An Overview of the Geothermal Energy Technologies

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ABSTRACT

Geothermal resources have been used by hominids since prehistoric times for bathing, curing wounds, and tempering hunting weapons. Even religious connections are observed in old civilizations. District heating application appeared in France during the 15^{th} century, while the first power plant was installed in Larderello, Italy, in 1913. Since then, power plant technologies and optimized geothermal resources are studied for large-scale renewable energy generation. Power plants require water temperature ranging from 95^{o}C to over 200^{o}C. Hydrothermal resources, presenting manifestations in the surface as geysers, hot springs, and fumaroles, can provide water or steam over 150oC. With crust's gradient temperature averaged as 30^{o}C/km, resources in dry rock systems come from 3 to 7 km depth. But the gradient varies on the crust, and some areas are more suitable for implementation of Enhanced Geothermal Systems or closed-loop systems. With over 458,000 wells connected to the oil and gas industry, Alberta, Canada, has a high potential to reuse part of those wells, around 7,900 wells, for electricity generation if converted to EGS or closed loop. SE and E areas of the province showed the potential to reach electricity generation temperatures at depths lower than 1 km.

SHORT HISTORICAL INTRODUCTION

Geothermal energy is a type of renewable energy source that uses the interior Earth heat (Lund, 2007). Geothermal sources have been used for different practices, such as bathing, mining, and electricity generation. According to Arriaga (2005), geothermal resources were used by hominids since prehistoric times, first by the *Homo Habilis* in the late Tertiary and basal Quaternary Periods (from 8 to 1.5 million years ago). It's been used for bathing since the Paleolithic (Cataldi, 1992). The first known geothermal spa was in China during the Qin dynasty (Figure 1). Other usages, such as utilizing the hot water and mud to cure wounds and tempering hunting weapons and religious connections are also present in the literature (Arriaga, 2005).

FIG. 1. First known geothermal spa in China during the Qin dynasty (Cataldi, 1992).

Following Lund et al. (2008), district heating with geothermal sources exists in Chaudes-Aigues, France, since the 15^{th} century, while the first industrial application happened in the early 1800's in Larderello, Italy, when geyser steam was used to extract boric acid from volcanic mud. That's is also the place of the first commercial geothermal power plant, in 1913 (Figure 2), with production's capacity of 250 kWe (Lund et al., 2008).

FIG. 2. First geothermal power plant in Larderello, Italy (Quick et al., 2010).

Geothermal power plants are evolving technologically and more efficient equipment is been installed on several places. Countries like United States and Philippines use their geographical advantage and are the top producers in the world (Lund et al., 2008). Canada is starting its investments on geothermal energy, showing a great potential to re-utilize oil and gas wells for heat generation (CanGEA, 2015), as well the implementation of closed-loop technology in Alberta (Eavor, 2021).

EARTH INTERNAL TEMPERATURE

Earth's internal structure is divided into main layers (Figure 3) based on their geology and geophysical differences (Fowler, 2004). The external part of the Earth (the exposed rocks), is known as *crust*. It's thickness varies from an average of 7-8 km beneath the oceans, and 38 km in the continents, and is rich in silica. The next layer is the *mantle*, with thickness of around 2900 km, differs both physically and chemically to the crust, and is rich in magnesium silicates. Next comes the *core* which, itself, is divided into two parts: the outer core (liquid, rich in iron), and inner core (solid, rich in iron and nickel).

The planet's internal temperature increase with depth, and the main source of heating is the decaying of radioactive elements, predominantly U, Th, and K (Arevalo et al., 2009). Figure 3 shows it's gradient from the atmosphere to the center on Earth. The crust, from where humans can "extract" geothermal energy, has an average gradient of $30^oC/km$. In other words, at 4 km deep in the crust, we can expect a temperature of 120^oC (this varies locally, as it will be shown later).

RESOURCES AND POWER PLANTS

It's observed that Earth's internal temperature increases with depth. The next steps are to understand how to have access to those higher temperature areas, how to use them, and what type of technologies can optimize its efficiency.

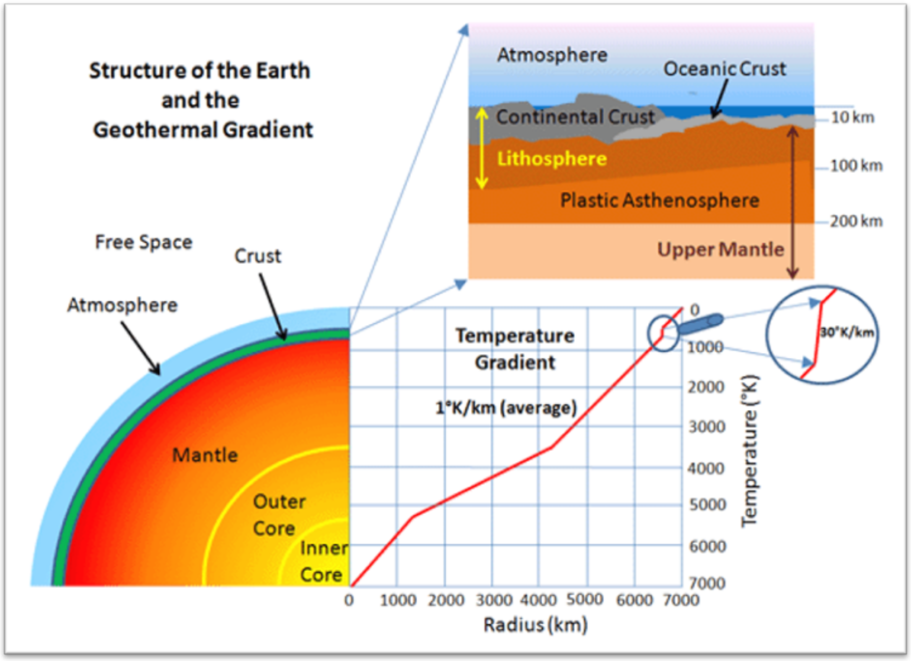

FIG. 3. Earth internal structure and gradient temperature. Source: Geology In (2014).

Power Plants

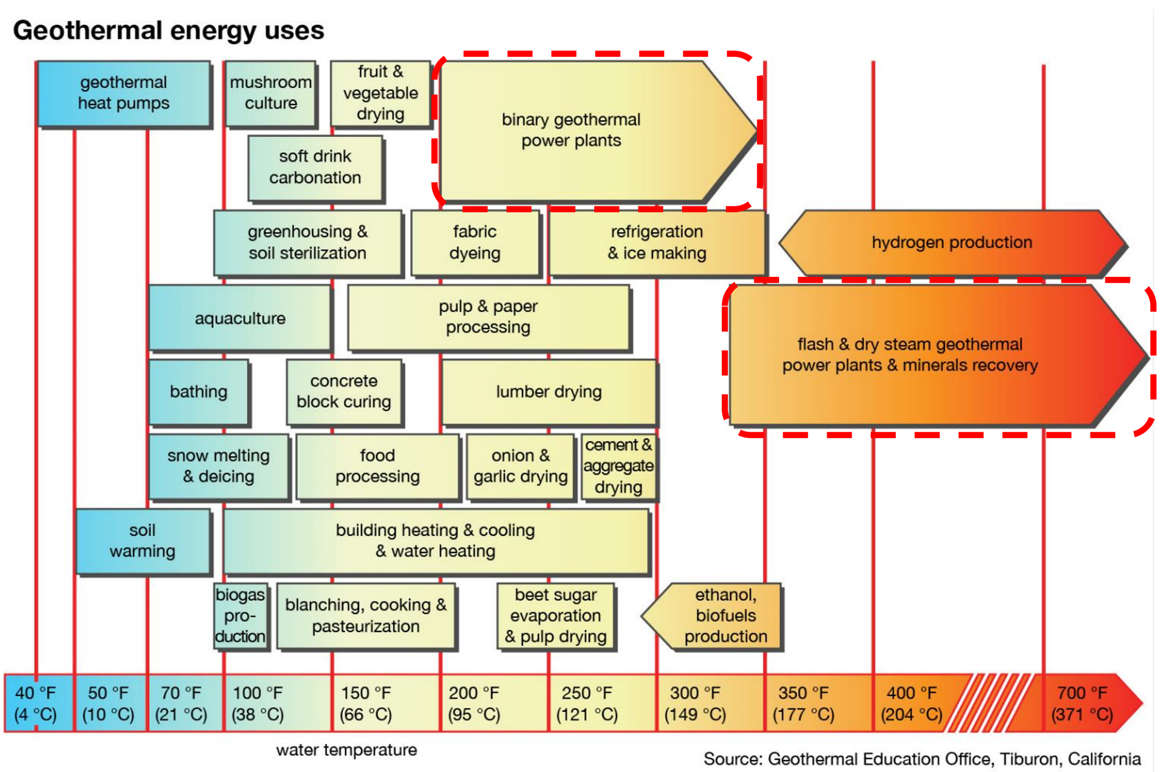

FIG. 4. Geothermal uses per temperature. Source: Geothermal Education Office (2017).

First, we need to define in what the geothermal energy will used for and what temperature is required, and it is illustrated in Figure 4 (Geothermal Education Office, 2017).

Different applications require different ranges of temperature. Here we are focused on the electricity generation, that are the highlighted application in Figure 4: the *binary geothermal power plants* (temperature range from 95^{o}C to 150^{o}C) and the *flash and dry steam geothermal power plants* (temperature range from 140^{o}C to 370^{o}C).

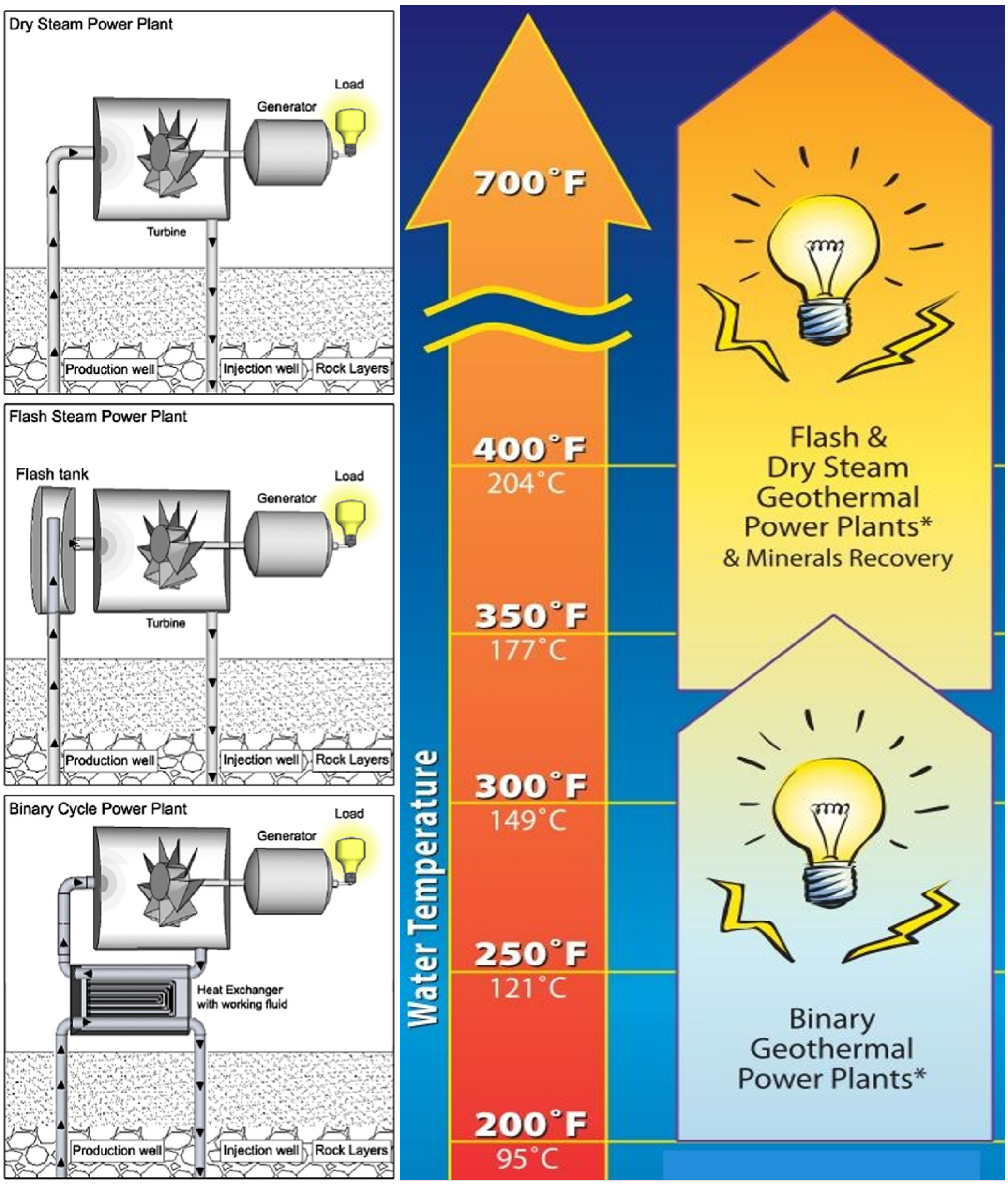

FIG. 5. Power plants technologies and their required water temperature. Figure modified from Al-Douri et al. (2019) and Geothermal Education Office (2017).

Geothermal power plants, in general, use high pressured vapor to rotate a turbine for electricity generation (Figure 5), requiring, usually, temperatures over 150^{o}C, unless a secondary fluid with low boiling point is included in the system. Different types of technologies are cite by Lund (2007). The *Dry Steam Power Plant* uses steam directly from the geothermal resource to rotate the turbine, and requires very high resources temperatures (>200^{o}C). *Flash Stream Power Plant* is a different concept on which high pressured hot water is connected to the turbine chamber that is in lower pressured, evaporating the hot water to rotate the turbine. It requires geothermal resources with 150^{o}C or higher. Finally, the *Binary Cycle Power Plant* never boils the water. Instead, it uses the hot water from a geothermal resource to to evaporate another fluid with lower boiling point in high pressure, and then the steam rotates the turbine. Required temperatures can be as low as 95^{o}C.

Types of Resource

There are different types of geothermal resources (Table 1, Figure 6), that can occur in few locations (when hot water feeds the geothermal reservoir naturally), or can be "created" artificially (enhanced geothermal systems).

Table 1. Geothermal resource types (Lund, 2007).

Resource Type	Temperature Range (^{o}C)
Convective hydrothermal resources	
Vapor dominated	240
Hot-water dominated	20 to 350+
Other hydrothermal resources	
Sedimentary basin	20 to 150
Geopressured	90 to 200
Radiogenic	30 to 150
Hot rock resources	
Solidified (hot dry rock)	90 to 650
Magma	>600

Table 1 lists different geothermal resource types and their temperature range (Lund, 2007), ranging from 20^{o}C to over 600^{o}C. For electricity generation, usually resources above 100^{o}C are used, but different technologies are decreasing the required geothermal resource temperature, such as the Chena Hot Springs Resort in Alaska using a geothermal resource of 74^{o}C (Lund, 2007). Lower temperatures cam be used for houses heating and cooling.

Resource type from Table 1 are explained and linked to the Figure 6 in the items below:

- *Vapor dominated* (Figure 6a): natural water feeds a high temperature and low permeability rocks, boiling, and travels upwards to the geysers. the steam can be used to produce electricity.
- *Water dominated* (Figure 6b): water circulates through permeable heated reservoirs is large volumes, and then follows the upflow zone at the center of the structure. New water downflows to the reservoir usually by the sides of the convection cell. The hot water can manifest in the surface as hot springs, fumaroles, geysers, or have no surface manifestation (blind resource).
- *Sedimentary basins* (Figure 6d): areas with geothermal gradient larger than the crust average of 30^{o}C/km caused by low thermal conductivity, high heat flow, or both.
- *Geopressured* (Figure 6f): hot water in permeable rock reservoirs with temperature equal or larger then the average geothermal gradient. The water is trapped by low permeability rocks in sedimentary basins. Drilling is require to access this resource.

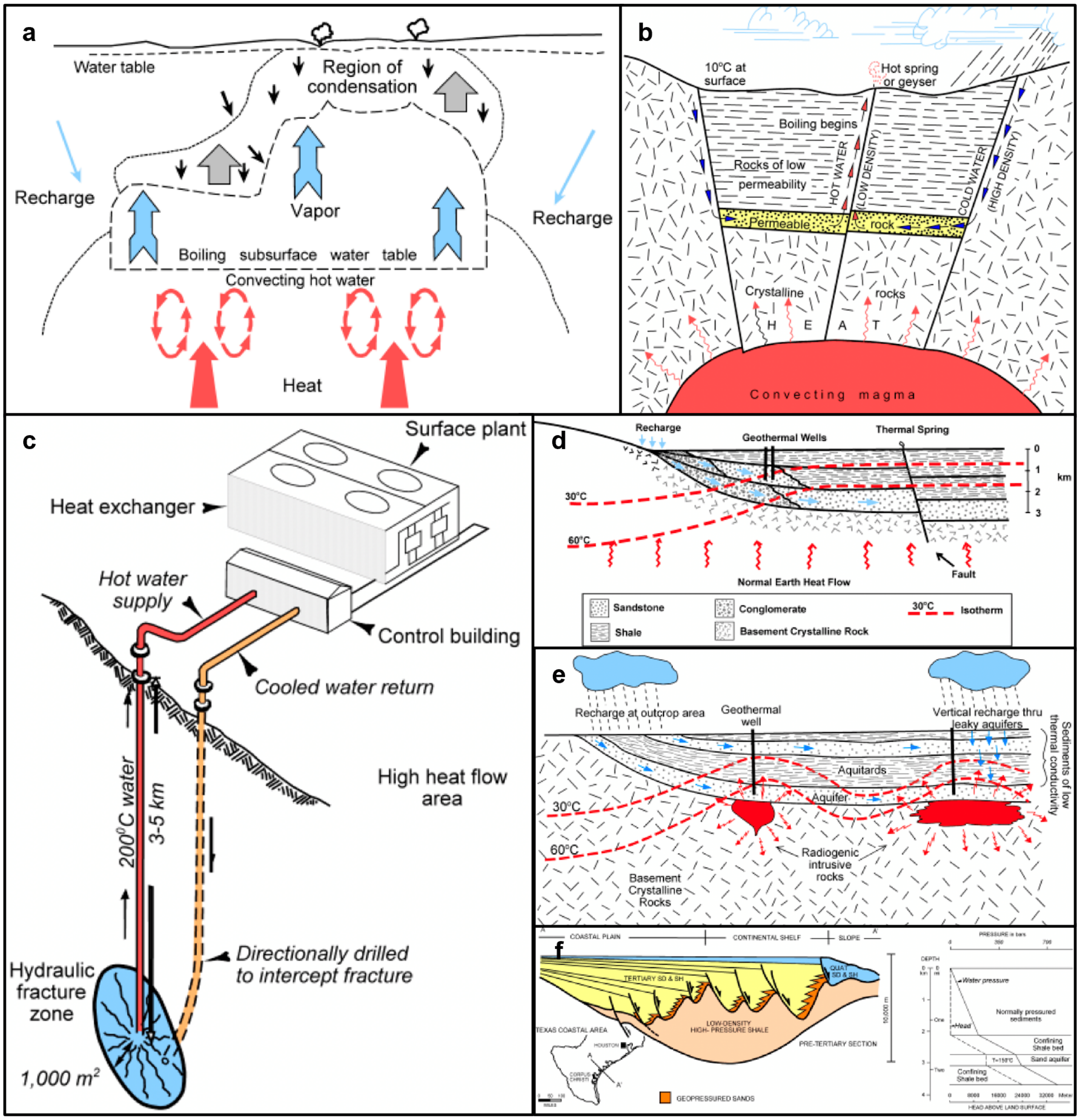

FIG. 6. Geothermal uses per temperature. Source: Lund (2007).

- *Radiogenic* (Figure 6e): water is locally heated from the decay of radiogenic minerals such as thorium, potassium, and uranium. This type of resource can occur at lower depths.

- *Hot dry rock* (Figure 6c): the resource usually contains little or no water and lor permeability. Resources are commonly deep (4+ km), and cold water is injected on a fractured reservoir, heated, and extracted to feed different applications (usually power plants, called *enhanced geothermal systems*). It has the advantage to be used anywhere on Earth, but requires a large initial investment.

- *Magma*: uses molten rocks to generate energy. An experiment was done in Iceland by drilling in areas of volcanic activity and boiling water. It was used for space heating for over a decade and them abandoned after the surrounding water cooled.

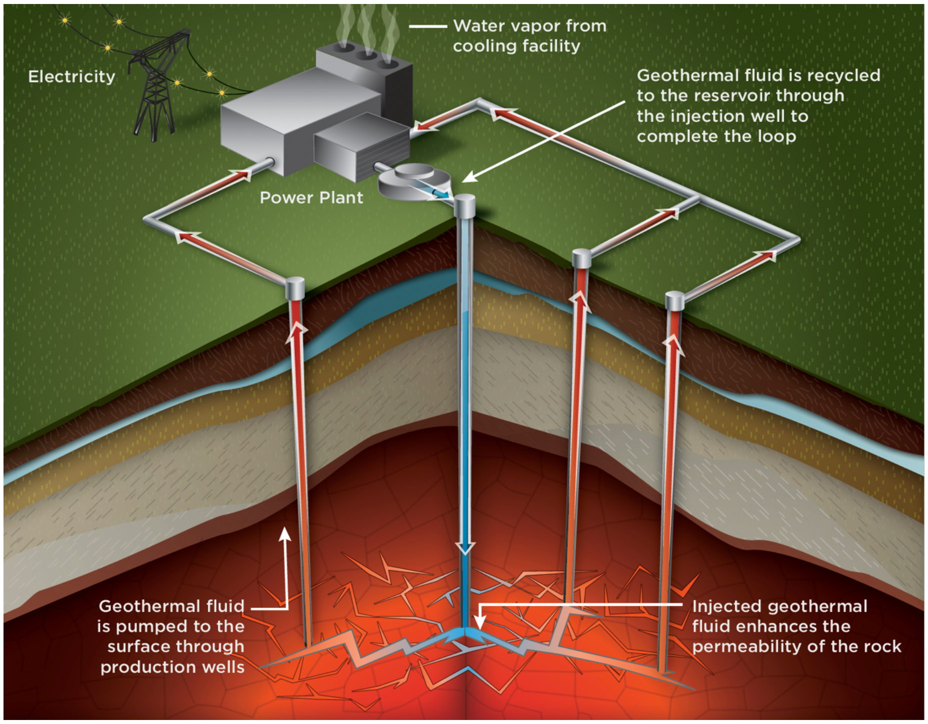

FIG. 7. Enhanced Geothermal Systems, or EGS (Fang et al., 2011).

Most of the resources cited occur on different locations, but not everywhere. Usually geothermal potentials are connected to the border of tectonic plates (Geothermal Education Office, 2017). The exception is the *hot dry rock*, which virtually can be used anywhere. *Enhanced Geothermal Systems*, or EGS (Huenges, 2016), are economically enabled geothermal reservoirs by increasing its initial low permeability with hydraulic, thermal, or chemical stimulation. Cold water is injected from a well to the reservoir, heating the water, which is then extracted back to the surface to a power plant to generate electricity (Figure 7).

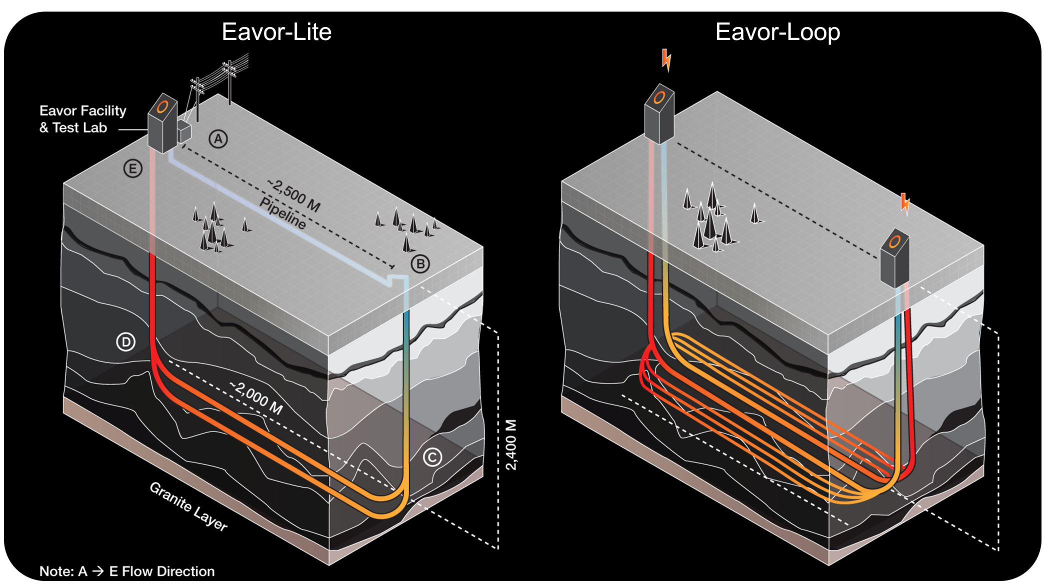

FIG. 8. Eavor-Lite and Eavor-Loop technologies. Source: Eavor (2021).

Fracking a geothermal resource can be controversial to the public opinion for the environmental side. Also, fracking can, although rare, trigger earthquakes. An example is the magnitude 5.4 earthquake connect to a EGS power plant in Pohang, South Korea, injuring 135 people and caused an estimated 300 billion won (US$290 million) in damage. One way to use the heat from dry rocks without fracking is the *closed loop* (Figure 8). This system consists on connecting two distant vertical wells with one or more horizontal boreholes. Cold water is injected in one well, heated while traveling through the horizontal holes (without fracking and, sometimes, without casing), and extracted by the second well to generate energy. The cooled water is sent to the first well using a pipeline and injected to the reservoir again. Eavor (2021) is currently testing their Eavor-Lite (Figure 8 left) in Alberta, Canada. Their Eavor-Loop proposal (Figure 8 right) is an optimization of the Eavor-Lite, where injection and extraction wells are drilled in two distant power plant locations, connecting them with several horizontal wells. Those types of technologies are promising and bring the potential to install geothermal power plants virtually anywhere on the surface, with low environmental and disaster risks.

ALBERTA'S POTENTIAL

EGS and closed-loop systems can use existing oil and gas wells to install geothermal power plants. According to the Government of Alberta (2021), Canada, the province had, as of October, 2021, approximately 458,000 total wells, and, of these, 329,000 require closure, meaning that many of those wells could be used for geothermal electricity generation.

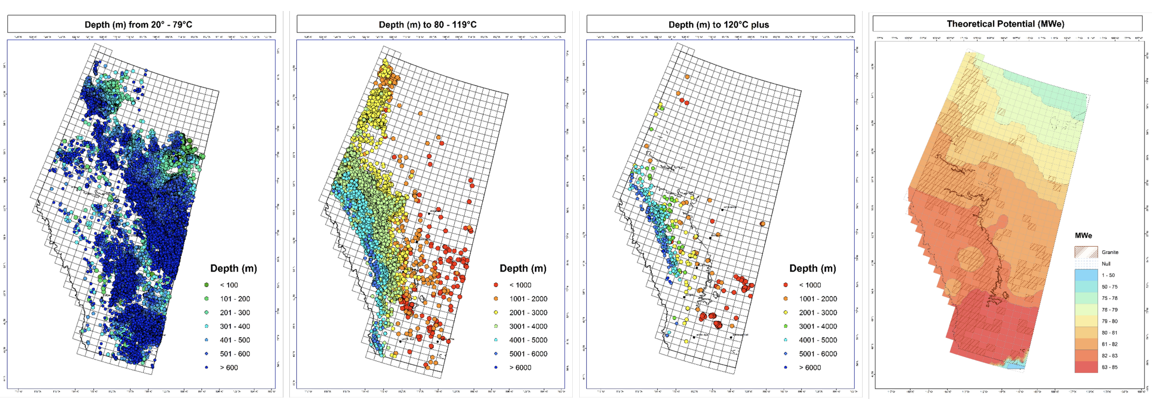

FIG. 9. Temperature per depth and Alberta's theoretical potential (CanGEA, 2015).

CanGEA (2015) measured Alberta's geothermal potential using bottom borehole temperature from over 60,000 wells with geothermal energy potential. Figure 9 shows a teaser of the report. The three first plots from left to right are the depth of the wells with temperatures between 20^{o}C and 79^{o}C (53,000 wells), 80^{o}C and 119^{o}C (7,200 wells), and 120^{o}C over (500 wells). The fourth plot is the Alberta potential, in MWe. Southeast and East of Alberta can reach temperatures higher the 80^{o}C in depths lower than 1 km (high temperature gradient), making those areas very attractive for geothermal energy generation. Most of those wells could be reused and converted to EGS or close-loop systems.

CONCLUSIONS

Geothermal resources have been used by hominids since prehistoric times for bathing, curing wounds, and tempering hunting weapons. Even religious connections are observed in old civilizations. District heating application appeared in France during the 15^{th} century, while the first power plant was installed in Larderello, Italy, in 1913. Since then, power plant technologies and optimized geothermal resources are studied for large-scale renewable energy generation.

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REFERENCES

Al-Douri, Y., Waheeb, S., and Johan, M., 2019, Exploiting of geothermal energy reserve and potential in saudi arabia: A case study at ain al harrah: Energy Reports, **5**, 632–638.

Arevalo, R., McDonough, W. F., and Luong, M., 2009, The k/u ratio of the silicate earth: Insights into mantle composition, structure and thermal evolution: Earth and Planetary Science Letters, **278**, No. 3, 361–369. URL `https://www.sciencedirect.com/science/article/pii/S0012821X08007711`

Arriaga, M.-C. S., 2005, A short story of the long relationship between the human race and geothermal phenomena: Proceedings World Geothermal Congress. URL `https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0257.pdf`

CanGEA, 2015, Alberta's (and other hsa areas') strategic potential for geothermal power: Canadian Geothermal Energy Association. URL `https://www.cangea.ca/`

Cataldi, R., 1992, Review of historiographic aspects of geothermal energy in the mediterranean and mesoamerican areas prior to the modern age: Geo-Heat Center Quarterly Bulletin; (United States), **15:1**. URL `https://www.osti.gov/biblio/5459545`

Eavor, 2021, Eavor-lite demonstration facility: Eavor Technologies. URL `https://www.eavor.com/eavor-lite/`

Fang, K., Zhang, R., Isaacs-Smith, T., Johnson, R., Andarawis, E., and Vert, A., 2011, Thin film multichip packaging for high temperature digital electronics.

Fowler, C. M. R., 2004, The Solid Earth: An Introduction to Global Geophysics: Cambridge University Press, 2 edn.

Geology In, 2014, Corporate energy consumption.
URL `https://www.geologyin.com/2014/12/geothermal-gradient.html`

Geothermal Education Office, 2017, Geothermal energy: City of Calgary.
URL `https://geothermaleducation.org/`

Government of Alberta, 2021, Oil and gas liabilities management | alberta.ca.
URL `https://www.alberta.ca/oil-and-gas-liabilities-management.aspx`

Huenges, E., 2016, Enhanced geothermal systems: Review and status of research and development: Geothermal Power Generation: Developments and Innovation, 743–761.

Lund, J., Bjelm, L., Bloomquist, G., and Mortensen, A., 2008, Characteristics, development and utilization of geothermal resources - a nordic perspective: Episodes, **31**.

Lund, J. W., 2007, Characteristics development and utilization of geothermal resources: Geo-Heat Center Quarterly Bulletin, **28**, No. 2.
URL `https://www.osti.gov/servlets/purl/1209249`

Quick, H., Michael, J., Huber, H., and Arslan, U., 2010, History of international geothermal power plants and geothermal projects in germany: Proceedings World Geothermal Congress.
URL `https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0605.pdf`