Geothermal for Industrial Steam:

Evaluating Levelized Cost of Heat

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Summary

- This work set out to determine whether technological advances from oil and gas make geothermal steam economically competitive, and found the following…
  - Technological advances from oil and gas upset the conventional understanding that geothermal is limited to areas with high resource quality by decoupling well cost and resource quality, making facility size the predominant factor determining the levelized cost of heat
  - This cuts the levelized cost of heat for the reference steam facility in half, from $14/MMBtu to $7/MMBtu, making it economically competitive with new gas boilers (at $8/MMBtu) and electric heat pumps ($17/MMBtu)
- Other important takeaways from this work include…
  - Geothermal steam requires lower temperatures and avoids the efficiency loss of converting to electricity, making it possible to utilize resources unsuitable to electricity and at a lower relative cost
  - Project financing remains a challenge for geothermal steam, but the fact that these same technological advances facilitated the shale gas boom of the 2010's suggests that geothermal steam could experience a similar trajectory in the coming years

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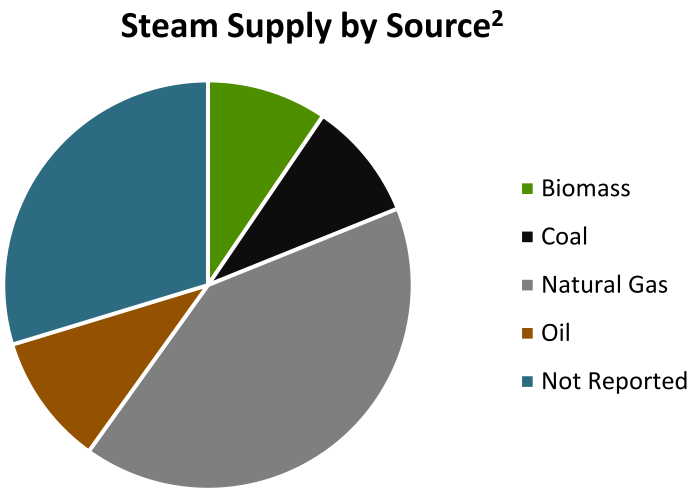
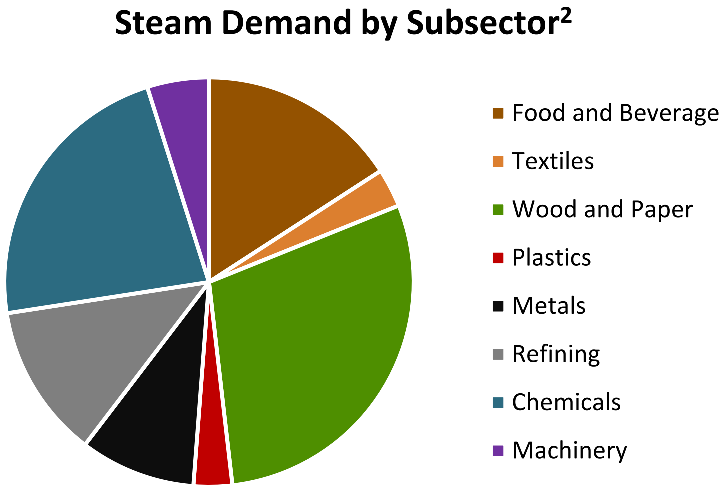
Context

Importance of Industrial Steam

- Industry accounts for about a third of global emissions[1], and roughly 15% of industrial energy is in the form of steam
- Steam is critical to a variety of subsectors, including food and beverage, wood and paper, refining and chemicals, where it is utilized for…
  - concentrating, melting, and evaporating substances
  - driving chemical reactions
  - combining and separating materials
- At least 60% of steam is met with fossil fuels[2]

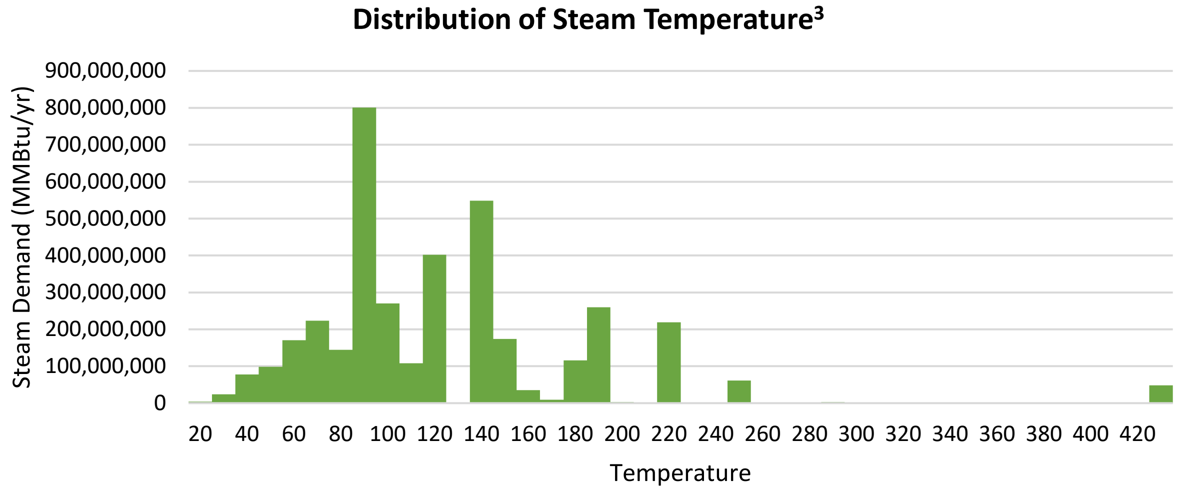


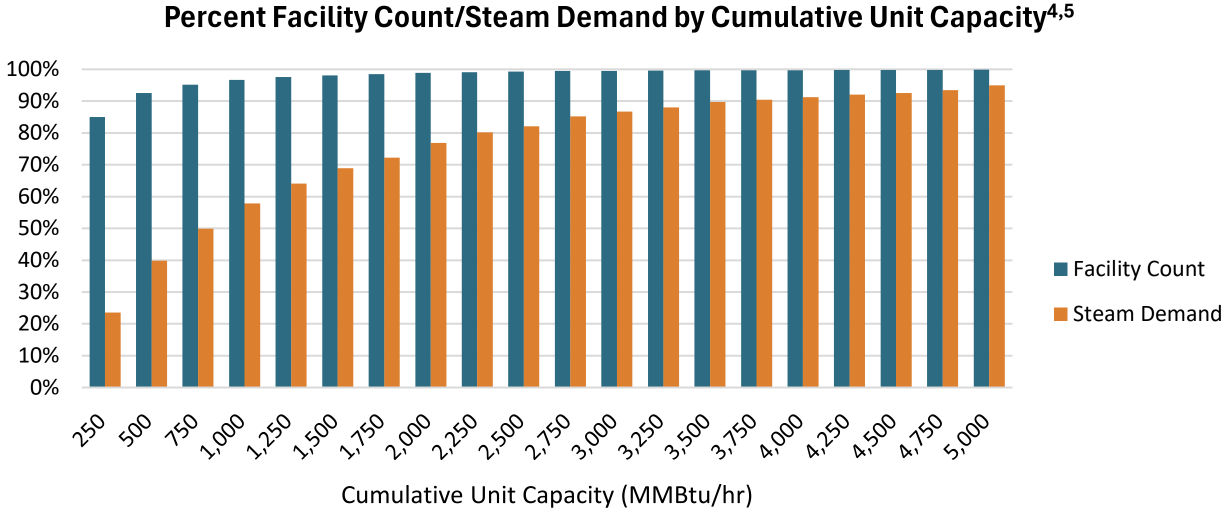


[1] Thiel, G., Stark, A. (2021). To decarbonize industry we must decarbonize heat. Joule. https://doi.org/10.1016/j.joule.2020.12.007
[2] Energy Information Agency. (2018). Manufacturing Energy Consumption Survey. https://www.eia.gov/consumption/manufacturing/

Steam Requirements

- Different processes require different steam temperatures, which range from 100 to 400 degrees Celsius
  - Weighted average temperature is 125 degrees[3]
  - 80% of steam is less than or equal to 150 degrees, while 90% of steam is less than or equal to 200 degrees[3]
- There are a lot of facilities with a small steam capacity, and a few facilities with a large steam capacity
  - 95% of facilities have a capacity less than or equal to 750 MMBtu/hour, but account for only 50% of steam energy[4,5]

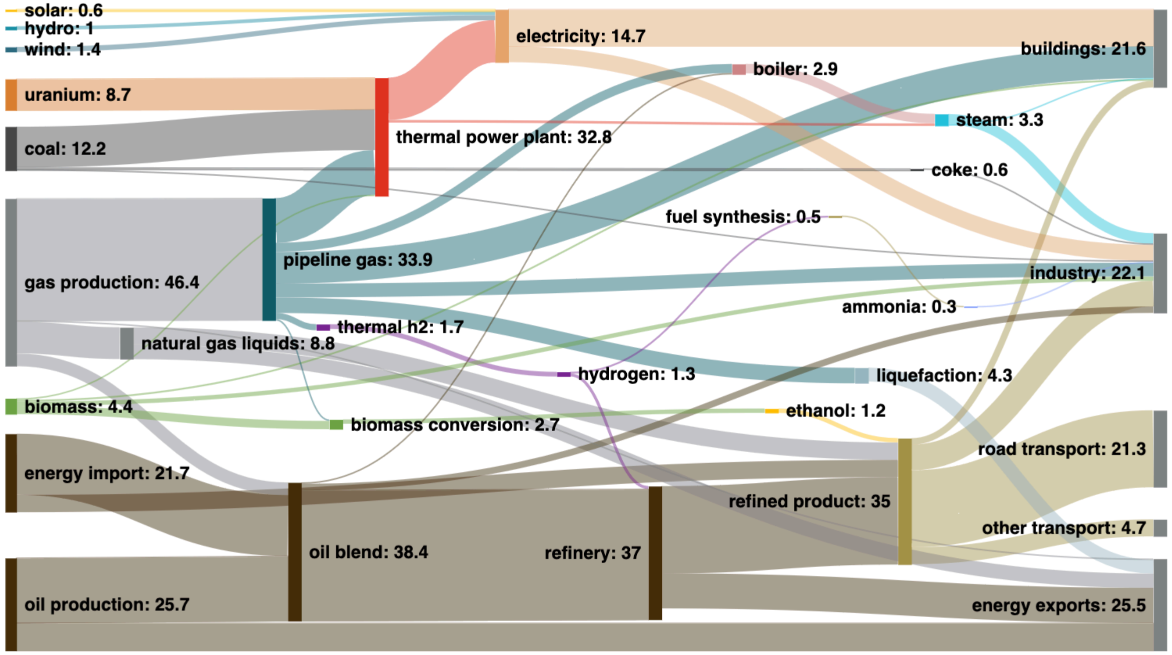




[3] National Renewable Energy Laboratory. (2019). Manufacturing Thermal Energy Use In 2014. https://data.nrel.gov/submissions/118
[4] Schoeneberger, C., Zhang, J., McMillan, C., Dunn, J. B., & Masanet, E. (2022). Electrification potential of U.S. industrial boilers and assessment of the GHG Emissions Impact. *Advances in Applied Energy*. https://doi.org/10.1016/j.adapen.2022.100089
[5] Energy Information Agency. (2024). Form 923. https://www.eia.gov/electricity/data/eia923/

Strategy for Decarbonizing Industrial Steam

FIGURE 16. Sankey diagram for 2021 (Exajoules)



- Unlike industrial process heat, which is highly specialized, steam is produced by many different sources and consumed for many different uses
- It can be thought of as an energy carrier, like electricity or natural gas, meaning…
  - There are multiple options for decarbonizing steam supply, including electric heat pumps and low carbon fuel boilers
  - Decarbonizing steam will have an impact across all the subsectors with steam demand, in a sector which is notoriously difficult to decarbonize

[6] Evolved Energy Research. (2023). Annual Decarbonization Perspective. https://www.evolved.energy/2023-us-adp

Geothermal Energy

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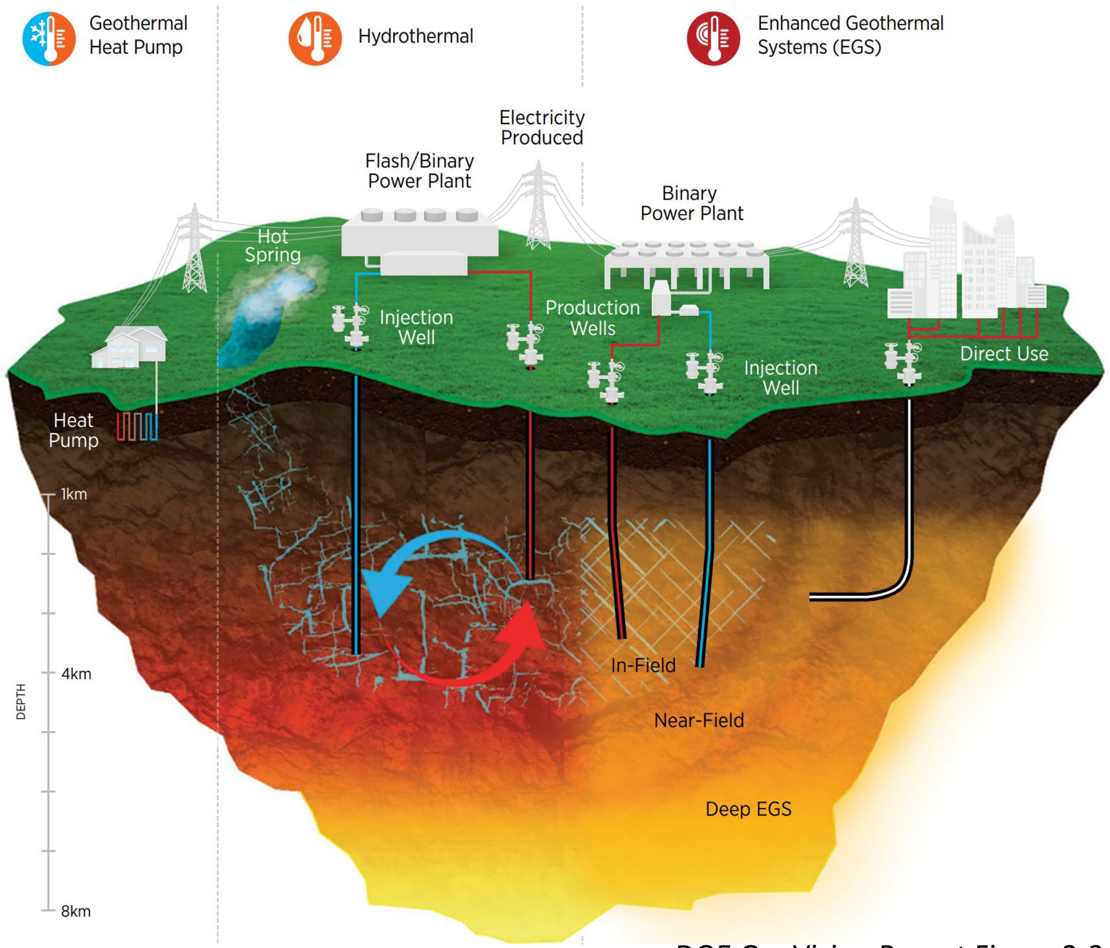
- Geothermal energy originates in the earths core, where the decay of radioactive elements generates temperatures comparable to the surface of the sun
  - The heat which flows from the earths core to its surface is estimated to be approximately 45 TW of power, roughly twice global energy requirements[7]
- Unlike other sources of sustainable energy, such as solar and wind, geothermal offers constant and reliable power, with a relatively small footprint, though the challenge is that it is trapped thousands of meters underground



DOE GeoVision Report Figure 2-3

[7] US DOE. (2019). *GeoVision: Harnessing the Heat Beneath Our Feet.* https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf

Geothermal Electricity vs Steam

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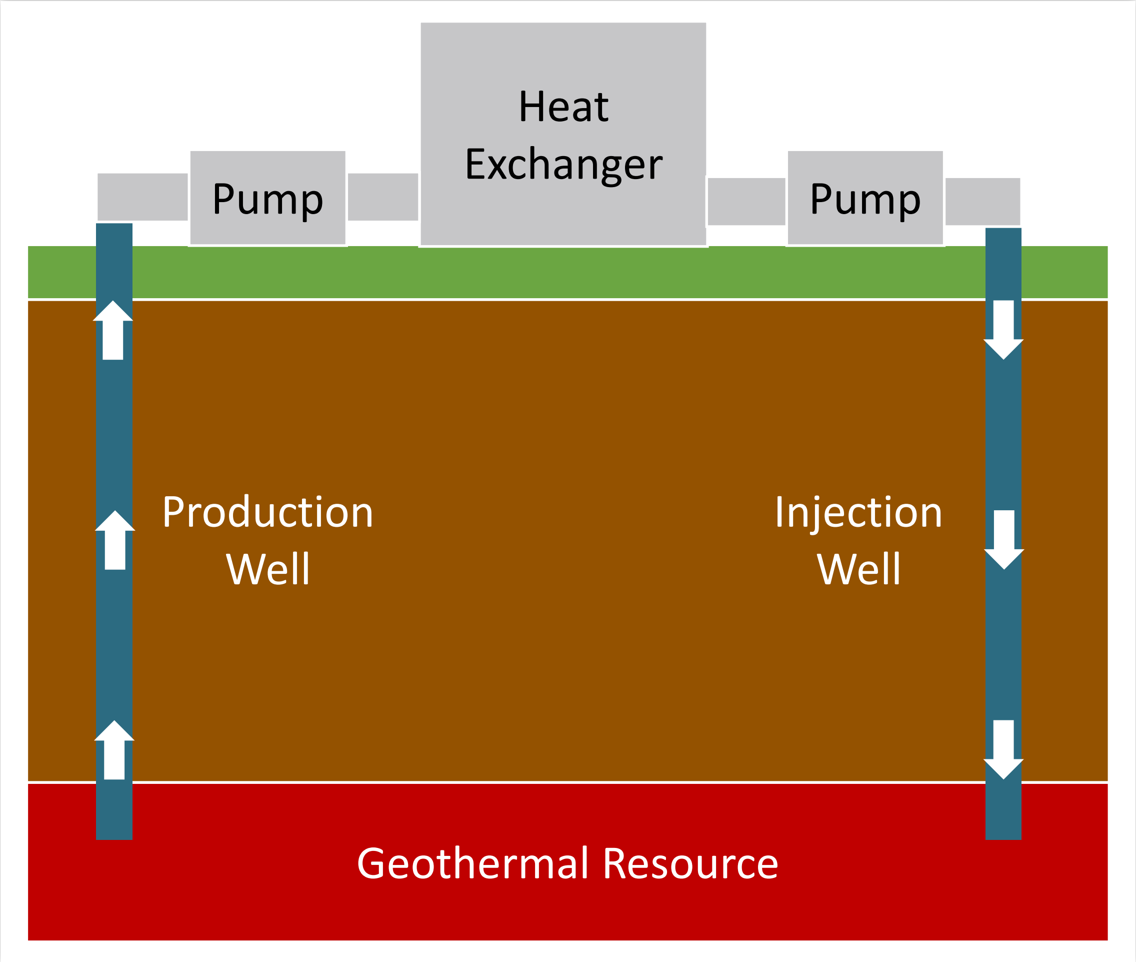
- Advantages of Steam over Electricity
  - Steam requires lower temperatures (150 rather than 250+ degrees) and tolerates higher temperature variability, making it possible to utilize otherwise unsuitable geothermal resources[7]
  - Utilizing steam directly, rather than to spin a turbine and power a generator, avoids a ~80% efficiency loss
- Disadvantages of Steam over Electricity
  - Steam is not an easily tradeable commodity like electricity, so whereas electricity can be produced at one facility and consumed in another, steam must generally be produced and consumed in the same facility

The DOE Enhanced Geothermal Shot aims for a geothermal electricity price of $45/MWh by 2035[20], which is marginally competitive with other forms of low-carbon electricity. However, this is approximately equivalent to a steam price of $4/MMBtu, which is very competitive for low-carbon heat.

[7] US DOE. (2019). *GeoVision: Harnessing the Heat Beneath Our Feet.* https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf
[20] DOE. (2024). Enhanced Geothermal Shot. https://www.energy.gov/eere/geothermal/enhanced-geothermal-shot

Overview of a Geothermal Steam Facility



- A geothermal steam facility consists of injection and production wells, a network of pipes and pumps, and a heat exchanger
- Fluid is pumped into the subsurface, heated by the earth, and pumped back to the surface
- The heated fluid is piped to a heat exchanger, creating steam, and the cooled fluid is piped back to the well system, completing the cycle
  - If needed, geothermal steam can be supplemented with other units, such as a natural gas boiler or an electric heat pump
  - The system is a closed loop, separate from equipment on the other side of the heat exchanger

[7] US DOE. (2019). *GeoVision: Harnessing the Heat Beneath Our Feet.* https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf

Limited Geothermal Resources

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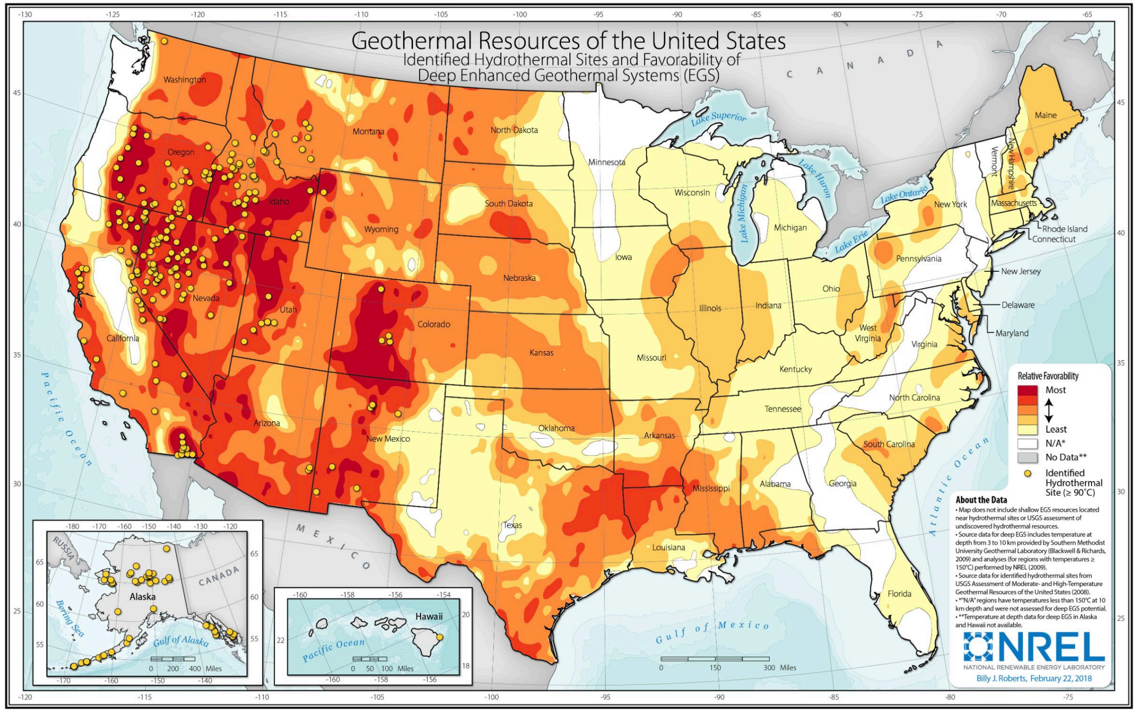
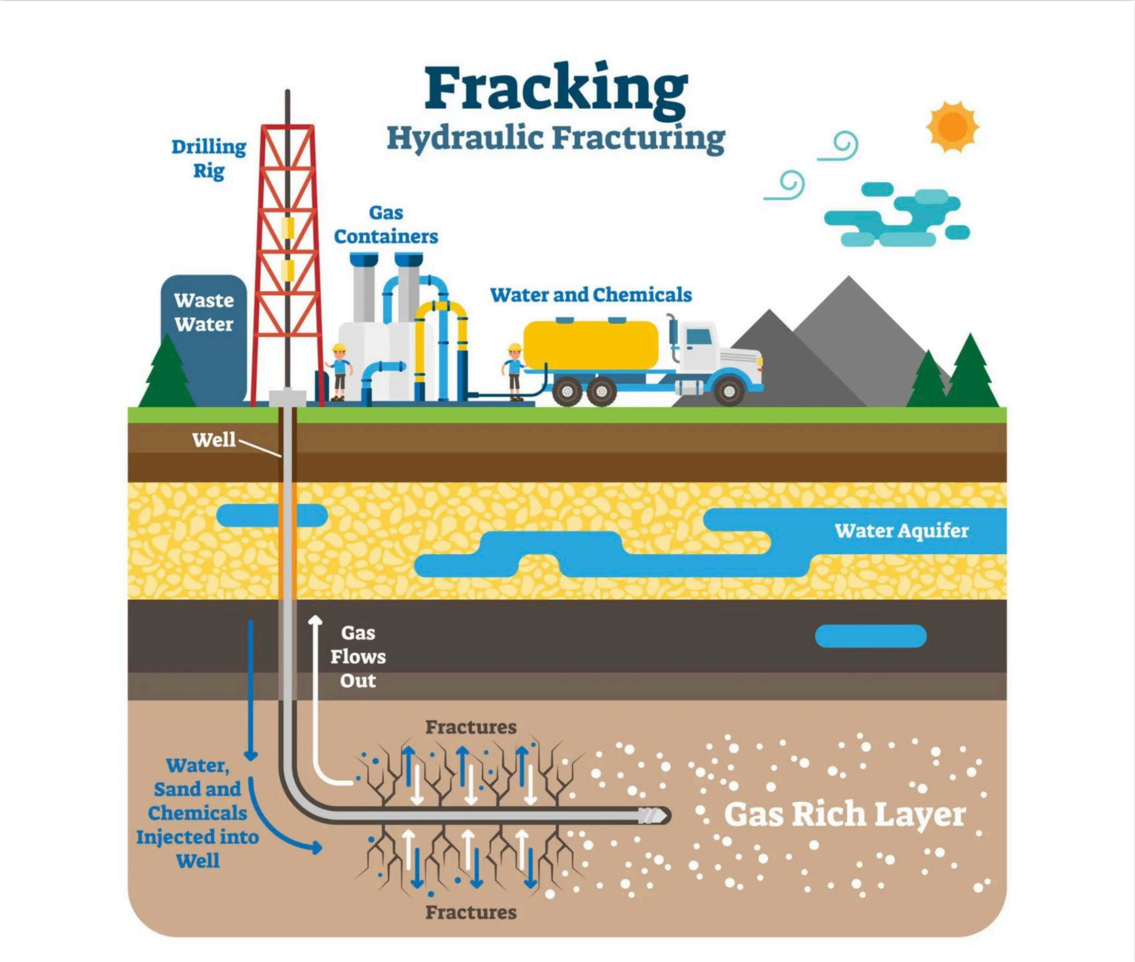
- Geothermal resource quality depends on subsurface temperature gradient, as well as subsurface connectivity and fluid content[8]
  - The temperature gradient determines how deep a well must be to reach the required temperature
  - The connectivity and fluid content determines how quickly and easily fluid flows through the system
- Conventional wisdom is that geothermal energy is only feasible in areas with high quality resources (shallow and with naturally occurring connectivity and fluid content), generally limited to specific locations in the western U.S.[9]



[8] Tester, J. W., Beckers, K. F., Hawkins, A. J., & Lukawski, M. Z. (2021). The evolving role of geothermal energy for decarbonizing the United States. *Energy & Environmental Science*. https://doi.org/10.1039/d1ee02309h

[9] National Renewable Energy Laboratory. (2018). Geothermal Resource Data, Tools, and Maps. https://www.nrel.gov/gis/geothermal.html

Lessons from Oil and Gas

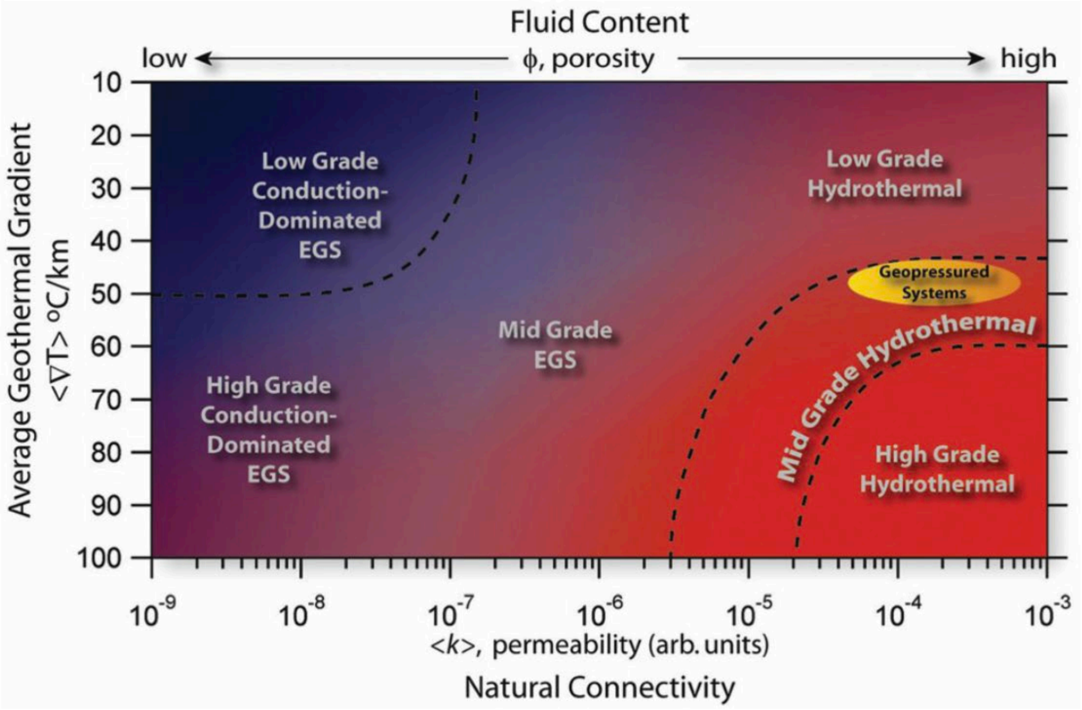


- Advances from oil and gas, such as improved drilling techniques, hydraulic fracturing, and horizontal drilling, could have important implications for geothermal
  - Hydraulic fracturing involves pumping fluid (containing proppants suspended with thickening agents) into a well at high pressures to create small fractures, allowing gas and oil that was otherwise trapped in small disconnected pockets, to flow freely and be extracted[10]
  - Horizontal drilling involves drilling down into and then horizontally across a reservoir, allowing greater access to the reservoir and taking up less surface area[10]

[10] Environmental Protection Agency. (2024). Unconventional Oil and Natural Gas Development. https://www.epa.gov/uog/process-unconventional-natural-gas-production#:~:text=Hydraulic%20fracturing%20produces%20fractures%20in,sections%20extending%20thousands%20of%20feet.

Breakthrough with Enhanced Geothermal Systems

- With traditional hydrothermal systems, site testing is used to locate high quality geothermal resources (shallow and with naturally occurring connectivity and fluid content), however, these resources are severely limited
- With enhanced geothermal systems (EGS), connectivity and fluid content is created artificially through well stimulation, a process very similar to hydraulic fracturing[8]
- Combined with improved drilling techniques, which makes it easier to access deeper resources, these technological advances from oil and gas could greatly expand the scope of suitable geothermal resources



[8] Tester, J. W., Beckers, K. F., Hawkins, A. J., & Lukawski, M. Z. (2021). The evolving role of geothermal energy for decarbonizing the United States. *Energy & Environmental Science*. https://doi.org/10.1039/d1ee02309h

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Objective

Questions

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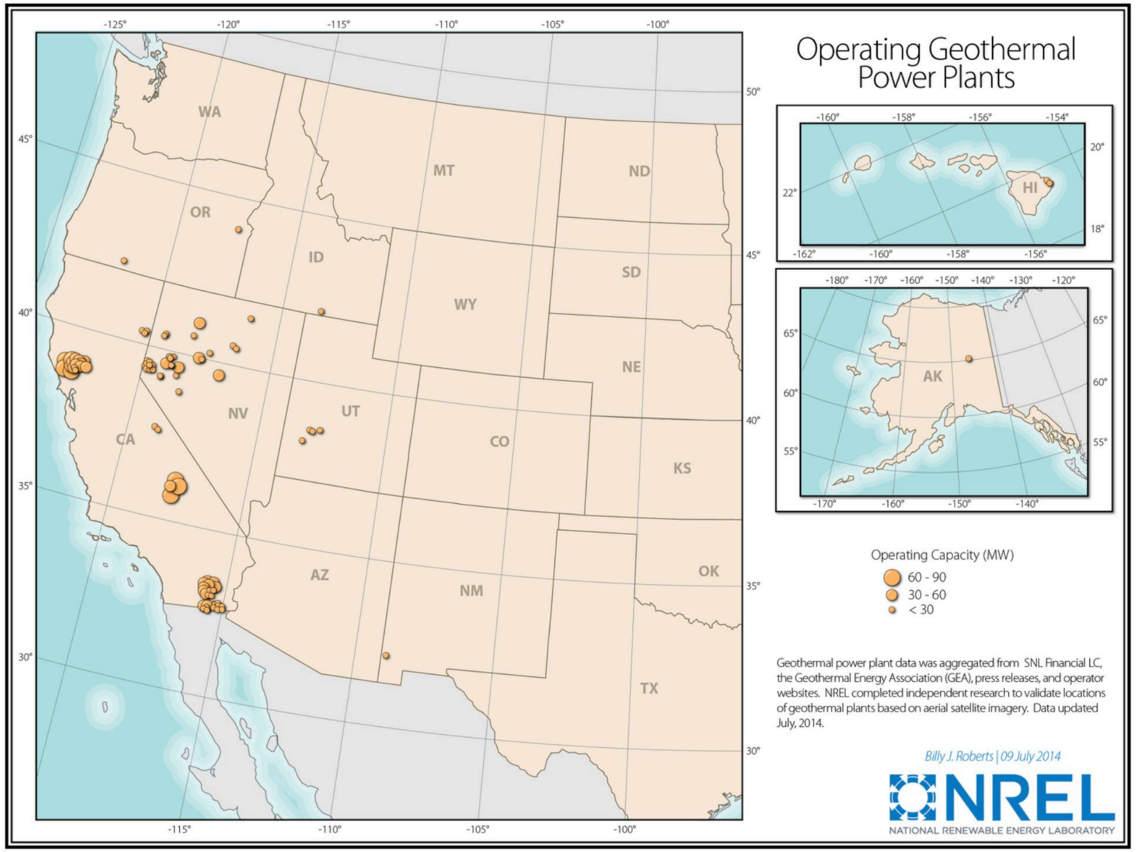


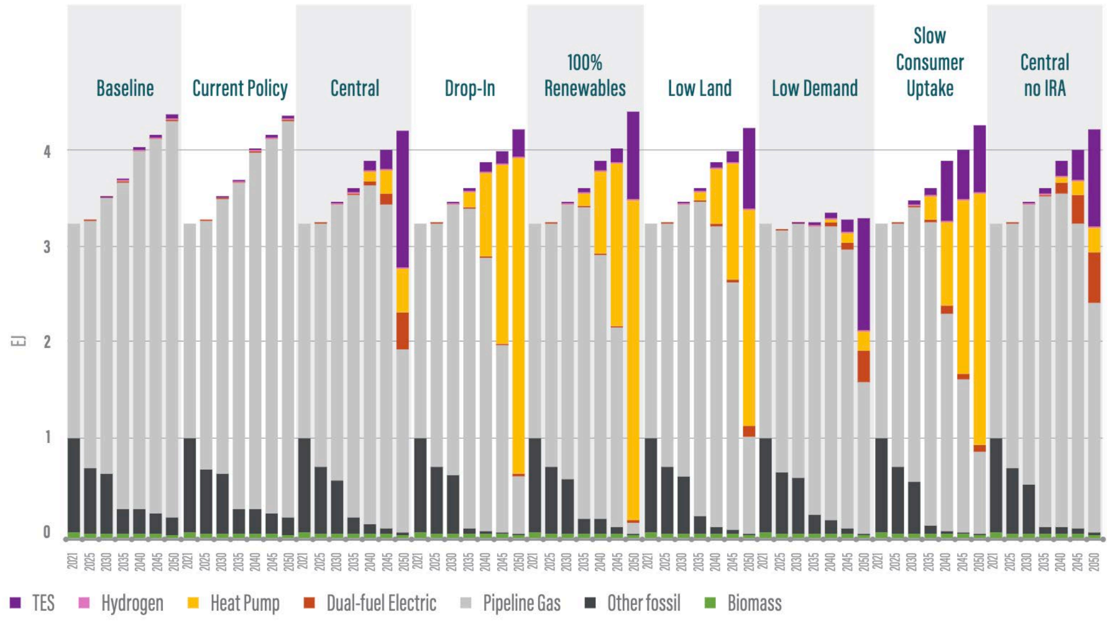
- Does applying technological advances from oil and gas to geothermal applications upset the conventional understanding that geothermal is limited to locations with high quality resources?
- What is the relative importance of resource depth and facility size for the levelized cost of heat from geothermal?
- Is geothermal steam economically competitive with other forms of steam generation, such as natural gas boilers and electric heat pumps?

[11] National Renewable Energy Laboratory. (2014). Geothermal Resource Data, Tools, and Maps. https://www.nrel.gov/gis/geothermal.html

Project Goal and Deliverables

- Incorporate geothermal steam into RIO, allowing geothermal to compete with existing steam generation options, including natural gas, electricity, bioenergy, and hydrogen
- Step 1: Collect a data set of steam requirements and geothermal resource quality
- Step 2: Create a techno-economic model which inputs this data and outputs CAPEX and OPEX of meeting industrial steam with geothermal for a given facility
- Step 3: Calculate the resulting Levelized Cost of Heat (LCOH) from geothermal using the CAPEX, OPEX, and steam requirements

FIGURE 42. Steam production by technology across scenarios



[6] Evolved Energy Research. (2023). Annual Decarbonization Perspective. https://www.evolved.energy/2023-us-adp

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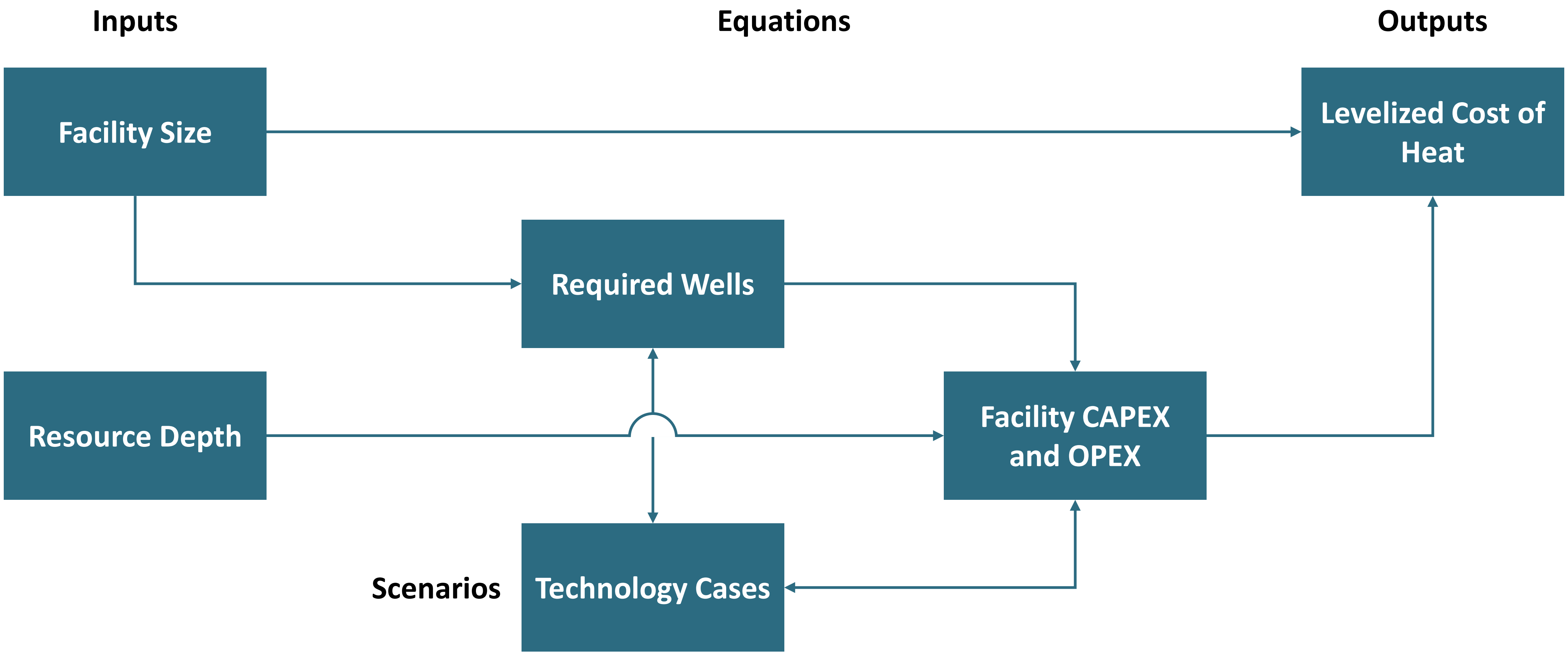
Methodology

Techno-economic Model



Inputs: Resource Depth and Facility Size

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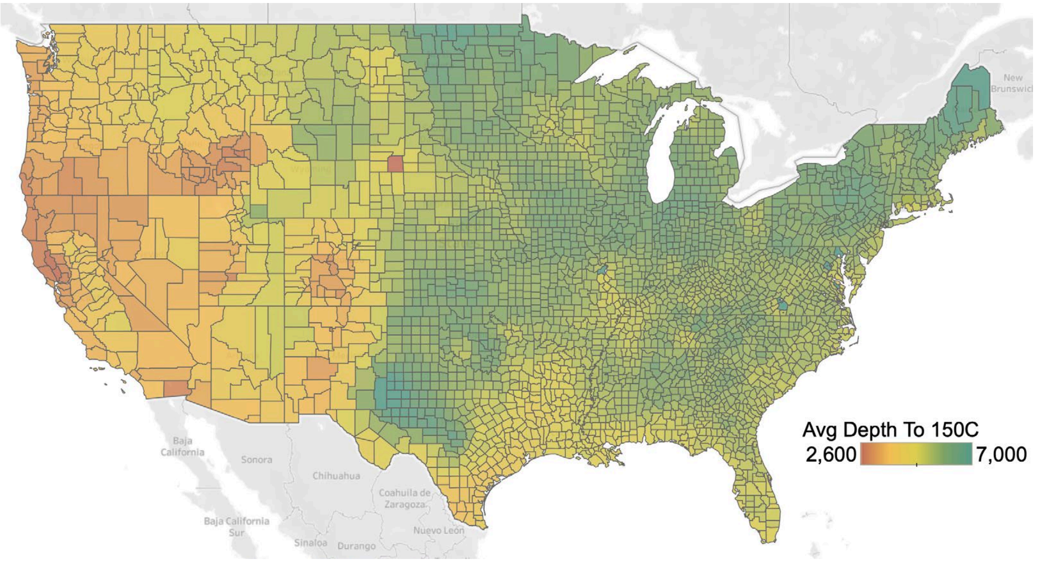
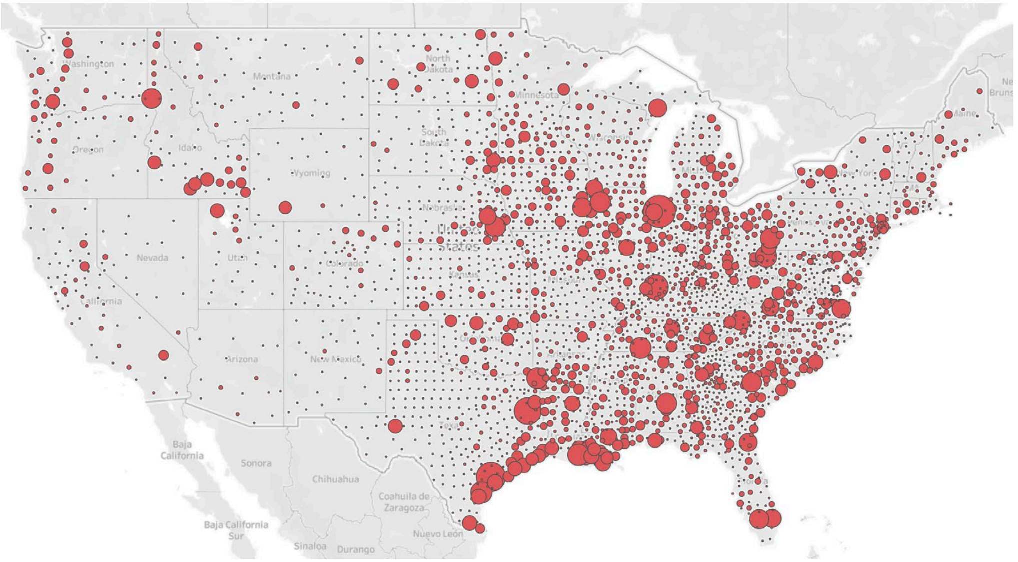
- Temperature at depth data from Stanford Thermal Earth Model[12]
  - Temperature between 1000 to 7000m in increments of 1000m, with resolution of $18km^2$



Depth to 150 degrees Celsius

- Boiler inventory from NREL[13], cogeneration inventory from EIA Form 923[14]
  - Inventory of boilers and cogeneration units by capacity, NAICS code, and county

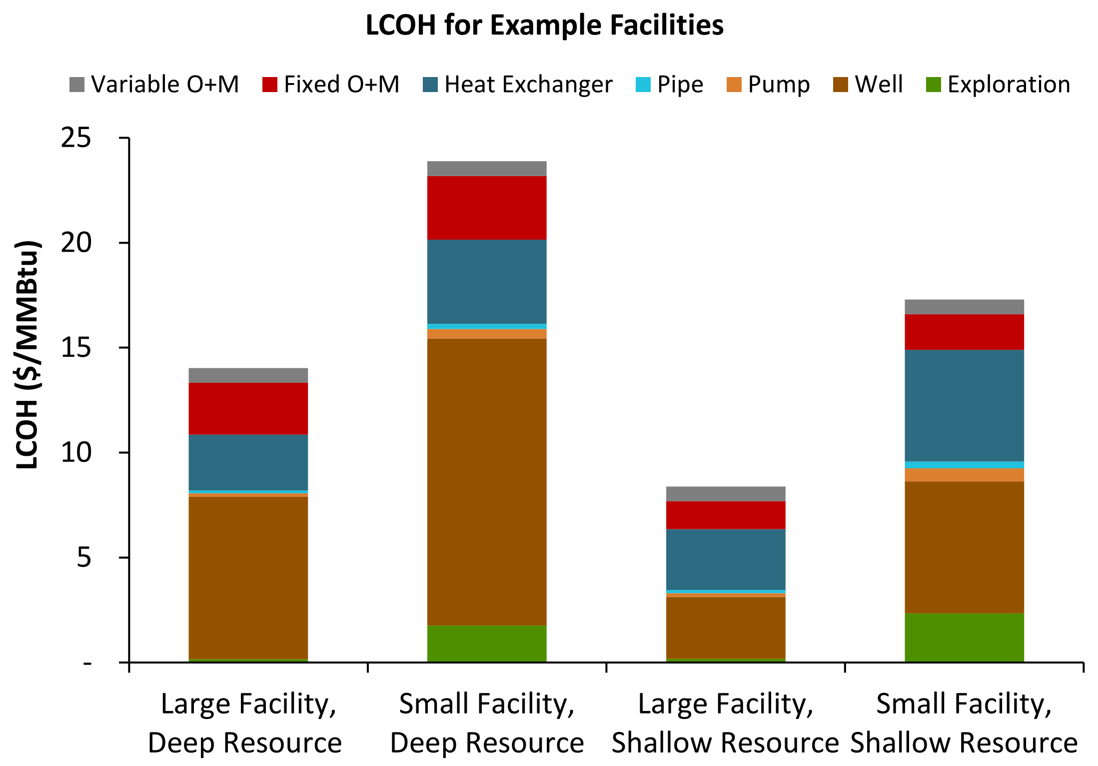


Total Boiler Capacity

[12] Stanford University. (2024). Stanford Thermal Earth Model for the Conterminous United States. https://dx.doi.org/10.15121/2324793.
[13] Schoeneberger, C., Zhang, J., McMillan, C., Dunn, J. B., & Masanet, E. (2022). Electrification potential of U.S. industrial boilers and assessment of the GHG Emissions Impact. *Advances in Applied Energy*. https://doi.org/10.1016/j.adapen.2022.100089
[14] Energy Information Agency. (2024). Form 923. https://www.eia.gov/electricity/data/eia923/

Equations: Required Wells and Facility Costs

- Required number of wells is determined by:
  - Steam capacity
  - Temperature extracted
  - Flow rate
- Facility CAPEX is composed of:
  - Exploration (fixed cost)
  - Well (depends on resource depth and drilling cost)
  - Piping (depends on number of wells)
  - Pump (depends on steam capacity)
  - Heat exchanger (depends on steam capacity)
- Facility OPEX is composed of:
  - Fixed equipment maintenance (percent of capital)
  - Variable pump operation (percent of output)



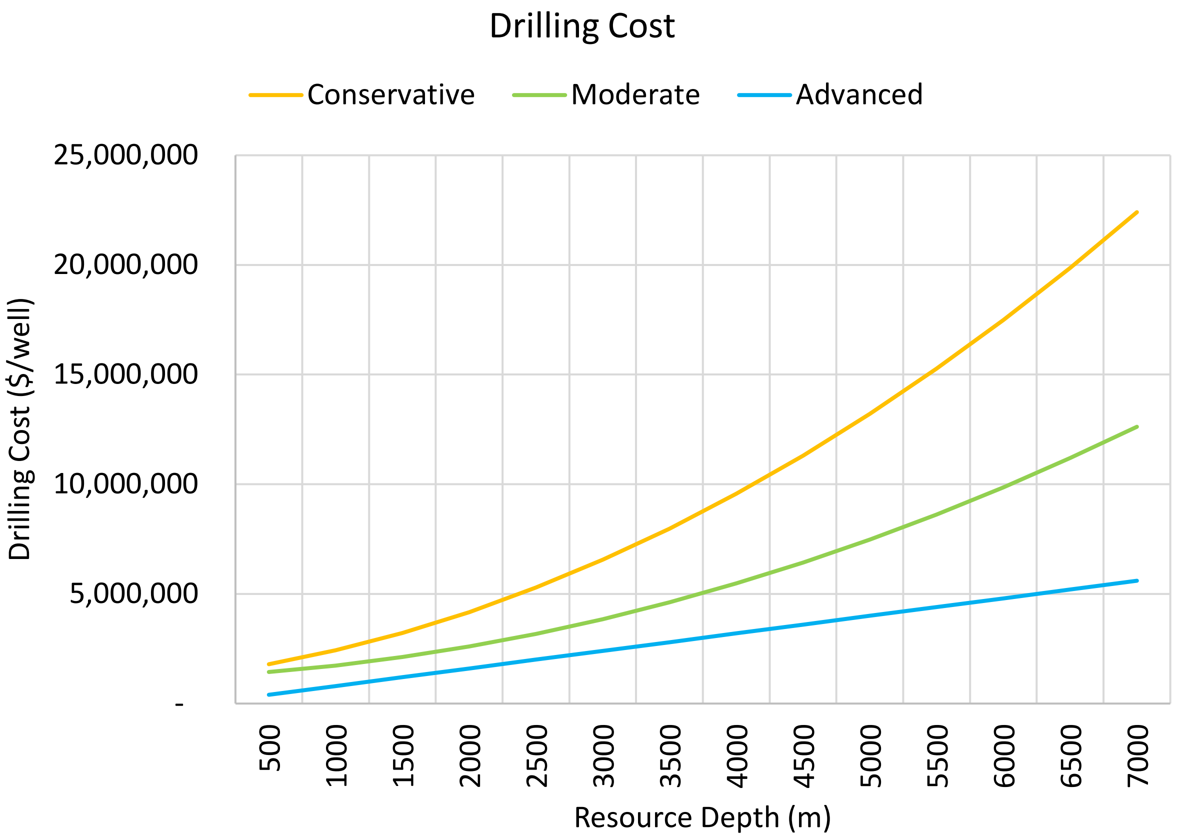
To understand how these contribute to the levelized cost of heat, consider some example facilities: a small facility has 1,000,000 MMBtu/yr of steam demand, a large facility has 7,000,000 MMBtu/yr of steam demand, deep resources are 6000m, shallow resources are 2000m

Scenarios: NREL ATB

Scenarios are defined by key parameters:

- Key cost parameter is drilling cost
- Key production parameter is flow rate
- Key risk parameter is well success

	Flow Rate	Well Success
Conservative	60 kg/s	60.8%
Moderate	80 kg/s	68.0%
Advanced	110 kg/s	90.3%



[15] NREL. (2024). *Annual Technology Baseline: Geothermal Electricity.* https://atb.nrel.gov/electricity/2024/geothermal
[16] NREL. (2023). *Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office.* https://www.nrel.gov/docs/fy23osti/84822.pdf

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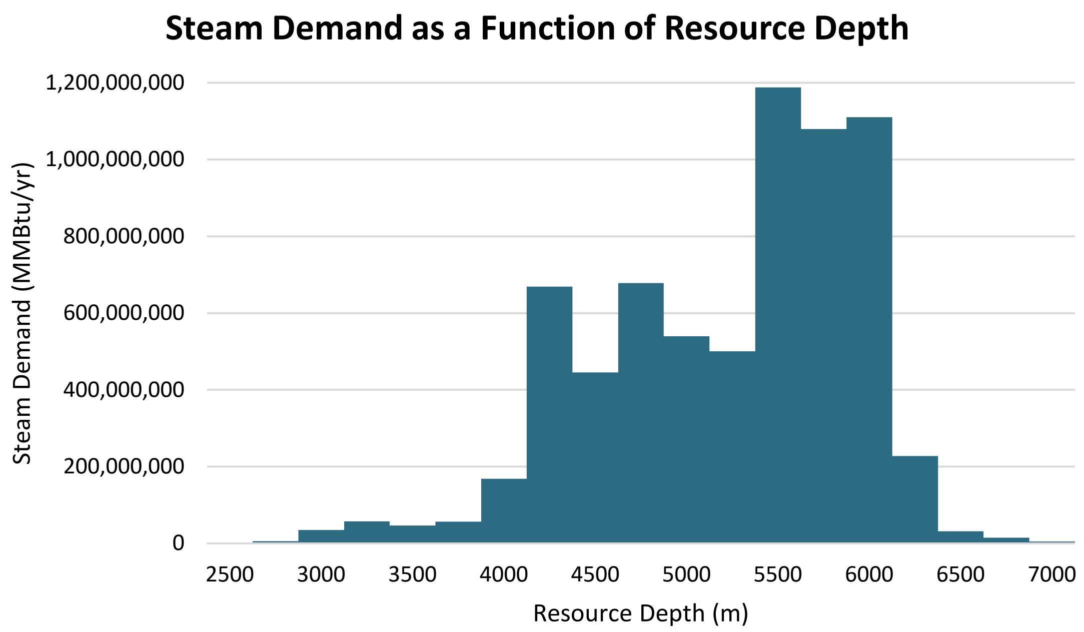
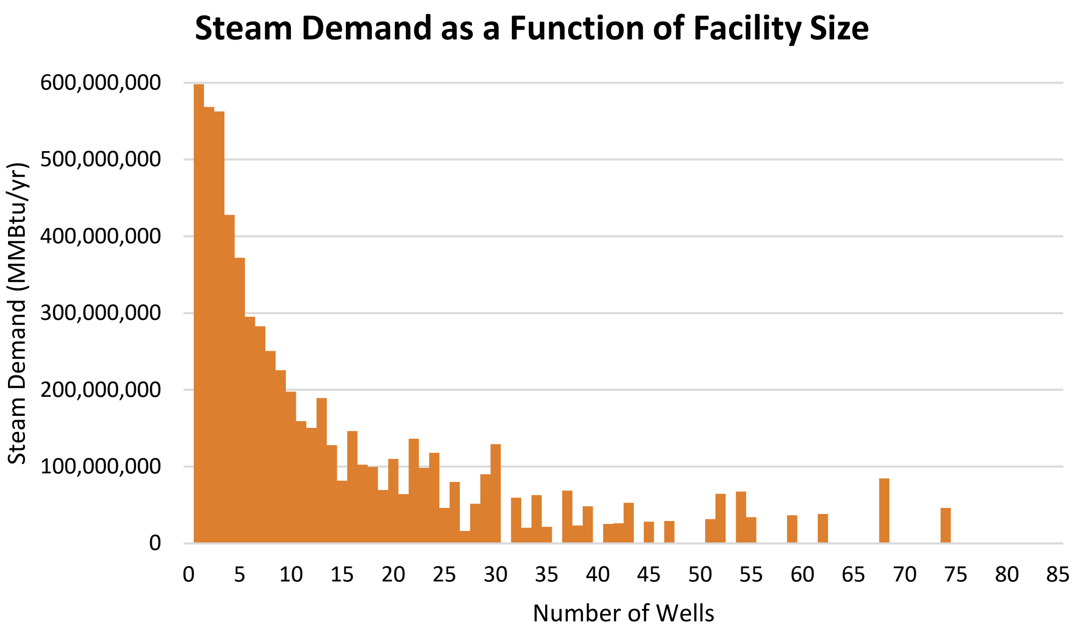
Results

Distribution of Resource Depth and Facility Size



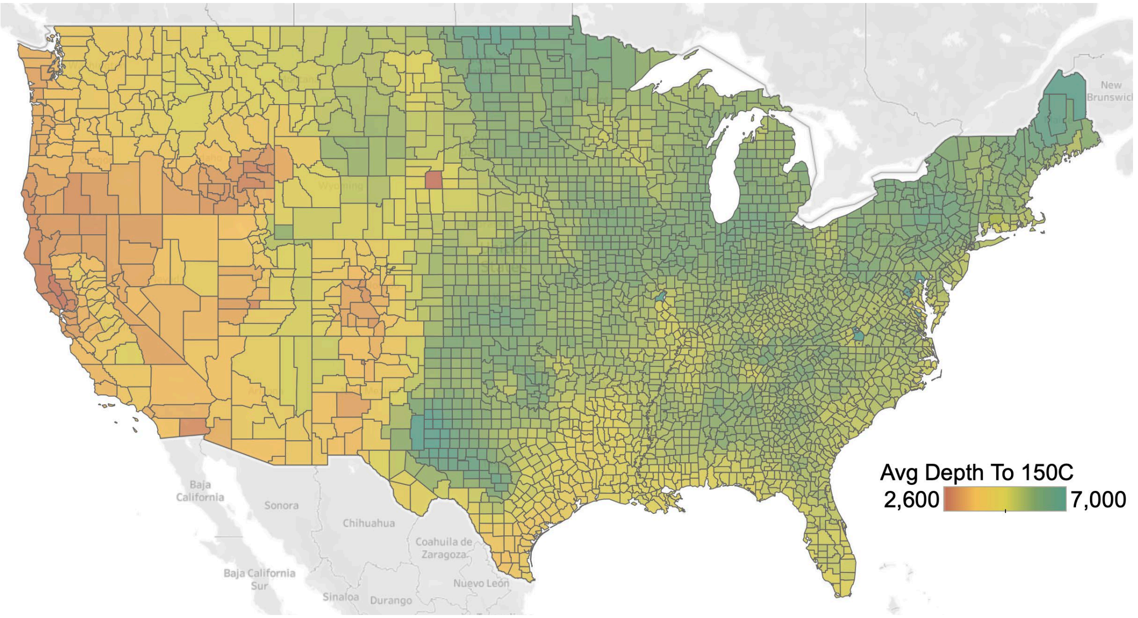


Aside from the level of technological advancement, feasibility of geothermal steam is influenced primarily by resource depth and facility size. Deeper resources means higher drilling cost and smaller facility size means fixed costs are divided over less output.

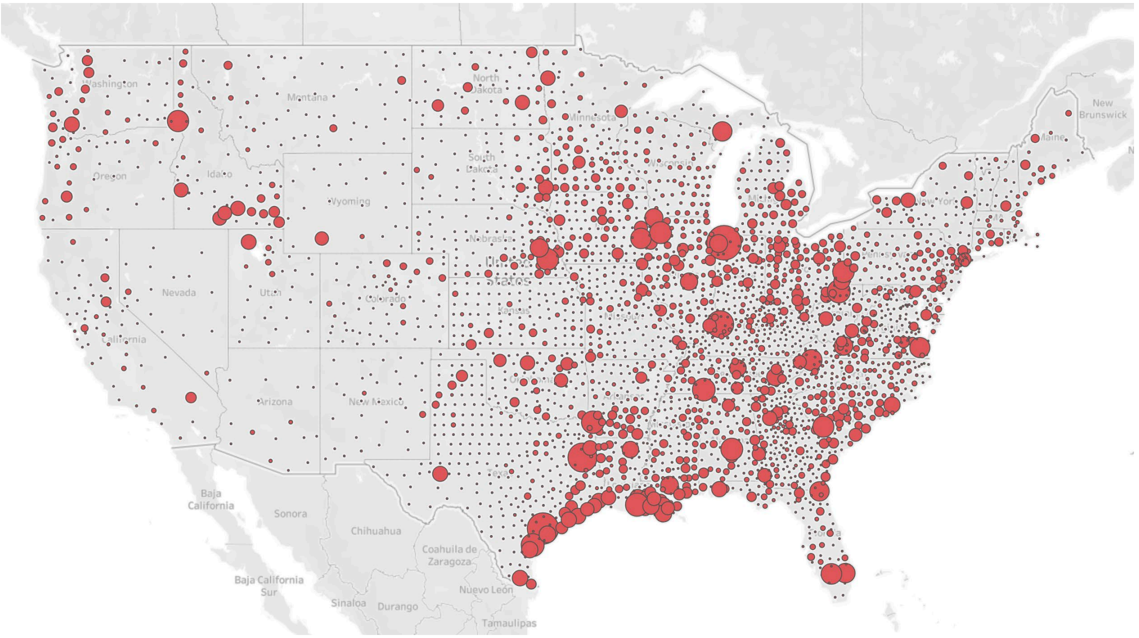
Most facilities have deep geothermal resources and small steam demand.

Distribution of Resource Depth and Facility Size

Depth to 150 degrees Celsius[12]



Total Boiler Capacity[13,14]

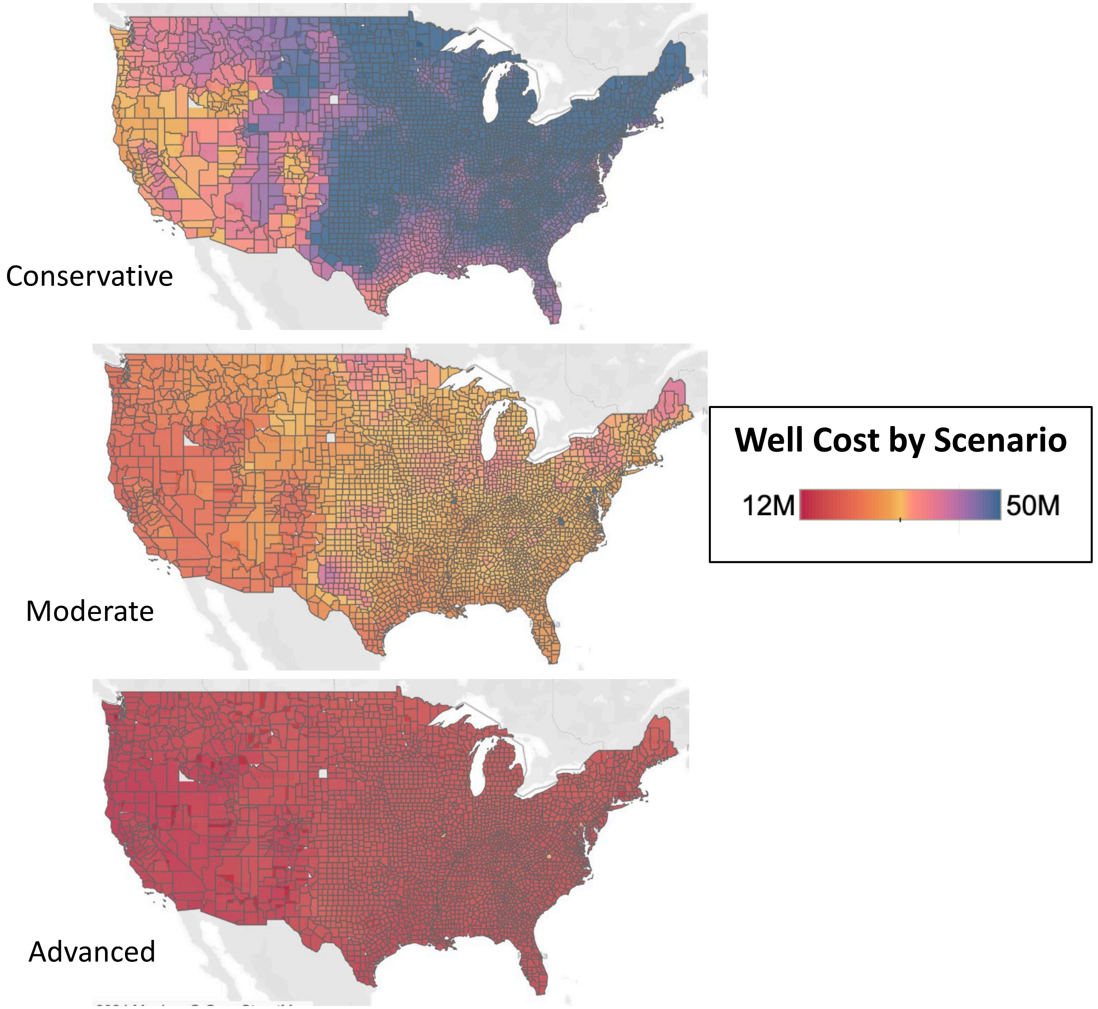


The mismatch between resource depth and facility size is largely due to the fact that geothermal resources are concentrated in the west, while steam demand is concentrated in the east.

[12] Stanford University. (2024). Stanford Thermal Earth Model for the Conterminous United States. https://dx.doi.org/10.15121/2324793.
[13] Schoeneberger, C., Zhang, J., McMillan, C., Dunn, J. B., & Masanet, E. (2022). Electrification potential of U.S. industrial boilers and assessment of the GHG Emissions Impact. *Advances in Applied Energy*. https://doi.org/10.1016/j.adapen.2022.100089
[14] Energy Information Agency. (2024). Form 923. https://www.eia.gov/electricity/data/eia923/

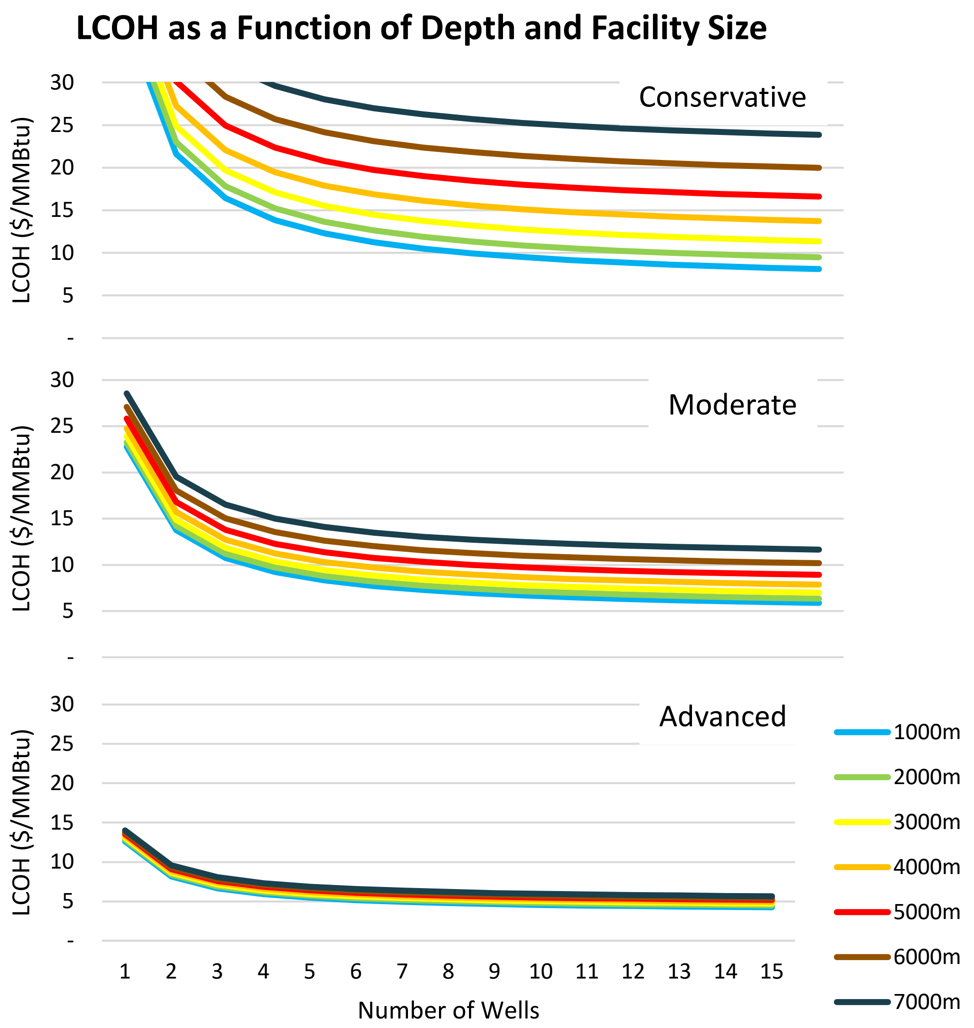
Impact of Technological Advances

- EGS improves flow rate and well success by artificially creating connectivity and fluid content, and combined with improved drilling techniques which make it cheaper to drill deeper, these technological advances essentially decouple well cost from resource quality
- This decoupling upsets the conventional understanding that geothermal is limited to locations with high quality resources, as it means that geothermal can be reasonably accessed anywhere, and importantly, it can be accessed where steam is needed

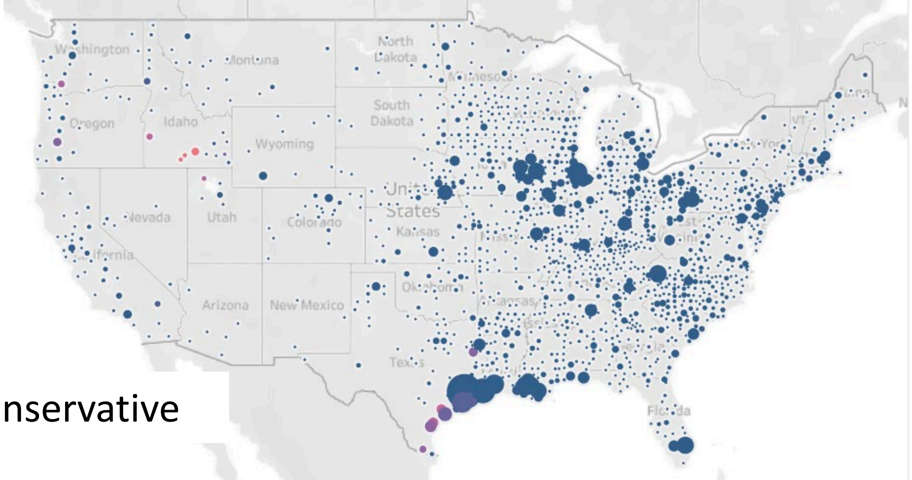


Levelized Cost of Heat

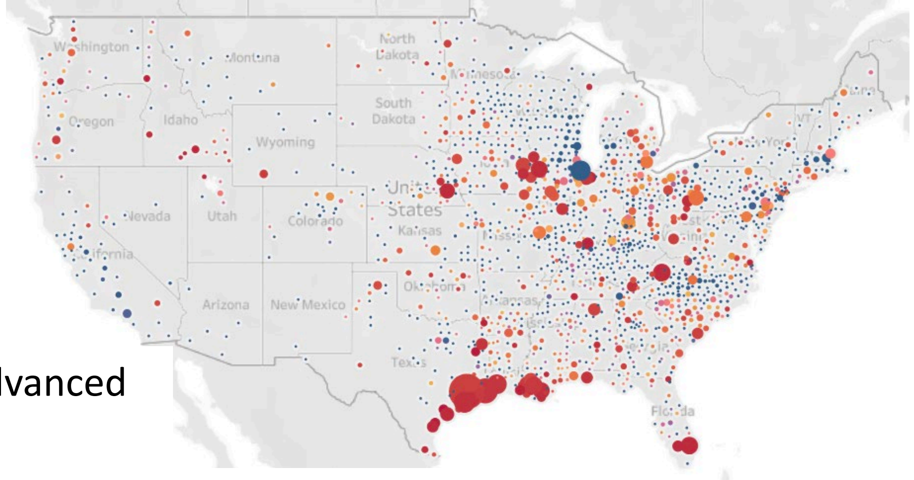
- The levelized cost of heat has been predominantly influenced by the depth of geothermal resources
- However, technological advances decoupling well cost from resource depth means that economy of scale comes to the forefront, and the levelized cost of heat is predominantly influenced by facility size
- This means that facilize size, rather than resource depth, is the deciding factor in determining feasibility of geothermal steam



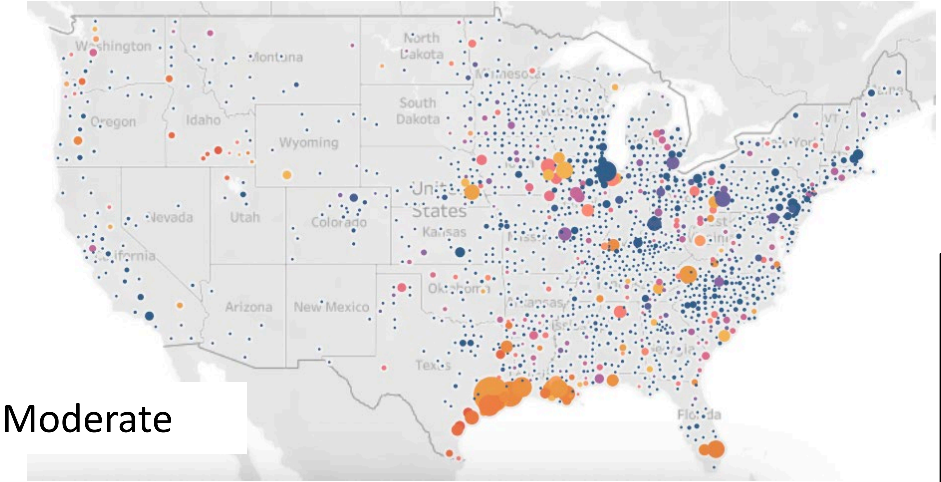
Levelized Cost of Heat



Conservative



Advanced



Moderate

With technological advancement, large facilities become inexpensive while small facilities remain expensive, regardless of location

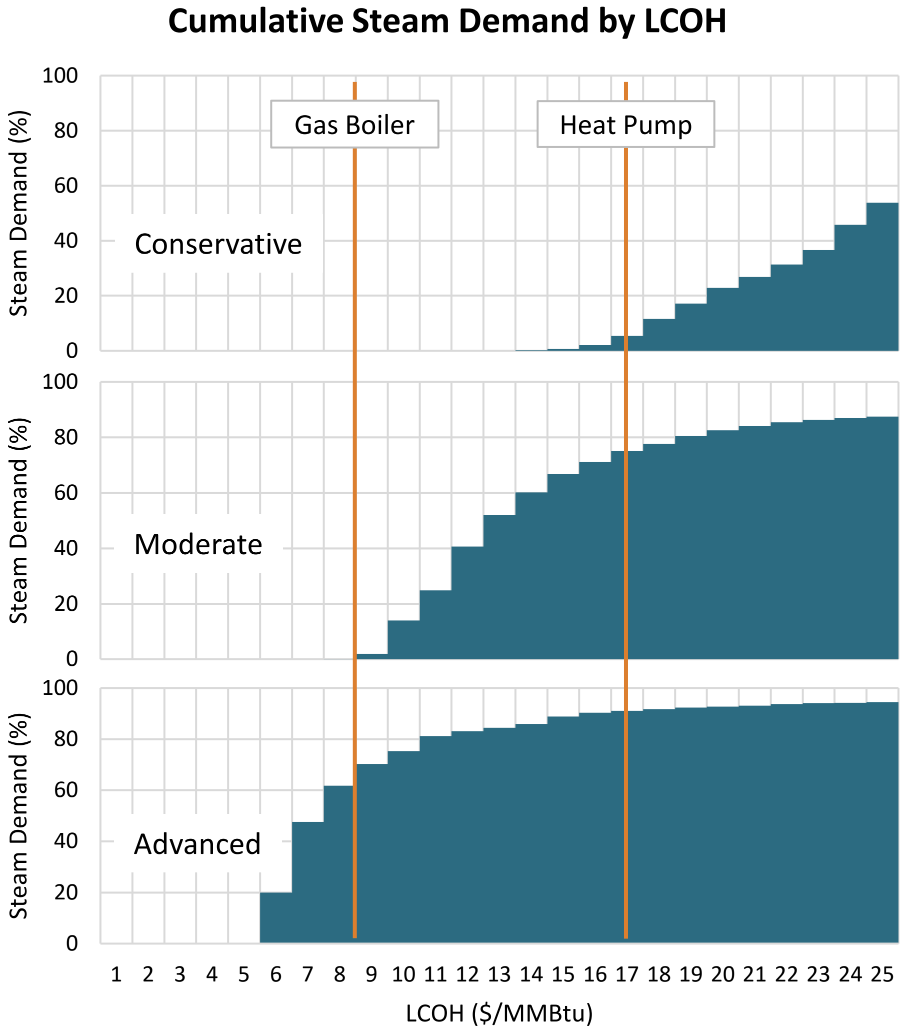
Levelized Cost of Heat by Scenario

Avg. LCOH ($/mmBTU)

6 20

Implications for Economic Competitiveness

- The levelized cost of heat for the reference geothermal steam facility drops from $14/MMBtu in the conservative case, to $9/MMBtu in the moderate case, and $7/MMBtu in the advanced case
- This is in comparison to a levelized cost of heat for a gas boiler at $8/MMBtu, and for an electric heat pump at $17/MMBtu



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Takeaways

Outlook for Geothermal Steam

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- Technological advances from oil and gas upset the conventional understanding that geothermal is limited to locations with high resource quality
  - Decoupling well cost from resource quality reduces the relative importance of resource depth and raises the relative importance of facility size in determining the feasibility of geothermal steam
- This significantly expands the economic competitiveness of geothermal steam, with LCOH for the reference facility being cut in half, from $14 to $7/MMBtu (compared to $8/MMBtu for a gas boiler and $17/MMBtu for an electric heat pump
- Project financing remains an important challenge given the inherently risky cost structure of geothermal steam
- Geothermal steam systems involve extremely large upfront costs, whereas boilers and heat pumps are dominated by continuous fuel costs, meaning facilities are locked in their decision for decades, regardless of how the landscape for decarbonized steam may change
- However, the fact that these same technologies facilitated the shale gas boom of the 2010’s suggests that geothermal could experience a similar trajectory in the coming years

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Appendix

Techno-economic Model: Number of Wells

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$$Q = mC\Delta T$$

$$\frac{Q}{period} = \left(\frac{mass}{time} \cdot \frac{time}{period}\right) C\Delta T \times number\ of\ wells$$

$$number\ of\ wells^{*} = steam\ demand\left(\frac{mmBTU}{yr}\right) \div$$

$$\left[flowrate\left(\frac{kg}{s}\right) \cdot \left(\frac{1000g}{kg}\right) \cdot \left(\frac{8760hr}{yr}\right) \cdot \left(\frac{3600s}{hr}\right) \cdot \left(\frac{4.186J}{g°C}\right) \cdot (temp\ extract\ °C) \cdot inefficiency \cdot capacity\ factor \cdot \left(\frac{BTU}{1055J}\right) \cdot \left(\frac{mmBTU}{10^{6}BTU}\right) \right]$$

*To account for production and injection wells, this is ultimately multiplied by two

Techno-economic Model: Site Testing

- Surface testing cost[21]: $250,000 per facility
  - To characterize subsurface
- Exploratory drilling cost[21]: $5,000,000 per facility
  - To further characterize subsurface, small diameter wells
- Well testing cost[21]: $500,000 per facility
  - To confirm success or failure of full-size wells

[21] Augustine, Chad et al. (2019). *GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration.* https://www.nrel.gov/docs/fy19osti/71833.pdf

Techno-economic Model: Well CAPEX

- Drilling cost[15]: cost per well, depth to target temperature in meters
  - Conservative case: $\$0.317 \cdot (m)^2 + \$793.65 \cdot (m) + \$1{,}317{,}460$
  - Moderate case: $\$0.189 \cdot (m)^2 + \$302.7 \cdot (m) + \$1{,}240{,}564$
  - Advanced case: $\$800 \cdot (m)$
- Stimulation cost[21]: $1,250,000 per well

[15] NREL. (2024). *Annual Technology Baseline: Geothermal Electricity.* https://atb.nrel.gov/electricity/2024/geothermal
[21] Augustine, Chad et al. (2019). *GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration.* https://www.nrel.gov/docs/fy19osti/71833.pdf

Techno-economic Model: Facility CAPEX

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- Pump cost[22]: $3 \cdot [\$1750 \cdot hp^{0.7} + \$5750 \cdot hp^{0.2}]$
  - $capacity(hp) = pump\ energy \left(\frac{mmBTU}{yr}\right) \cdot \left(\frac{10^6 BTU}{mmBTU}\right) \cdot \left(\frac{1}{capacity\ factor}\right) \cdot \left(\frac{kWh}{3412\ BTU}\right) \cdot \left(\frac{1\ yr}{8760\ hr}\right) \cdot \left(\frac{1.34\ hp}{kW}\right)$
  - Discounting replacement every 3 years gives present value 3 times initial pump cost
- Pipe cost[22]: $\$0.4249 \cdot D^2 - \$0.0472 \cdot D + \$40.863$
  - Average diameter of 10 inches gives $82.9/ft
  - Average distance of 1640 ft to facility gives $135,925 per well
- Heat exchanger cost[7]: $150/kw

[22] Mines, Gregory. (2016). *Geothermal Electricity Technology Evaluation Model (GETEM) User Manual*. https://workingincaes.inl.gov/SiteAssets/CAES%20Files/FORGE/inl_ext-16-38751%20GETEM%20User%20Manual%20Final.pdf
[7] US DOE. (2019). *GeoVision: Harnessing the Heat Beneath Our Feet.* https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf

Techno-economic Model: Fixed and Variable OPEX

- Fixed operation cost[23]: $total\ CAPEX(\$) \cdot 0.03$
  - Maintenance and other fixed costs
- Variable operation cost[23]: $pump\ energy\left(\frac{kWh}{yr}\right) \cdot electricity\ price\left(\frac{\$}{kWh}\right)$
  - Pumping energy is 3% of energy output

[23] Project Interspace. (2024). TechnoEconomic Sensitivity Tool (TEST). https://geomap.projectinnerspace.org/test/

Techno-economic Model: Levelized Cost of Heat

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$$LCOH = \frac{(CAPEX \cdot CRF) + OPEX}{annual\ production}$$

$$CRF = \frac{r}{1-(1+r)^{-n}} = \frac{0.09}{1-(1.09)^{-15}} = 0.12406$$

Assumptions

- Steam temperature: 148 degrees (50 reinjection)
- Capacity factor: 80%
- Efficiency: 80%
- Lifetime: 30 years (15 year book life)
- Discount rate: 9%
- Financing cost multiplier: 1.35
- Artificial economy of scale:
  - Base cost is 30% of reference facility CAPEX, replace 30% of CAPEX for all facilities with this base cost
  - Reference facility size is 40MW electric equivalent with a resource depth of 2000m
- Indirect cost multipliers applied to component costs to account for installation[21]
  - 1.05 for exploration and well
  - 1.12 for pump and pipes
  - 2.79 for heat exchanger
- Risk multiplier applied to subsurface costs to account for possible well failure[15]
  - 1.64 for conservative case
  - 1.47 for moderate case
  - 1.11 for advanced
- Contingency multiplier applied to surface costs to account for overages: 1.15[21]

[21] Augustine, Chad et al. (2019). *GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration.* https://www.nrel.gov/docs/fy19osti/71833.pdf
[15] NREL. (2024). *Annual Technology Baseline: Geothermal Electricity.* https://atb.nrel.gov/electricity/2024/geothermal

Comparable LCOH Assumptions

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- Gas Boiler ($8.39/MMBtu)
  - CAPEX: $155/kw
  - OPEX: $1.2/kw
  - Efficiency: 1/1.077
  - Capacity factor: 0.8
  - Fuel cost: $7/MMBtu
  - Lifetime (book): 15 years
  - Discount rate: 9%
- Heat Pump ($16.90/MMBtu)
  - CAPEX: $1,258/kw
  - OPEX: $37.8/kw
  - Efficiency: 1/0.5
  - Capacity Factor: 0.8
  - Fuel cost: $0.06/kWh
  - Lifetime (book): 15 years
  - Discount rate: 9%