Geothermal 101–
The Heat Beneath Our Feet

Dave R. Boden, PhD, CPG
Professor Emeritus of Geoscience
Truckee Meadows Community College
dboden@tmcc.edu

GRC

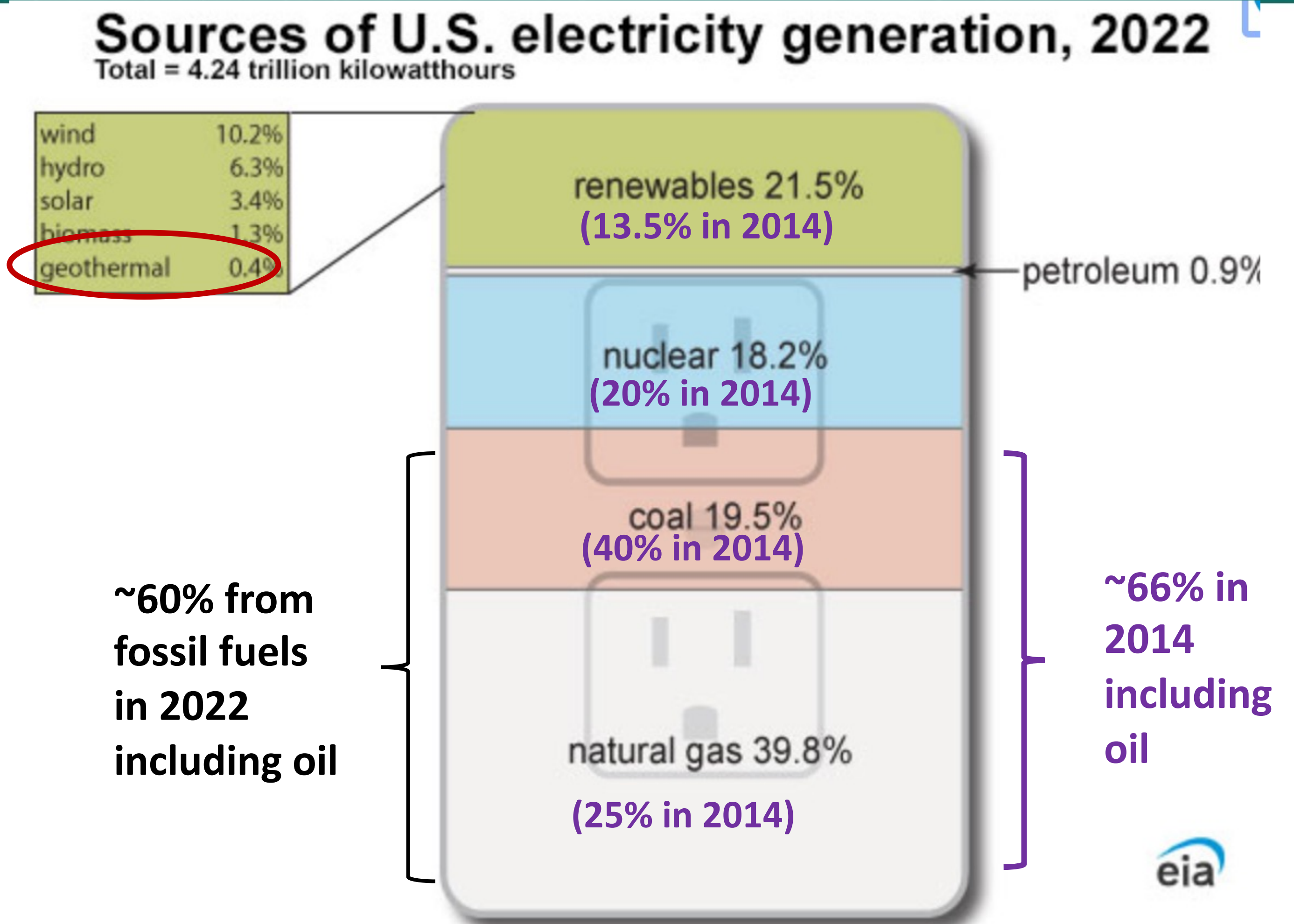
GEOTHERMAL RISING CONFERENCE
OCTOBER 1-4, 2023 • RENO, NV

Agenda

- Some background: What are current sources of electricity and how are energy and power related?
- Where does Earth's heat come and how does heat move?
- What is geothermal energy and how does depth and temperature impact use of geothermal energy?
- What criteria are needed to make a geothermal fluids viable for development?
- What are some key attributes and challenges of geothermal energy?
- Where are most developed geothermal systems found?
- What makes the Great Basin of the western U.S. so prospective for geothermal energy?
- What are some exciting new technologies for expanding geothermal energy, including recovery of critical minerals?

Some Background on Current and Recent Past Sources of Electricity Generation

- In CA, geothermal electricity accounted for about 6% of state's electrical production (CEC report, 2020)
- In Nevada, geothermal accounted for ~10% of state's electrical generation **(Highest per capita usage of geothermal energy in the U. S.!)**

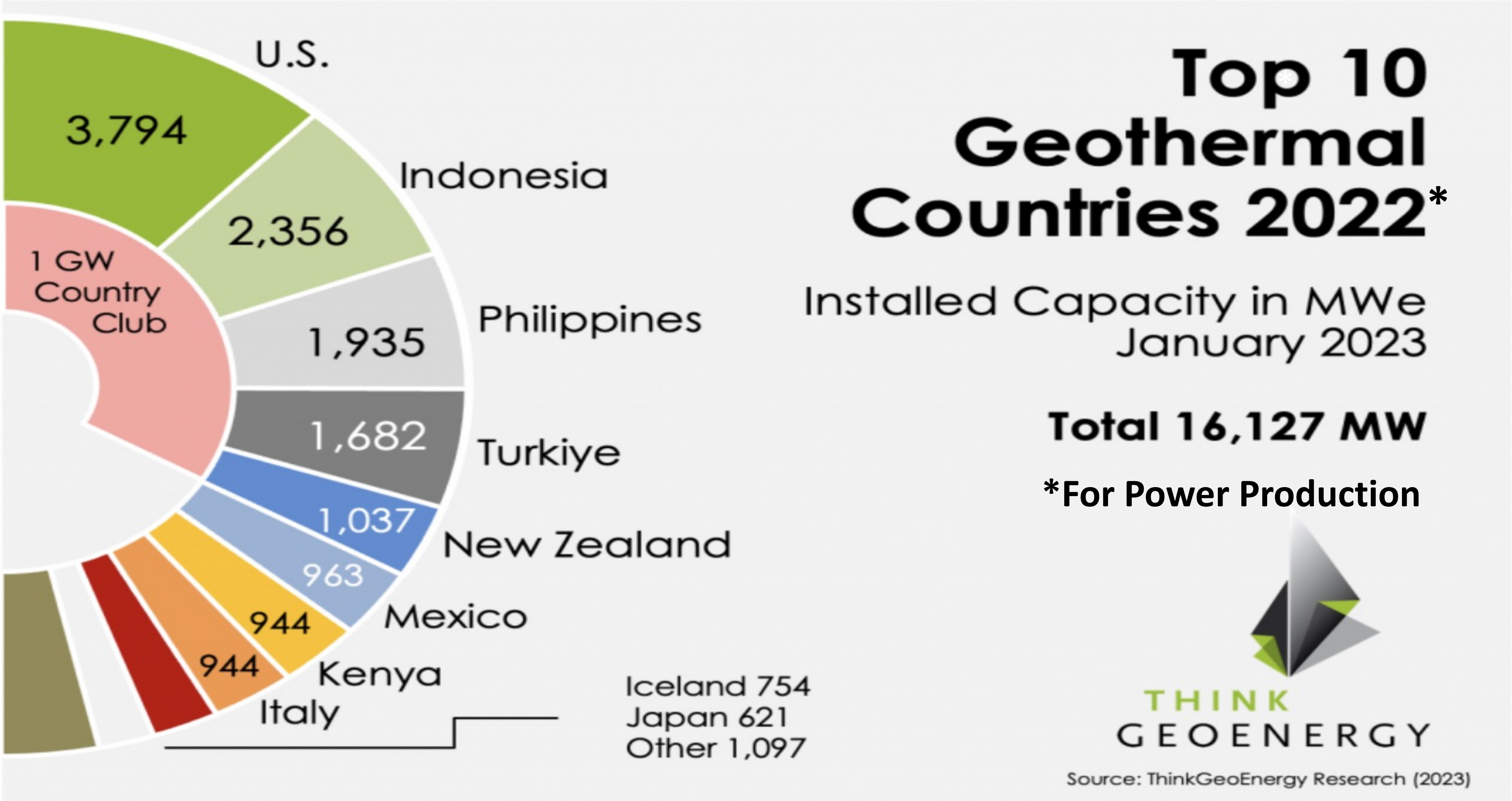


Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2023, preliminary data
Note: Includes generation from power plants with at least 1,000 kilowatts of electric generation capacity (utility-scale). Hydro is conventional hydroelectric. Petroleum includes petroleum liquids, petroleum coke, other gases, hydroelectric pumped storage, and other sources.

Boden 2023

Measuring Energy and Power

- Basic unit of **Energy is Joule**; basic unit of **Power is Watt**
- **1 Watt of Power** = **1 Joule** per second (**P** = **E**/t)
  - One kiloWatt (1 kW) = 1000 Joules/second; one MegaWatt (1 MW) = one million joules/s
  - MW is typically used in rating delivery of energy output of power plants or rate of energy output for geothermal wells
  - **One MW of power serves about 850 homes**
- **Energy = Power** x time → kiloWatt x time (in power industry unit of time is hour)→ kWh on your power bill
  - Energy generated from power plants measured in **MegaWatt-hour (MWh)** or **GigaWatt-hour (GWh)** → Palo Verde nuclear plant in Arizona (4.0 GW of power x 24 hrs/day = 98 GWh of energy per day)
    - Serves 70% of AZ energy needs and no GHG emissions!


U.S.
3,794
Indonesia
2,356
1 GW
Country
Club
Philippines
1,935
Turkiye
1,682
New Zealand
1,037
963
Mexico
944
Kenya
944
Italy
Iceland 754
Japan 621
Other 1,097
Top 10
Geothermal
Countries 2022*
Installed Capacity in MWe
January 2023
Total 16,127 MW
*For Power Production
THINK
GEOENERGY
Source: ThinkGeoEnergy Research (2023)

Boden 2023

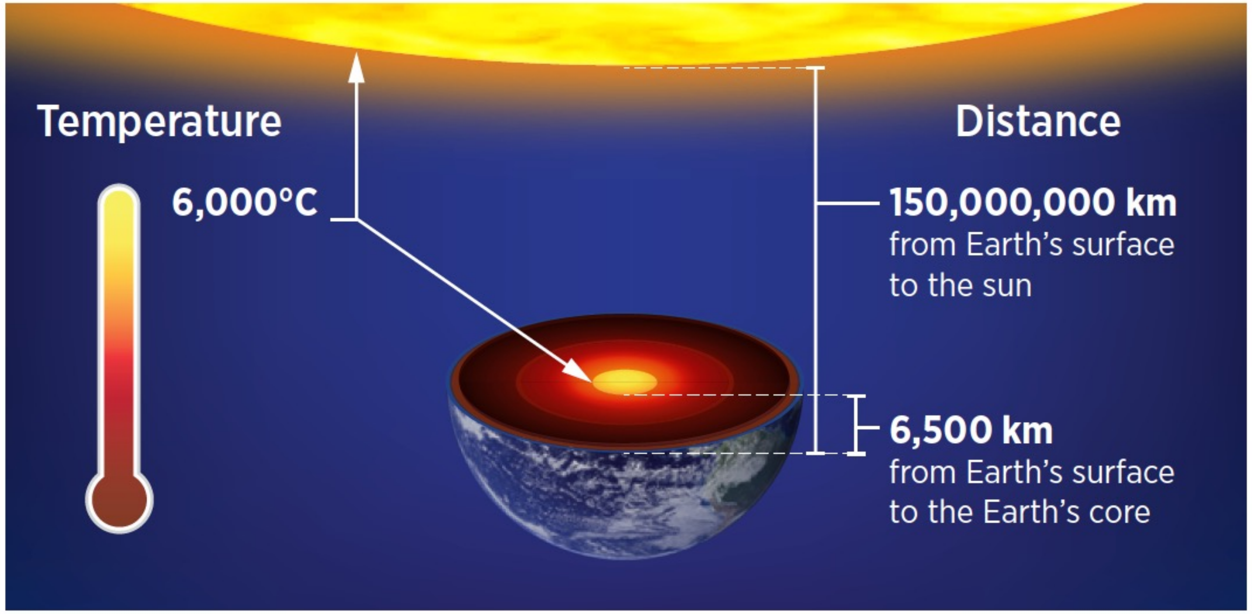
Earth's Interior Contains Heat

- Earth is a giant heat engine→ ability to do work
- What might be examples of this work?
  - Erupting Volcanoes
  - Earthquakes
    - 2011 9.0 M Tohoku EQ heaved ~1500 km of ocean floor 50 m (*released enough energy in a few seconds to power Los Angeles for an entire year or could satisfy the energy consumption of the U. S. for about 2 months!*)
  - Continually moving great chunks of Earth's crust and upper mantle over great distances for a long time (heat energy that drives plate tectonics)
- Thermal energy is vast!
  - Tapping <1/1000th of one percent of thermal energy of upper crust would equal the US energy consumption in a given year

Free flowing well at Beowawe, NV

Where Does the Earth's Heat Come From?

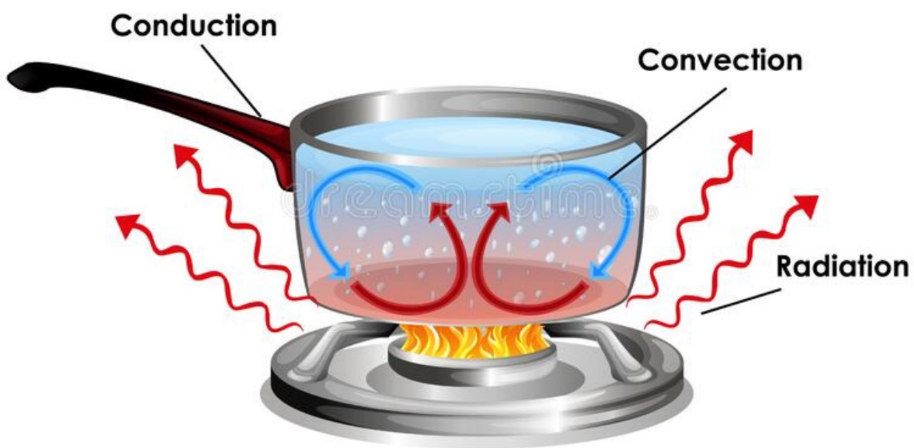
- Two main sources:
  1. Residual heat left over from Earth's formation 4.6 Ga
     - Earth grew from accretion of debris, where kinetic energy was converted to thermal energy
     - Earth's core is about the same temperature as the surface of the Sun (~6000°C)
  2. Radioactive decay of U, Th, and K
- Each component contributes about 50% of Earth's heat output



Source: https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf

How is heat transferred in the Earth?

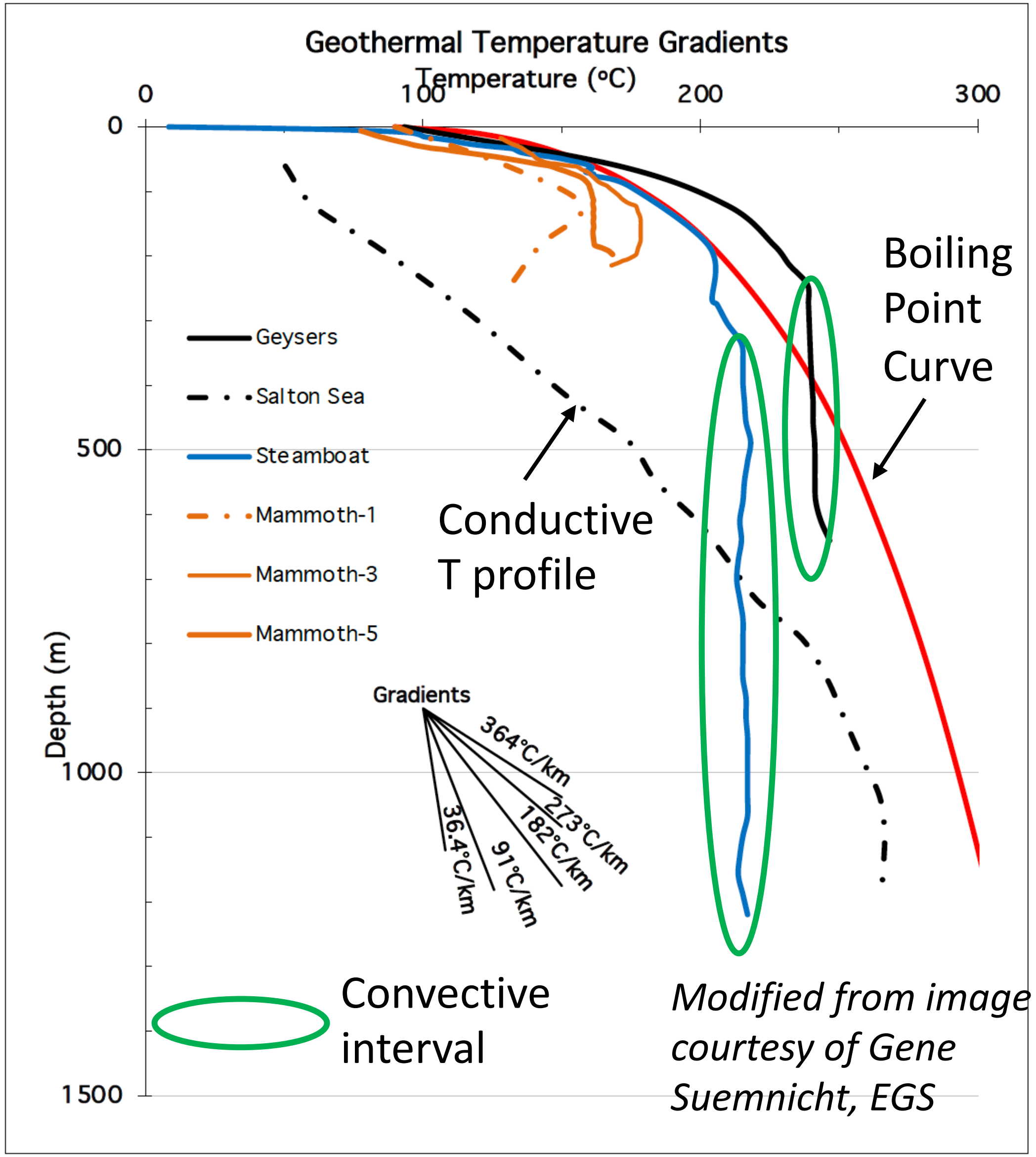
1. Conduction–transfer of heat by contact
   - Transfer of heat through solid rock
   - Slow as rocks are poor conductors (good insulators)
   - Temperature increases with depth (geothermal gradient)
     - Average upper crustal geothermal gradient is about 25°C/km; need higher gradient to be favorable for conventional geothermal development
2. Convection–transfer of heat by motion
   - More efficient, faster heat transfer than conduction
   - Critical for developing geothermal systems for power
   - Will T change much with depth?
     - No due to convective mixing
   - **Requires good permeability and water in order to transport or convect heat**



Boden 2023

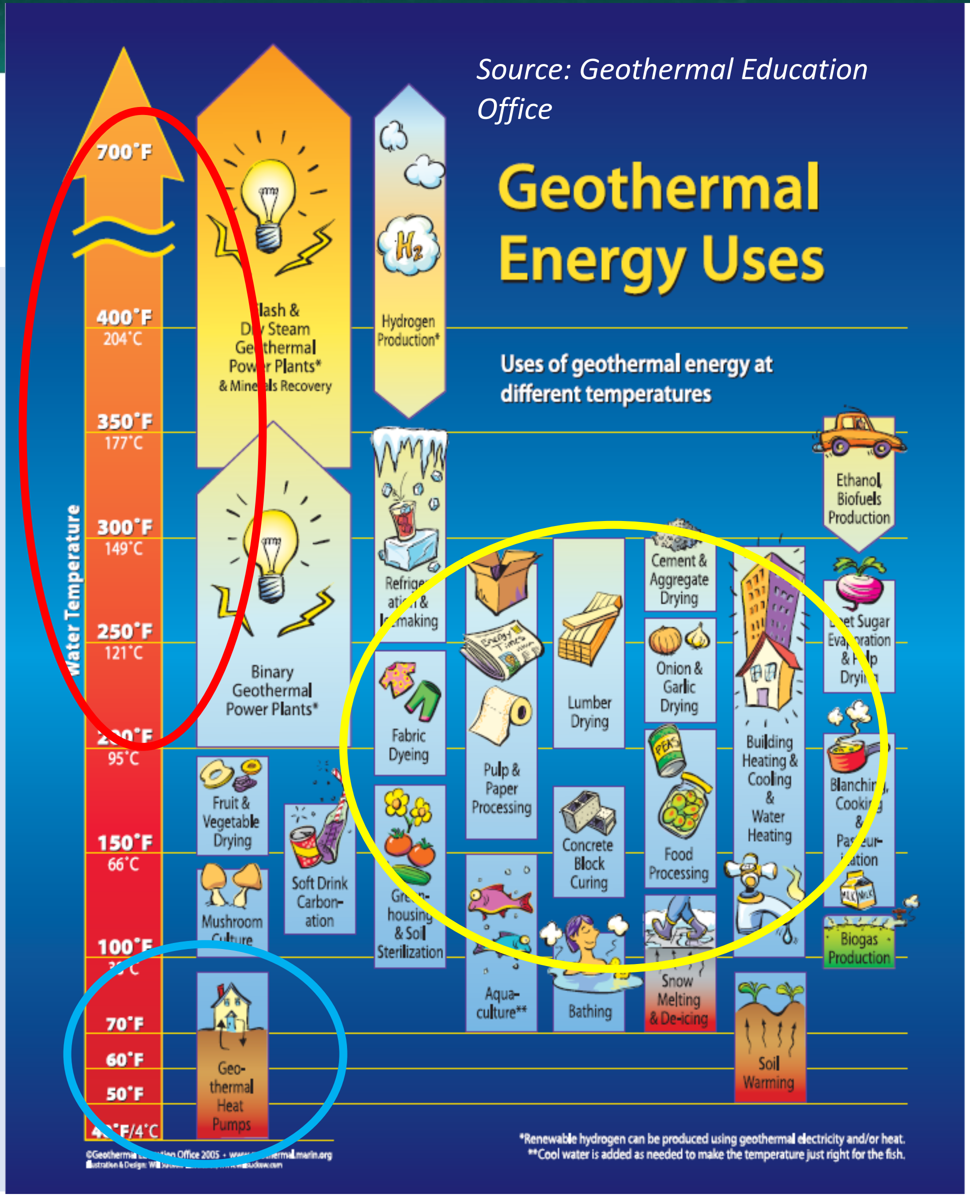
Profiles of Drill Temperature with Depth

- Profiles of temperature with depth distinguish conductive from the convective zones of heat transfer.
- Convective zones identify geothermal reservoirs
  - Note isothermal profile



What is Geothermal Energy and How is It Used?

- Harnessing Earth's heat for benefit of society
- What are some uses?
  - Produce electrical power (T >~100℃)
  - Direct use of geothermal fluid (T >~40℃)
    - More energy efficient than power production
    - Heat (cool) buildings and homes
    - Aquaculture (fish hatcheries)
    - Greenhouses and fruit/vegetable drying
  - Geothermal Heat Pumps (T 10°– 15℃)
    - Can be used anywhere
    - Use Earth as a thermal bank
    - Reduce energy costs by as much 40%. Why?
      - More efficient to move energy than produce energy
    - Largest application of direct use (71%)



Boden 2023

Uses of Geothermal Energy with Depth and Temperature

Heat Pumps

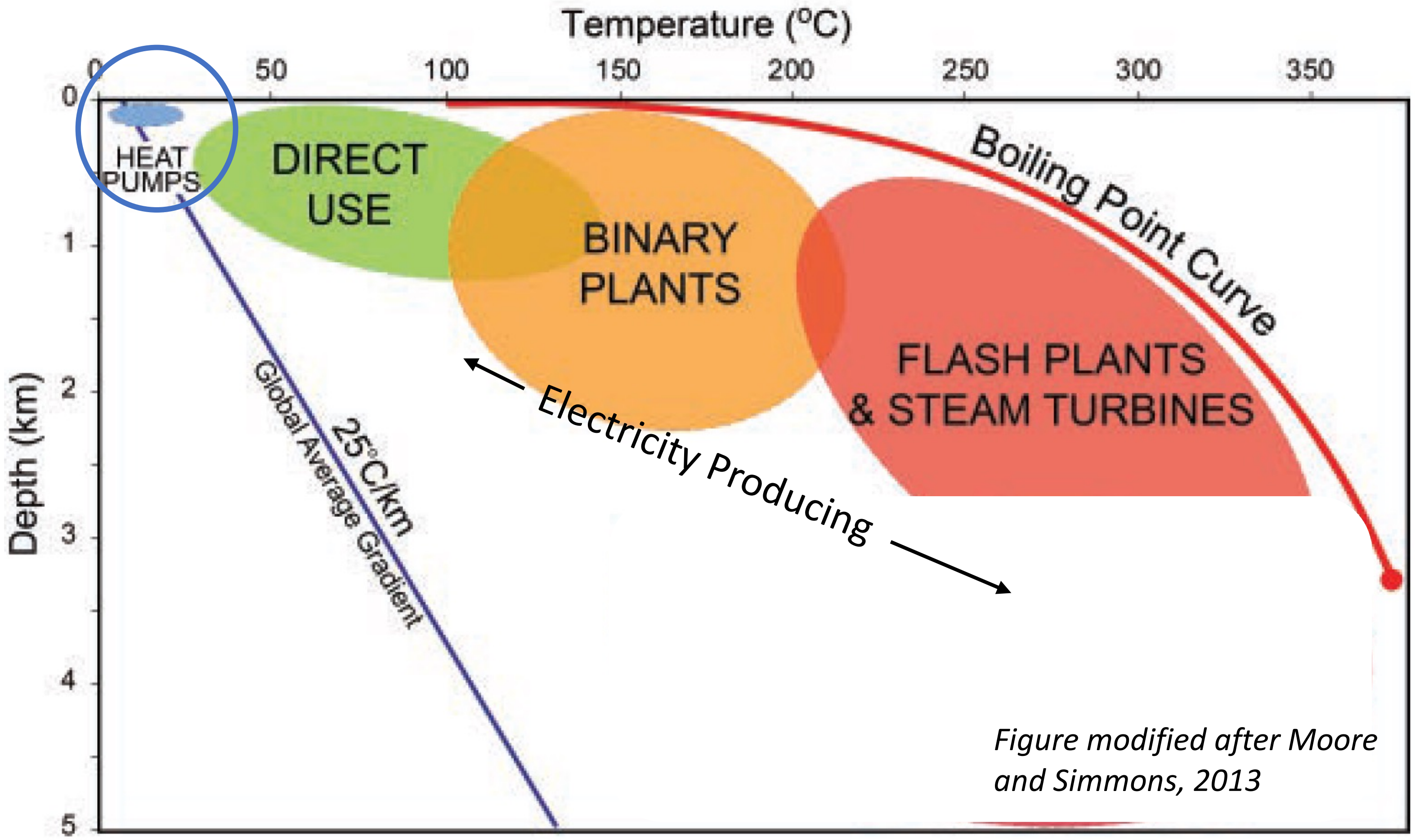


Figure modified after Moore and Simmons, 2013

Boden 2023

Geothermal Heat Pumps (heating and cooling–home scale)

- Also called ground source heat pumps (GSHPs)
- More efficient to transfer energy than to produce energy
- For every unit of electricity used, system gleans or dissipates 3-4 units of heat
- About 40% more efficient than air-source heat pumps
  - For about every 400 homes on GSHPs, a MW of electricity is removed from the grid (*Z. Magavi, Heet co-director, GR conference, 2023*)
    - NV has about 1.25M housing units with a state power consumption of 4.2 GW
    - If all housing units converted to GSHPs, **state power consumption could be reduced by about 75%!**
- Downside: More expensive upfront costs (ROI about 3-6 years for new construction and varies depending on climate)
- Upside: 30% tax credit to defer costs (Inflation Reduction Act)

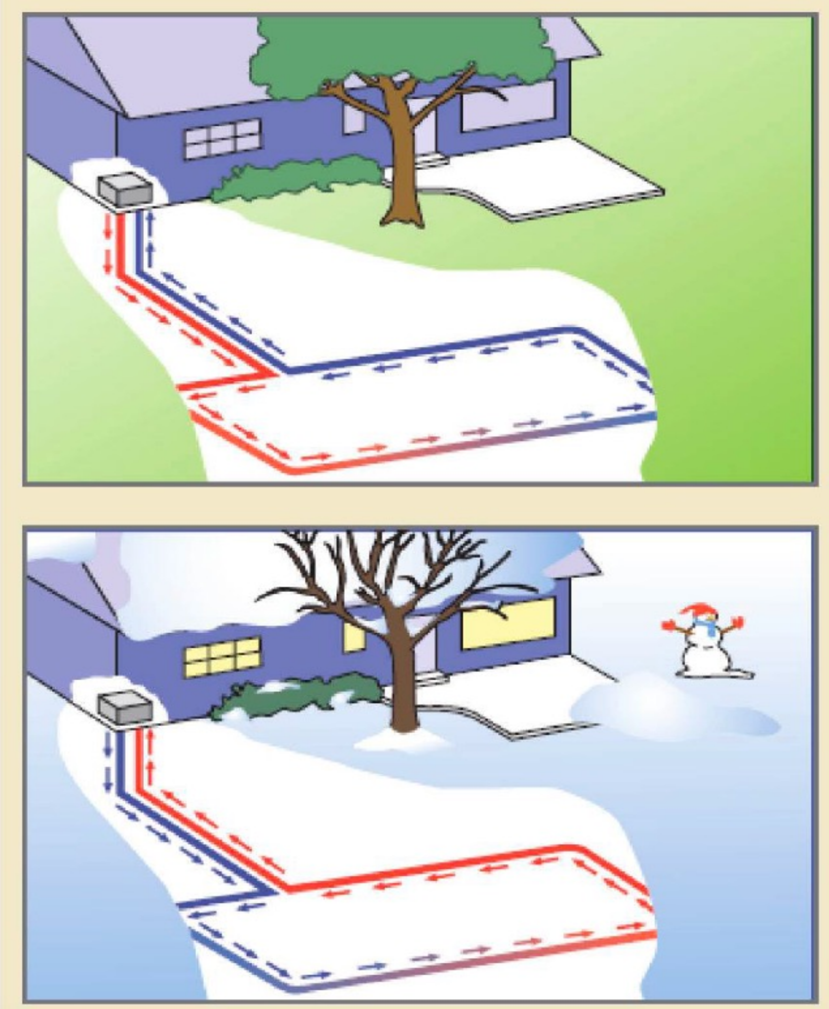
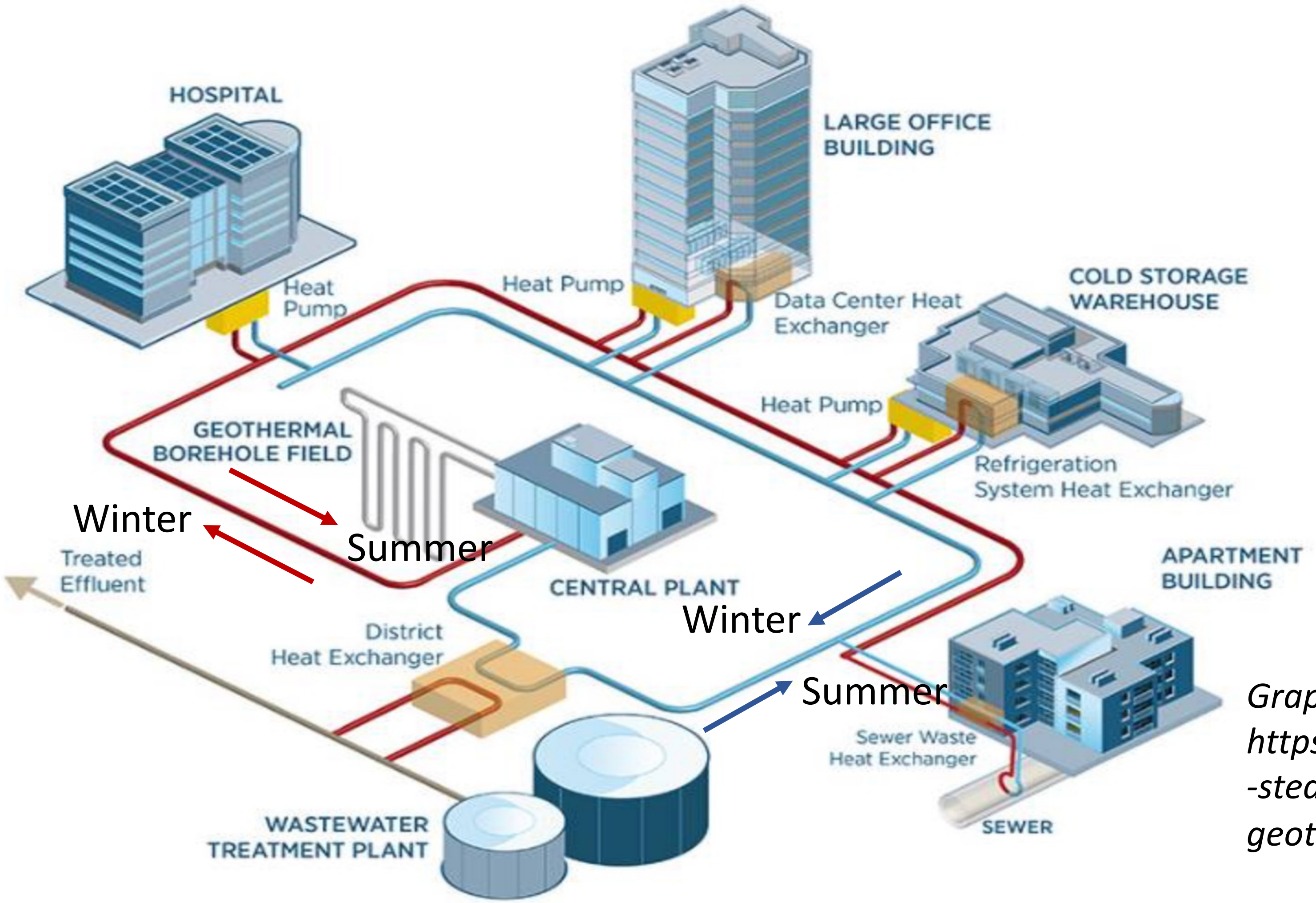


Figure Source: Duffield and Sass, 2003

Geothermal Heat Pumps (heating and cooling–district scale)



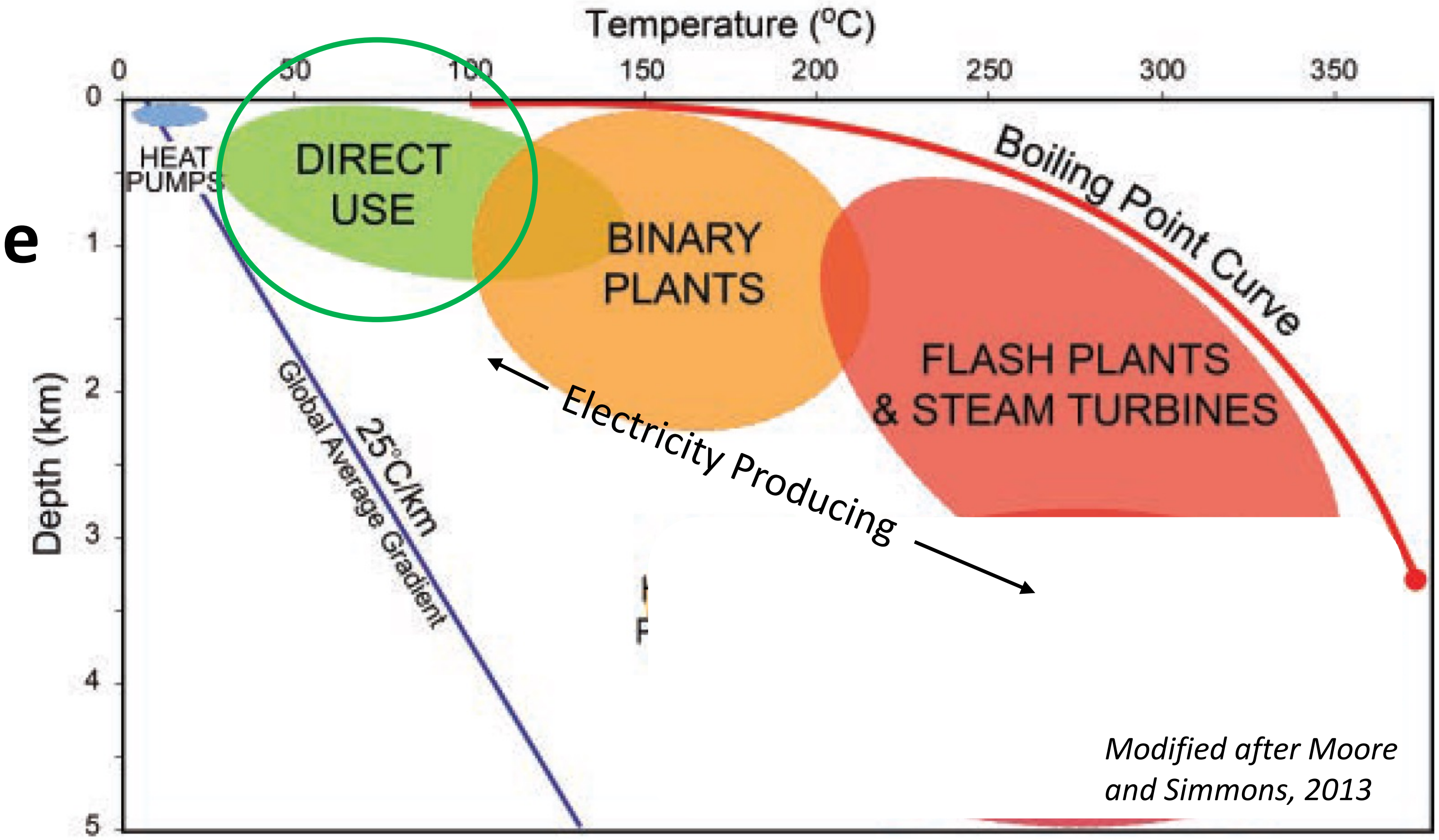
- Converting commercial buildings to district scale GSHPs, would further significantly reduce demand on power grid already afforded by converting residential homes.
- **Bottom line: GSHPs could make a huge impact on reducing power and energy usage (energy we save is energy we don't need to produce).**

Graphic modified from NREL: https://www.nrel.gov/news/features/2023/full-steam-ahead-unearthing-the-power-of-geothermal.html

Boden 2023

Uses of Geothermal Energy with Depth and Temperature

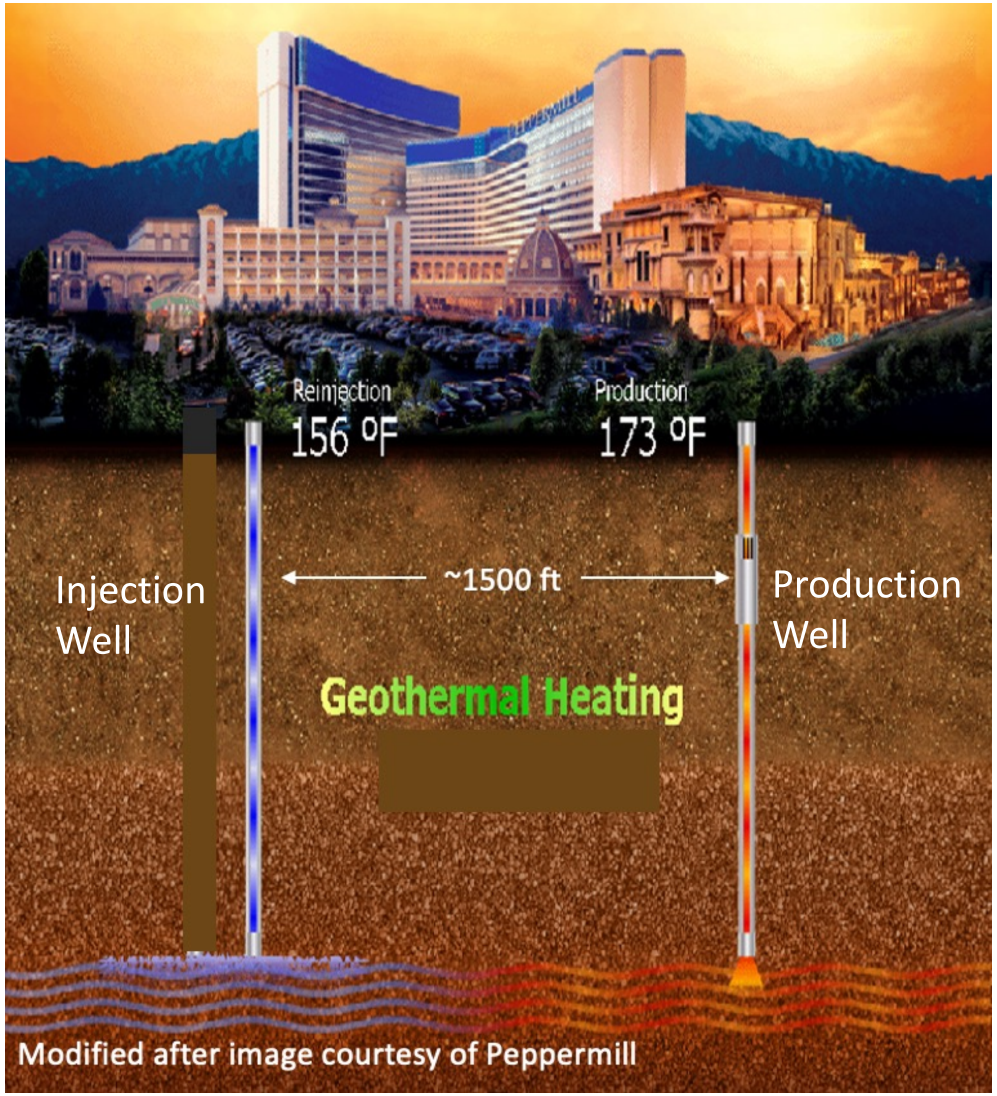
Direct Fluid Use



Modified after Moore and Simmons, 2013

Peppermill Geothermal Direct Use

- Major conversion to direct use in 2007-2009
- Drilled two new wells, one for production and one for injection
  - Production well ~4400 ft deep produces ~1500 gpm at a T of 170°–174°F (77°-79°C)
  - Injection well ~3900 ft deep accepts 2000 gpm (pump assisted) located
- Heats entire campus
- Reduced NG consumption by ~85% saving ~$2.25M/yr in 2010
- ROI ~3.5 years!



13

Boden, 2022

Direct Use of Geothermal Fluids

- Boise, ID district geothermal heating system
  - Largest in U. S.
  - Began in 1890 (not a typo!)
  - System now heats about 7.5M ft^2 in about 100 buildings
  - Fluid T: 72-75℃
- Paris, France district geothermal system
  - Established in 1969
  - Exploits the Dogger aquifer at 1.5–2 km depth with geothermal fluids at 60°C
  - Serves 2M people in about 250,000 homes using 50 heating networks, each consisting of a doublet production / injection well system

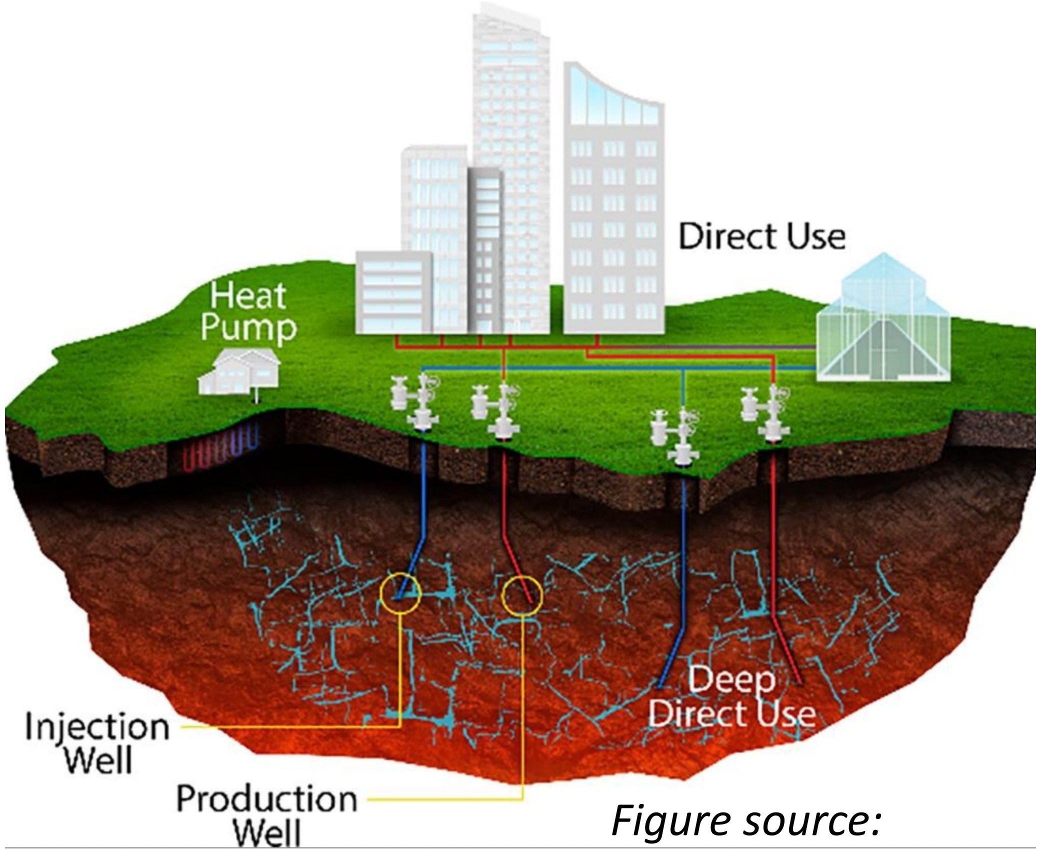


Figure source: Beckers et al., 2021

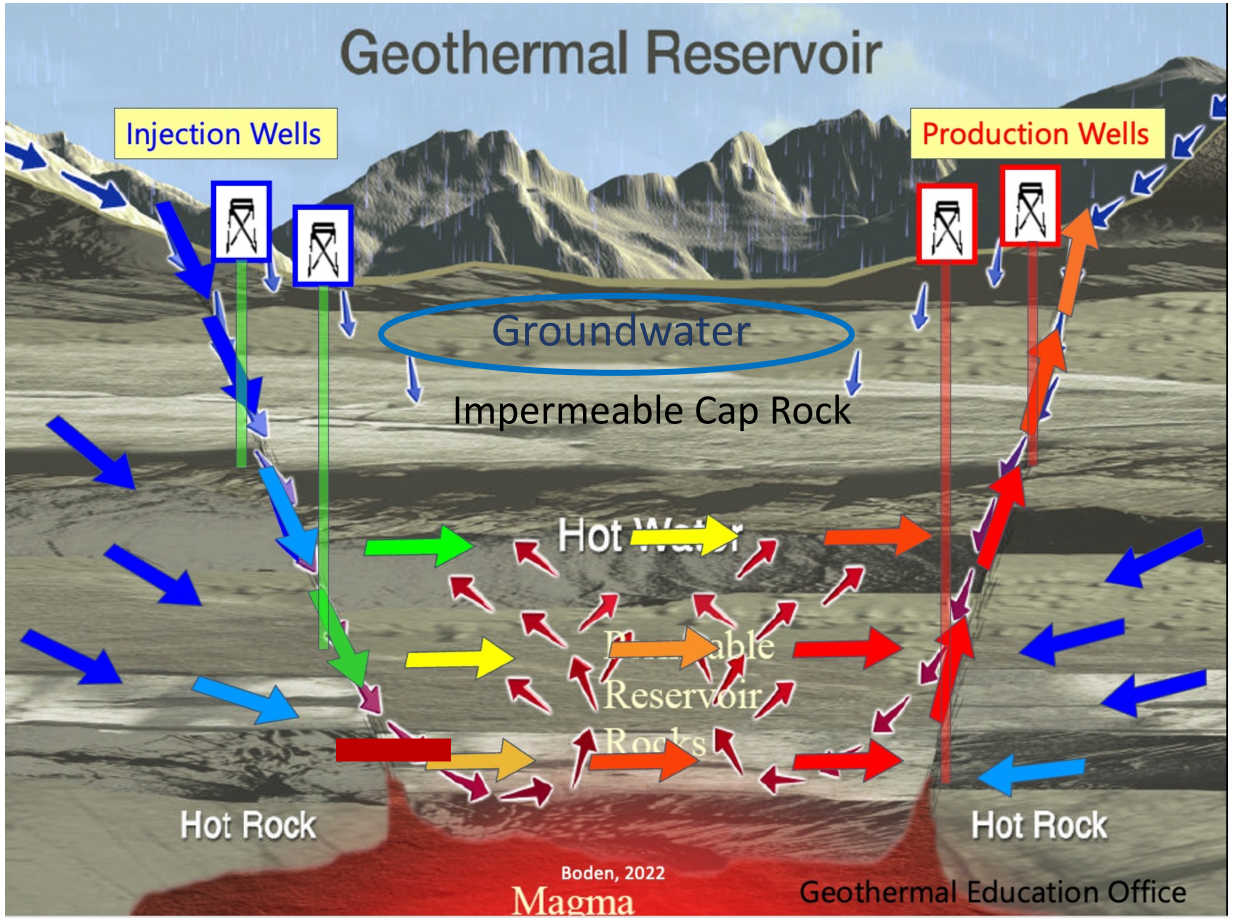
Direct Use of Geothermal Fluids

- Mineral ore processing for heap leach Au mines
  - Rate of leaching of Au increases 5-17% per degree Celsius of leaching solution (*Pasta et al., 2015*)
  - Heap leaching stops when solution is <~4°C
  - Round Mountain Au-Ag mine, NV
    - Produced about 250,000 ounces (~7000 kg) of Au in 2021
    - Geothermal fluids (~80°C) pass through heat exchanger at 70l/s to heat Au-leaching solution
    - Geothermal fluids allow year-round leaching without having to heat leaching solution by burning fossil fuels
  - Florida Canyon Au-Ag mine, NV
    - Recovered 905 kg of Au (2015) from geothermally heated leaching solution

What is Needed to Make Geothermal Fluids Viable for Development?

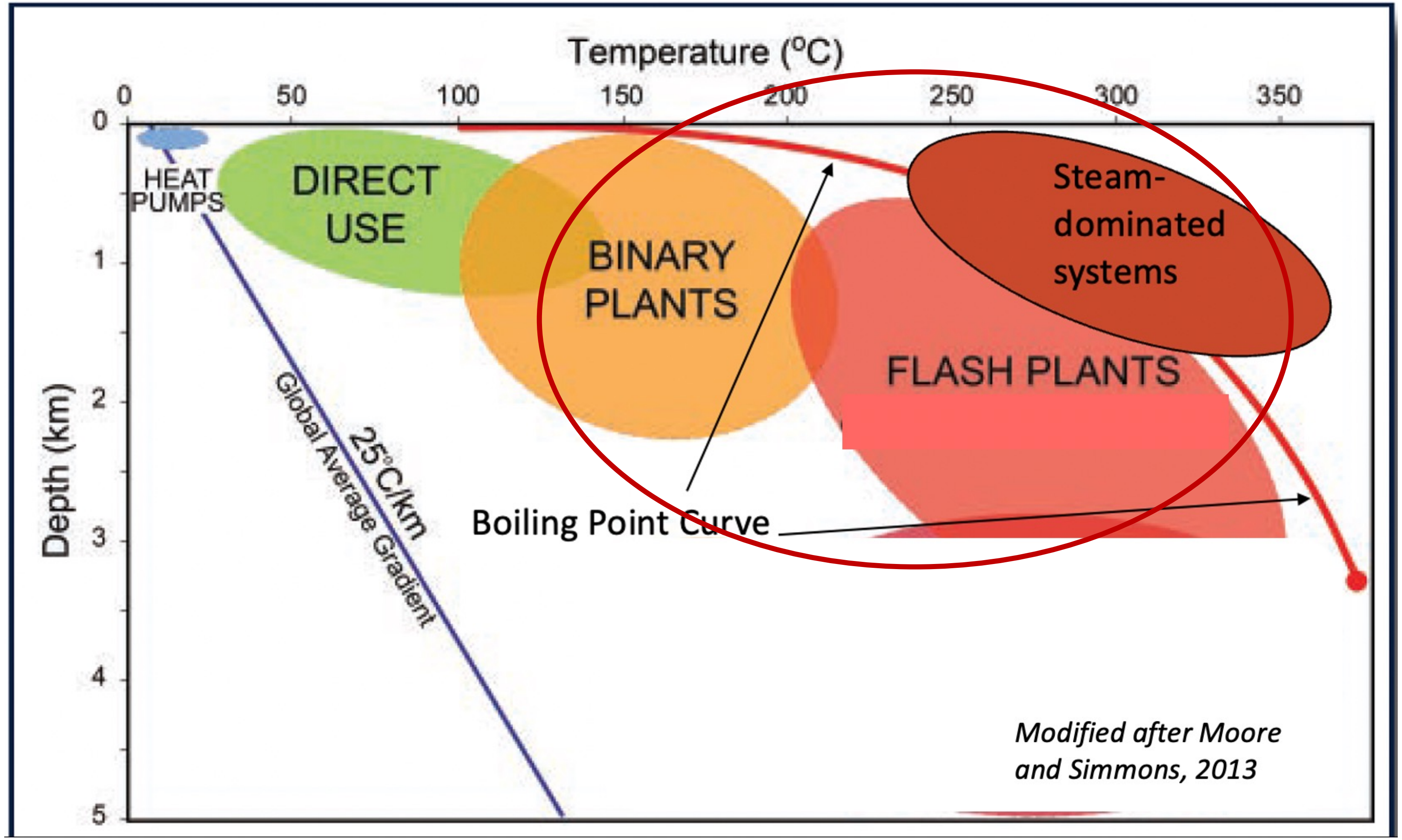
- Five main criteria to make a hydrothermal resource economically viable:
  1. Large heat source
  2. A permeable reservoir
  3. A supply of water
  4. A impermeable cap rock
  5. A steady recharge mechanism

Image courtesy of M. Coolbaugh as modified from GEO



Uses of Geothermal Energy with Depth and Temperature

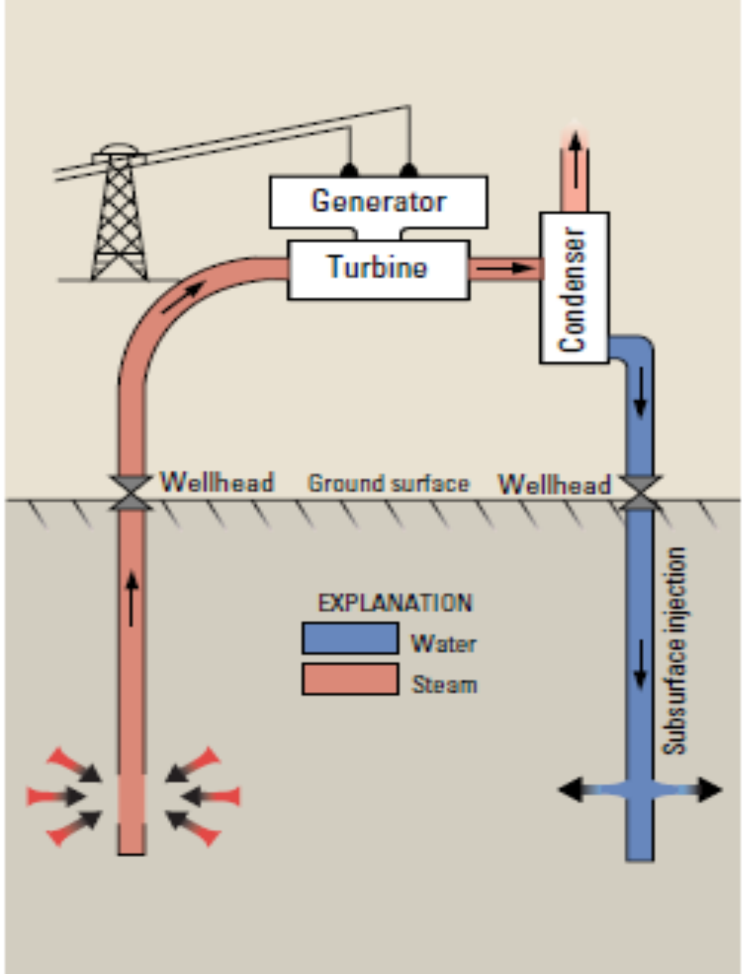
Electricity Producing Systems



Boden 2023

Types of Geothermal Systems and Related Power Plants

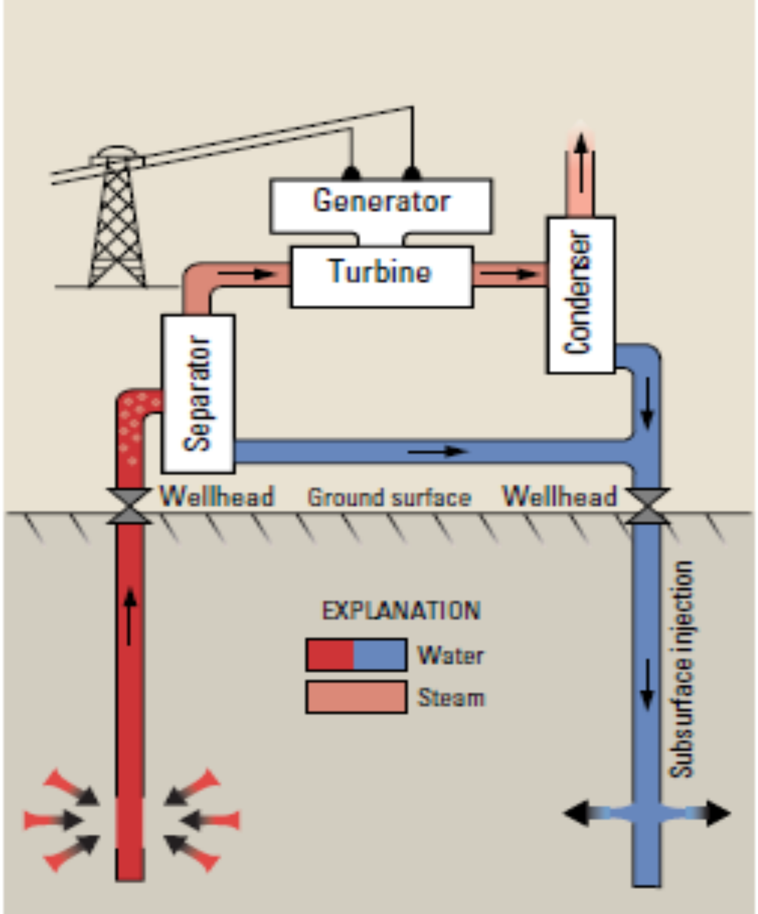
- Vapor (steam)-dominated
  - Provide greatest amount of power per mass of fluid
  - Because reservoir is already steam, all fluid mass goes to turbine
  - In order for fluid to occur as steam, reservoir is underpressured compared to surrounding rock—**geologically rare conditions**
  - World class examples are The Geysers, CA and Larderello, Italy (the first commercially produced geothermal reservoir for power generation in 1913).



After Duffield and Sass, 2003

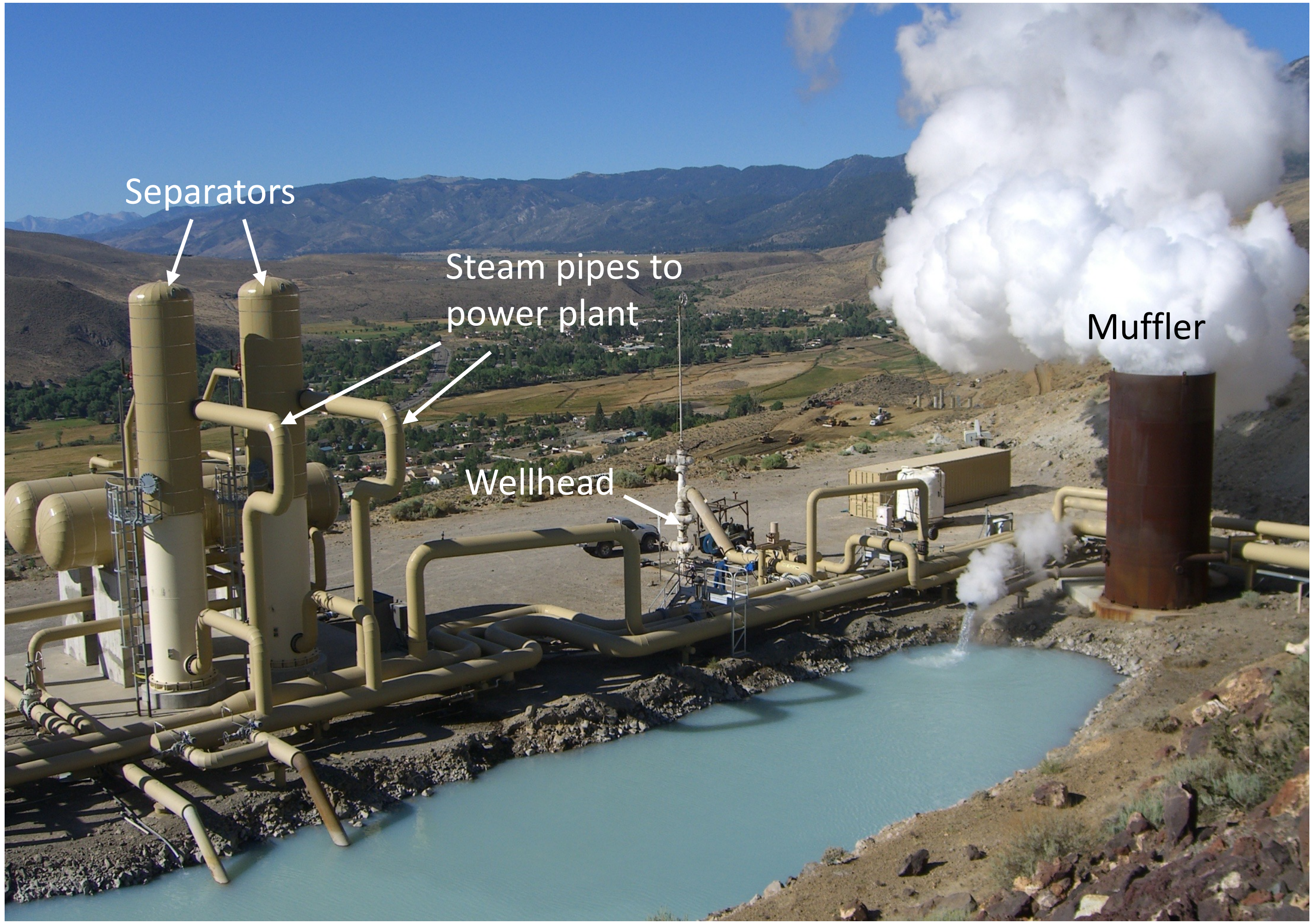
Types of Geothermal Systems and Related Power Plants

- High-temperature, liquid-dominated
  - T ≥ ~180°C
  - Original mainstay of the industry (flash)
  - Fluid exists as a liquid in reservoir
  - Fluid starts to boil as pressure falls when fluid rises up well (mixture of steam and liquid—2 phase fluid)
  - From wellhead, 2-phase fluid goes to separator where steam rises to top and liquid goes to bottom
  - Only steam goes to turbine, and brine is re-injected
  - Energy is partitioned between steam and brine unlike vapor-dominated reservoirs



After Duffield and Sass, 2003

Artesian Geothermal Well 24-5 Upper Steamboat Field, NV

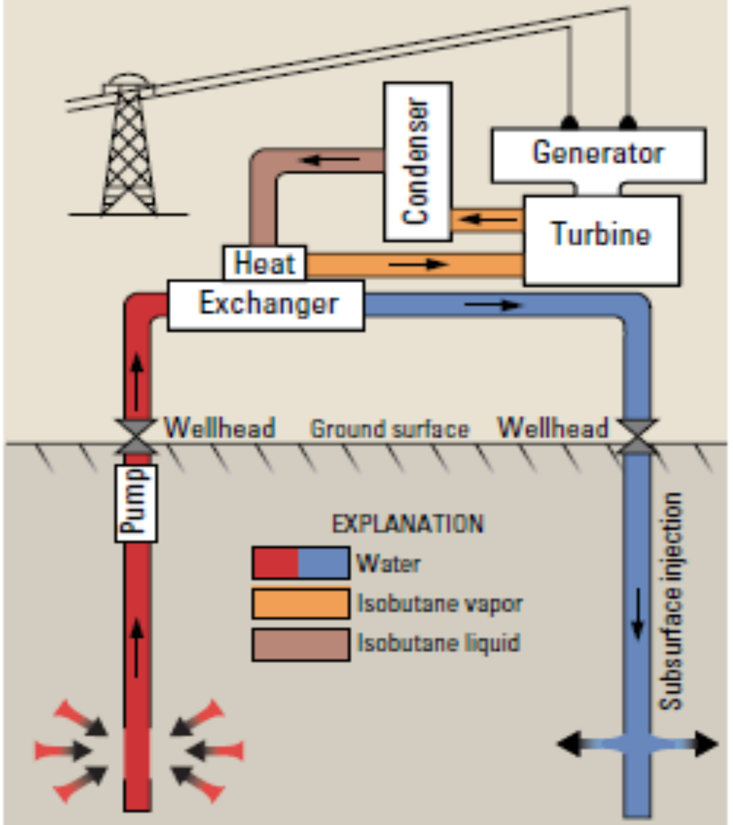


After shut-in and servicing, fluid in well is allowed to flow to muffler until T is high enough to bring steam to power plant.

Boden 2023

Types of Geothermal Systems and Related Power Plants

- Moderate-temperature, liquid-dominated
  - T > ~100 - 180°C
  - Provide an increasing proportion of power. Why?
    - Lower T systems are more common than high T systems
  - Binary systems
    - Two fluids—the geothermal fluid provides the heat, and a working fluid that serves the turbo-generator
    - Geothermal fluid passes through heat exchanger to flash working fluid having a low boiling point to generate more steam pressure than water
    - Both geothermal and working fluids form closed loops therefore **no emissions of GHGs**

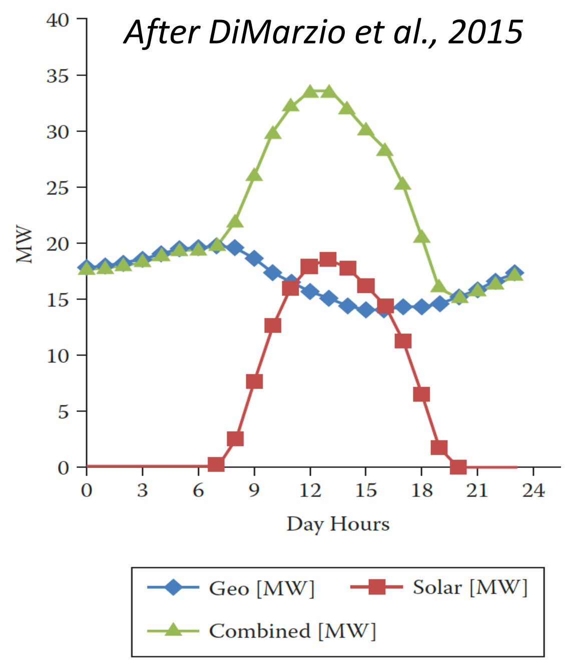


After Duffield and Sass, 2003

Boden 2023

Types of Geothermal Systems and Related Power Plants–Synergistic Configurations

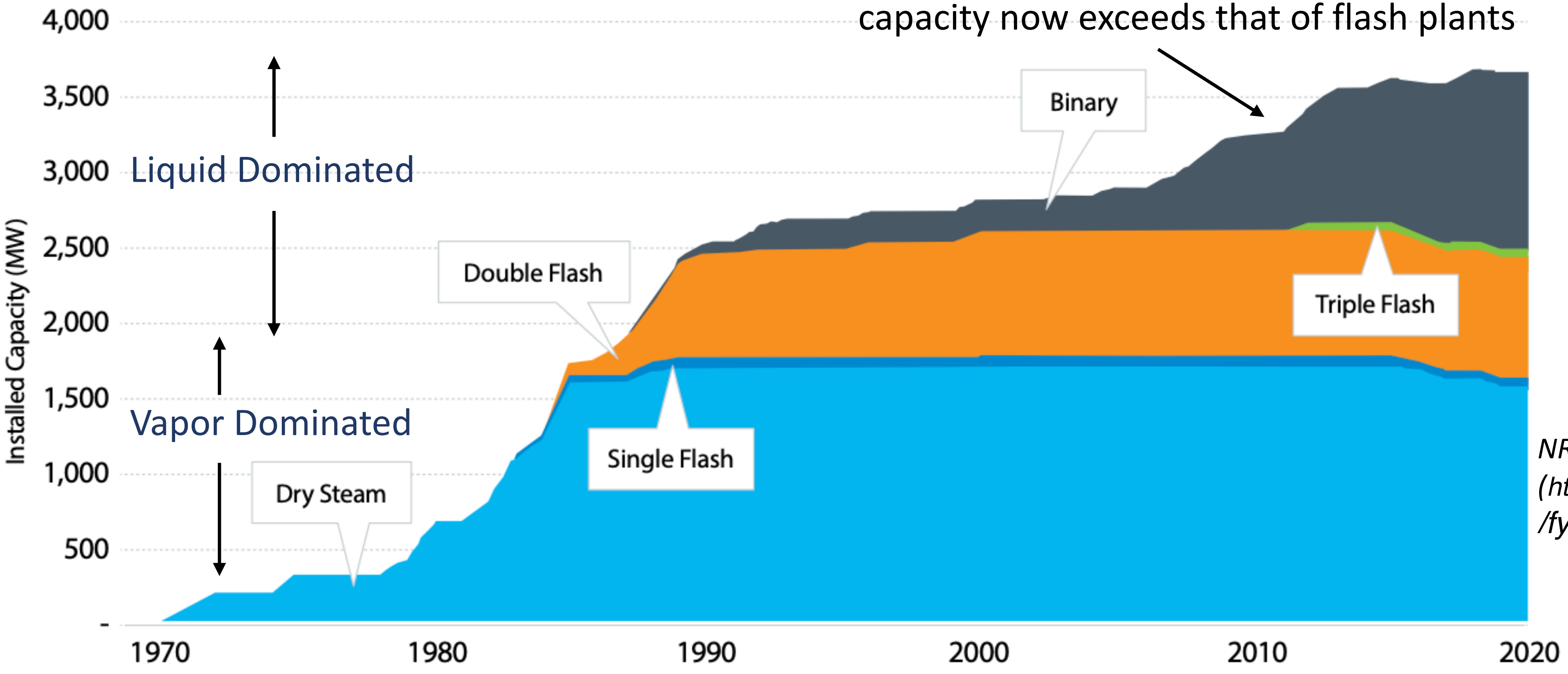
- Integrated Flash-Binary
  - Brine goes to a bottoming binary plant to produce power prior to reinjecting
- Hybrid Binary Geothermal and Solar Facilities
  - Stillwater Triple Hybrid Facility
    - 33 MW capacity geothermal
    - 53 MW solar PV (boosts power output during summer)
    - 2 MW solar thermal (adds enthalpy to produced geothermal fluids)
  - Tungsten Mountain
    - 62 MW installed capacity binary geothermal facility
    - 7 MW solar PV array to offset power used in plant operation to increase net output



- Hybrid geothermal and hydropower
  - Enel's Cove Fort, UT – 25 MW installed geothermal power capacity and 0.6 MW hydropower
  - Submersible downhole generator placed in injection well
  - Back pressure of turbine prevents 2-phase flow and vibration that could otherwise damage equipment

Installed U. S. Geothermal Power Capacity (Resource Type/Technology)

Note increasing proportion of binary power plants beginning about 2008 whose power capacity now exceeds that of flash plants

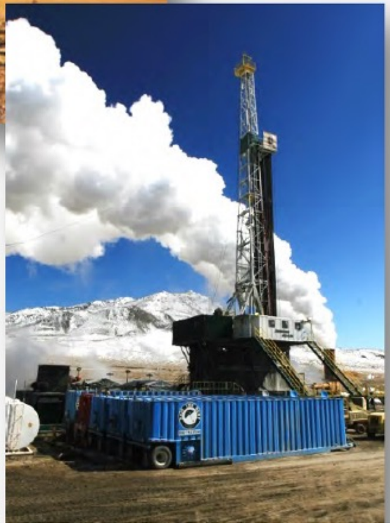


NREL report, 2021 (https://www.nrel.gov/docs/fy21osti/78291.pdf)

Comparative Production Rates

Water well – 5 to 50 gpm ($40–$400/day)

Oil well – 20 gpm
650 barrels/day
(~$58,000/day at $90/barrel as of 09/20/23)



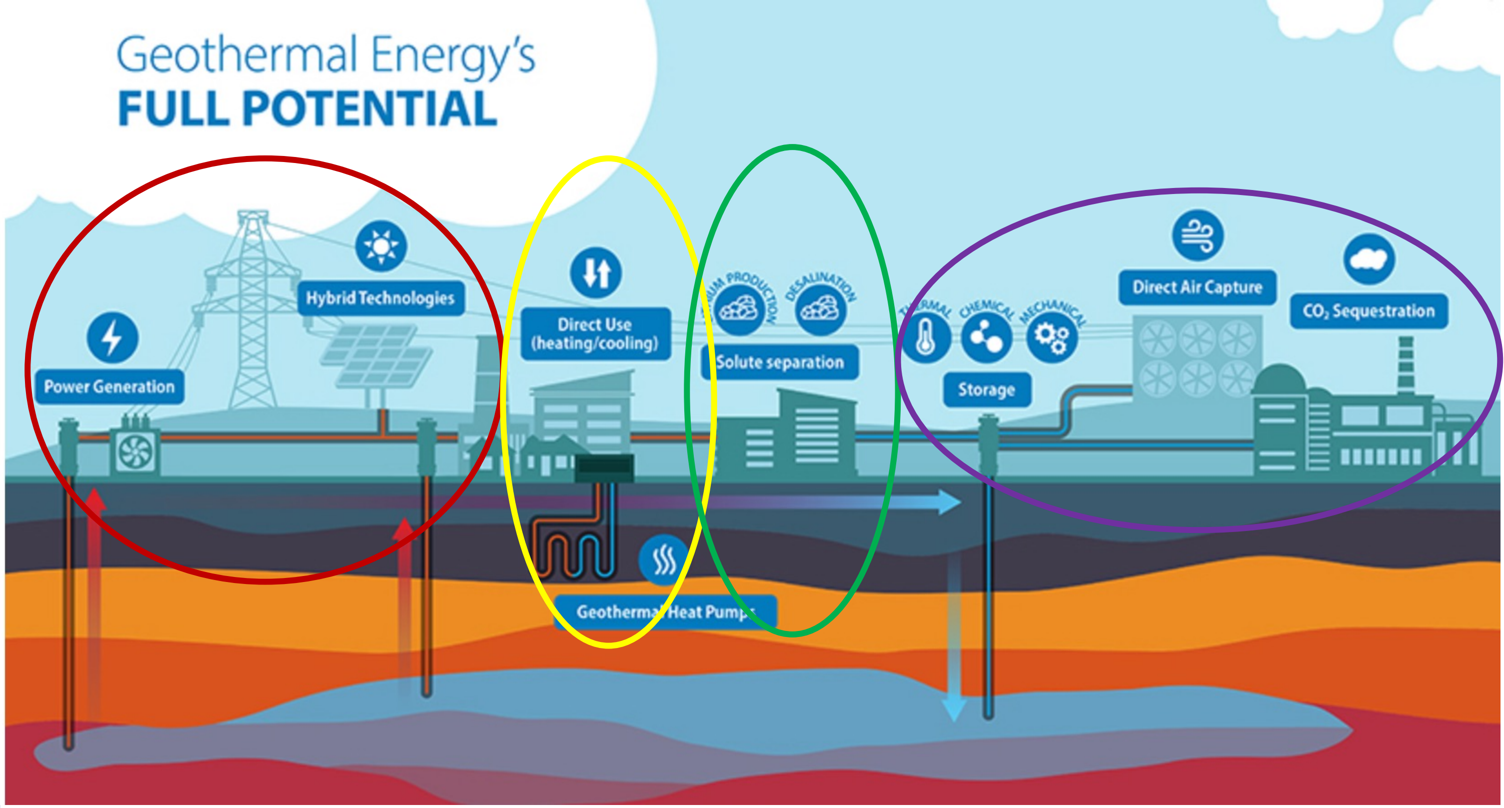
Geothermal well
2000 gpm
(~$6000 –$12,000/day depending on T)

Li recovery from Salton Sea geothermal brine could yield a gross revenue of **~$100k/day**

Modified from image courtesy of Gene Suemnicht, EGS

Geothermal Energy's Value

- Base load electrical power generation
  - Green H production during offpeak
- Integrated with solar PV and thermal
  - E.g., Stillwater and Tungsten Mountain hybrid geothermal-solar power plants, NV
- Direct use heating and cooling (~40% of energy used in U.S. is to heat water and heat and cool buildings)
- Green lithium extraction and desalination
- Energy storage and CO_2 sequestration



Graphic modified from NREL: https://www.nrel.gov/news/features/2023/full-steam-ahead-unearthing-the-power-of-geothermal.html

Geothermal Energy Attributes

1. Base load power (available 24-7 unlike wind and solar);
   - New technology allows for load following and dispatchable energy
   - 90%+ capacity factors (ratio of energy produced over a given time; only nuclear is comparable)
     - Solar and wind capacity factors typically 25-35%; coal- and natural-gas-fired power plants about 50-70%
2. Sits on top of energy source;
   - No fuel price exposure; price certainty; insulated from price volatility;
3. Proven resource, mature technology (dating back to 1913 in Italy and 1958 in NZ);
4. Can provide dispatchable power (load following);
   - Puna geothermal power plant, HI can ramp up or down from 22 MW to 38 MW at 2 MW/min
   - During off peak periods when intermittent renewable sources are abundant, geothermal can use its base load electricity to make green H or use produced power for pump hydrostorage

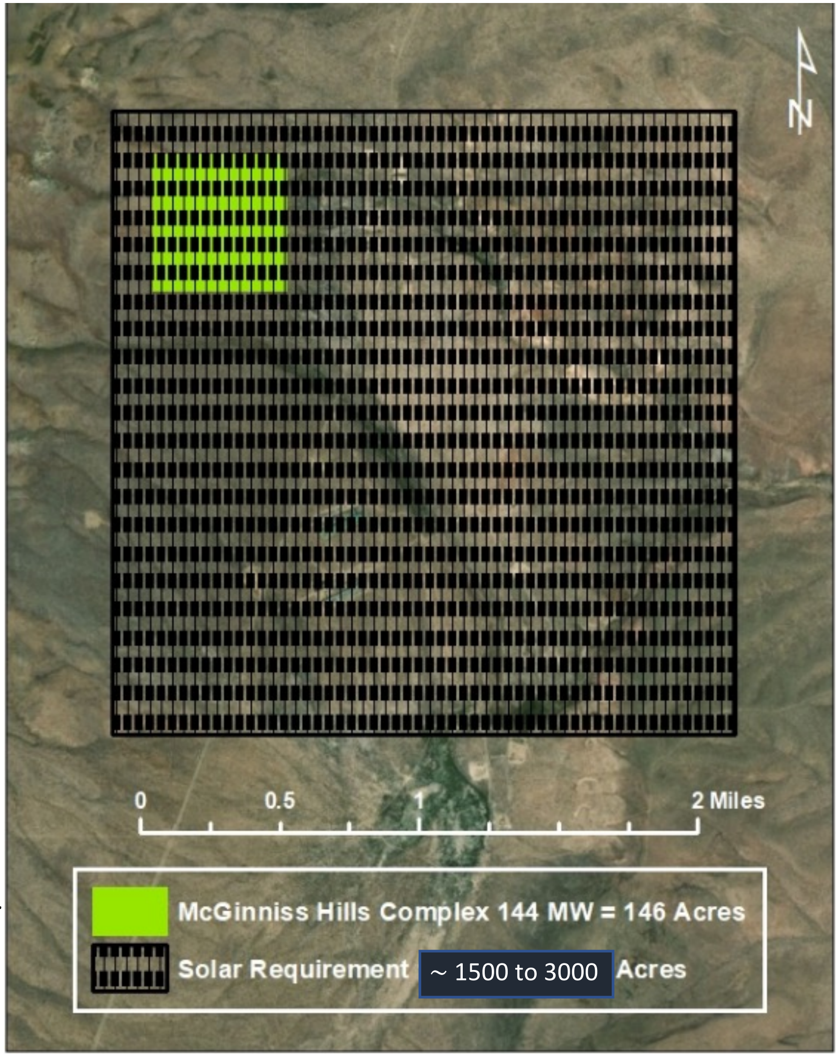
Geothermal Energy Attributes

5. Economic impact on construction/operation: number of jobs per MW;
   - CalEnergy Salton Sea: ~390 MW; ~240 employees (about 1 employee for every ~1.6 MW produced)
   - Comparably sized natural gas plant: 15 employees; commercial solar/wind plant: 10-15 employees (1 employee for every 25-34 MW produced)
6. Minimal environmental impacts:
   - Minor or no greenhouse gas emissions
     - Conventional geothermal flash plant releases only 2% GHG emitted by NG-fired power plant
     - Binary plants have **ZERO** greenhouse gas emissions
   - Small footprint for power produced (1-3 acres/MW compared to an average of 85 acres/MW for wind (*NREL/TP-6A2-45834, 2009*) and about 10 acres/MW for solar (https://betterenergy.org/blog/the-true-land-footprint-of-solar-energy/)
   - Land available for multiple use

GEOTHERMAL FOOTPRINT IS SMALL

- At McGinness Hills, NV about 1 acre is required for every MW
- Solar PV requires about 10 acres/MW* (varies depending on latitude, efficiency of installed panels, time of year, and setbacks and zoning restrictions)

*Does not include storage facilities for round-the-clock power availability as with geothermal. If so, then then solar footprint increases to about 15-20 acres/MW

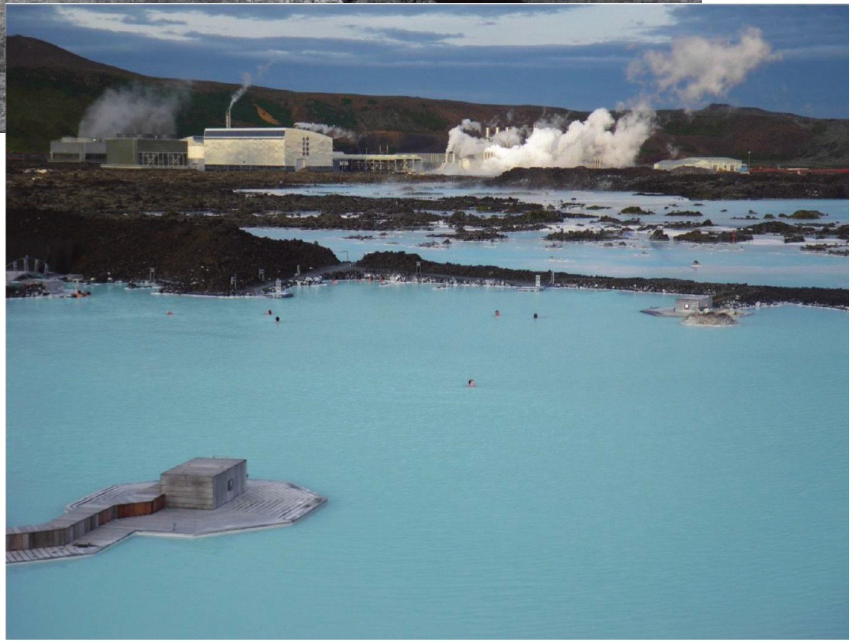


Modified after image courtesy of P. Thomsen, Ormat Technologies

Boden 2023

Land Available for Multiple Use

Miravalles geothermal field, Costa Rica. *After DiPippo, 2012*



Blue Lagoon Spa at Svartsengi geothermal plant, Iceland

Geothermal plant in Imperial Valley, CA. *Source: NREL Image Gallery*

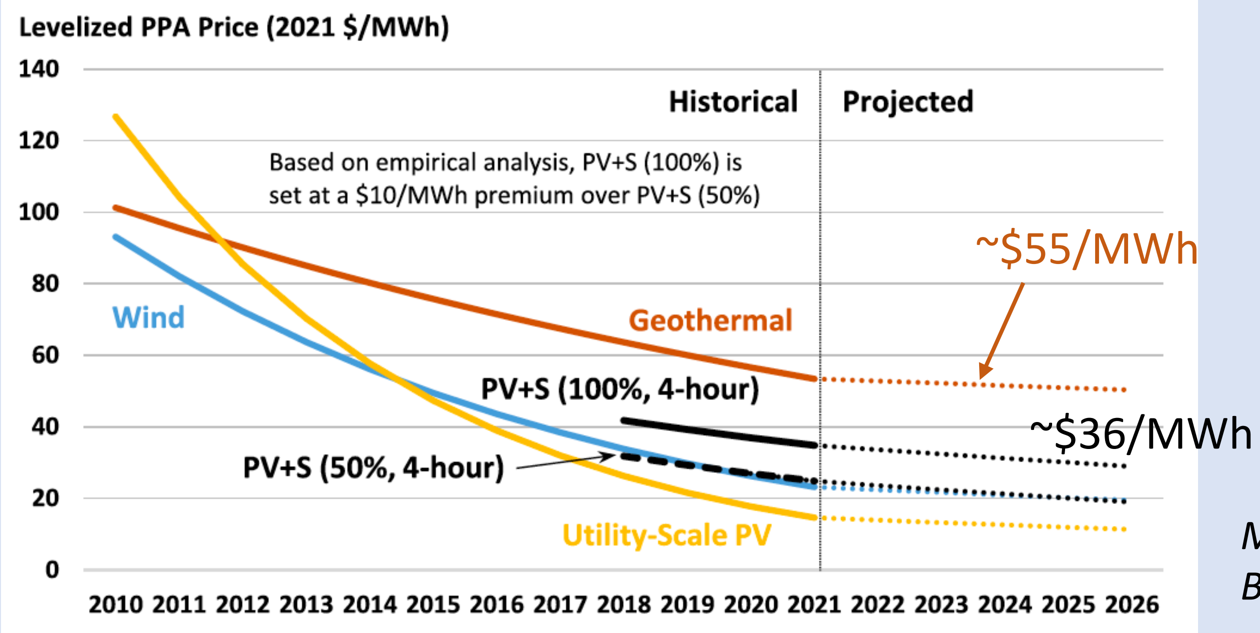
Challenges for Geothermal Development

- **1. Currently developed geothermal systems are location restricted**
  - Presently biggest problem for more widespread geothermal application
  - Require a special orchestration of geologic processes not widely met:
    - Elevated heat flow
    - Permeable rock reservoir
    - Ample supply of water and recharge
    - Conditions most commonly satisfied near boundaries of tectonic plates or widely scattered geologic hot spots, like Hawaii or Yellowstone
  - Solutions include:
    - Develop more widespread hot dry rock by creating artificial reservoirs (EGS)
    - Enhanced drilling technologies, such as downhole heat exchangers and cased lateral drill legs

Discussed more later

Challenges for Geothermal Development

- **2. Higher cost compared to solar PV and wind**
  - Reflects higher risk and expense to develop geothermal resources

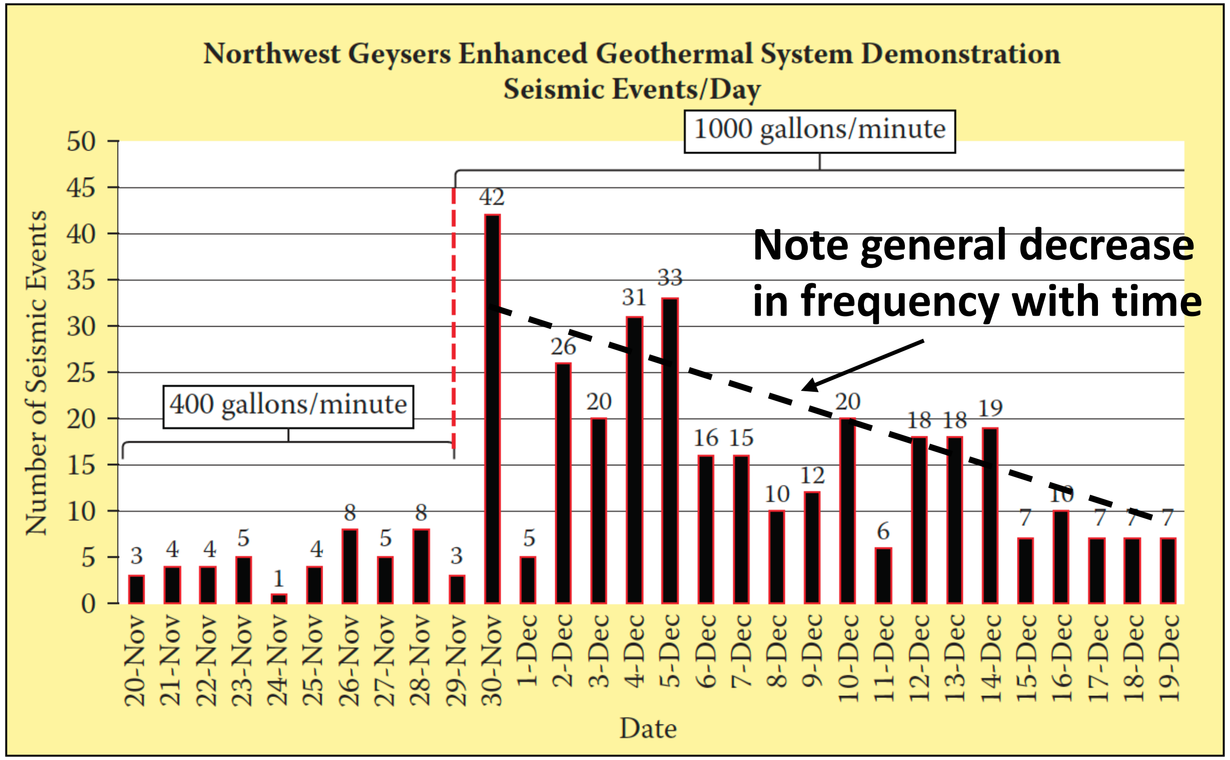


Modified after Bolinger et al., 2023

- A solution: Policy intervention to promote non-intermittent renewable energy sources
  - e. g., 2021 CPUC Energy Procurement Order requires an additional 2000 MW of geothermal by 2035
  - Expand oil and gas exploration efficiencies that currently do not require EA or EIS under NEPA to include geothermal

Challenges for Geothermal Development

- **3. Induced Seismicity**
  - Can occur from both production and injection of fluids (rock contraction from withdrawal of fluids and cooling during injection)
  - Generally small magnitude events, mainly <0 to about 2 (most can't be felt)
  - Largest at The Geysers about 4.5M; largest on record is Pohang event in South Korea at 5.5M
  - Basel EGS project cancelled due to a swarm of EQs (largest being 3.4M related to injection during reservoir stimulation in 2009
  - Solution:
    - Inject at lower rates
    - Spread injectate (via drill legs) over a larger volume of rock limiting pore water pressure in any given fracture to retard large slipping

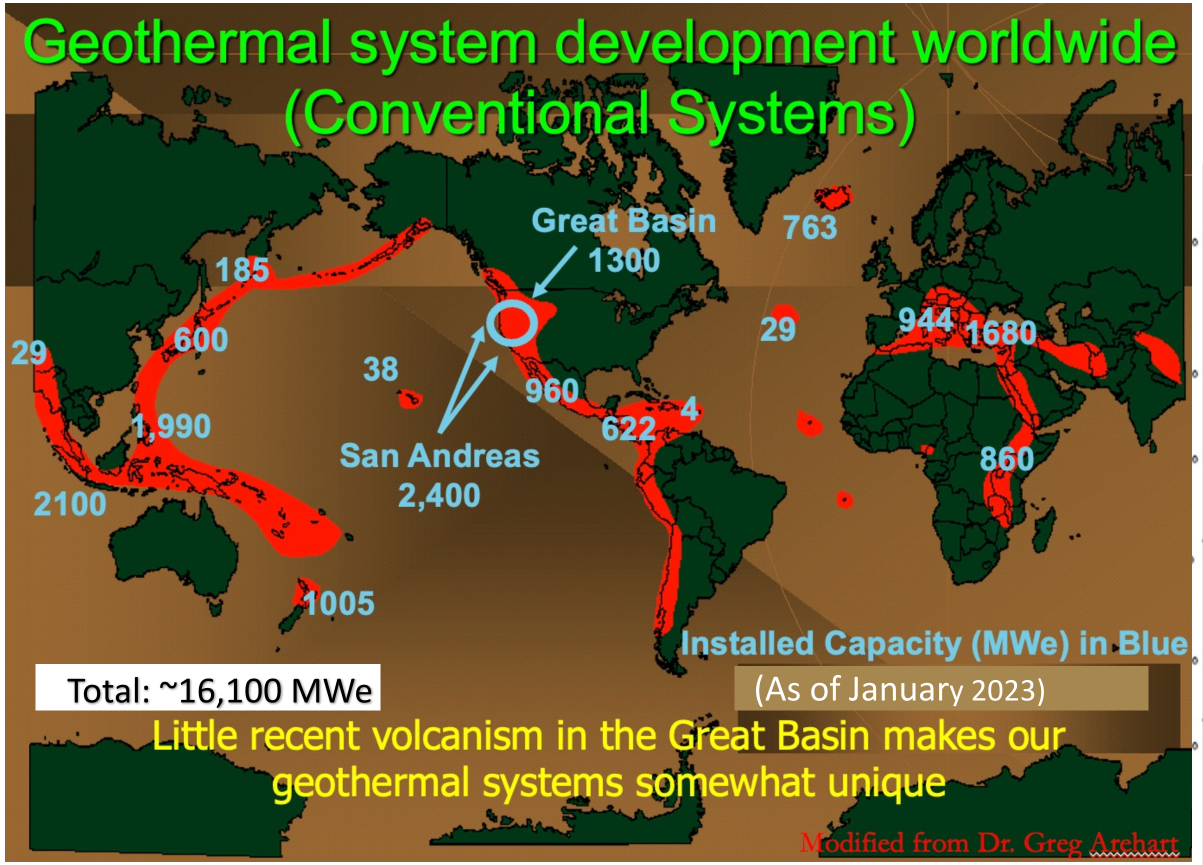


After: J. Garcia et al., 2012

Challenges for Geothermal Development

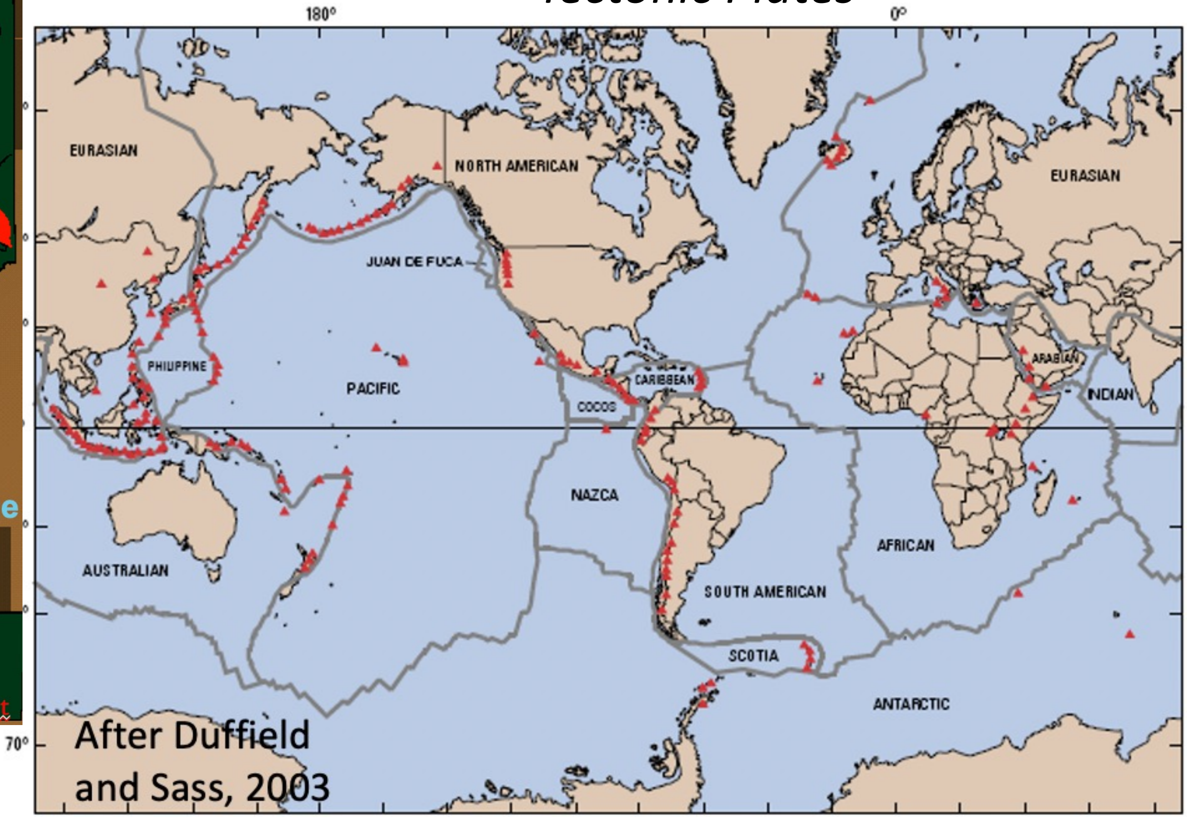
- **4. Potential degradation of surficial hydrothermal phenomena**
  - Geysers, fountaining hot springs, thermal pools can dry up if geothermal reservoir improperly managed;
  - Geyser Valley NZ in the 1950s and today
    - https://teara.govt.nz/en/video/5437/geyser-valley-1950s
    - Today only whiffs of steam observed. Why?
    - Consequence of Wairakei not reinjecting effluent for about 30 years
  - Solution:
    - Reinject effluent into reservoir to maintain fluid pressure
    - May require make-up water to account for water loss from evaporative cooling towers, e.g., The Geysers
    - Use closed loop binary technology and air condensers (fluid conservative) → e.g., Ngatamariki, NZ (100 MW installed capacity)

Worldwide Distribution of Geothermal Systems



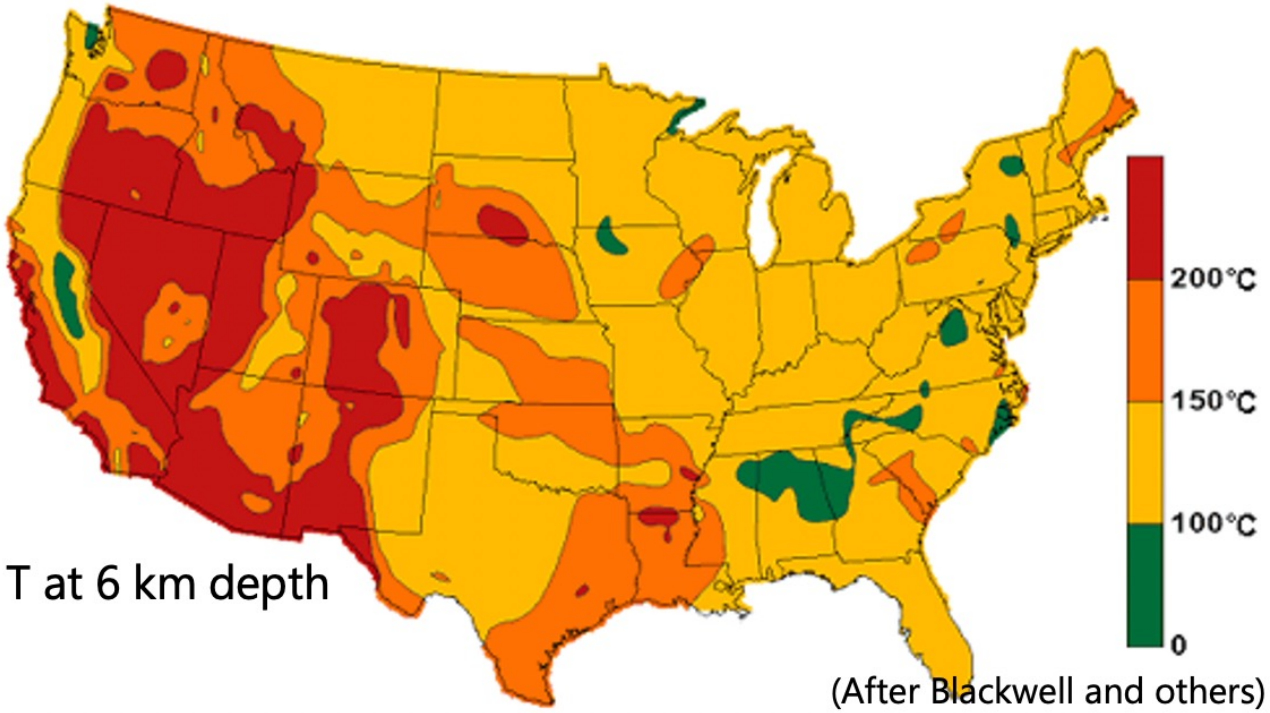
Note correspondence between distribution of geothermal systems and boundaries to tectonic plates

Tectonic Plates



What Makes the Great Basin and Nevada so Prospective for Geothermal Energy?

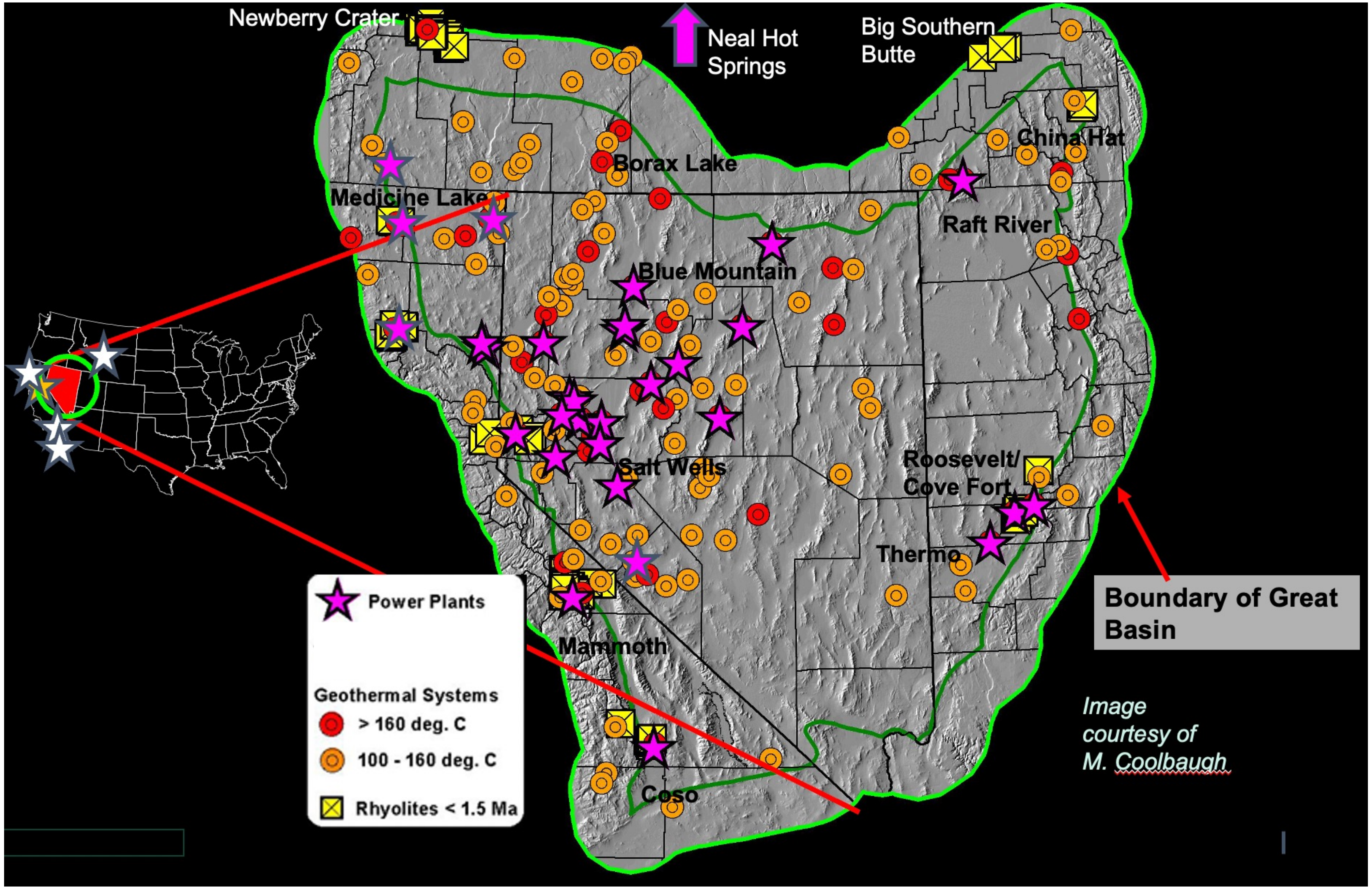
- Crust is being stretched and thinned
  - Results in high heat flow
  - Hot rocks of mantle are closer to surface
- As crust is stretched, rocks break to make fractures (faults)
  - Allows for deep circulation of fluids and conduits of good permeability



(After Blackwell and others)

Geothermal Systems in Nevada & Great Basin, USA

- 2023 Great Basin Geothermal Power Plant Capacity is ~1300 MWe
- NV = 827 MWe from 26 power plants
- NVnet = ~580 Mwe

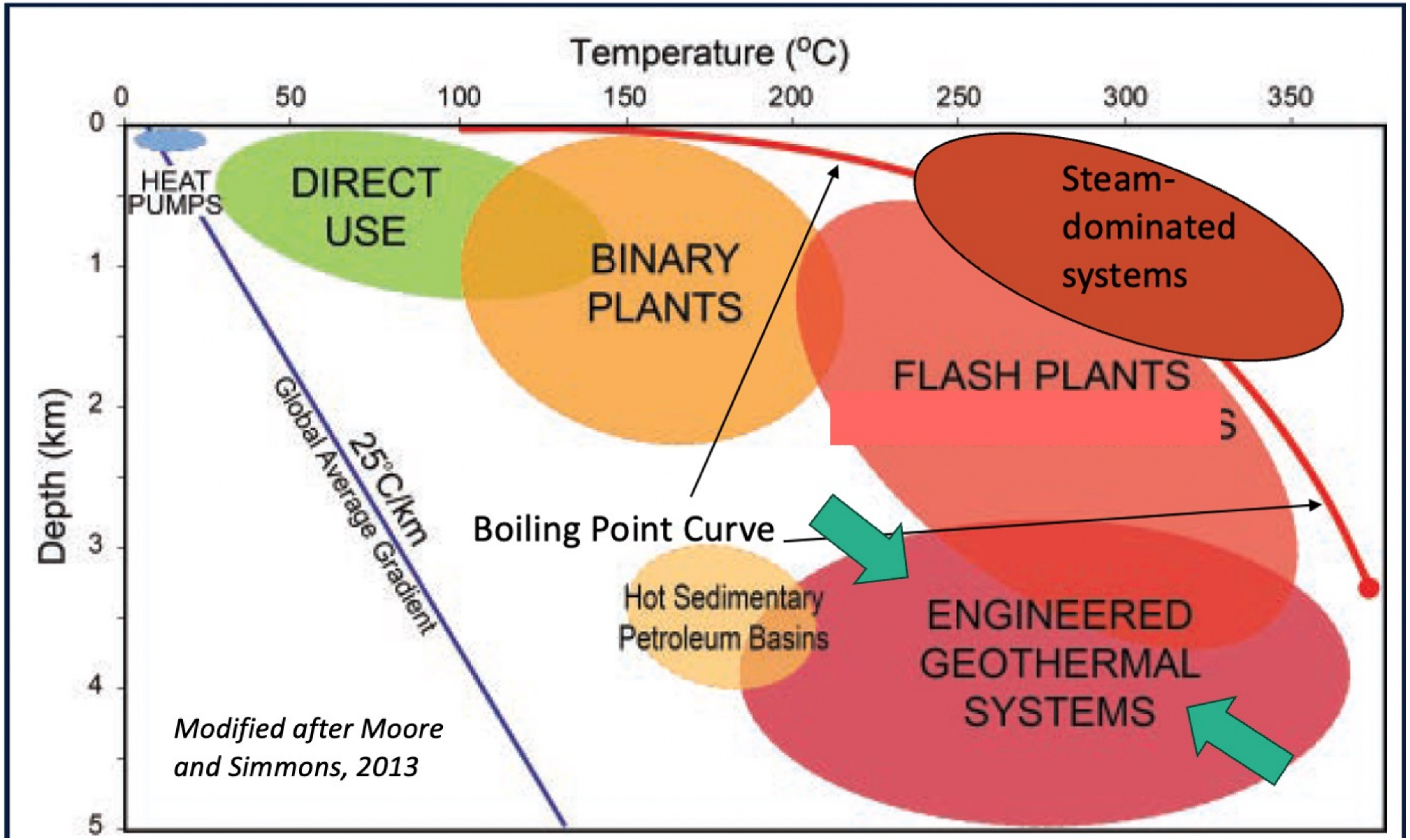


Boden 2023

Exciting Emerging Pursuits

- Generating Artificial Geothermal Reservoirs (Engineered Geothermal Systems or EGS)
  - DOE's FORGE program
  - Fervo Energy's Project Red at Blue Mountain, NV
- Developing Hot Sedimentary Aquifers
- Repurposing oil/gas wells for coproduction or depleted wells for geothermal
- Harnessing Superhot/Supercritical Geothermal Reservoirs
- Using Supercritical CO_2
- Applying Closed-Loop Technologies
- Recovering Li From Geothermal Brines ("Green Li")

Exciting Emerging Pursuits (EGS)

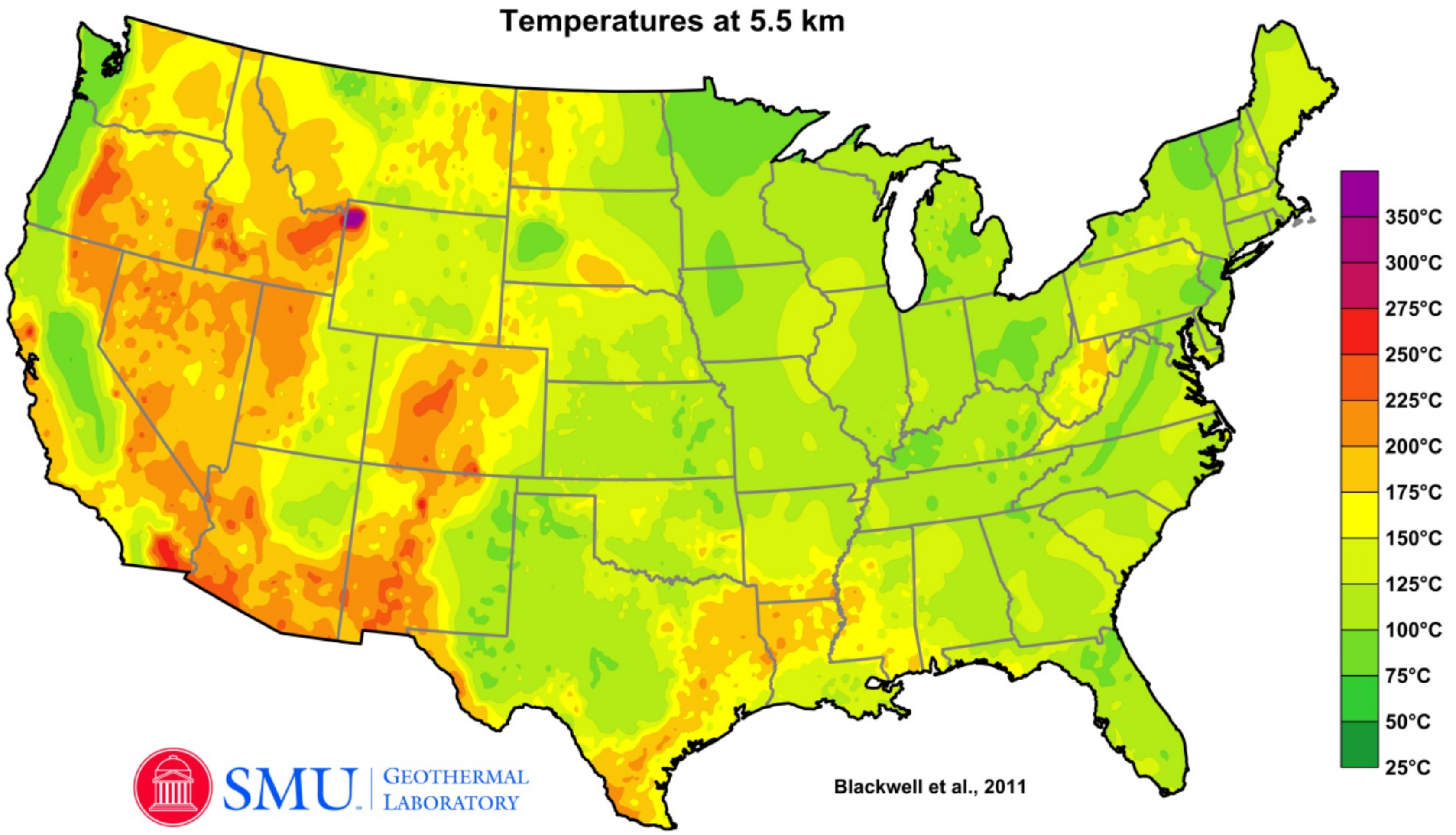


Boden 2023

Engineered Geothermal Systems (EGS)

- Artificially generated convecting hydrothermal system. How?
  - Inject water deep underground (3-5 km)
    - To improve permeability via thermal shocking (hydroshearing) and hydrofracking
    - Hot rocks contract and fracture when exposed to cold injected fluid improving permeability (hydroshearing)
    - Hydrofracking fluids pumped down under high pressure to stimulate fracture permeability
    - Fracture permeability achieved in stages via zonal isolation (using bridges and plugs) to maximize size of engineered reservoir
- Upside:
  - Have the potential to increase current geothermal power output by 1 to 2 orders of magnitude (Tester et al., 2006). Why?
    - Hot rock is much more widely distributed than hot rock with circulating water (currently developed conventional systems)
    - Much less restricted to specific geological favorable regions, such as along and near plate tectonic boundaries
  - Significant reduction in CO_2 emissions by displacing fossil-fuel-fired power plants by making geothermal power more widespread than currently developed

EGS Resource Base

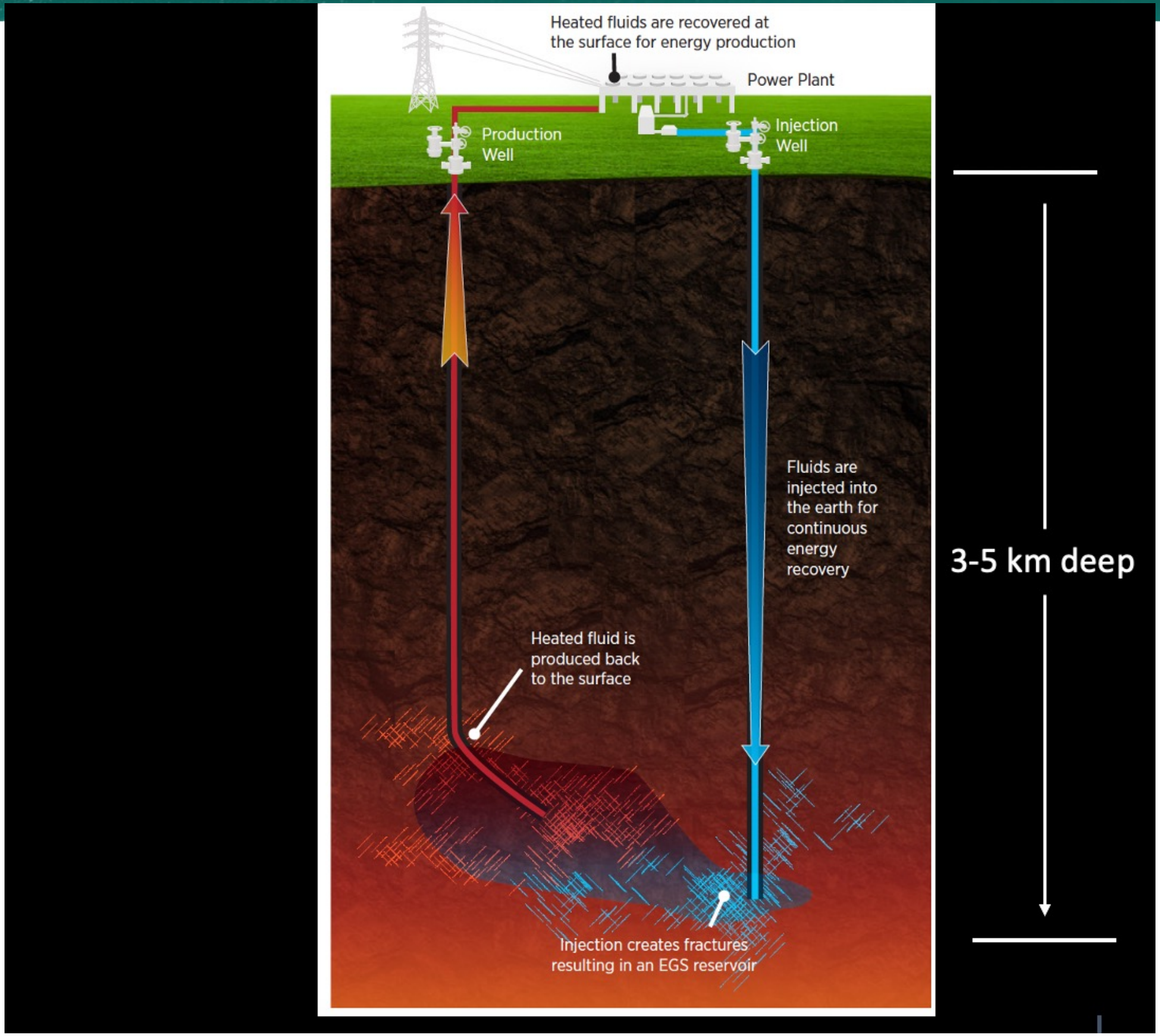


Electricity producing

Direct Use

Boden 2023

EGS–Basic Concept



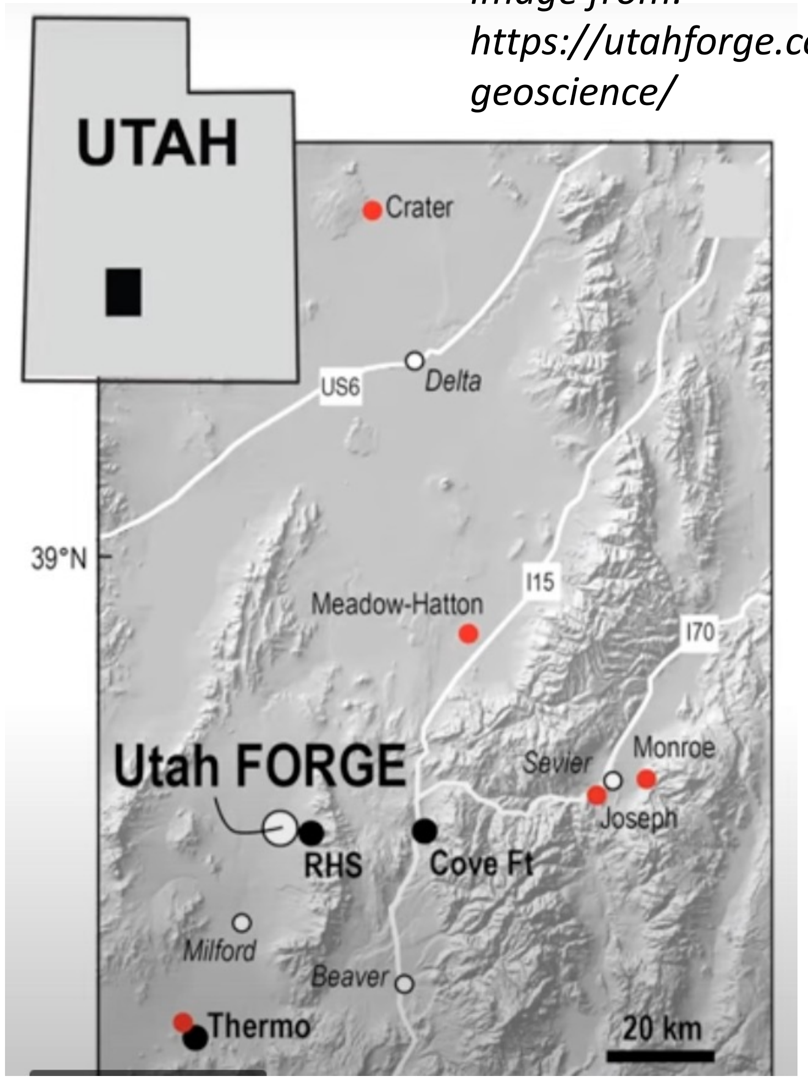
Source: DOE, GeoVision Report, 2019 (https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf)

Boden 2023

EGS (DOE-Supported FORGE Venture)

- Located in southwest Utah
- Nearby operating geothermal power plants are:
    - Thermo (14.5 MW-binary)
    - Roosevelt or Blundell (34 MW–integrated flash-binary)
    - Cove Fort (25 MW-hybrid binary-hydroelectric)
- Goal to develop a productive geothermal reservoir in impermeable granitic rock

Image from: https://utahforge.com/laboratory/geoscience/



Boden 2023

EGS (DOE-Supported FORGE Project)

- Injection well shown in blue; production well shown in red. Physical separation of two wells in reservoir ~150 m.
- Each well drilled over a period of 2.5-3 months with TD in each well of about 11k feet (~8000 ft deep with about 3000 feet lateral legs
- Bottom hole T about 230℃, reservoir T 175° to 225℃
- Injection well stimulated in 3 stages
- Demonstrated permeability connection between injection/production wells in granite host rock in July 2023
- Future work:
  - Stimulate injection well in ~7 stages (winter 2024)
  - Begin multi-week circulation tests (spring 2024)

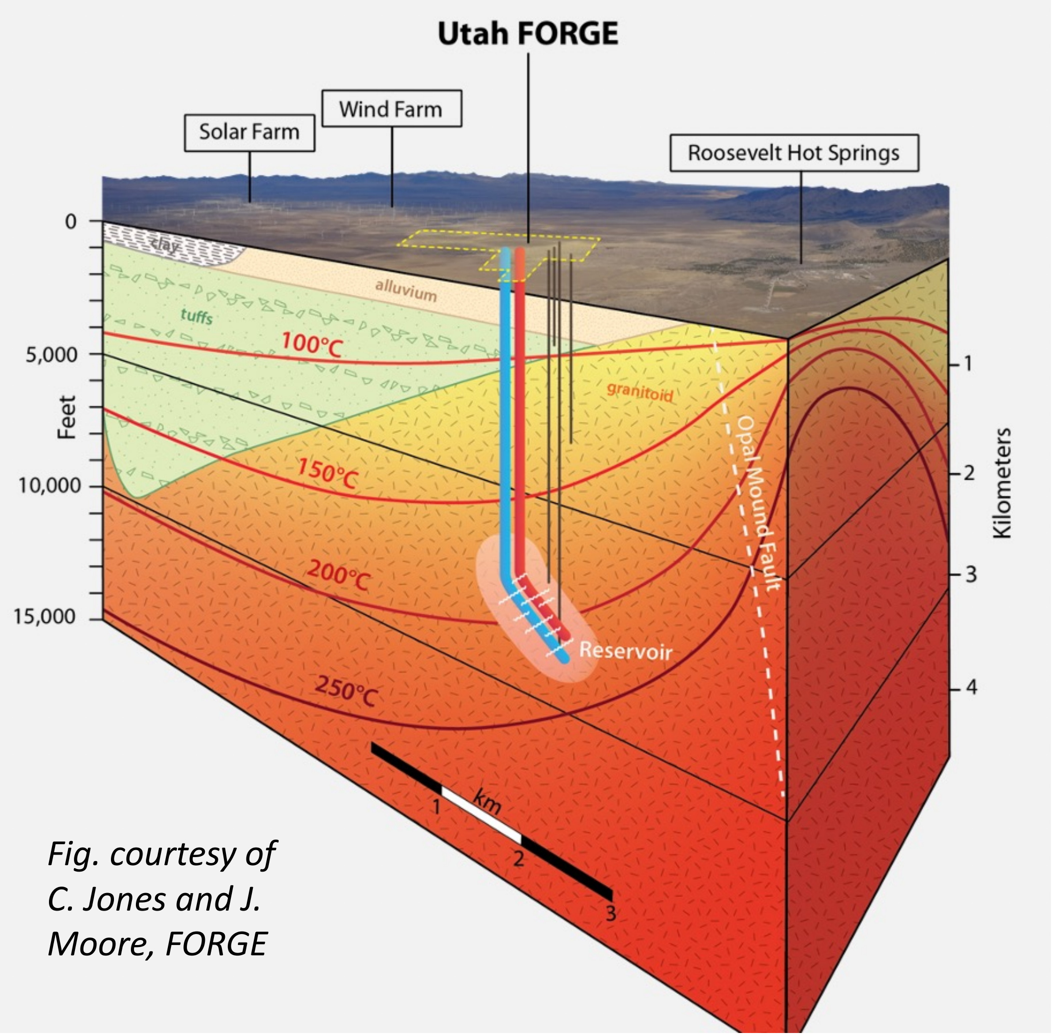
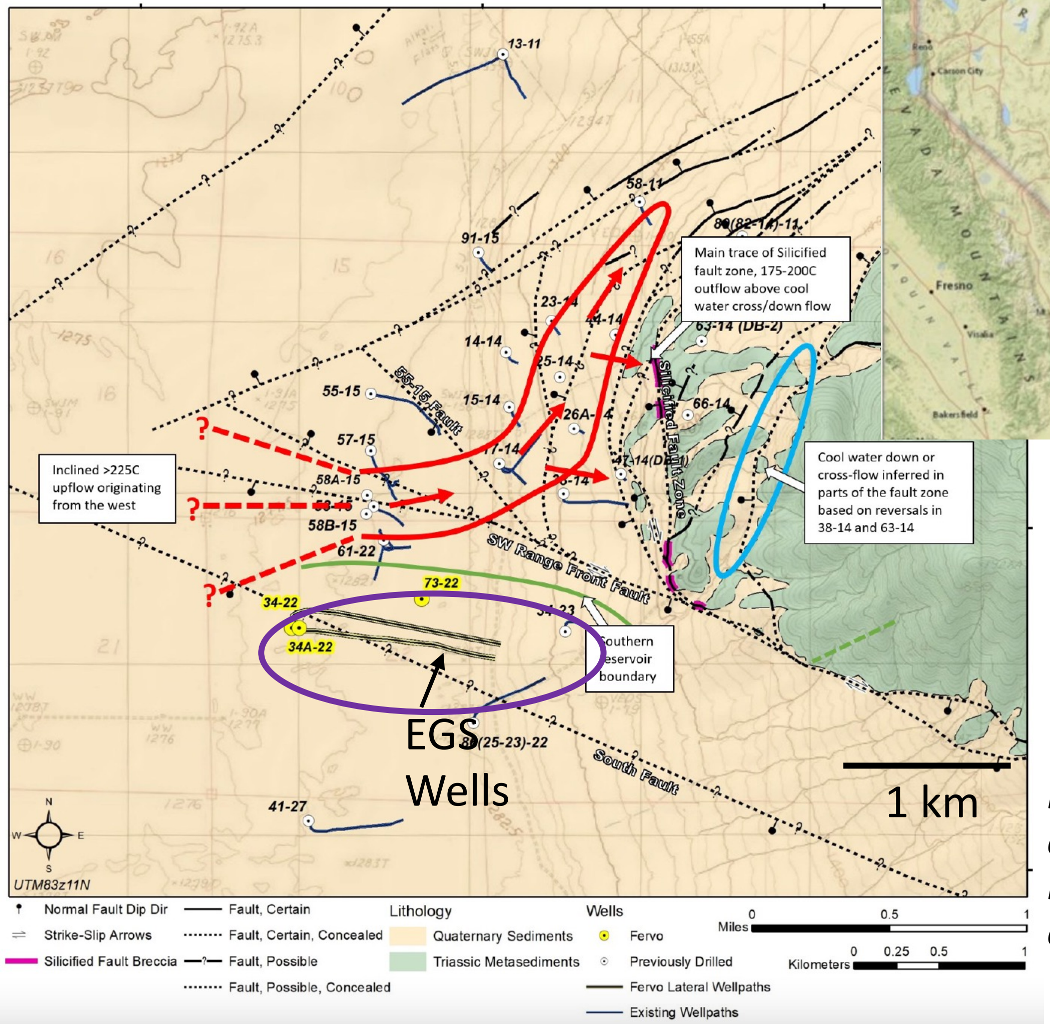


Fig. courtesy of C. Jones and J. Moore, FORGE

Boden 2023

Fervo Energy: Blue Mountain EGS Project, Nevada

- Successfully drilled injection/production well doublet (7700 feet vertical and 3200 feet lateral legs) outside of extant hydrothermal system in about 6 months
- Stimulated both injection and production wells in multiple stages to artificially create a fracture controlled permeable reservoir
- Thermal modelling studies suggest about a 10-year lifespan at the current rate of injection and production

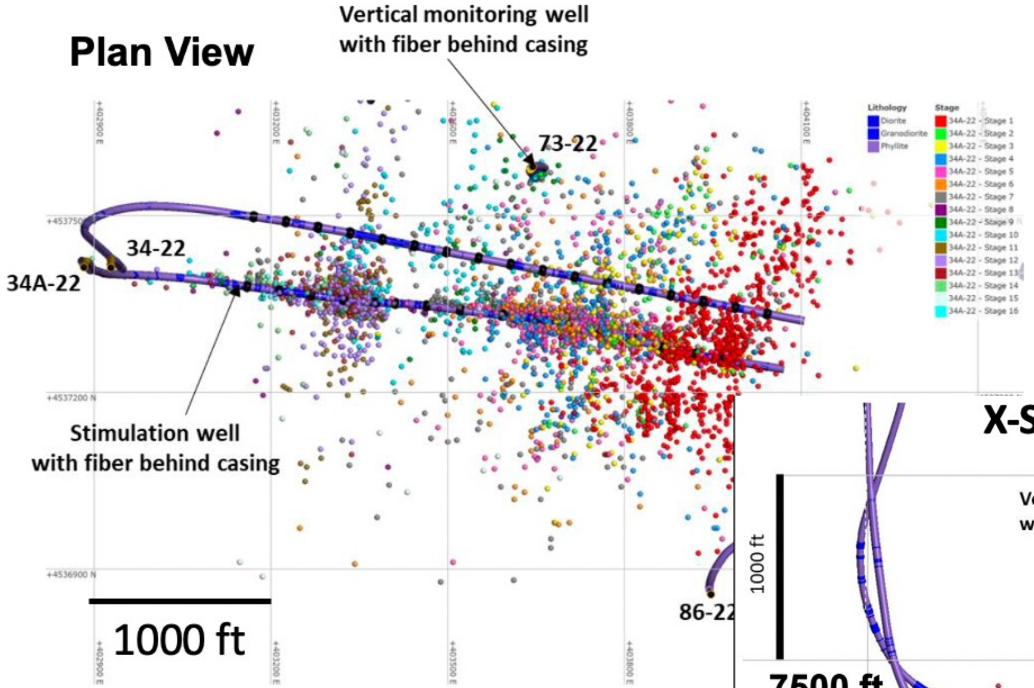


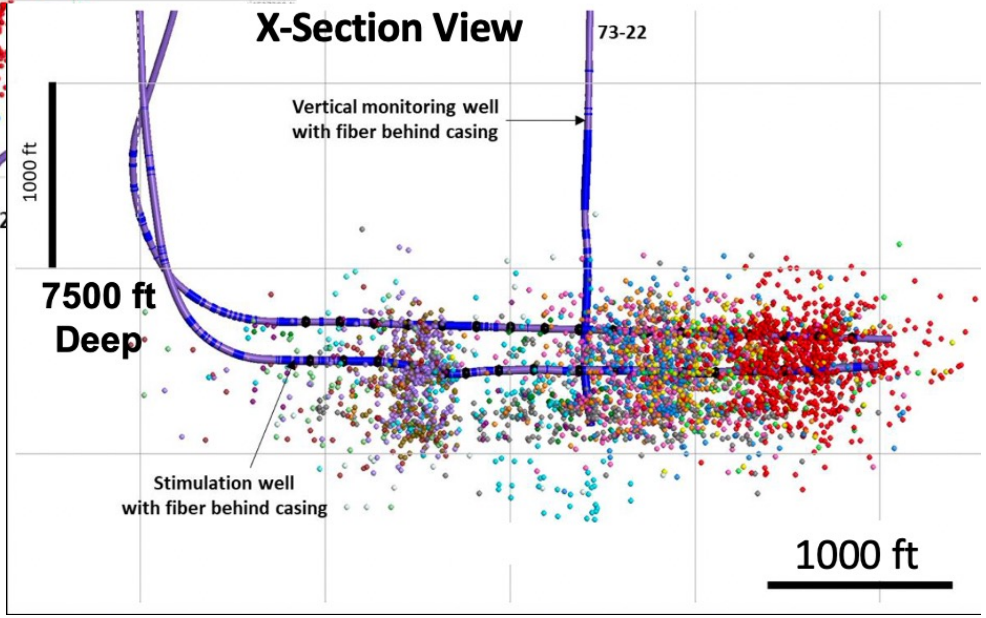
Modified after Fercho et al., 2023

Boden 2023

Fervo Energy EGS Project at Blue Mountain, NV

- Injection well stimulated in 16 stages
- Dots are microseismic events color coded to the stage of stimulation
- Resounding technical success
  - Pair of wells capable of producing 80 kg/s of fluid at 175°C to 190°C which yields about 5.1 MWe (*Fetchko et al., 2023*)
- Economic? Not yet (~$10M/MW v. ~$1M/MW for conventional geothermal wells)





Figures after Norbeck et al., 2023

Boden 2023

Engineered Geothermal Systems (EGS)–Challenges

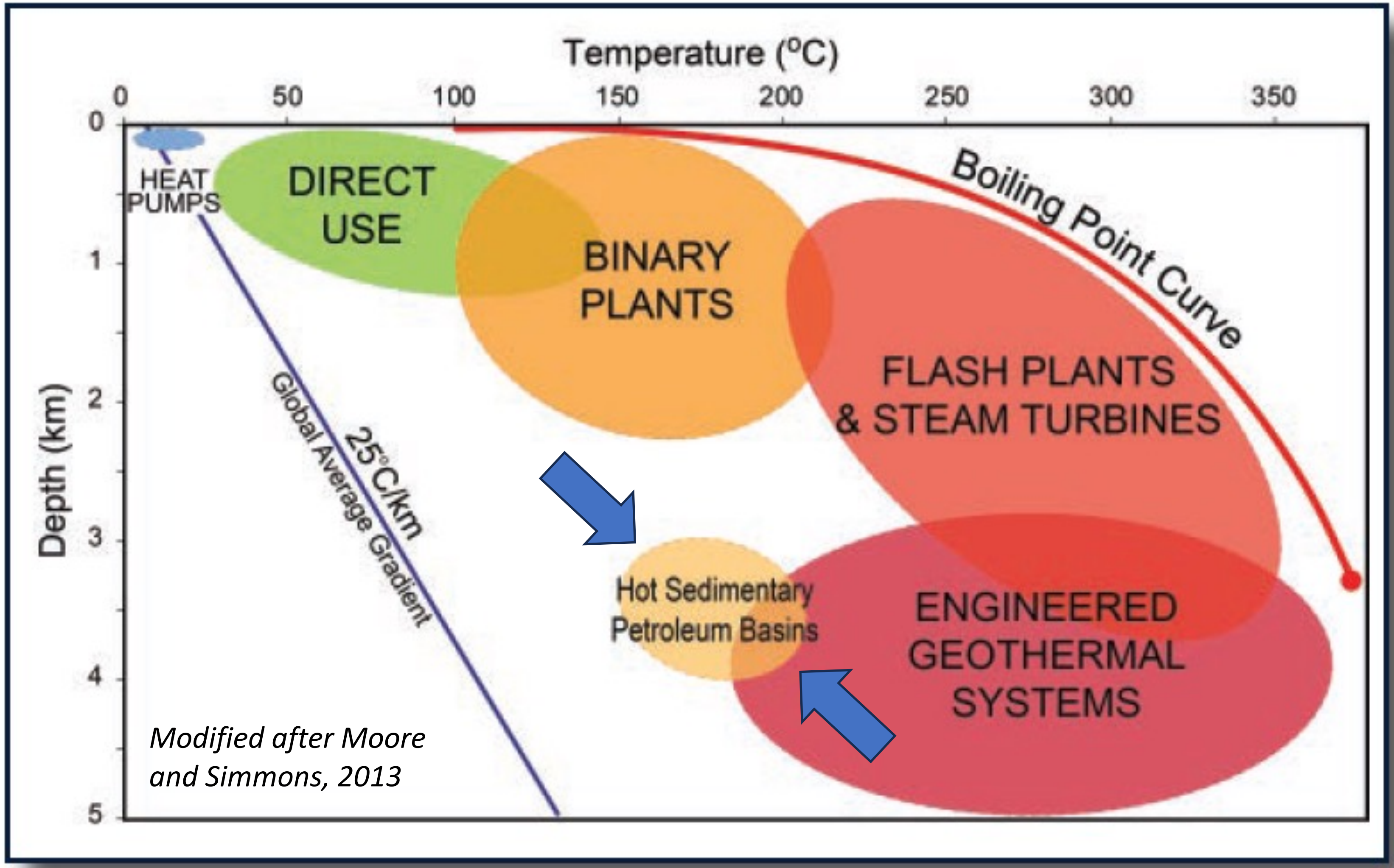
- Financial: Must drill deeper with deep horizontal legs which are expensive
- Water: A large source of water needed to pressurize reservoir, especially for creating a permeable reservoir large enough to fuel a geothermal power plant of impactful size (> ~100 MW)
- Potential Induced Seismicity: Injecting cold water causes hot rock to fracture creating small earthquakes (good for permeability) that may be felt by people
- Heat Recovery Over Time: Imperfectly known on the time frame how repeated injection of relatively cool water will lead to cooling of the reservoir
- Changes in Permeability Over Time: Changes in pressure and temperature can cause fluids to precipitate minerals in fractures as they circulate from injection to production wells

Hot Sedimentary Aquifers

- Deep (3-5 km) rock layers having good permeability
- Occur in areas having elevated heat flow (>90 mW/m^2)
- Have large surface areas of >100 km^2 compared to <10 km^2 of currently producing fault-controlled systems in Nevada
- May serve as a bridge between conventional systems and EGS
- Potential to provide hundreds of MWs of power

Boden 2023

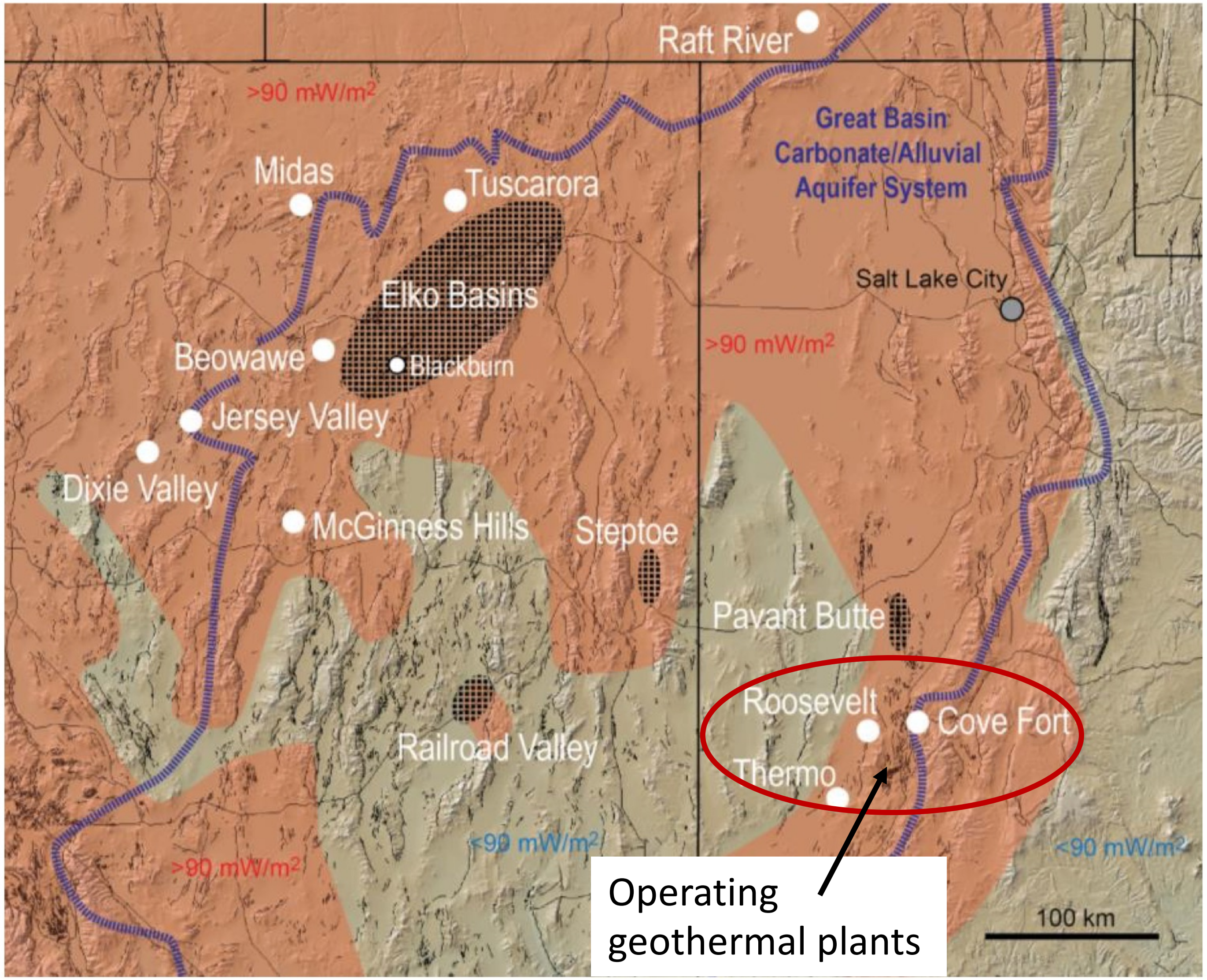
Hot Sedimentary Aquifers



Boden 2023

Hot Sedimentary Aquifers

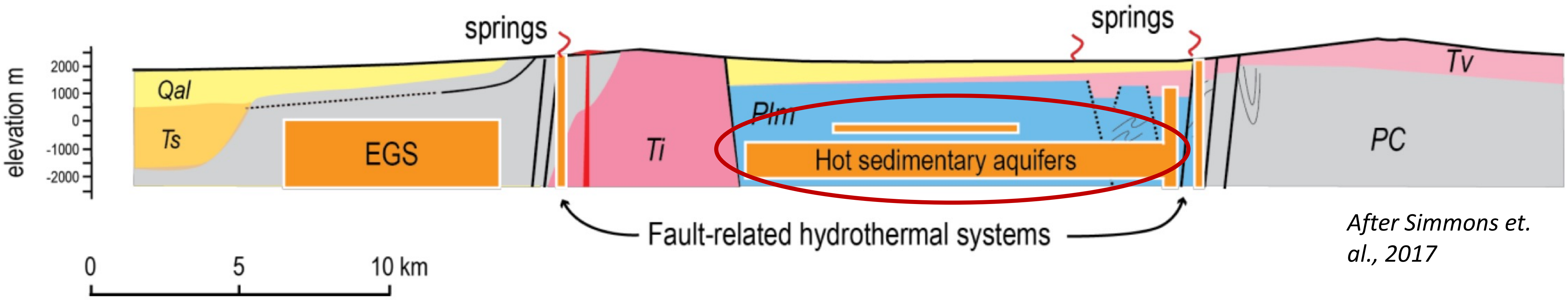
- Require permeable sedimentary layers at depths of 3-5 km in regions of elevated heat flow (orange areas >90 mW/m^2) to achieve power generation temperatures of >150°C.
- Potential aquifer basins include:
  - Elko and Steptoe, NV
  - Black Rock Desert and Pavant Butte, UT



Modified after Simmons et. al., 2017

Hot Sedimentary Aquifers

- Schematic Cross Section

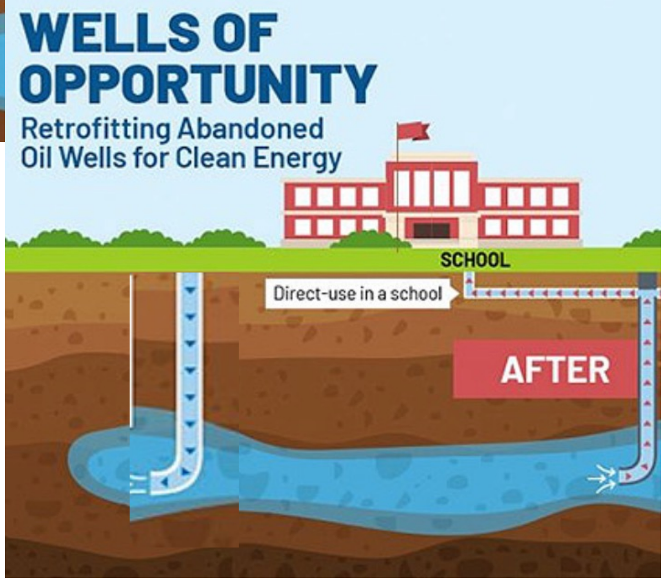


After Simmons et. al., 2017

Note the large surface area of hot sedimentary aquifers compared to fault-related geothermal systems developed by current geothermal power facilities in Nevada

Repurposing oil/gas wells

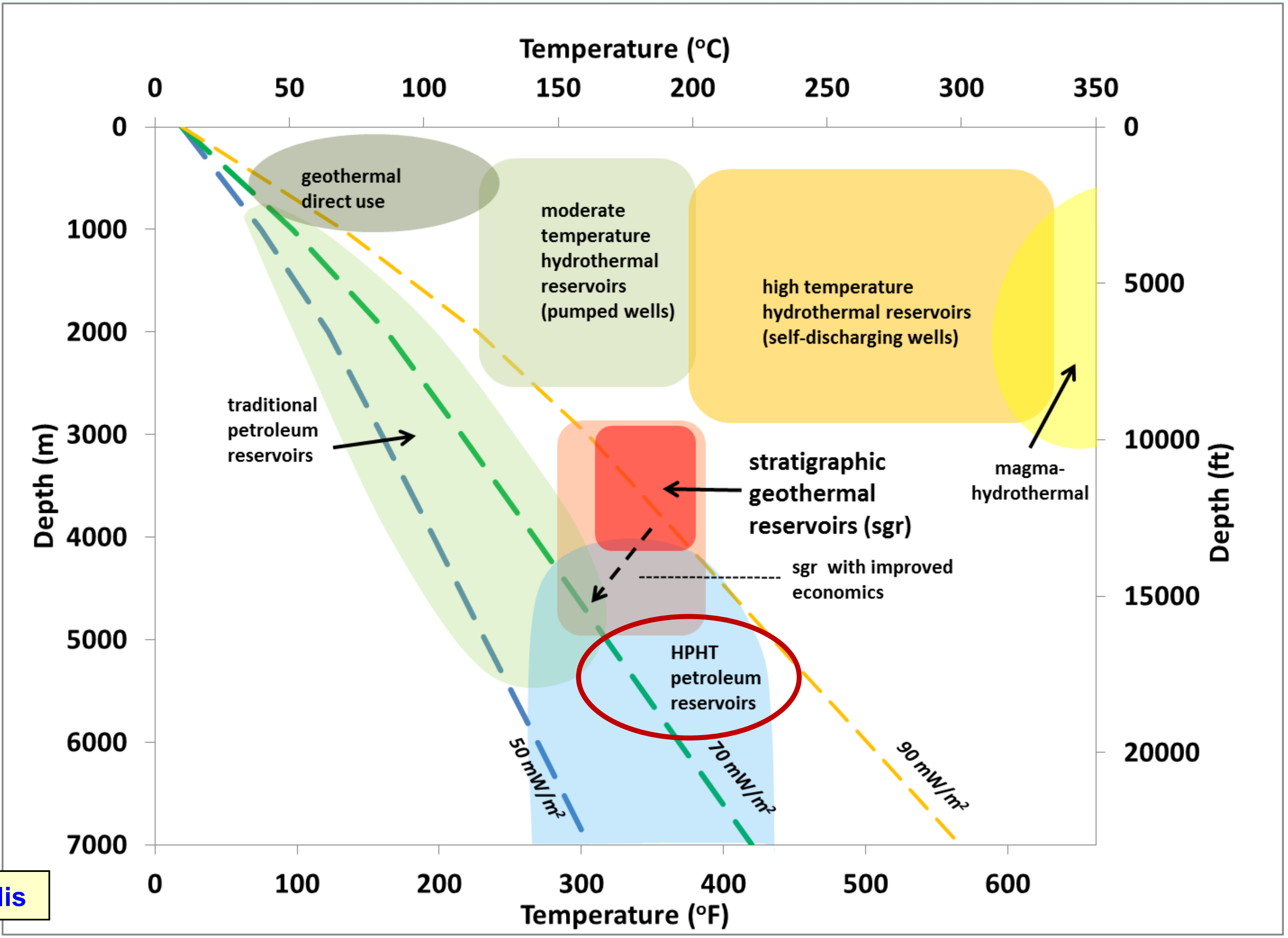
- Coproduction
  - Reconfigure wells to coproduce hydrocarbons and geothermally heated water
  - Heated water applied for direct use to heat and cool buildings
- Depleted oil/gas wells
  - Depending on T, residual water in reservoir can be used for:
    - Direct use, if hot enough (>~40℃)
    - A geothermal heat pump (geoexchange system)



Graphic modified from NREL publication Full Steam Ahead: https://www.nrel.gov/news/features/2023/full-steam-ahead-unearthing-the-power-of-geothermal.html

Hot Petroleum Aquifers

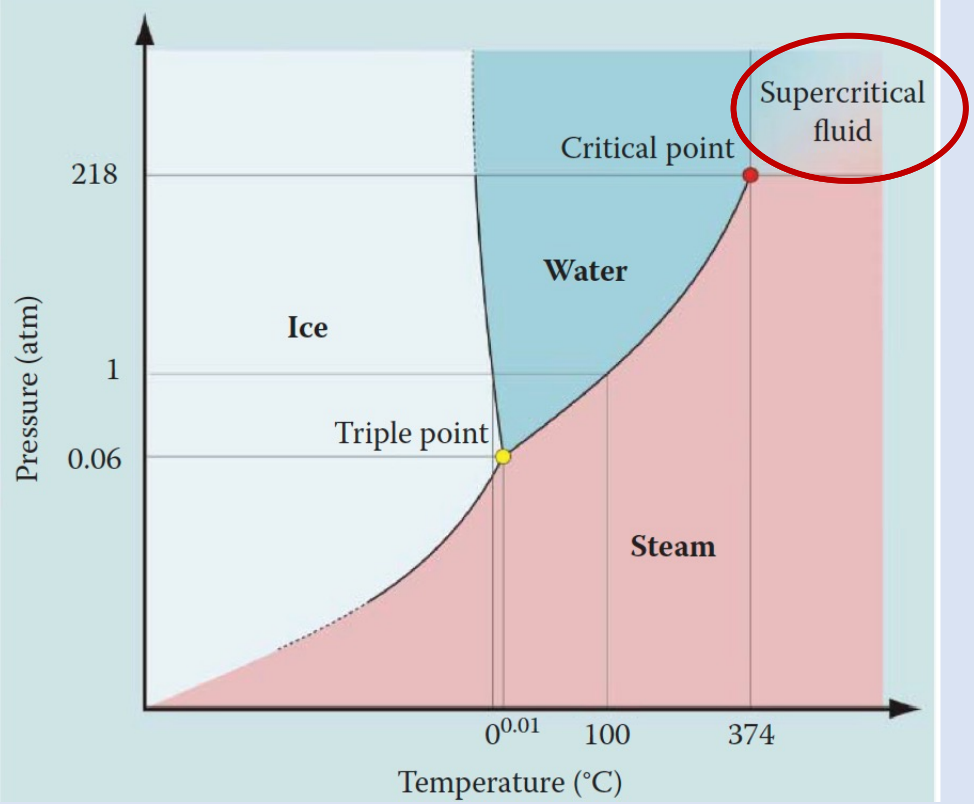
Developing hot stratigraphic petroleum reservoirs for geothermal purposes is analogous to water flooding in secondary oil recovery – **except we are sweeping heat, not oil.**



From Schelling et al., 2013; slide courtesy Rick Allis

Superhot/Supercritical Geothermal Systems

- Being explored by Iceland Deep Drilling Project (IDDP), Supercritical Geothermal Project in Japan, Geothermal: The Next Generation in New Zealand, and NREL's DEEPEN Initiative in the U.S.
- What is supercritical water?
  - Fluid with properties intermediate between liquid and gas (density of liquid but mobility of gas)
  - No surface tension at these conditions resulting in high buoyancy to viscous forces and mass transfer
  - Well tapping supercritical reservoir would have 5x –10x power output of a conventional well
    - **5 to 10 times fewer wells needed, saving ~$30M–$60M**



Boden 2023

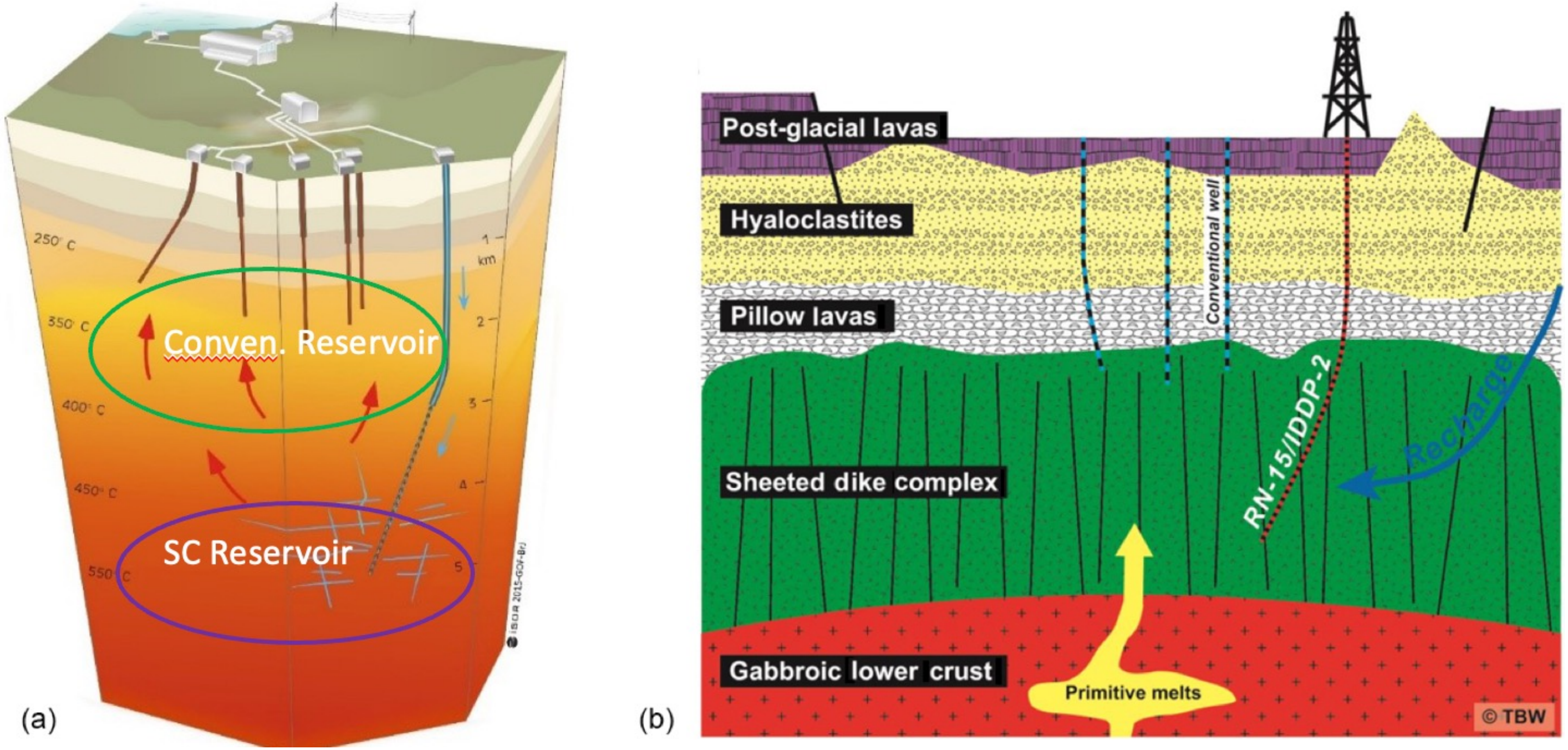
Superhot/Supercritical Geothermal Systems

- IDDP-2 Well, Reykjanes, Iceland
  - Drilled to a vertical depth of ~4500m
  - T $\geq 426℃$, P=340 bars at TD
  - These T and P values exceed super-critical conditions for seawater (Cp = 406℃, P = 298 bars)
  - After ~2 years of flowing cold water to stabilize well and stimulate reservoir only achieved a few kg/s wellhead flow
    - Casing failure, inferred blockage at depth, and likely diversion of upwelling fluids into fracture zones


Image from Stefansson et al., 2021

Superhot/Supercritical Geothermal Systems

- Schematic View of IDDP-2

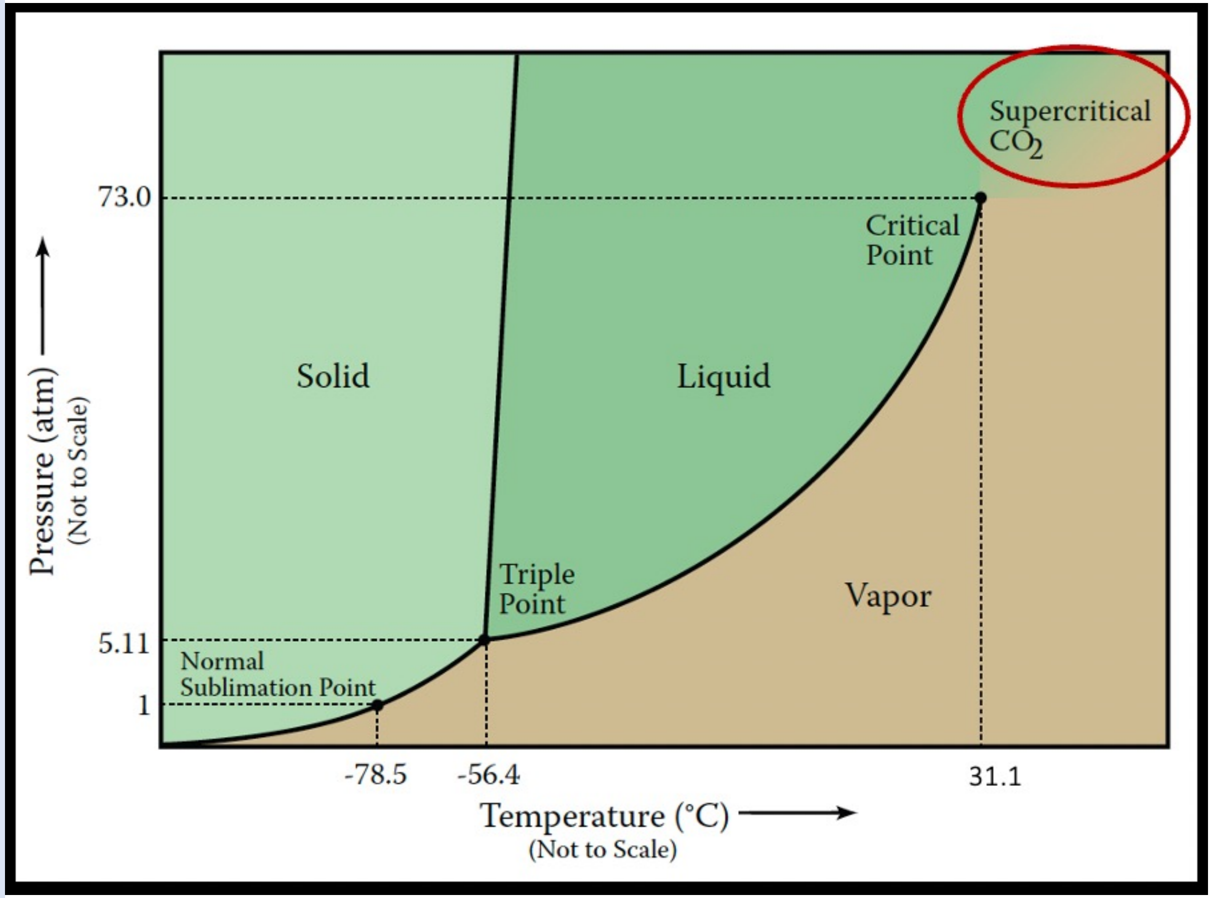


Modified after Fridleifsson et al., 2017

Boden 2023

Using Supercritical CO_2 ($ScCO_2$)

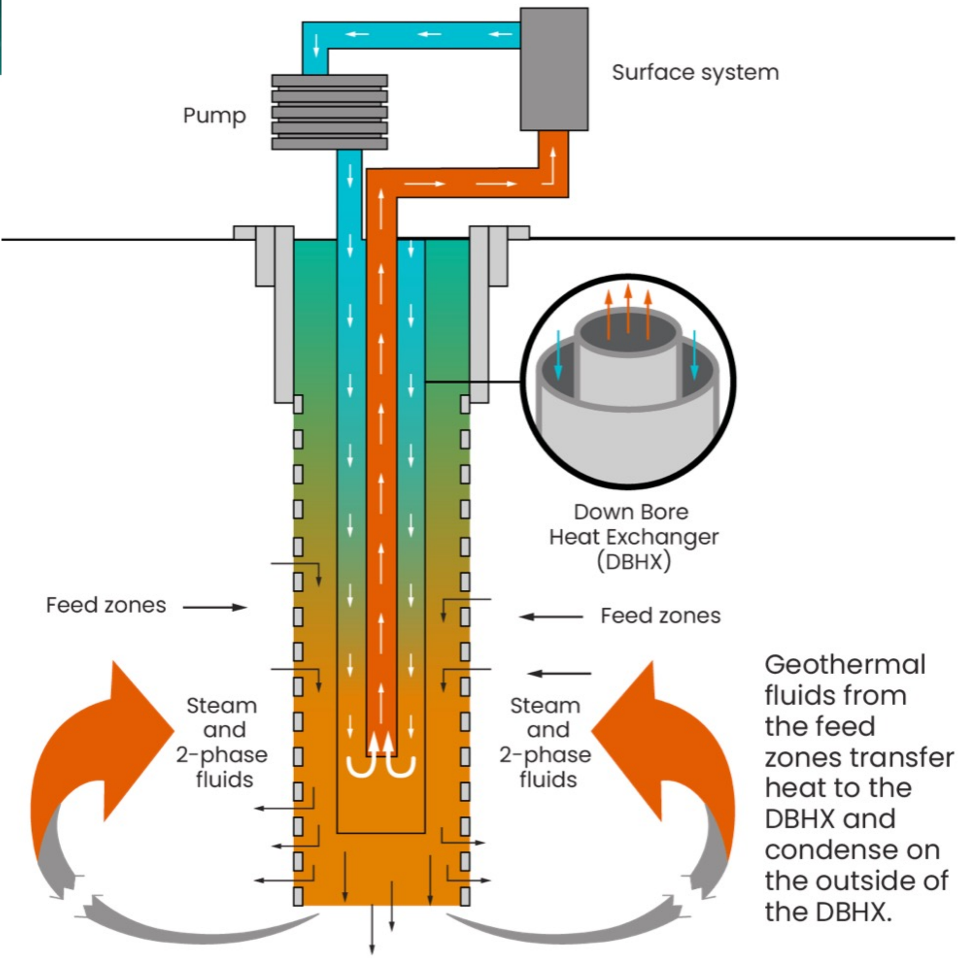
- Advantages:
  - 3x–5x higher mass flow rates than water
  - Large density contrast between cold and hot $ScCO_2$ means strong buoyant forces reducing power consumption for pumping
  - Can help sequester CO_2 produced from fossil-fuel fired power plants
  - Less scaling or corrosion of equipment as $ScCO_2$ is not an ionic compound
- Challenges:
  - Getting CO_2 from power plants or extraction from air is currently expensive
    - Ave. coal-fired power plant emits 2.5Mt of CO_2/yr; capture CO_2 costs ~\$50/t→\$125M!
  - Unknown possible reactions with wall rocks and water at depth that could precipitate carbonate minerals reducing permeability



Boden 2023

Closed-Loop Technologies

- Two different configurations being explored:
  - 1. Modify existing nonproductive wells (GreenFire's GreenLoop technology)
  - 2. Drill deep well with multiple laterals at depth to extract heat (Eavor technology)
- GreenLoop Technology
  - Utilizes down borehole heat exchanger
  - Induces convection outside of borehole
  - Mainly for steam-dominated and 2-phase geothermal reservoirs
  - Steam condenses on outside of borehole transferring additional latent heat to injected fluid from that provided by conduction alone



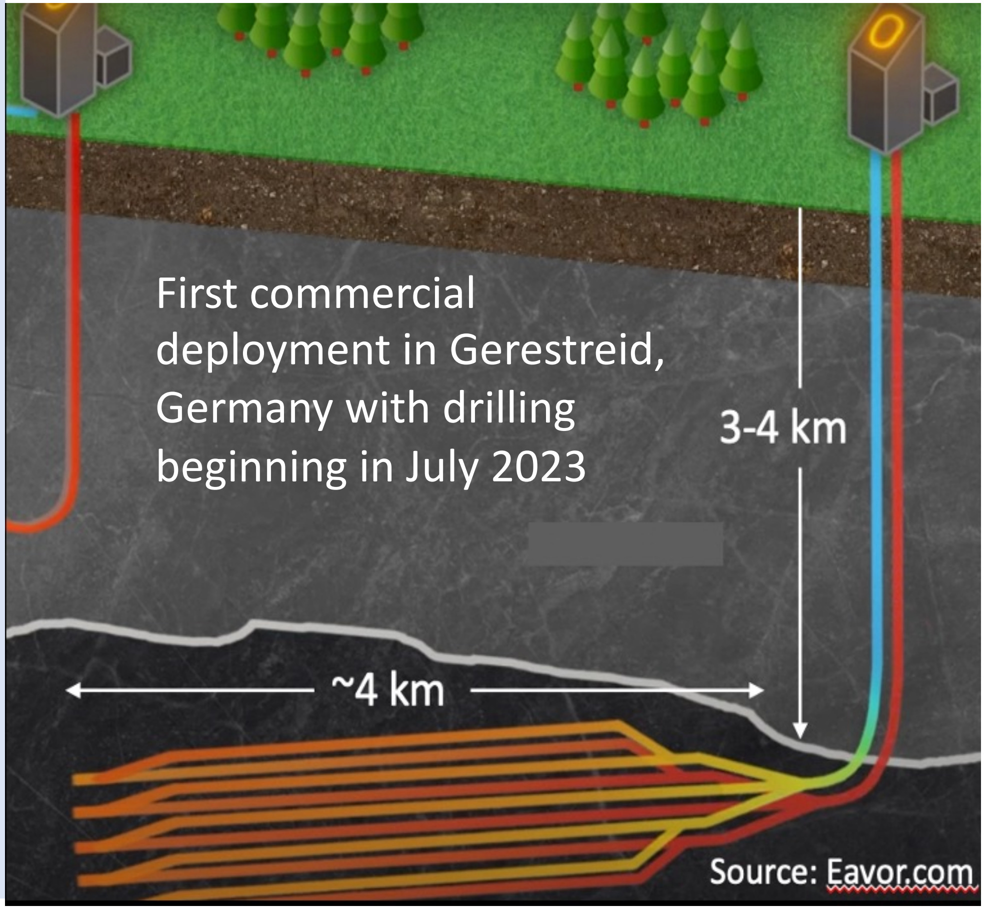
Steam GreenLoop and 2-Phase GreenLoop Designs

Source: https://www.greenfireenergy.com/greenloop-technology/

Boden 2023

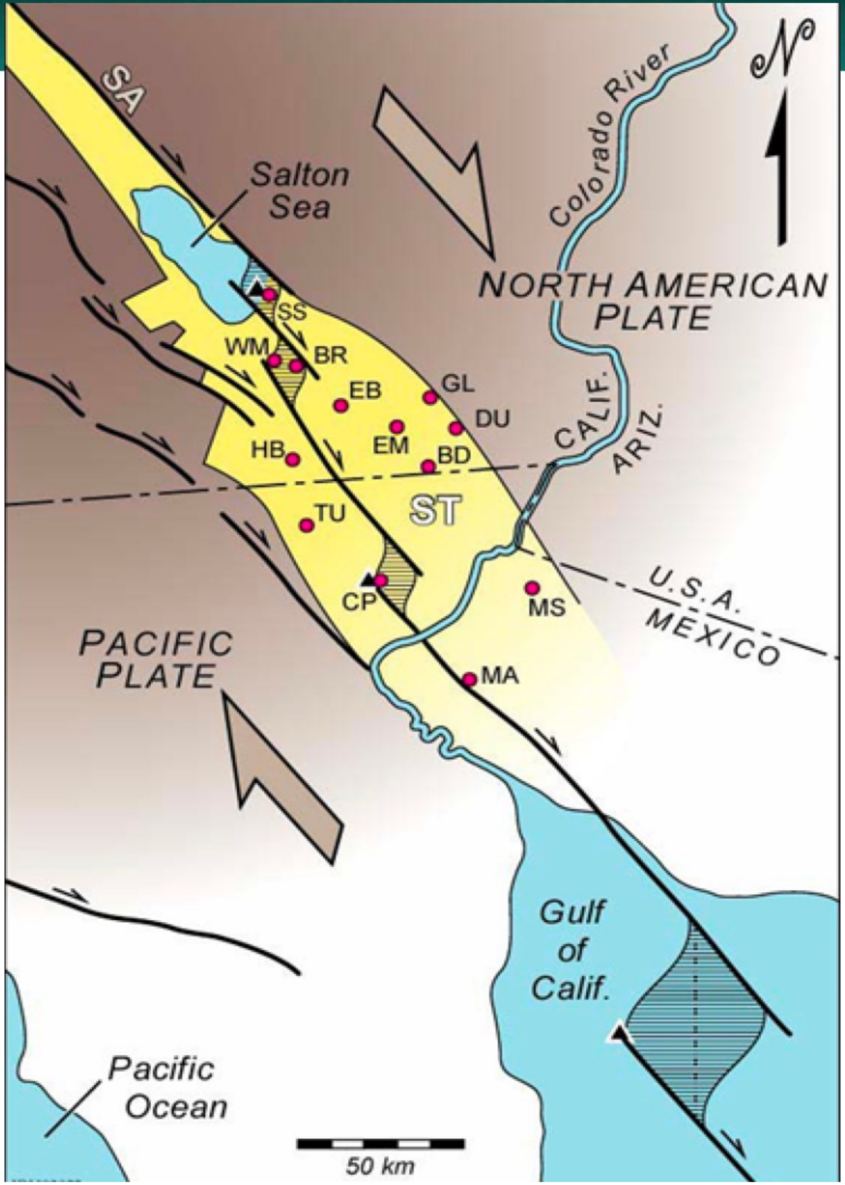
Closed-Loop Technologies

- Deep Lateral Wells Configuration (Eavor Technology)
  - A fluid with a low boiling point is injected into a series of piping laterals at depth where it picks up heat to return to the surface to fuel a power plant and then reinjected
- Potential Advantages:
  - Can be applied anywhere (scalable)
  - No need to find zones of natural permeability
  - No need to artificially induce permeability via rock fracturing (EGS)
  - Avoids potential problems of producing from geothermal fluids (scaling and corrosion of equipment)
  - No added or make-up water needed
- Potential Challenges:
  - Potential cooling of working fluid with time (working fluid heated by conduction (slow heat transfer) compared to convection)
  - Initial high cost due to technologically advanced drilling technology (deep lateral well configuration and casing)



Li From Geothermal Brines

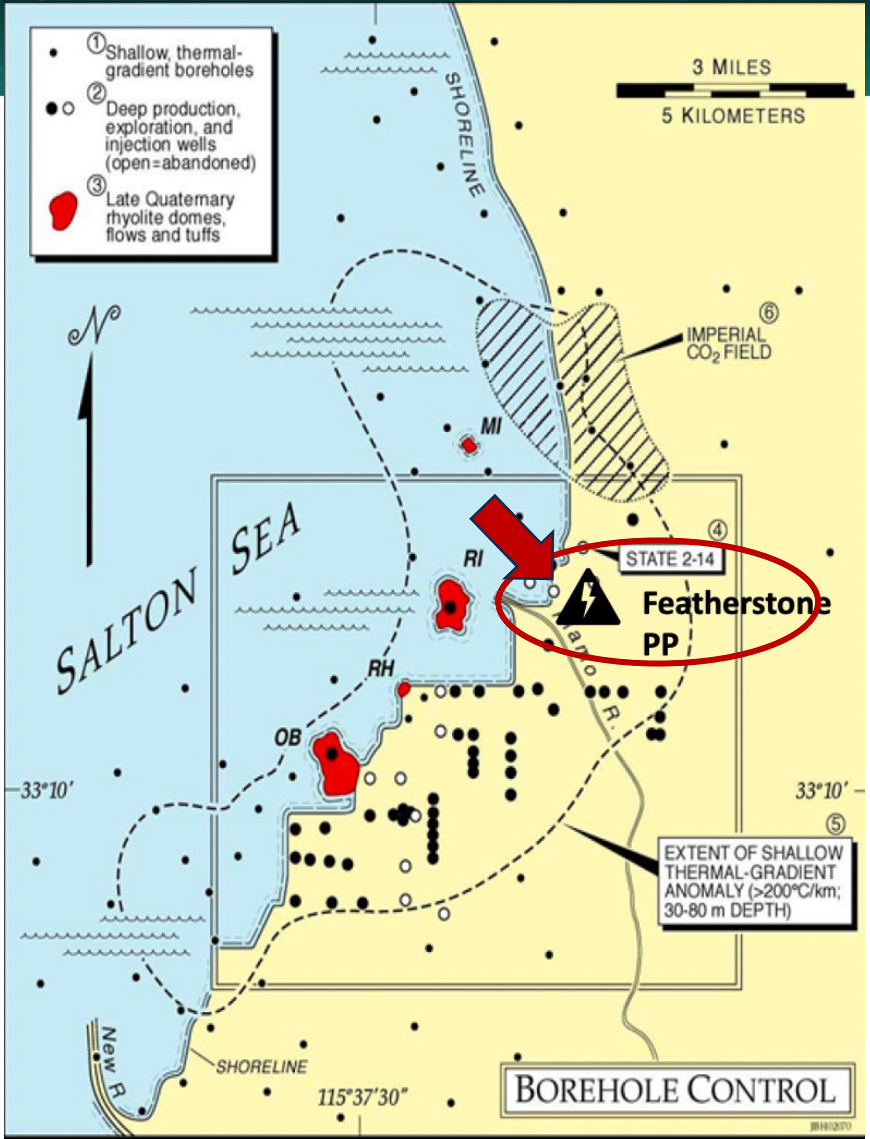
- Salton Sea geothermal field in SE CA has an installed geothermal power capacity of about 440 MW from 11 power stations
- Salton Sea geothermal brines contain 250,000–300,000 ppm TDS
  - Enriched in Mn, Zn, Ag, and **Li**
  - Li concentration as high as 440 ppm; average ~200 ppm (*Neupane and Wendt, 2017; Humphreys et al., 2023*)



Modified after Hulen et al, 2002

Li From Geothermal Brines

- Cyrq Energy's 55 MW Featherstone (Hudson Ranch) Power Plant
  - Produces about 480,000MWh electrical energy per year
  - Gross annual power revenue ~$25M–$30M
  - Energy Source Minerals pursuing development of Li recovery plant on site to yield a planned 19,000 tons of LiOH/yr slated to begin operating in 2025-26
  - Current price of LiOH (9/29/2023) is $26k/tonne→**gross revenue ~$500M/yr!**
    - A 100 kWh Tesla battery requires the Li content held in ~50kg of LiOH
    - Above planned production of LiOH would be enough to make **~380,000 Tesla batteries/yr**



Modified after Hulen et al, 2002

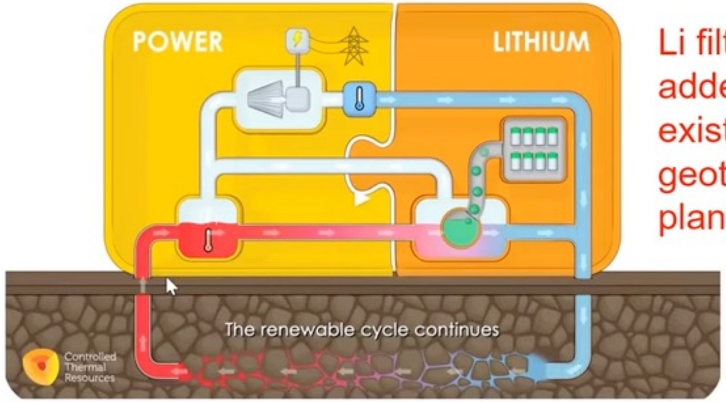
Li From Geothermal Brines

Geothermal brine DLE: smallest footprint: closed-loop process, no huge evaporation ponds, no blasting, no pits.

Chilean salar brine:
3,100 acres

Australian hard rock:
465 acres

Geothermal lithium:
50 acres



CTR

Li filter added to existing geothermal plant

Note small footprint of geothermal Li recovery

Proposed location of Li recovery plant

55 MW Hudson Ranch (Featherstone) Geothermal Plant

Slide modified after McKibben, 2023 (https://lirric.lbl.gov/2023/03/march-15-michael-mckibben-usriverside/ accessed 09/25/23)

- Recovery of Li from geothermal brines will be least destructive and most environmentally sound of current Li production methods including:
  - Hard rock mining
  - Salar brines of SA

Li From Geothermal Brines

- Salton Sea geothermal field has a resource potential of 600,000 tons/year of Li carbonate (Li_2CO_3) equivalent (*CEC Report, 2020: https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-020.pdf*)
  - Rivals entire 2022 global production of 680,000 metric tons of lithium carbonate equivalent
  - Above Salton Sea Li resource potential is enough to make about **18M 100kWh Tesla batteries/year**
  - Estimated total resource ranges between 4 and 21M metric tons of lithium carbonate equivalent (McKibben, 2023)
  - If realized, the Salton Sea Li resource would produce about 7–10 times the planned production of Thacker Pass Li open-pit mine (projected 40k to 80k Mtpa of Li_2CO_3 – largest identified minable clay-hosted Li resource in NA)
- Depending on the price of Li carbonate of estimated resource, a potential revenue of **$7B to $30B per year** could be realized
  - Effectively lowering price of geothermally produced power
  - Infusing much needed prosperity for an economically depressed region
  - Dramatically increase domestic production of Li– 90% of which is currently imported from Chile and Argentina (*Source: https://www.energy.gov/eere/vehicles/articles/fotw-1225-february-14-2022-2016-2019-over-90-us-lithium-imports-came*)

Agenda (Epilogue)

- What are current sources of electricity and how are energy and power related?
- Where does Earth's heat come and how does heat move?
- What is geothermal energy and how does depth and temperature impact use of geothermal energy?
- What criteria are needed to make a geothermal fluids viable for development?
- What are some key attributes and challenges of geothermal energy?
- Where are most developed geothermal systems found?
- What makes the Great Basin so prospective for geothermal energy?
- What are some exciting new technologies for expanding geothermal energy, including recovery of critical minerals?

THANK YOU!

dboden@tmcc.edu

Tolhuaca geothermal prospect, Chile

Image credit: GeoGlobal Energy Corp.

References

Beckers, K.F., Kolker, A., Pauling, H., McTigue, J. D., and Kessili, D., 2021, Evaluating the feasibility of geothermal deep direct-use in the United States. Energy Conversion and Management, v. 243, 114335

Blackwell, D. M., Richards, M. F., Batir, J., Ruzo, A., Dingwall, R., and Williams, M., 2011, Temperature at depth maps for the conterminous U. S. and geothermal resource estimates. Geothermal Resources Council Transactions, v. 35, p. 1545-1550

Bolinger, M., Millstein, D., Gorman, W., Dobson, P., and Jeong, S., 2023, Mind the gap: Comparing the net value of geothermal, wind, solar, and solar+storage in the western United States. Renewable Energy, v. 205, p. 999-1009.

DiMarzio, G., Angelini, L., Price, W., Chin, C., and Harris, S., 2015, The Stillwater triple hybrid power plant: Integrating geothermal, solar PV, and solar thermal power generation. 2015 World Geothermal Congress (http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/38001.pdf)

DiPippo, R., 2015, Geothermal power plants: Principles, Application, Case Studies, and environmental impacts, 3rd edition, Elsevier, 762 p.

Duffield, W. A. and Sass, J. H., 2003, Geothermal Energy–Clean power from Earth's heat. USGS Circular 1249, 36 p. (https://pubs.usgs.gov/circ/2004/c1249/c1249.pdf)

Fercho, S., Norbeck, J., McConville, E., et. al., 2023, Geology, State of Stress, and Heat in Place for a Horizontal Well Geothermal DevelopmentProject at Blue Mountain, Nevada. 48th Stanford Workshop on Geothermal Reservoir Engineering (https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2023/Fercho.pdf)

Fridleifsson, G.O., Elders, W. A., Zierenberg, R. A., Stefansson, A., Fowler, A. P. G., Weisenberger, T. B., Hardarson, B. S., and Mesfin,K. G., 2017, The Iceland Deep Drilling Project 4.5km deep well, IDDP-2,in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target. Scientific Drilling, v. 23, p. 1-12

References (continued)

Garcia, J., Walters, M., Beall, J., Hartline, C., Pingol, A., Pistone, S., and Wright, M., 2012, Overview of the Northwest Geysers EGS demonstration project. 37th Stanford Workshop on Geothermal Reservoir Engineering (https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2012/Garcia.pdf)

Hulen, J., Kaspereit, D., Norton, D., Osborn, W., and Pulka, F., 2002, Refined conceptual modeling and new resource estimates for Salton Sea geothermal field: Geothermal Resources Council Transactions, v. 26, pp. 8

Humphreys, J., Brounce, M., McKibben, M. A., et al., 2023, Distribution, isotopic composition, and origin of Li in the Salton Sea Geothermal Field. 48th Stanford Workshop on Geothermal Reservoir Engineering (https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2023/Humphreys.pdf)

Moore, J. N., and Simmons, S. F., 2013, More power from below. Science, v. 340, p. 933-34.

Neupane, G., and Wendt, D. S., 2017, Assessment of Mineral Resources in Geothermal Brines in the US. 42nd Stanford Workshop on Geothermal Reservoir Engineering (https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2017/Neupane2.pdf)

Norbeck, J., Latimer, T., Gradl, C., et al., 2023, A Review of Drilling, Completion, and Stimulation of a Horizontal Geothermal Well System in North-Central Nevada. 48th Stanford Workshop on Geothermal Reservoir Engineering (https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2023/Norbeck.pdf)

Schelling, D., Allis, R. and Sprinkel, D., 2013. Role of seismic reflection profiles in delineating basin-centered geothermal reservoirs. *GRC Transactions*, *37*, p. 1051-1057. (https://publications.mygeoenergynow.org/grc/1030700.pdf)

Simmons, S., Allis, R., Moore, J., Gwynn, M., Hardwick, C., Kirby, S., and Wannamaker, P., 2017, Conceptual models of geothermal resources in eastern Great Basin, in Proceedings 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, 9p. (https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2017/Simmons.pdf)

Stefansson, A., Fridleifsson, G. O., Sigurdsson, O., and Gislason, P., 2021, The IDDP-2 DEEPEGS Drilling Experience and Lesson Learned. Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland (https://www.geothermal-energy.org/pdf/WGC/papers/WGC/2020/21025.pdf)