance equation:

$$\mathrm{div}\left(\underline{\underline{\sigma}}\right) + \rho_{\mathrm{m}} \vec{g} = 0$$

- Fluid diffusivity equation:

$$\frac{k}{\mu_{\mathrm{f}}} \nabla^2 p = \frac{1}{M} \frac{\partial p}{\partial t} + b \frac{\partial \varepsilon_v^e}{\partial t} - 3\alpha_m \frac{\partial T}{\partial t}$$

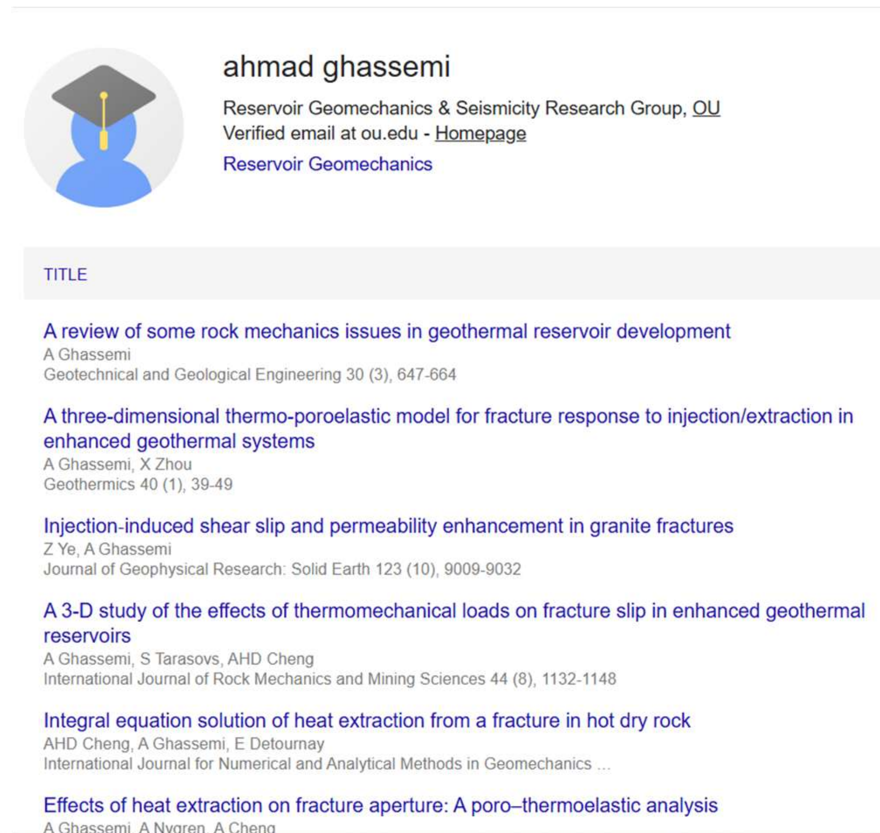
- Heat diffusivity equation:

$$\lambda \nabla^2 T = C_\varepsilon^b \frac{\partial T}{\partial t} - 3\alpha_m T_0 \frac{\partial p}{\partial t} + 3\alpha_b K_b T_0 \frac{\partial \varepsilon_v^e}{\partial t} - \frac{k C_p}{\mu_{\mathrm{f}}} \vec{\nabla} p . \vec{\nabla} T$$

Heat convection to fluid flow

Geomechanics in Geothermal Reservoir Engineering - Resources

- Shao, J. F. (1997). ***A Numerical Solution for a Thermo-hydro-mechanical Coupling Problem with Heat Convection***. International Journal of Rock Mechanics and Mining Science, 34(1), 163-166
- Geomechanics for Geothermal Energy - https://www.youtube.com/watch?v=ONmx2kvkA98 (Dr. Espinoza, UT Austin)
- Prof. Ahmad Ghassemi - https://scholar.google.com/citations?user=SP8r9YIAAAAJ&hl=en



Day 4

Nature of Geothermal Formations

- Common rock types in geothermal reservoirs include granite, granodiorite, quartzite, greywacke, basalt, rhyolite and volcanic tuff.

- Geothermal formations are, by definition, hot (production intervals from 160°C to above 300°C) and are often hard (240+ MPa compressive strength), abrasive (quartz content above 50%), and highly fractured (fracture apertures of centimeters).

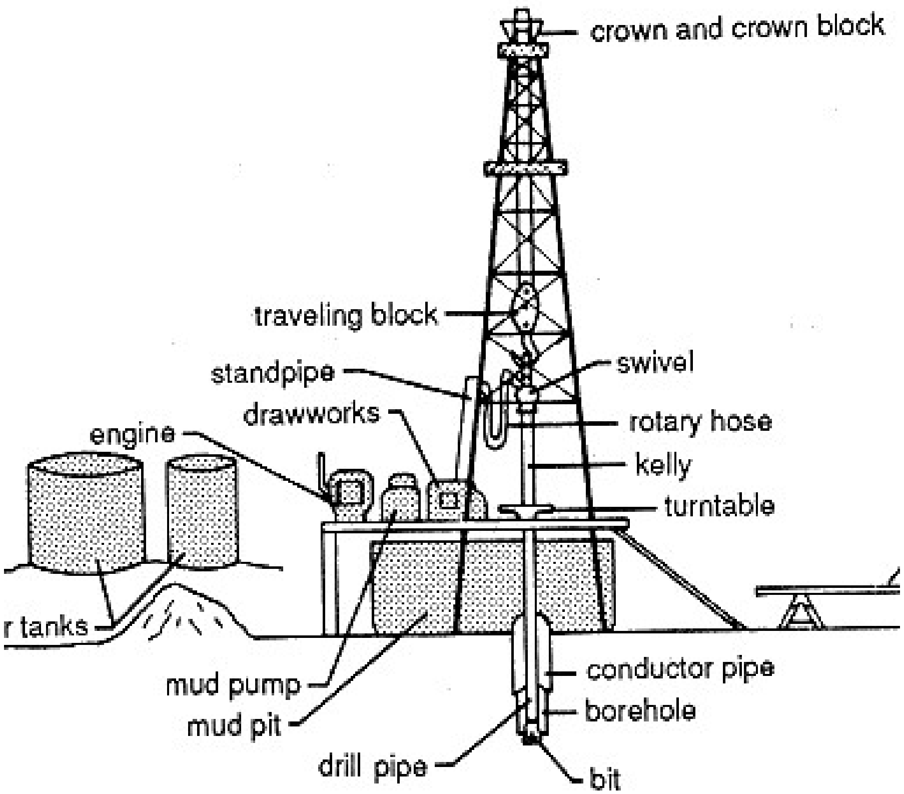
- They often contain corrosive fluids, and some formation fluids have very high solids content (TDS in some Imperial Valley brines is above 250,000 ppm).

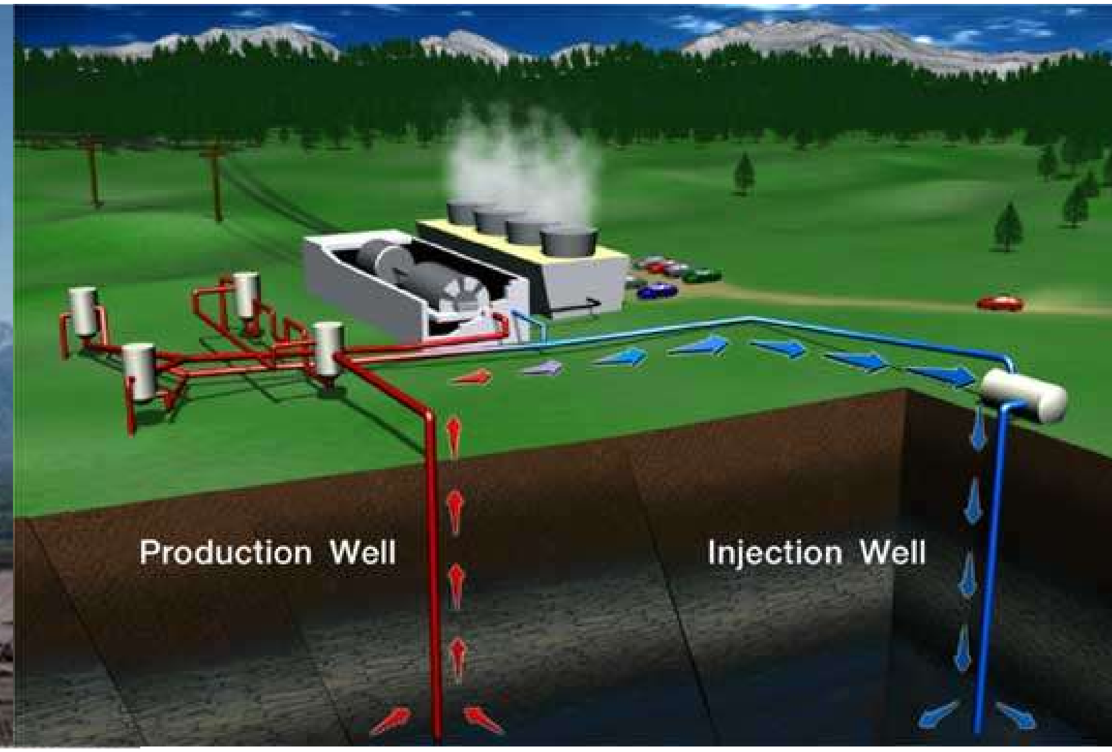
Nature of Geothermal Formations (2)

- Drilling is usually difficult—rate of penetration and bit life are typically low.
- Corrosion is often a problem.
- Common geothermal systems almost always contain dissolved or free carbon dioxide (CO_2) and hydrogen sulfide (H_2S) gases. H_2S in particular limits the materials that can be used for drilling equipment and for casing to the lower strength steels, because higher strength steels will fail by sulfide stress cracking. H_2S also presents a substantial safety hazard during the drilling process.
- These material limitations, and the associated safety hazards, increase the cost of drilling geothermal wells.
- Lost circulation is frequent and severe, and most of these problems are aggravated by high temperature.

Tapping the Resource

- A well – to bring the hot fluid to the surface;
- A mechanical system – piping, heat exchanger controls – to deliver the heat to the space or process; and
- A disposal system – injection well or storage pond – to receive the cooled geothermal fluid.





http://geothermal.marin.org/geopresentation/images/img031.jpg

Geothermal Wells: Temperature Gradient Heat Flow Wells

- Shallow (100 – 300 ft)
- 6 inch or smaller hole is typical
- Only requires a small drill rig
- Complete with 1-2 inch PVC or black iron pipe filled with water and annulus backfilled
- May be able to drill and complete two or three wells per day
- Costs $8/ft to $35/ft

Geothermal Wells: Slim-hole Exploration Wells

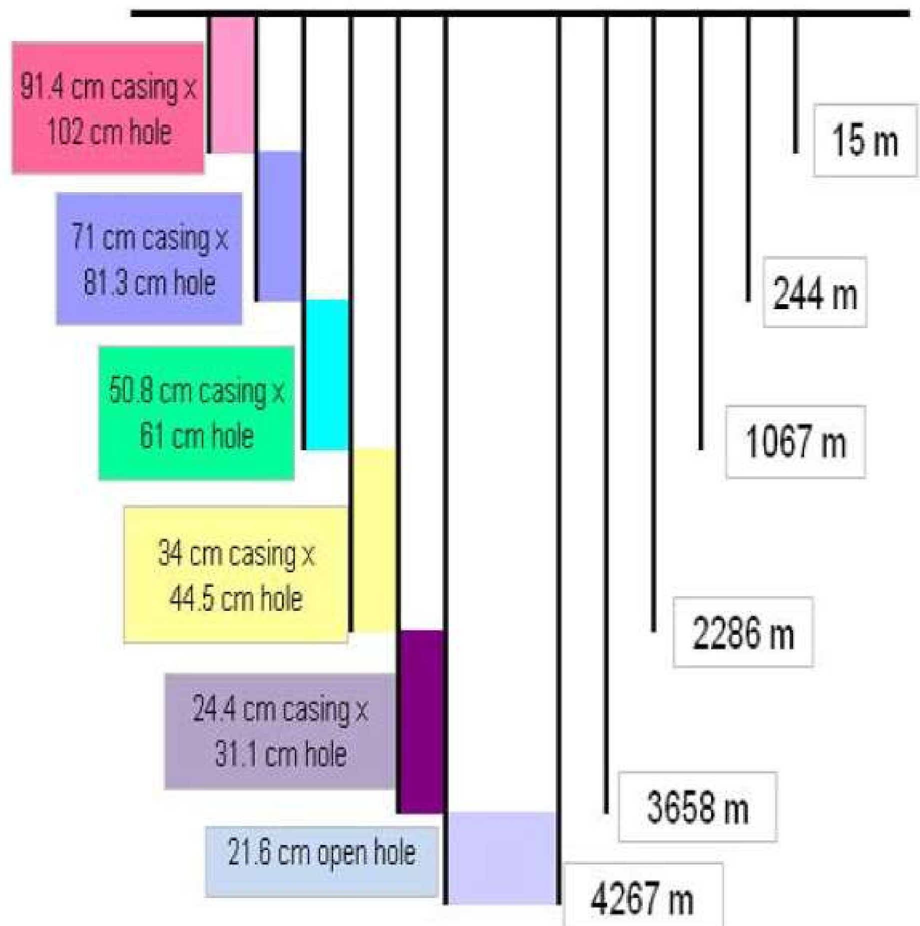
- Smaller diameter rotary holes
- 500 ft to 5000 ft depth
- Continuous wireline rotary core drilling
- Costs $75/ft to $150/ft

Geothermal Wells: Production and Injection Wells

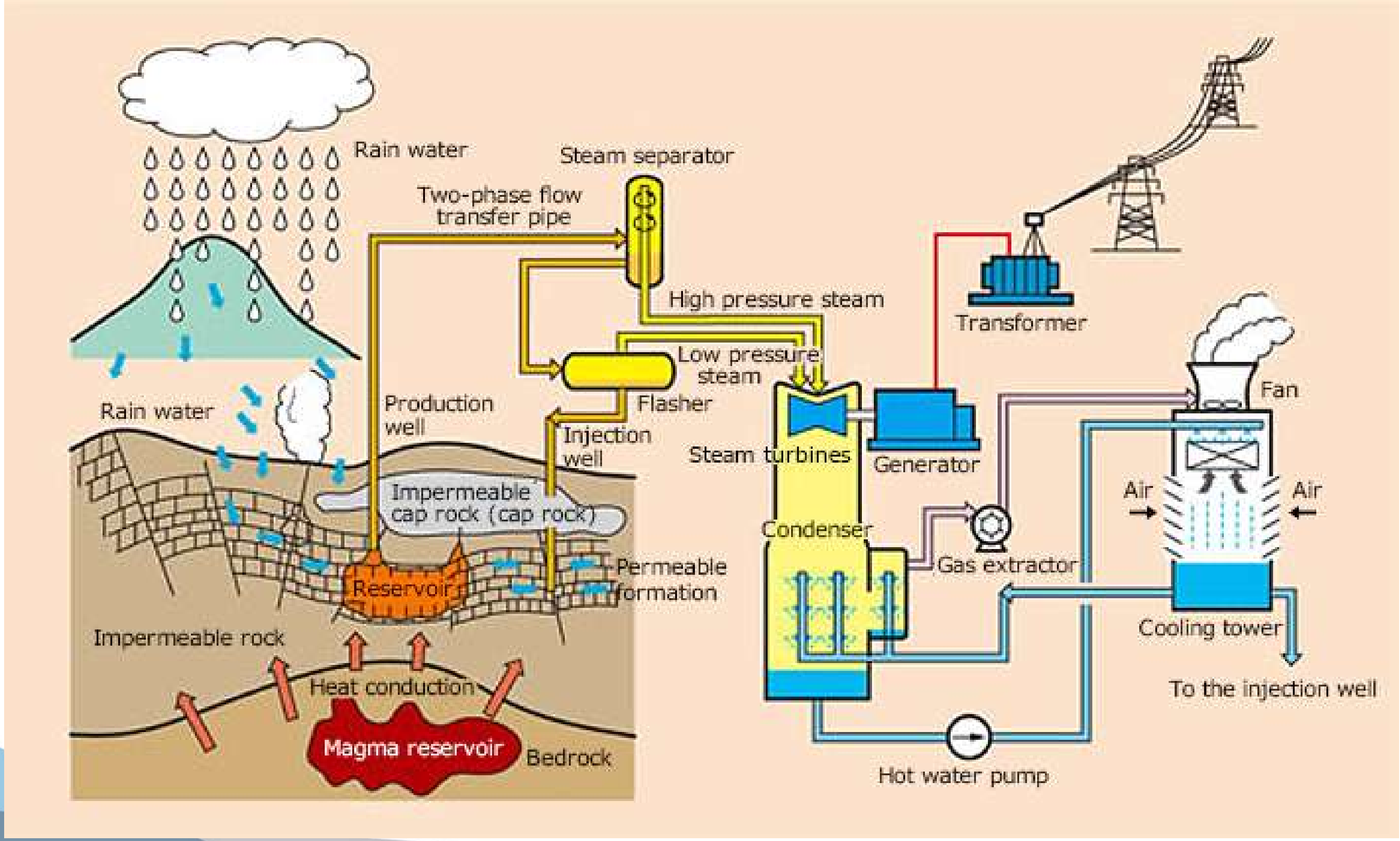
- Larger diameter
- Designed to host pump equipment
- Drilled to minimize formation damage
- Cost is highly variable - $75/ft to $400/ft

Well Design and Construction

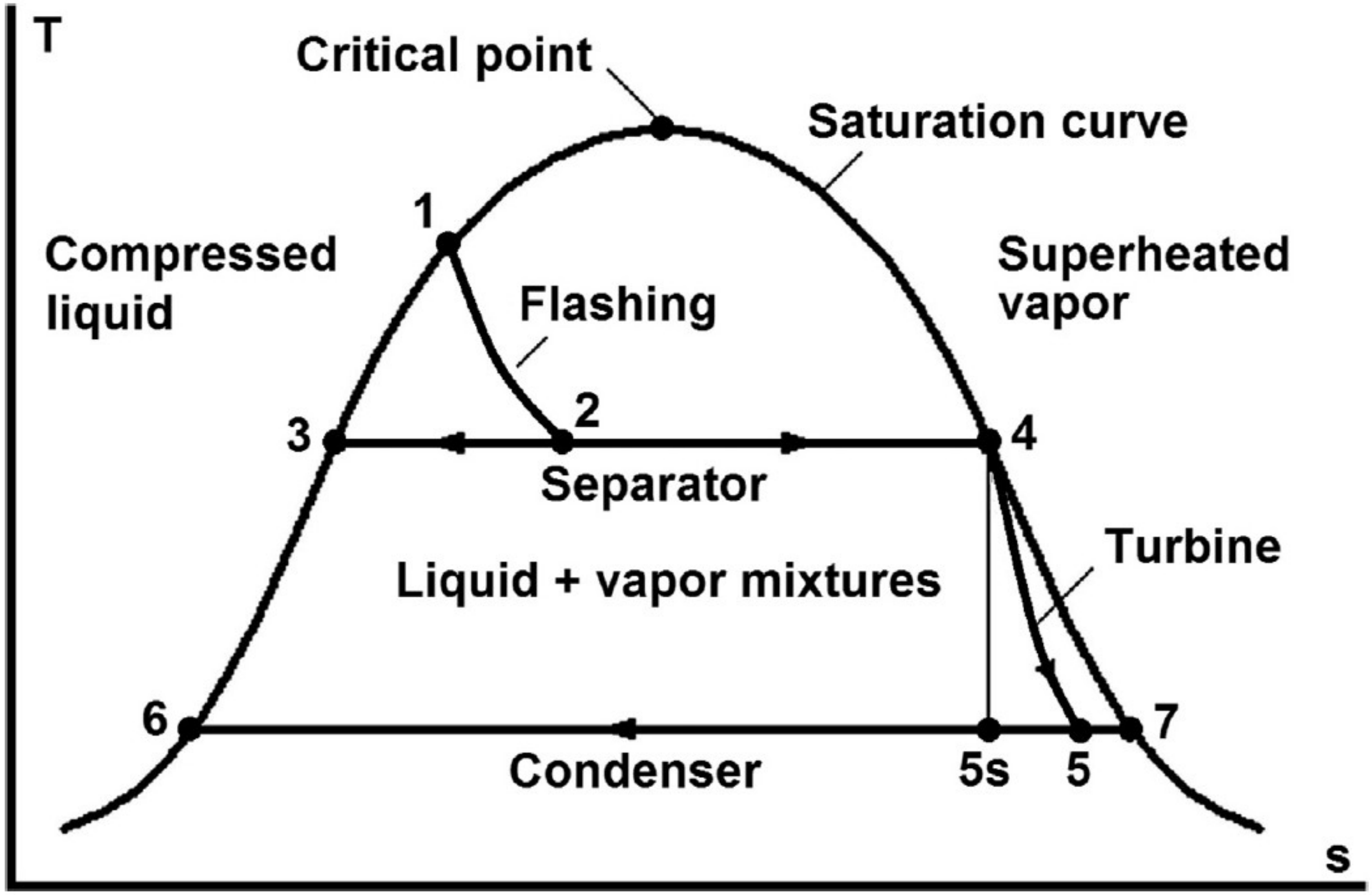
- Design of a geothermal well is a "bottom-up" process.
- Location of the production zone determines the well's overall length, and the required flow rate determines diameter at the bottom of the hole.
- Because of the large diameters in geothermal wells, casing and cementing costs form a relatively large share of the cost.



Surface Facilities



Temperature-entropy state diagram for single-flash plants



Power Plants

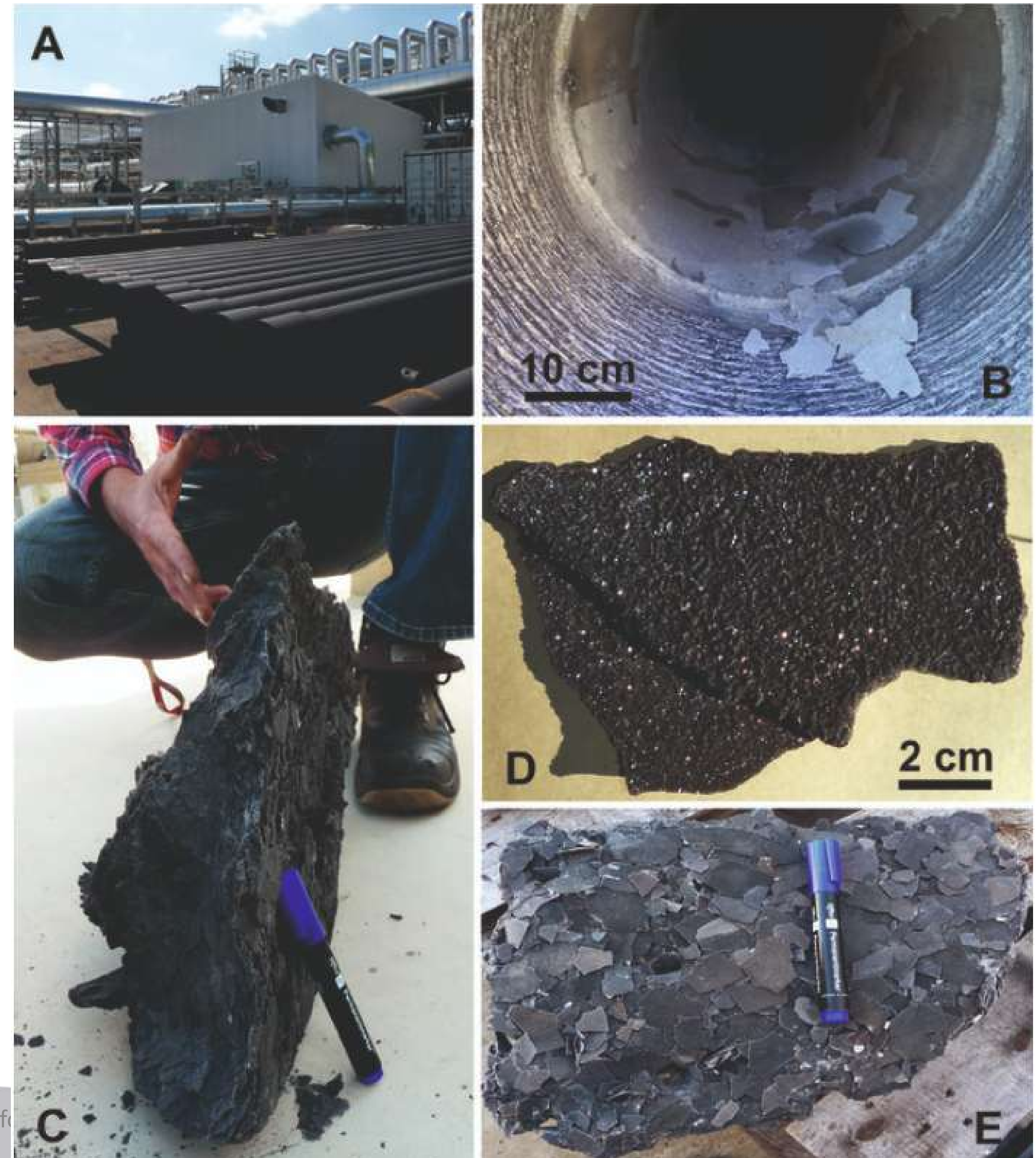
- https://www.youtube.com/watch?v=SPg7hOxFItI
- https://www.youtube.com/watch?v=XJH7AZG7J64

https://empoweringpumps.com/sulzer-on-site-overhaul-of-55-mw-geothermal-steam-turbine/

InterPore Academy

Scaling

- Scale forms in geothermal power plants when physical changes in process variables such as pH, temperature, and ion concentration cause minerals to exceed their thermodynamic solubility limit. This may cause mineral scale to form, thereby reducing flow and heat exchange.
- Management of Scaling:
  - Chemical Inhibitors
  - Mechanical and Chemical Cleaning



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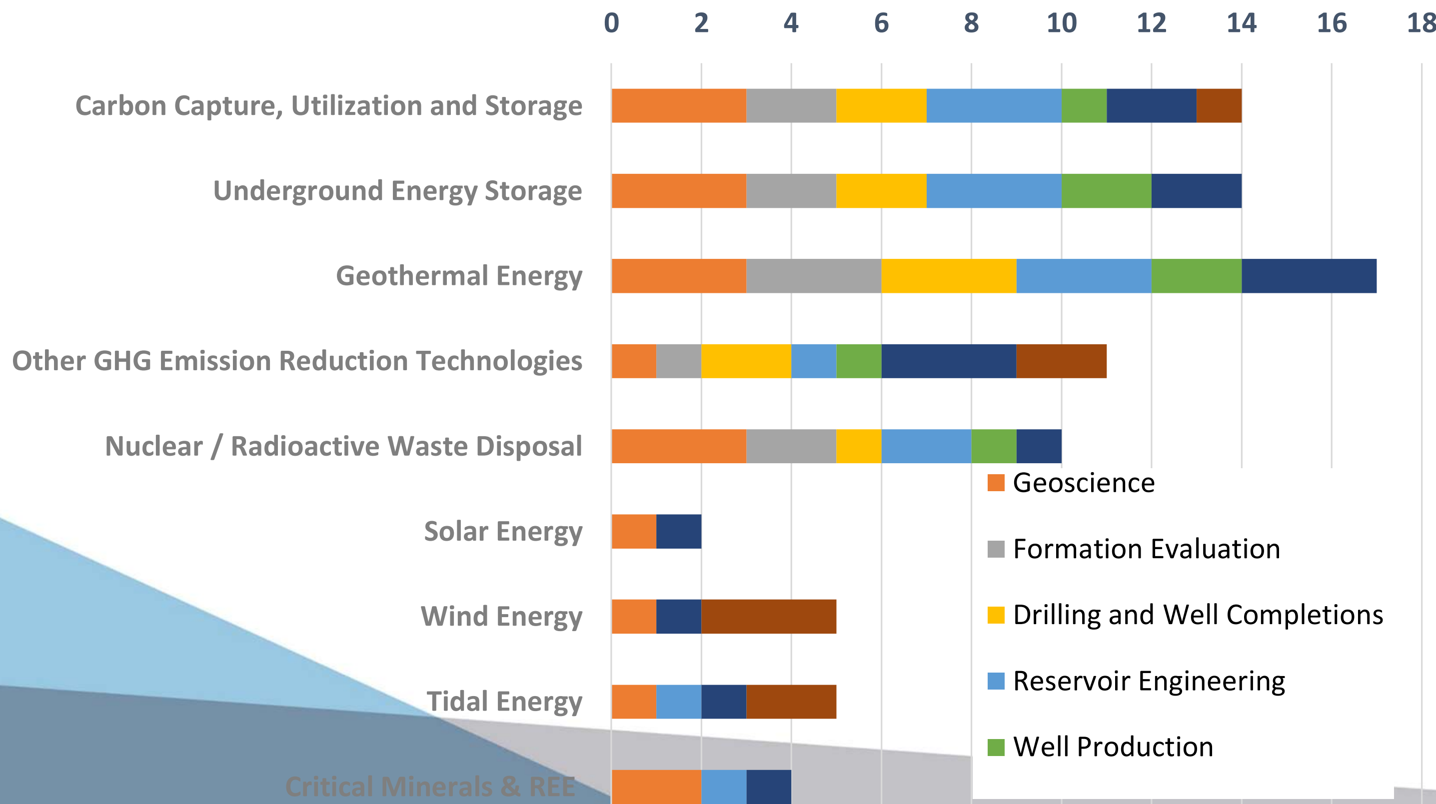
Mapping Skillsets for Low Carbon Energy Technologies

Both core and non-core oil and gas skills are transferable



Digital Skills enable energy efficiencies, improved safety, productivity, accessibility, and sustainability across the energy industry value chain

Non-Core Oil and Gas Competencies are relevant and transferable e.g.

- Health, Safety & Environment
- Project Management & Commissioning
- Supply Chain & Contract Management
- Human Resources Management
- Financial and Commercial Operations

https://jpt.spe.org/twa/transferable-skills-petroleum-engineering-and-geoscience-skills-are-shaping-the-low-emission-energy-transition

Estimating Power from a Geothermal Well

- Darcy equation for radial flow is used to estimate volumetric flow rate

$$q = \frac{2\pi kh}{\mu \ln(r_e/r_w)}(p_e - p_w)$$

- Assuming your well can produce 13,585.99 bbl/d of water. The fluid comes in at 200 °C, and the exit temperature is 25 °C. The specific heat capacity of the fluid is 4,000 J/(kg·°C), and the overall conversion efficiency of the power plant is 10%. Calculate the power that the well can supply.

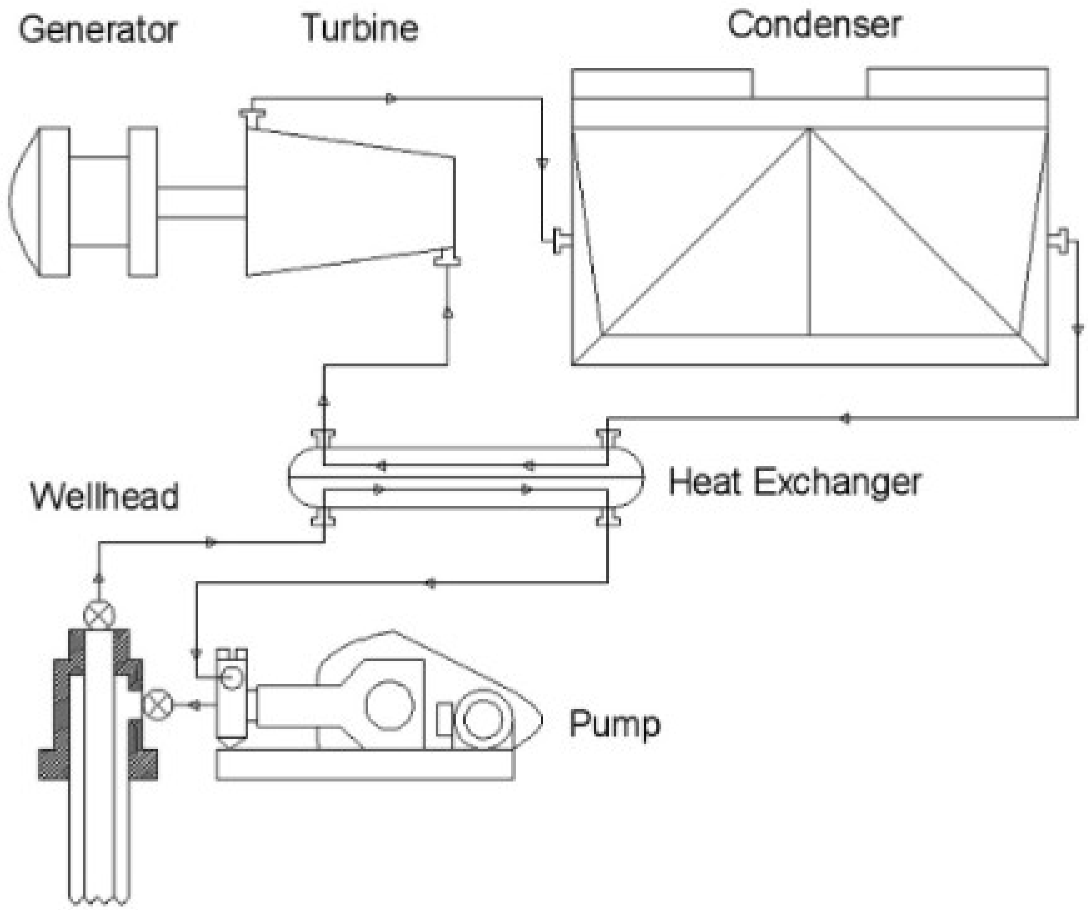
Estimating Power from a Geothermal Well

- 13 585.99 bbl/d = 25 kg/s
- ΔTemperature=Inlet Temperature−Outlet Temperature
- ΔTemperature=230°C−25°C=205°C

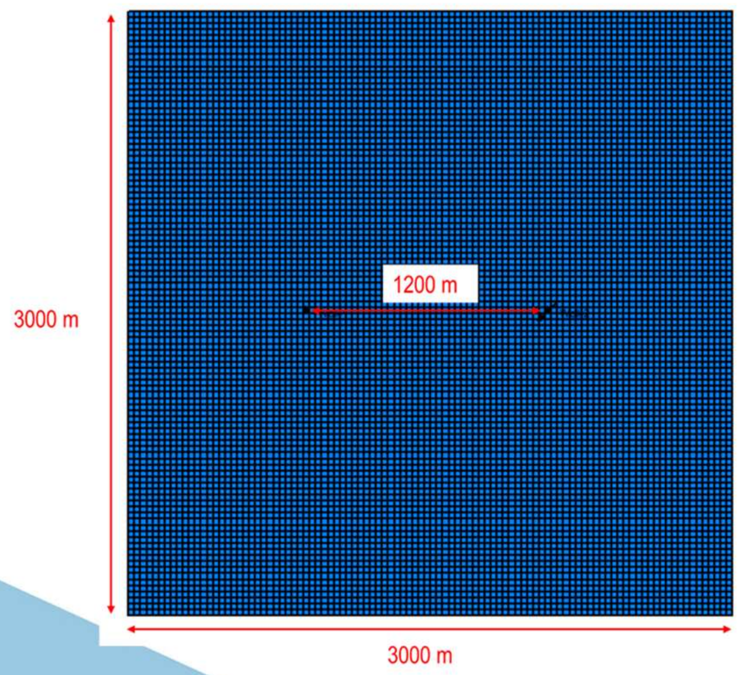
- Now, calculate the thermal power from the well:
- Heat rate=Mass Flow Rate×Specific Heat Capacity×Δtemperature
- =25 kg/s×4,000 J/(kg°C)×205° =2,050,000J/s

- Finally, calculate the electrical power:
- Electrical Power=Thermal power×Conversion Efficiency
- =2,050,000 J/s×0.10 =205,000W or 205 kW.

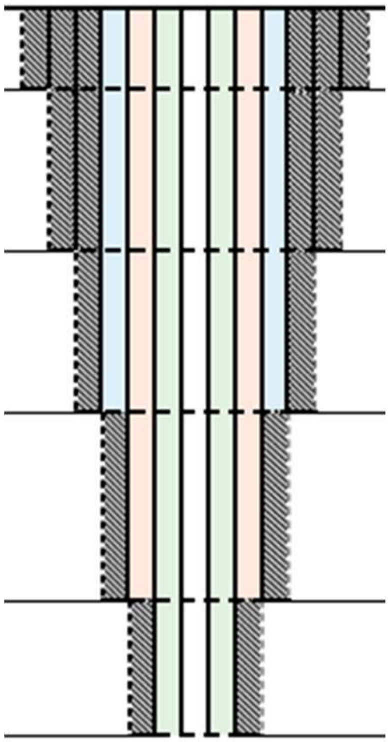
Abandoned Oil & Gas wells using water Net Power Estimation



Modeling Thermal Performance of Watered-out Wells

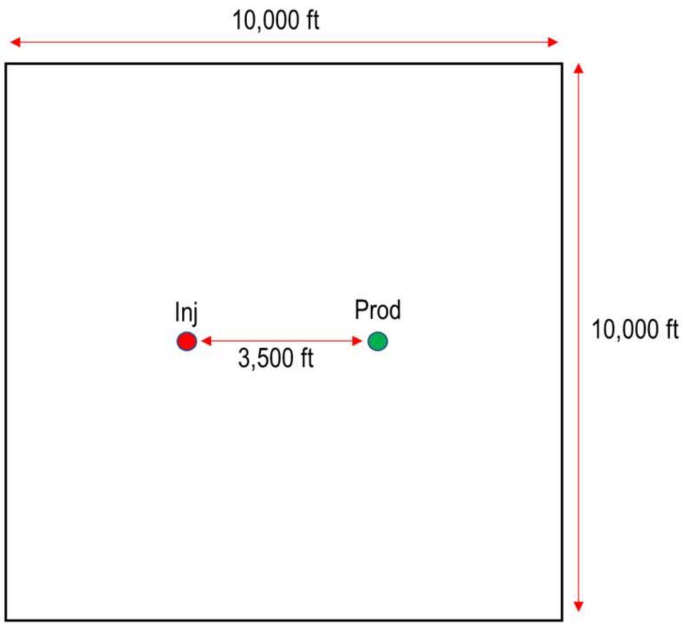


Reservoir Modeling



Wellbore Modeling

Reservoir Modeling



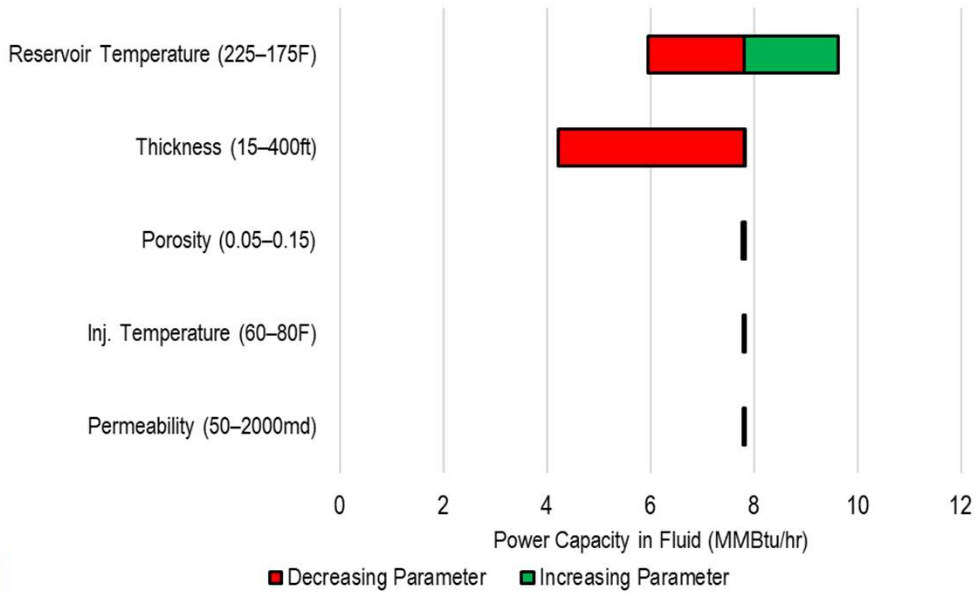
Base Model

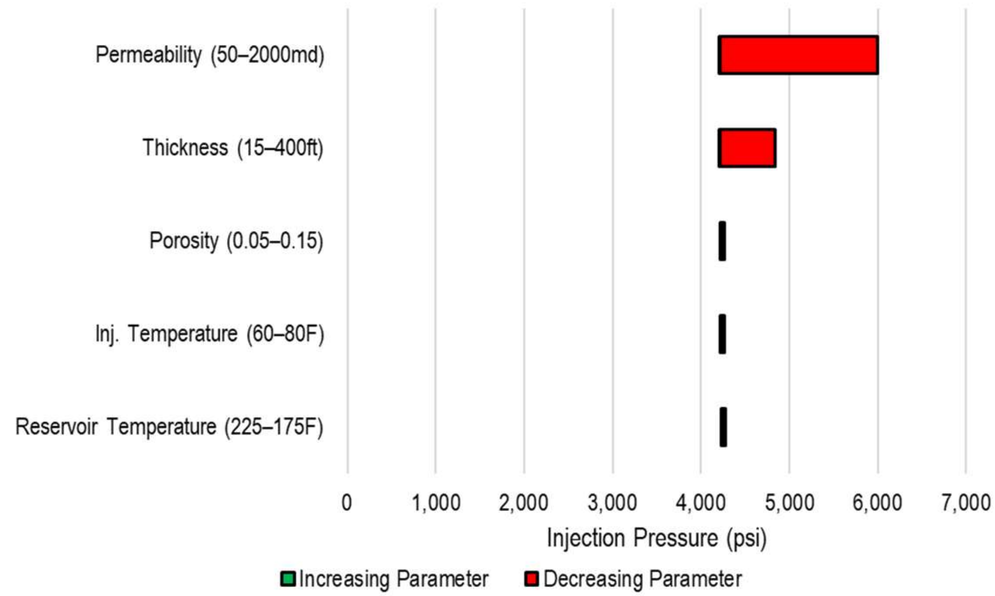
Symbol	Description	Value	Units
T_R	Reservoir temperature	250	F
φ	Porosity of the rock matrix	0.10	Fraction
k_h	Horizontal permeability	250	mD
k_v	Vertical permeability	$0.1k_h$	mD
C_r	Rock specific heat capacity	0.28	Btu/(lb.F)
ρ_r	Rock density	162	lb/ft^3
h	Reservoir thickness	400	ft
p_{frac}	Fracture parting pressure	6000	psi
$\bar{p}$	Average pore pressure	4000	psi
T_w	Injected water temperature	60	F
C_w	Water specific heat capacity	1	Btu/(lb.F)
C	Water compressibility	3×10^{-6}	psi^{-1}

Sensitivity ranges

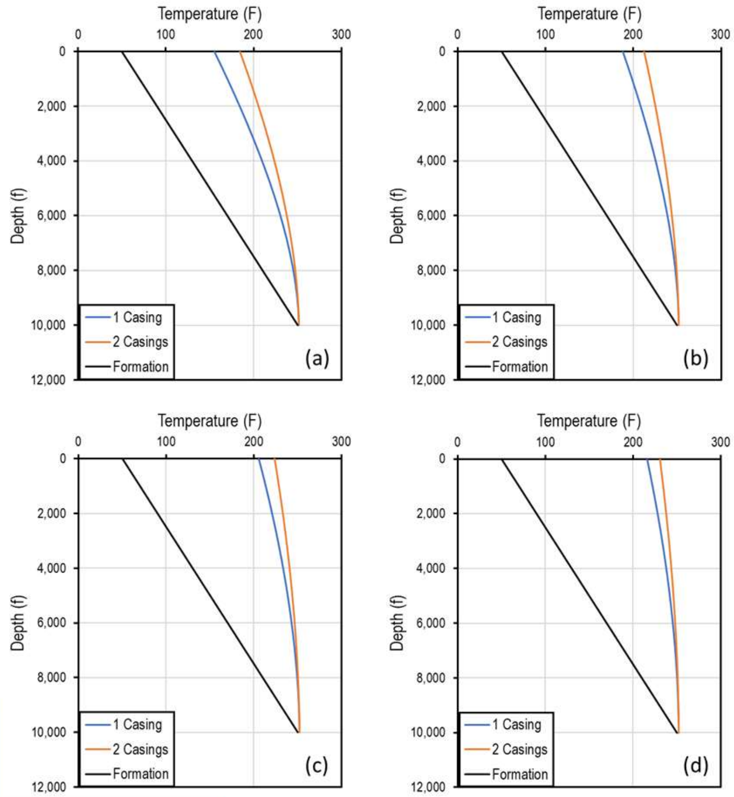
Parameter	Unit	Min	Max
Permeability	mD	50	2000
Porosity	Fraction	0.05	0.15
Thickness	ft	15	400
Injected Fluid Temperature	F	60	80
Reservoir temperature	F	225	275

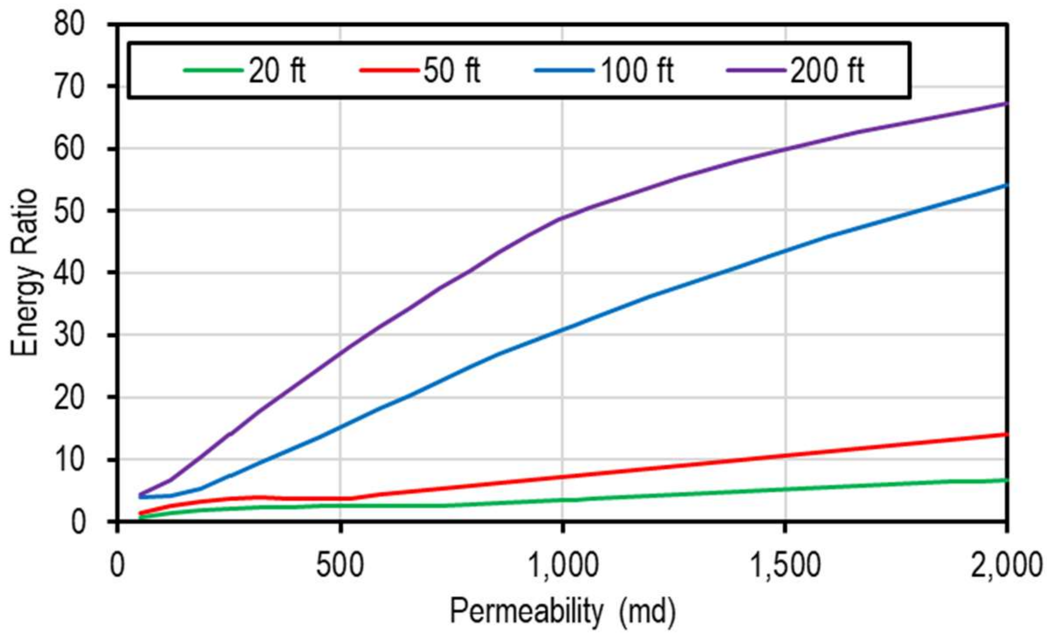
Modeling Results (1)





Modeling Results (2)





The figure shows the temperature profile for (a) 5,000 bbl/d, (b) 10,000 bbl/d, (c) 15,000 bbl/d, (d) 20,000 bbl/d.

Key Takeaways

- Reservoir Temperature and Thickness: These are the main factors influencing the selection of reservoirs for geothermal energy production. The temperature affects potential, while thickness and permeability control thermal breakthrough and well injectivity.
- Well Schematics and Heat Losses: The study examines how the well's design influences heat losses within the wellbore. Large casings are recommended to minimize parasitic pressure losses, but high fluid velocity is also needed to reduce heat losses.
- Velocity and Surface Temperatures: Flowing wells at higher velocities lead to higher surface temperatures, reducing the residence time of the fluid in the wellbore.
- Wellbore Schematic's Secondary Role: The wellbore schematic (number of casings and depths) mainly affects heat loss at lower fluid velocities. At higher velocities, it plays a secondary role to reservoir properties.

Parameter	Low rates	High rates
Reservoir temperature (depth/ gradient)	High	High
Reservoir thickness	Moderate	High
Reservoir permeability	Moderate	High
Reservoir porosity	Low	Low
Injected fluid temperature	Low	Low
Number of casings	High	Low
Depth of casings	High	Low

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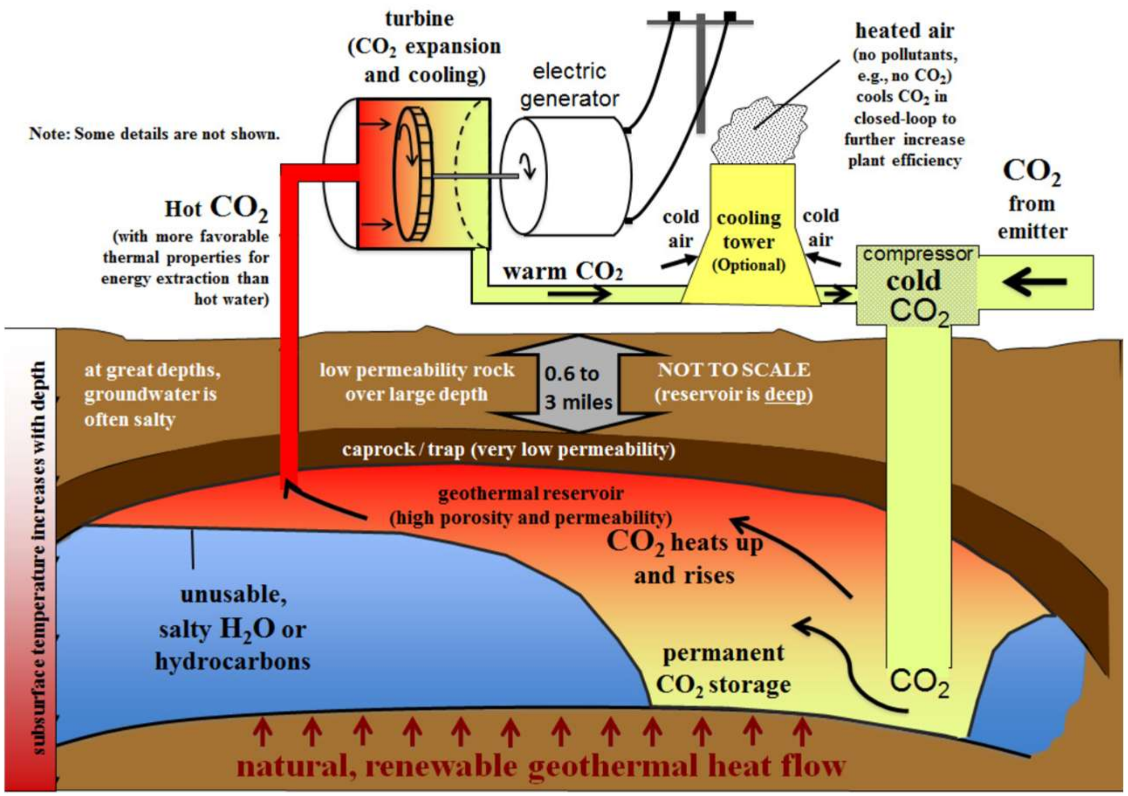
CO_2 Plume Geothermal (CPG)

- **Why CO_2**
- Self-convecting thermosiphon (Capability to self-circulate)
- (**Thermosiphon** (or **thermosyphon**) is a method of passive heat exchange, based on natural convection, which circulates a fluid without the necessity of a mechanical pump.)

- Low Viscosity
  - Reduce frictional losses through the reservoir
  - Enables electric power generation from reservoirs of low permeability and temperature
- Carbon Storage --- Save our environment!

Uniqueness of CPG

- Utilize sedimentary rock reservoirs
  - Naturally porous and permeable, ubiquitous worldwide
  - Non-fracture-based flow fields provide large specific areas in contact with the flowing CO2 --- Increase heat transfer

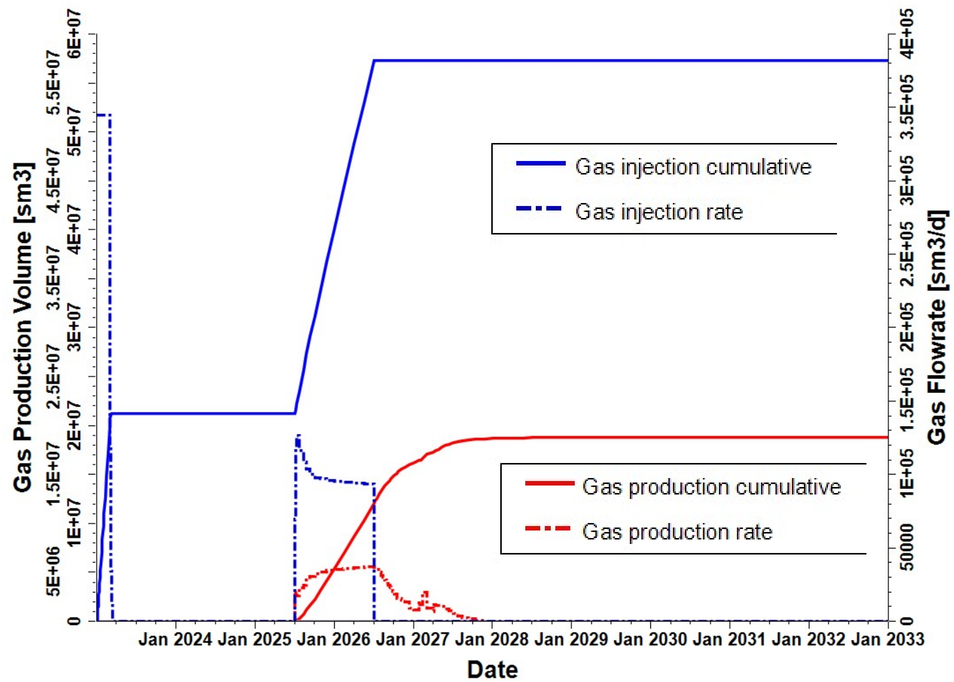


http://dx.doi.org/10.1016/j.renene.2020.11.145

Modeling of CPG

Parameter	Value	Unit
k_h	10, 50, **250**, 500, 1000	md
k_v/k_h	0.1, 0.2, **0.3**	frac
Φ	0.1, **0.2**, 0.3	frac
Kr	**1**, 1.5, 4.2	W/m/K
Cr	0.84, **1**, 1.5	kJ/kg/K
ρr	2200, **2650**, 2800	kg/m3
γ	0.02, **0.032**, 0.04	°C/m
h	20, 40, **60**, 80, 100	m
D	1000, **1500**, 2000, 2500	m
δ	**0**, 2, 5, 10, 15	°

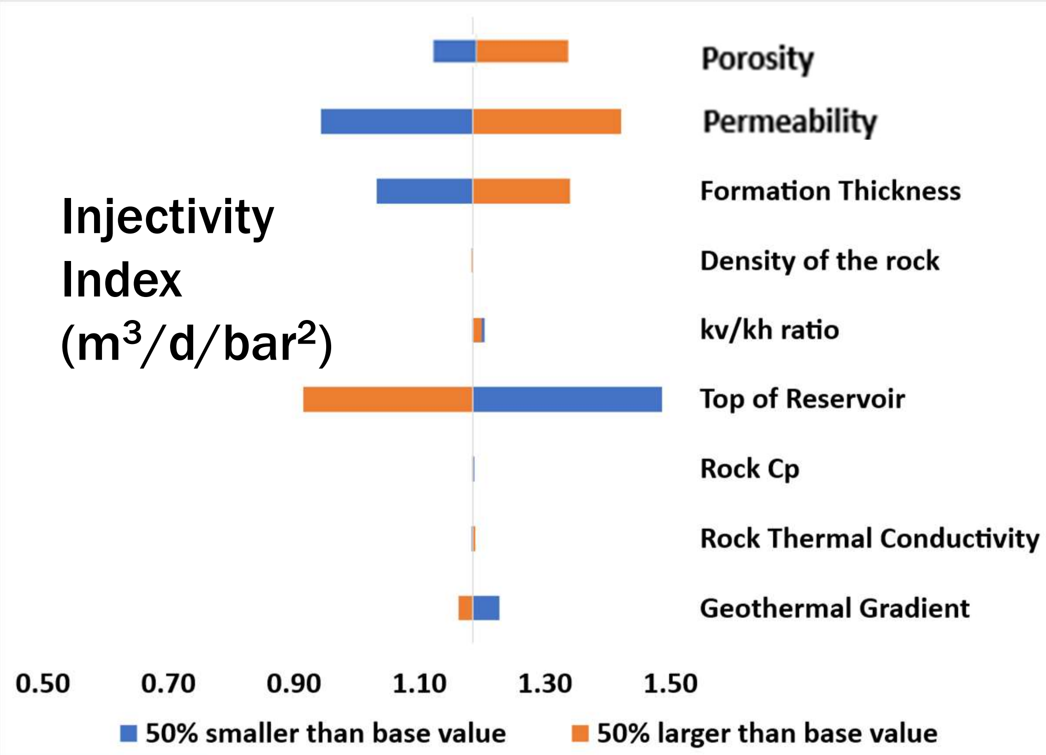
Parameters for Sensitivity Study

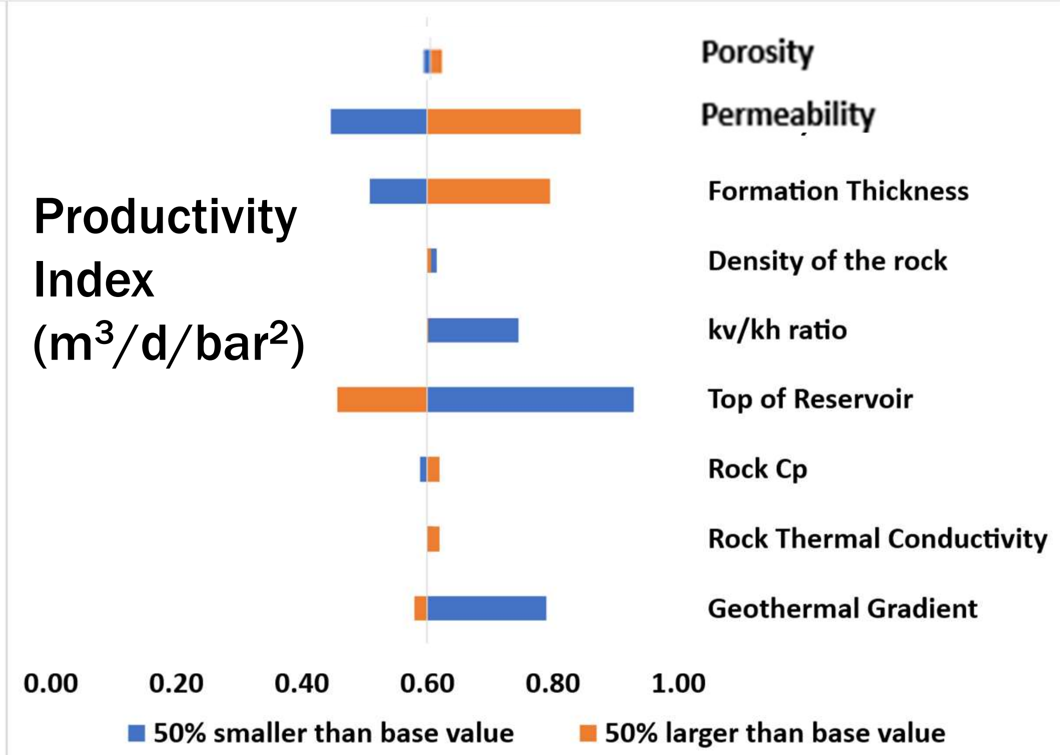


Parameters for Geomechanics Study

Symbol	Description	Value	Units
E	Rock Young's Modulus	15	GPa
ν	Poisson's Ratio	0.25	-
α	Linear thermal expansion coefficient of rock matrix	13×10^{-6}	1/K
UCS	Unconfined compressive strength	1000	bar
β	Biot elastic constant	0.5	-
θ	Friction angle	35	º

Results

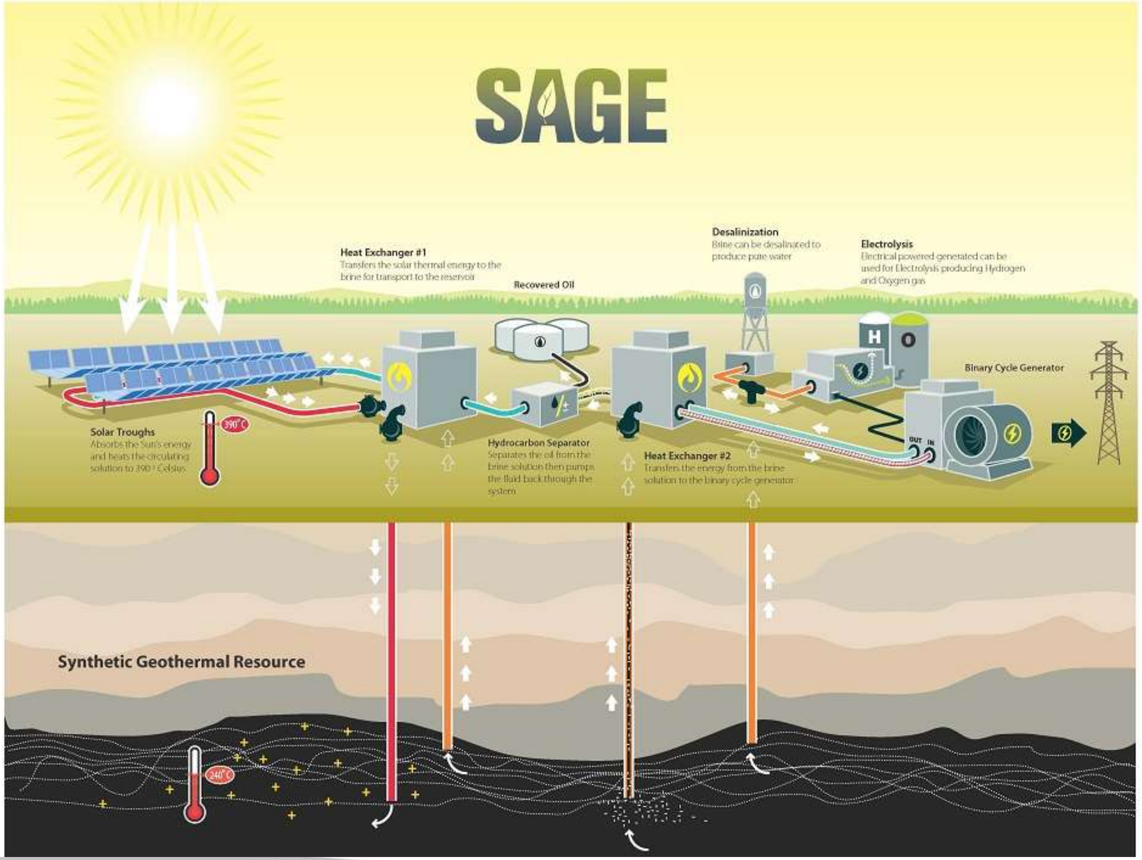




- The injectivity index in general was larger than the productivity index.
- Depth, permeability, and formation thickness were top-impacting parameters.

Synthetic Geothermal Reservoirs

- Uses solar radiance to heat water on the surface which is then injected into the earth.
- This hot water creates a high temperature geothermal reservoir acceptable for conventional geothermal electricity production, or for direct heat applications. Applied to sedimentary basins with formations that are water saturated and exhibit high porosity and high permeability.



https://www.sciencedirect.com/science/article/pii/S0960148120315081

Day 4 Project Presentation

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https://www.freepik.com/free-vector/business-meeting-project-presentation-people-corporate-seminar-team-group-vector-illustration_11060805.htm

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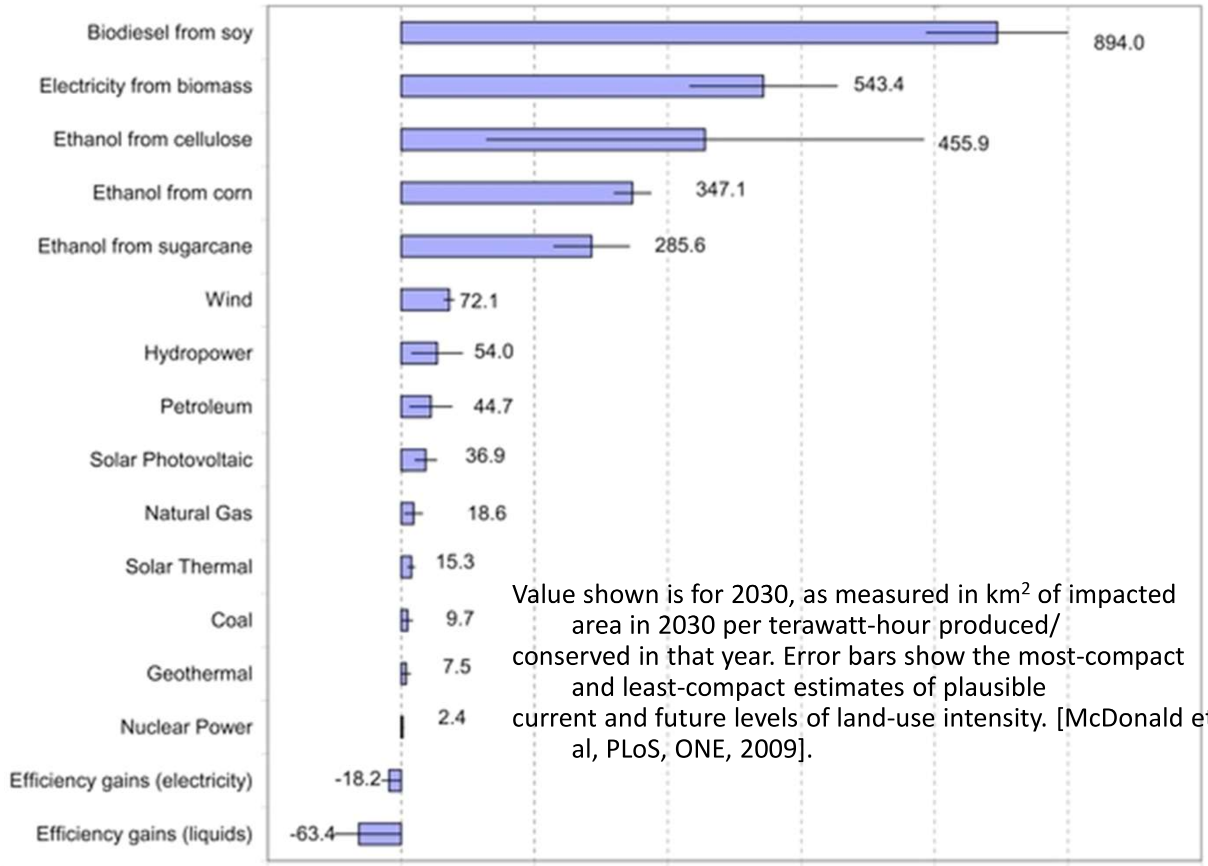
Another Advantage of Geothermal Energy

- Base-load (large capacity factors)
- Low emissions
- Small land-use
- Ubiquitous resource
- Large resource



Value shown is for 2030, as measured in km² of impacted area in 2030 per terawatt-hour produced/ conserved in that year. Error bars show the most-compact and least-compact estimates of plausible current and future levels of land-use intensity. [McDonald et al, PLoS, ONE, 2009].

Geothermal Plants Globally

The Geysers, CA

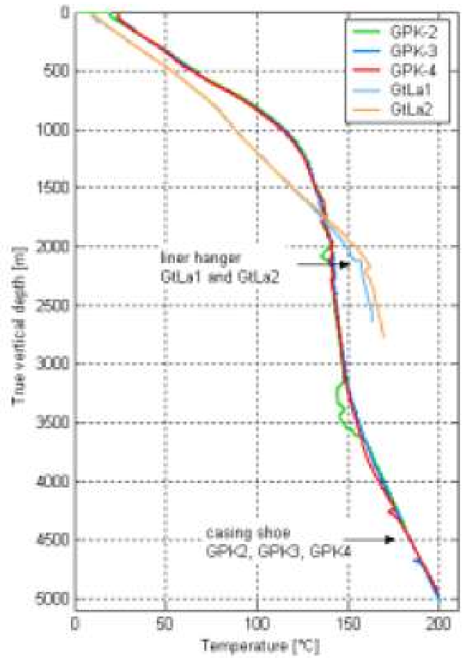
Geothermal Plants Globally

The Geysers, CA

Geothermal Plants Globally

Landau, Germany

- 70 kg/s flow, 175°C, 3MWe (Schellschmidt, Sanner, Pester, Schulz, WGC2010). Operating since 2007.



www.geox-gmbh.de

53

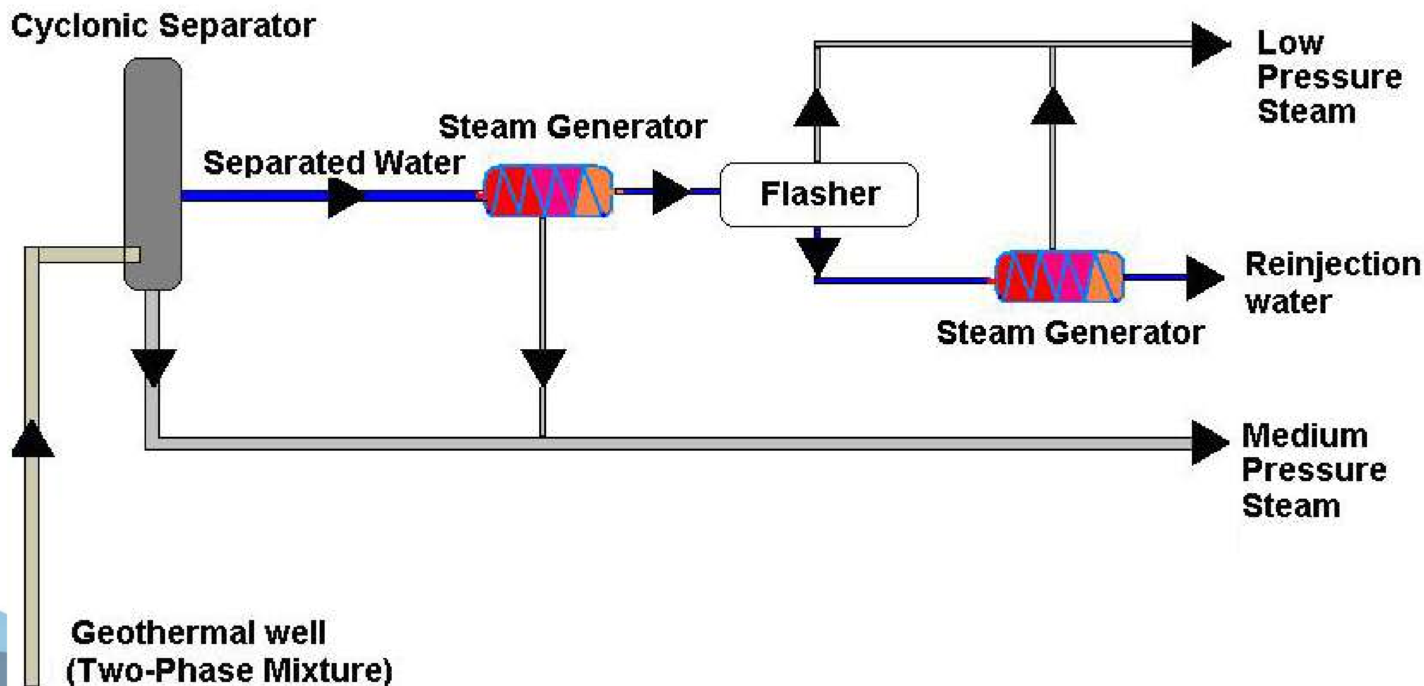
Geothermal and Solar Thermal Hybrids

- Ahuachapán, El Salvador, well AH-6.

Handal et al., 2007

Geothermal and Solar Thermal Hybrids

- Ahuachapán, El Salvador, well AH-6.



Alvarenga et al., 2008

Geothermal and Solar Hybrid

- 24-megawatt solar installation at Stillwater Geothermal Plant in Churchill County, Nevada, for peak addition to the 47 MW geothermal plant. Also includes 17 MW of concentrating solar power (CSP) parabolic troughs, using water as a circulating fluid.

Photo: Kasama Itthisawatpan, 2012

Geothermal and Solar PV Hybrid

- 24-megawatt solar installation at Stillwater Geothermal Plant in Churchill County, Nevada, for peak addition to the 47 MW geothermal plant.

Photo: Roland Horne, 2012

Puna, Hawaii – dispatchable power

Photo: Alamy

InterPore Academy

Rotokawa

Photo: Mighty River Power

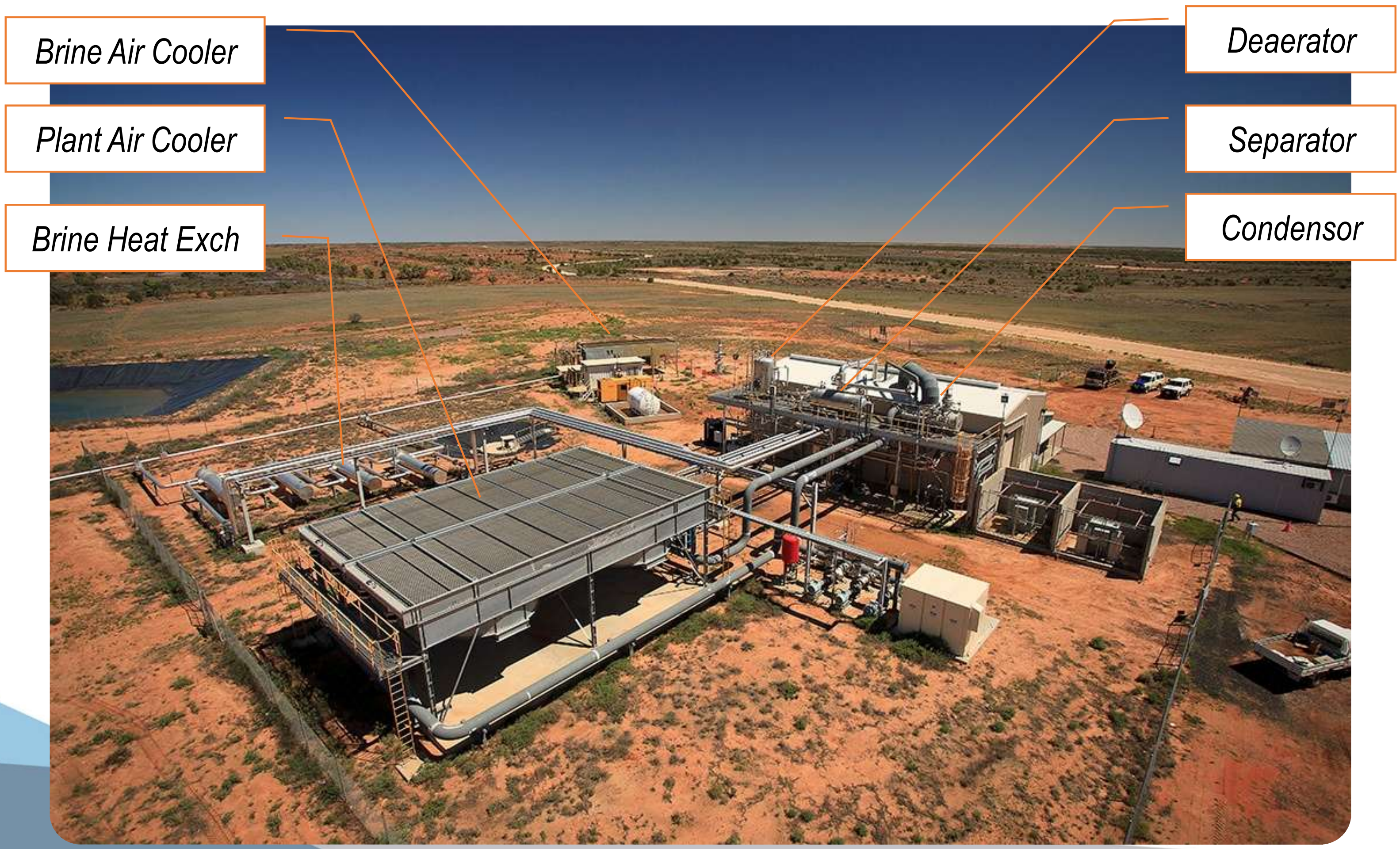
Cooper Basin, Australia

- March 2005: 20 kg/s at 210ºC. Later 30 kg/s.
- November 2012: Habanero 4 at 35 kg/s at 242º
- May 2013: in operation at 1 MWe.


Habanero #2 well – Cooper Basin
First HFR geothermal steam produced in Australia during clean-up flow test
23 April 2005

Hutchings and Wyborn, NZGW 2006

1MW Plant – Cooper Basin, Australia



Geodynamics (2013)

Lower Resource Temperatures

- Chena Hot Springs (74°C)

Photo: Roland Horne, 2007

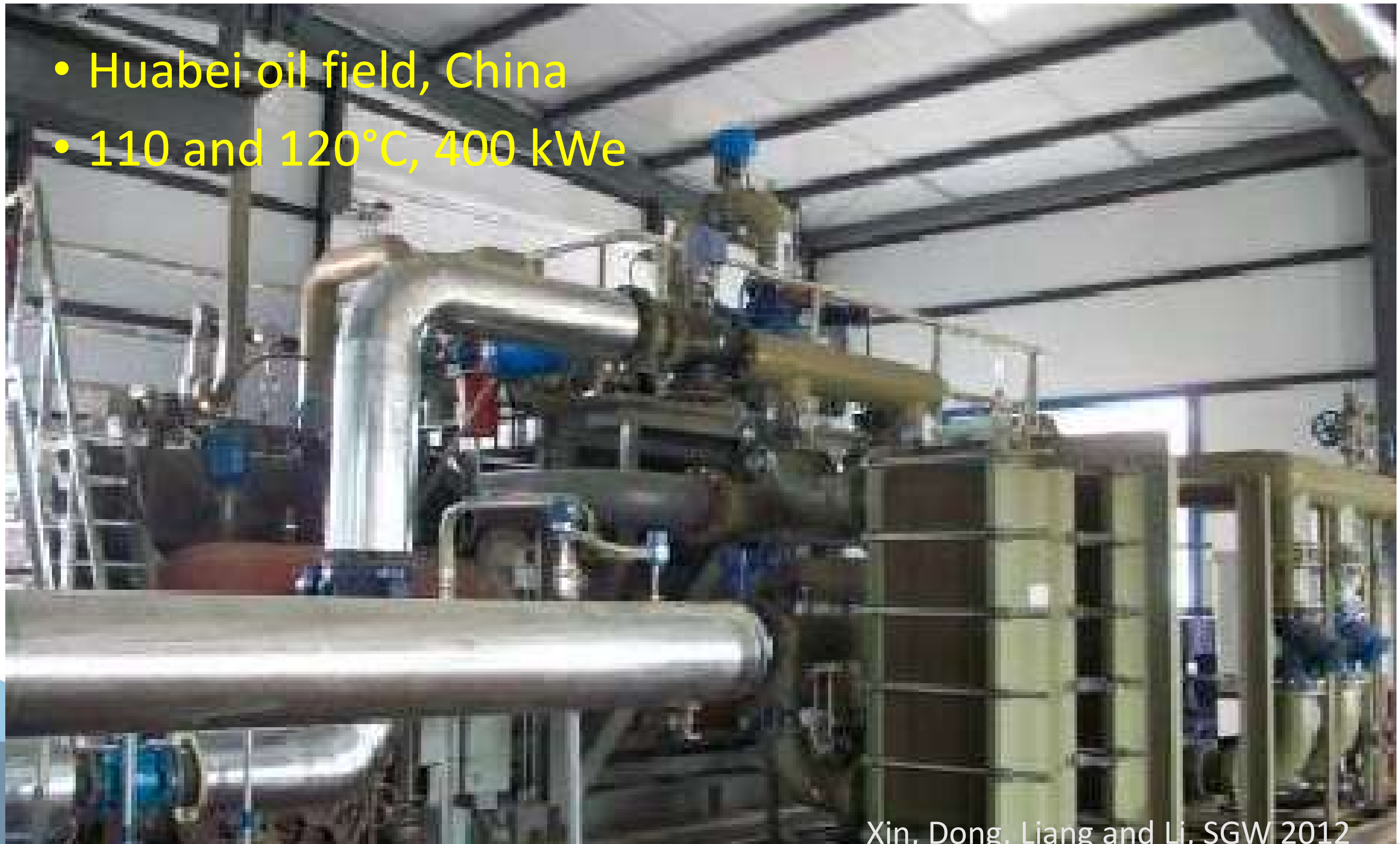
Coproduced Fluids

- Rocky Mountain Oilfield Testing Center
- 46 kg/s flow, 92°C, 216 kWe
- (25,000 bbl/day)

Walker and Johnson, SGW 2010

Coproduced Fluids

- Huabei oil field, China
- 110 and 120°C, 400 kWe



Xin, Dong, Liang and Li, SGW 2012

Thank you

Dr Rita E. Okoroafor
https://www.linkedin.com/in/rita-esuru-okoroafor-ph-d-19232b7/