Better Together: New Synergies and Opportunities From Hybrid Geothermal Projects

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ABSTRACT

The many options for utilizing geothermal energy – from shallow heat exchange for space heating and cooling, to direct utilization for district heating and industrial heat, to geothermal power production, to closed-loop systems and to Enhanced Geothermal Systems (EGS) – provide multiple value chains that have one thing in common: reducing the CO2 footprint of our energy systems. Additional synergies can be realized through combining geothermal with other technologies in hybrid applications. There are many such applications, starting with hybrids between different types of geothermal resources; for example, combined heat and power projects bring not only clean, baseload electricity but also a benefit to local communities through direct utilization. This paper explores the growing interest in four other hybrid solutions: geothermal + oil & gas in deep sedimentary basins; geothermal + solar; geothermal + wind; and geothermal + green hydrogen production. Each of these provides opportunities for innovative business models and synergistic relationships.

Oil & gas production from deep sedimentary basins has been ongoing for more than 100 years, resulting in a wealth of knowledge and technology associated with extracting hydrocarbons. Most producing oil & gas wells also produce water – depending on depth, some of this water is hot. This provides an obvious geothermal opportunity that has been previously recognized, but largely ignored until now. Considering the fundamental differences between 1) how oil & gas wells and geothermal wells are completed, 2) the difference in energy content between hydrocarbons and hot water, requiring comparatively high flow rates of hot water to be economic, and 3) the fact that most sedimentary basins are in areas with normal temperature gradients, geothermal production of hot waters in sedimentary basins is not without its challenges. However, oil & gas technologies have long been leveraged for geothermal drilling

and production, and operators entering the geothermal space are taking advantage of this history, working with geothermal experts to maximize energy production from geothermal resources. Taking advantage of the knowledge and the significant amount of data available from these basins, the geothermal + oil & gas hybrid is an obvious opportunity for increasing the amount of geothermal energy produced today.

Several geothermal operators in the United States have adopted the geothermal + solar hybrid model, particularly in arid areas with high summer temperatures, which decreases the conversion efficiency of air-cooled binary power plants. The addition of solar PV to this type of geothermal project enables geothermal operators to mitigate the decrease in geothermal output during periods of hot weather. Particularly where water cooling is not an option, the addition of solar PV helps maintain power generation at times when energy pricing may be at its peak. Concentrated Solar Power (CSP) also offers highly useful options for increasing geothermal output, using approaches such as boosting the temperature of the geothermal fluid to increase conversion efficiency and output, and using steam topping turbines to make an even bigger impact on the output of geothermal facilities, regardless of the temperature of the geothermal fluid. Thus, an intermittent energy source like solar creates a useful complement to baseload geothermal.

Geothermal + wind is similar to solar; however, in this hybrid, geothermal supports the continued provision of power from wind resources that vary daily and seasonally. Although no such hybrids exist today, there is potential for synergistic relationships between the two sources in areas where the wind power density is reasonably high. The highest power density is found offshore, but there are land areas around the world where the wind density is reasonably good, though more variable. One example is the wind belt in the central United States, which extends from Texas to the Canadian border. In this region, there are many deep basins that are developed for oil & gas production, many of which contain fluids at attractive temperatures for power generation. The installation of a modest increment of power produced from these fluids using binary power technology could add an increment of baseload power that improves the overall performance of wind projects.

The final hybrid discussed herein is using geothermal for the production of hydrogen, which is fast becoming the fuel of the future owing to its zero-emission characteristic and the fact that it is readily available through electrolysis of water. In addition, hydrogen is an important component for the production of ammonia, urea, methanol and melamine. Gray hydrogen (commonly using natural gas for electrolysis) becomes blue hydrogen when carbon capture, utilization and storage (CCUS) techniques are applied. Green hydrogen is produced by using clean energy sources for electrolysis. The current discussion around the production of green hydrogen is centered around solar power, but using geothermal power for electrolysis is a topic of increased interest, and would improve the efficiency of hydrogen production by using a clean baseload power source with a constant output. Although there are many more, this paper presents two scenarios that provide immediate and meaningful opportunities for the production of green hydrogen: 1) in island settings where demand is less than supply; and 2) where geothermal assets lack access to markets (because of remoteness, lack of transmission or both).

1. Introduction

It is widely understood that the reality of climate change requires nothing short of a wholesale transformation of our energy systems, particularly for electricity and transportation. This is creating new opportunities for geothermal energy, a significant source of clean baseload electricity that has been historically under-utilized in various markets because of factors such as:

- competition from "cheaper" sources with lower perceived development costs that do not consider:
  - environmental and health impacts (fossil fuels) and overall life cycle costs;
  - intermittent delivery (solar and wind); or
  - grid stabilization and renewables integration issues
- the high up-front costs and time requirements to discover, confirm and quantify geothermal resources, long in advance of revenue from power sales;
- traditionally uncompetitive regulatory and permitting timelines;
- frequently, remoteness from load centers and transmission systems; and, in some cases
- the inability of small projects to take advantage of the cost savings associated with economy of scale.

Solutions to the first two issues have included mandated power prices in some countries. This occurred in the United States in the 1980s after the passage of the Public Utilities Regulatory and Policy Act of 1978 (commonly referred to as PURPA), which opened the market for independent power producers (IPPs) to develop renewable energy and other qualifying projects by requiring payment for power at the off-taking utility's avoided cost (the cost to generate a similar amount of power from another facility). This alone was a significant driver; however, the monetary value of geothermal's high availability was recognized in some states (notably California), resulting in the implementation of capacity payments that were added to the power prices based on avoided cost. Much of the early geothermal growth in the US resulted from standardized contracts mandated by PURPA. Other countries seeking to expand their renewable power portfolios have set specific Feed-In Tariffs (FITs) for geothermal power that recognize the early investment requirements, risks and costs of developing geothermal power. Various risk mitigation funds have been formed to support the growth of geothermal power (typically in developing countries and regions), providing financial support that offsets exploration and early drilling costs, reducing the risk associated with discovering and confirming geothermal resources.

These solutions have indeed accelerated the pace of geothermal development, but geothermal power still remains only a small fraction of the electricity consumed in most places, with some notable exceptions in the following countries, all of which have significant additional geothermal potential:

- Iceland, where geothermal energy (power and heat) provides more than 60% of all energy consumed (Huttrer, 2020);
- Kenya, where 30% of electricity is provided from geothermal sources (Huttrer, 2020);
- New Zealand, where nearly 20% of all electricity consumed as of March 2021 came from geothermal power plants (Ministry of Business, Innovation and Employment, 2021); and

- The Philippines, where about 17% of all electricity consumed came from geothermal sources in 2020 (ERIA, 2021a).

At the low end of the spectrum, geothermal power accounts for:

- about 5% of all electricity consumed in 2020 in Indonesia (ERIA, 2021b), a nation that has massive additional geothermal potential (perhaps more than 20 GW);
- about 5% of the installed generation capacity in California, which has approximately 2.5 GW of installed capacity (see Table 2 in Robertson-Tait *et al.*, 2020) and has the potential for up to twice as much (see the P50 estimate in Table 1 of USGS Fact Sheet 2008-3082);
- just over 2% of the installed generation capacity in Japan (ERIA, 2021c), which is likely to have at least 5 GW and perhaps more than 10 GW of additional geothermal potential;
- about 0.5% of all electricity consumed in the United States, which has an estimated additional potential of at least 9 GW and possibly as much as 30 GW (USGS, 2008);
- about 0.2% of the installed generation capacity in Chile in 2019, which has an estimated additional geothermal potential of at least 3.8 GW (Mesa de Geotérmia, 2018), but only one operating geothermal power plant; and
- very little if any of the power supply in volcanic archipelagos such as the Aleutian chain in Alaska, the Eastern Caribbean, and islands in the South Pacific.

In the island regions noted above – in combination with factors such as an established fossil fuel supply for power generation – the lack of economy of scale has held back geothermal development. In contrast, geothermal resources along the Andean Cordillera (such as in Chile) are remote from load centers and therefore require long transmission lines to deliver power to the national grid. Some of the available geothermal power could be sold to captive local customers (for example, mining operations), but significantly more potential remains. In other countries, such as the Philippines and Indonesia, competition from other sources leaves a significant amount of geothermal potential remaining to be developed.

In all of these locations discussed above and more that are not mentioned, there are opportunities for geothermal hybrids, offering utilization opportunities for important geothermal resources that remain unused because of low demand, competition with cheaper energy sources, or limited access to transmission, making geothermal projects uneconomic to develop. In addition, geothermal resources that are lower temperature / lower overall quality can still provide value in the form of heat in various domestic and industrial processes.

Dual uses of the same geothermal fluid can be considered an "auto hybrid." The cascaded use of geothermal fluids for power and direct uses (*e.g.*, space heating and cooling, industrial process heat) and the recovery of critical minerals from geothermal fluids are well known and expanding hybrid uses that not only fill technological gaps and offset electricity demand, but also improve the economics for geothermal and the partnering technology. Although not a hybrid solution *per se*, the significant interest in clean baseload power for data centers and cryptocurrency mining is bringing new entities into the geothermal sector, with promise to reduce the carbon footprint of these activities while yielding economic benefits that exceed those in traditional power sales models.

This paper explores some of the many uses of geothermal power in tandem with other technologies, focusing on four hybrid solutions that provide interesting opportunities for different geothermal business models: geothermal co-production in deep oil & gas fields; geothermal + solar PV (and possibly solar thermal); geothermal + wind; and geothermal + green hydrogen production.

2. Geothermal + Oil & Gas in Deep Basins

Deep sedimentary basins have long been known to contain hot water, and became a topic of discussion in the early 2000s, typically among academic and research institutions. However, significant interest in developing deep sedimentary basins for geothermal heat or power production is a relatively new phenomenon. In 1998, GeothermEx was approached by an oil & gas operator who had found hot water (about 235°F) in the Ellenberger Formation at depths of 20,000+ feet and wanted to know if it could be used to supply a geothermal power plant. The results of the work were mixed: flow rates were attractive and binary power plant technology was improving, but the thermodynamic efficiency was very low considering the resource temperature, and the power price that would be paid was too low to justify the investment needed to optimize a project. This operator sensibly decided to develop a wind project instead.

Twenty-plus years later, the natural synergies related to the extraction of fluids from the subsurface and the desire by oil & gas companies to reduce CO2 emission associated with their operations – and develop stand-alone geothermal projects in some cases – is an important element of decarbonization and the supply of clean energy. In addition, there are two more motivators for the oil & gas sector: 1) using the significant technological advances in characterization, drilling and completion that have been made in the past few decades to extract a new product; and 2) avoiding the cost of abandoning wells that produce too much water – sometimes hot water.

Particularly considering the last item above, the use of geothermal fluid in oil & gas fields tends to begin by re-evaluating wells that have reached (or soon will reach) a specified abandonment condition (too much water, too little oil or gas, or both, making them uneconomic to produce). Many of these wells stand idle and others have been orphaned; meaning that the costs to plug and abandon (P&A) these wells are being deferred. Delaying P&A operations may have a silver lining for some wells: conversion to geothermal production.

Although this is an obvious solution, there are vast differences in the energy content of the produced fluids, and there are fundamental differences between how oil & gas wells and geothermal wells are completed:

- Oil & gas wells are selectively perforated over short intervals that correspond to specific pay zones, maximizing hydrocarbon production and (at least for a time) minimizing water production.
- Typical geothermal wells have long production intervals and limited if any zonal isolation, maximizing water production.

If subsurface conditions exist that enable the production of hot water at reasonably high flow rates – ideally 25,000 barrels per day, which is equivalent to about 730 gallons per minute (gpm), or more – oil & gas operators have a clear opportunity to re-purpose wells in the field that are have reached or are close to reaching the abandonment condition, while continuing to produce hydrocarbons from the same wells and from other wells in the field. In addition to reducing CO2 emissions and deferring P&A costs, hot water production can create a revenue stream separate from that associated with oil & gas production (*e.g.*, selling the hot water to a nearby greenhouse operation), or offset the operator's power consumption in the field (*e.g.*, for pumping or for the power need of a production platform). Continued co-production of hydrocarbons in sub-commercial wells can contribute to the revenue stream, particularly in the early years of a project. In addition, these accretive value streams can extend the economic life of a well or a field, adding reserves and delaying the timeline for P&A expenses.

Most deep sedimentary basins are located in areas of normal temperature gradient, meaning that even at bottomhole (where the temperature is highest), temperatures are modest compared to many geothermal wells. Nevertheless, as shown in Figure 1, binary power plants can and do produce power at relatively low temperatures (see McKenna and Blackwell, 2005 [citing Pritchett, 2000 and Mines, 1997]). As described in therein, the blue triangles on Figure 1 represent the theoretical power production from the aggregated (hot) water cut from oil & gas production in three counties, as derived from state records. The hot water cut comprises up to 95% of the total production in these areas.

- Location 1 is in southern Arkansas. The total hot water production rate in this county was about 35,000 barrels per day (BPD), which is equivalent to about 1,000 gpm. The hot water was produced from a typical depth of about 7,600 feet (2,300 m), at a temperature of 210°F (99°C). Locations 2 and 3 are both in southwestern Alabama.
- The Location 2 county produced less hot water than Location 1 (about 9,000 BPD / 270 gpm) but at a higher temperature (325°F / 162°C), a result of the significantly greater average production depth (about 21,500 feet or 6,600 m).
- The county referred to as Location 3 produced 22,000 BPD / 640 gpm from average depths of about 15,500 feet (4,700 m) at a temperature of about 270°F (132°C).

Figure 1 includes some additional data points (black circles) that are not specifically identified but are referenced by McKenna and Blackwell (2005) as McKenna, 2004 (unpublished data).

In the three locations shown in Figure 1, McKenna and Blackwell (2005) note that most of the produced fluid is passed to a central facility that separates the hydrocarbons from the water, which could facilitate the use of the hot water for power generation. However, because of heat loss, the temperatures at the separation facility – and at the wellheads of individual production wells – will be significantly lower than the temperatures measured at depth. The typical oilfield completion (with production through tubing) limits the flow rate, which leads to significant heat loss between bottomhole and the wellhead. In contrast, the flow rate of a typical large-diameter geothermal well is not limited by a small diameter, and the high flow rate enables the well to heat up from bottom to top after production is initiated, preserving the temperature at the wellhead.

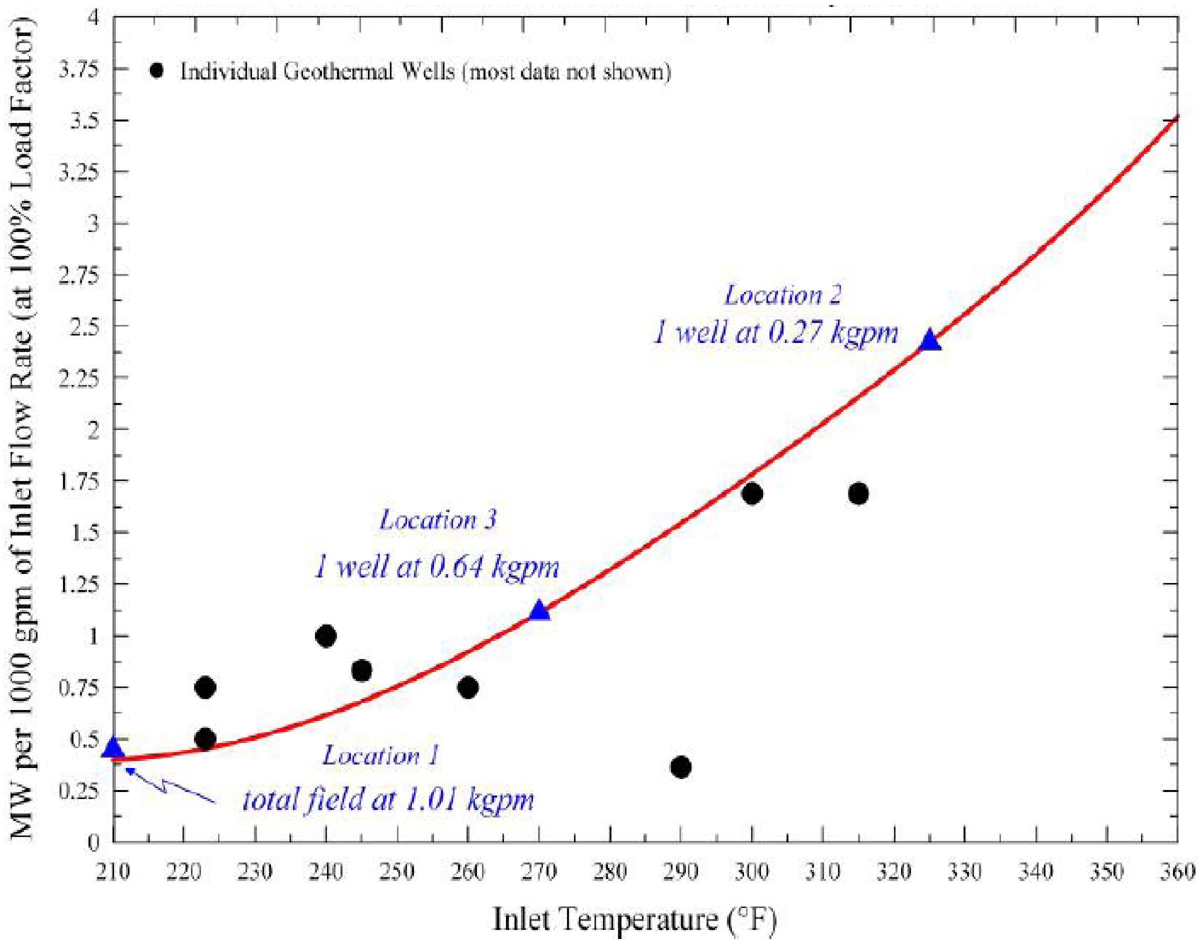

Figure 1: Power generation potential (expressed as MW per 1,000 gpm) from moderate temperature geothermal fluid as a function of power plant inlet temperature (°F). The generation levels shown include the power plant's parasitic load, but exclude pumping power requirements (McKenna and Blackwell, 2005).

Modest re-completion operations can make an oil or gas well into a better geothermal well, by pulling the tubing (instantly increasing wellbore diameter) and perforating the deep zones to maximize hot water production zones. Purposefully deepening wells into permeable zones known or anticipated to contain hot water offers the potential for significant flow rate improvements. Some oil & gas operators are beginning their geothermal journey with these relatively simple activities, using the fluids to supply small binary plants for pumping power and other local use, and others are selling the hot water to nearby users for process heat, greenhouses and other space heating needs. Considering their considerably higher P&A costs, interest is growing for geothermal production from offshore wells, supplying the platform with heat and/or power.

Binary technologies have advanced by binary plant manufacturers since the early 2000s, particularly in terms of conversion efficiency improvements for projects with low resource temperatures. Recent entries by new manufacturers of self-contained binary plants with a small footprint (sometimes referred to as micro-ORC plants, with capacities of up to few hundred kW) can operate at temperatures as low as 175°F (80°C). Such units can be supplied by individual wells or groups of closely located wells, providing power for pumping or other local needs, such as power on offshore platforms. However, as shown in Figure 1, as temperature decreases, more fluid needs to be produced to enable each increment of generation, increasing the pumping requirements. As in dedicated geothermal projects, operators may consider buying power from the local grid for pumping (which is permitted in many if not most jurisdictions) instead of self-generating the pumping power. This may have implications for compliance with particular ESG (Environment, Social and Governance) initiatives to reduce the carbon footprint of oil & gas operations.

Finally, operators need to adjust to having new types of equipment at their well sites and a new suite of service companies involved in operations. In addition to a natural focus on their core business of producing hydrocarbons, this has been a potential barrier to testing the operating efficiency of coupled geothermal + oil & gas operations. Although synergies definitely exist, operators need to fully understand the requirements and impact of these synergies from the outset.

Nevertheless, there is significant interest in geothermal-hydrocarbon hybrids, which is not only broadening the footprint of geothermal by using the heat contained in deep sedimentary basins, but is also leading some oil & gas operators toward stand-alone (non-hybrid) geothermal projects. The cases discussed above in Arkansas and Alabama show the potential in the southern and southeastern tier of the United States. There is more potential in other states, particularly Texas, which hosts very attractive deep geothermal resources and offers interesting opportunities for geothermal-natural gas hybrid projects.

3. Geothermal + Solar

An interesting current-day geothermal hybrid example is provided by several geothermal + solar projects that are operating in the western United States today. Because of the scarcity of water for cooling, these projects use binary power plants that are air-cooled. The thermodynamic efficiency of such power plants decreases with increased ambient air temperature, both daily and seasonally. With power pricing often at a premium during peak demand times on hot days, three geothermal developers have responded by operating their air-cooled binary power plant plants in Nevada in a hybrid mode with solar power to maximize power delivery.

3.1 Patua, Nevada

In September 2017, Cyrq Energy began operating a 10 MW solar PV project adjacent to its 25 MW binary geothermal power plant at Patua, located about 50 miles east of Reno in Churchill County, Nevada. Figure 2 shows the binary plant and the solar PV arrays, which cover an area of about 80 acres. As reported by the General Contractor for the solar project (Hunt Electric Inc.), more than 40,000 325-watt solar PV panels and all other required equipment (including substation relay controls and optimization software for the solar panels) were installed in 90 days, one month ahead of schedule. This fully integrated geothermal-solar PV project combines two co-located renewable power technologies to optimize power delivery, particularly on hot summer days when geothermal generation efficiency experiences a decline. The project engendered praise from the Governor and one of Nevada's Senators. Power from the Patua Geothermal-Solar hybrid project is sold to the Sacramento Municipal Utility District, a community-owned electric utility in California that serves Sacramento County and parts of neighboring Placer County.

Figure 2: Cyrq Energy's 48 MW binary geothermal + 10 MW solar PV project at Patua, Nevada (GeothermEx photo)

3.2 Tungsten Mountain, Nevada

Ormat Technologies, Inc. began producing power from 7 MW of solar PV in mid-2019 at its 24 MW binary geothermal power project at Tungsten Mountain, Nevada, which is also located in Churchill County (about 100 miles east of Patua). As described in a press release (Ormat, 2019), the Tungsten Mountain geothermal plant started up in late 2017, and the power is sold to the Southern California Public Power Authority (SCPPA), a 'Joint Powers Authority' that was created in 1980. Comprised of 11 municipal utilities (including the Los Angeles Department of Water and Power) and an irrigation district, SCPPA supplies about 16% of California's power (http://www.scppa.org). Ormat and SCPPA entered into an innovative portfolio contract that recognized the value of renewable power as a way to transition from coal while maintaining system resilience. As noted in the US Bureau of Land Management's Decision Record for the solar project (BLM, 2018), the power from the solar project at Tungsten Mountain helps offset the internal power consumption of the geothermal power plant, enabling more clean power to be delivered to southern California at a price of about $0.075 per kW-hour (CleanTechnica, 2018).

3.3 Stillwater, Nevada

ENEL Green Power North America was the first geothermal operator to develop a geothermal-solar hybrid project. This occurred at another geothermal field in Churchill County, Nevada: Stillwater, located in the Carson Sink about 35 miles east of Patua. As described in DiMarzio *et al.* (2015), ENEL's 33 MW binary geothermal power plant was installed at Stillwater in 2009.

Three years later, seeking to increase overall output, ENEL installed 89,000 solar panels in a 240-acre area adjacent to the geothermal plant. This not only led to awards from Power Magazine and the Geothermal Energy Association, it also significantly increased output during periods of peak demand, as shown in Figure 3 below.

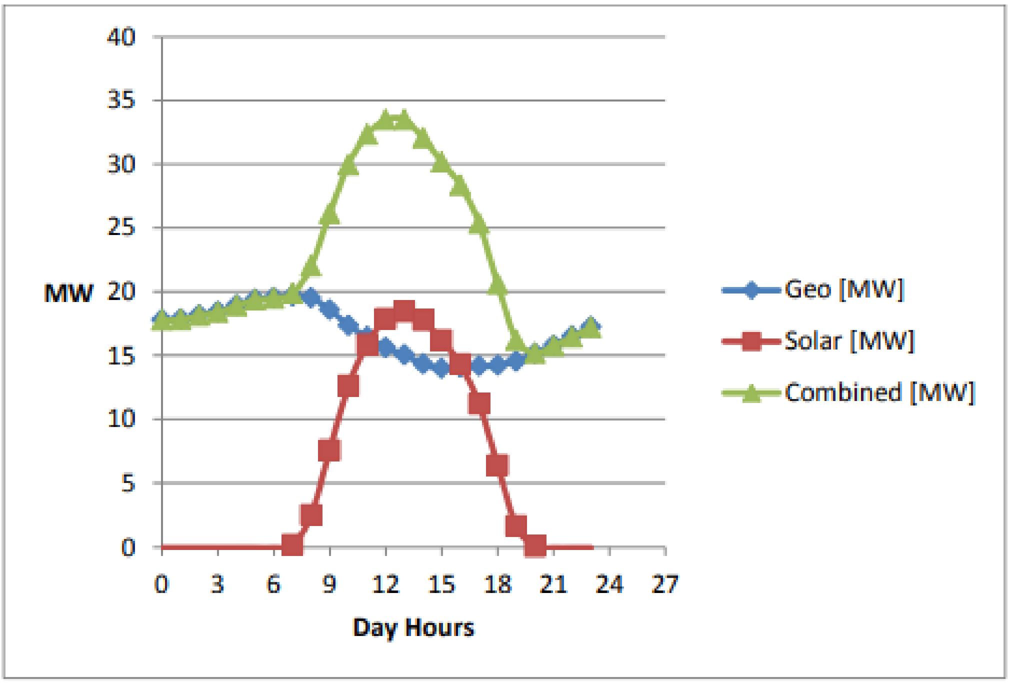

Figure 3: Power output from geothermal and solar PV on a "typical spring day" at ENEL's hybrid geothermal-solar facility at Stillwater, Nevada (from DiMarzio *et al.*, 2015)

ENEL continued to innovate at Stillwater by adding solar thermal capacity (*i.e.*, concentrated solar power, CSP) to boost the temperature of the geothermal brine to reach the design input temperature. This approach has advantages compared to drilling new wells: 1) lower risk, while still extending the longevity of the geothermal resource supply; and 2) increased generation efficiency and output from the binary geothermal plant. Linear parabolic trough technology was used to concentrate the solar power and heat the geothermal fluid; the CSP array can be seen at the top center of Figure 4 below. Innovative engineering design has enabled the three technologies to work together in a complementary and effective way in this first-of-its kind triple hybrid geothermal project.

These three geothermal + solar hybrid projects are only the beginning; significantly more can be expected, particularly in arid areas with good solar irradiance.

Figure 4: Aerial view of the Stillwater triple hybrid project (photo courtesy of ENEL Green Power North America). The CSP array is at the top of the photo.

3.4 Concept for Raft River, Idaho

McTigue *et al.* (2018) present an alternative use of solar thermal for improving the output of binary geothermal power plants, based on an analysis of the 13.5 MW Raft River geothermal project in SW Idaho, which is supplied by a 280°F (138°C) geothermal resource. The output of the plant has been lower than the maximum value specified in the power purchase agreement, providing impetus for this analysis. The authors demonstrate that using CSP to supply small, high-pressure steam topping turbines is a more efficient process that boosting the temperature of the geothermal brine. The process that was modeled (see Figure 5 below) was found to have twice the conversion efficiency of 1) pre-heating the entire flow of geothermal fluid before it passes through the heat exchangers (a process that is relatively easy to implement) and 2) re-heating a portion of the geothermal fluid downstream of the heat exchangers. This result is achieved through three related processes: 1) the addition of the topping cycle, which is supplied with high pressure steam resulting from the CSP's ability to generate temperatures up to 700°F (370°C); 2) heating the geothermal working fluid (pentane) using the exit flow of the steam topping cycle; which 3) lowers the exit temperature of the brine by increasing the brine by increasing the flow rate of the working fluid, effectively restoring the efficiency of the binary turbine.

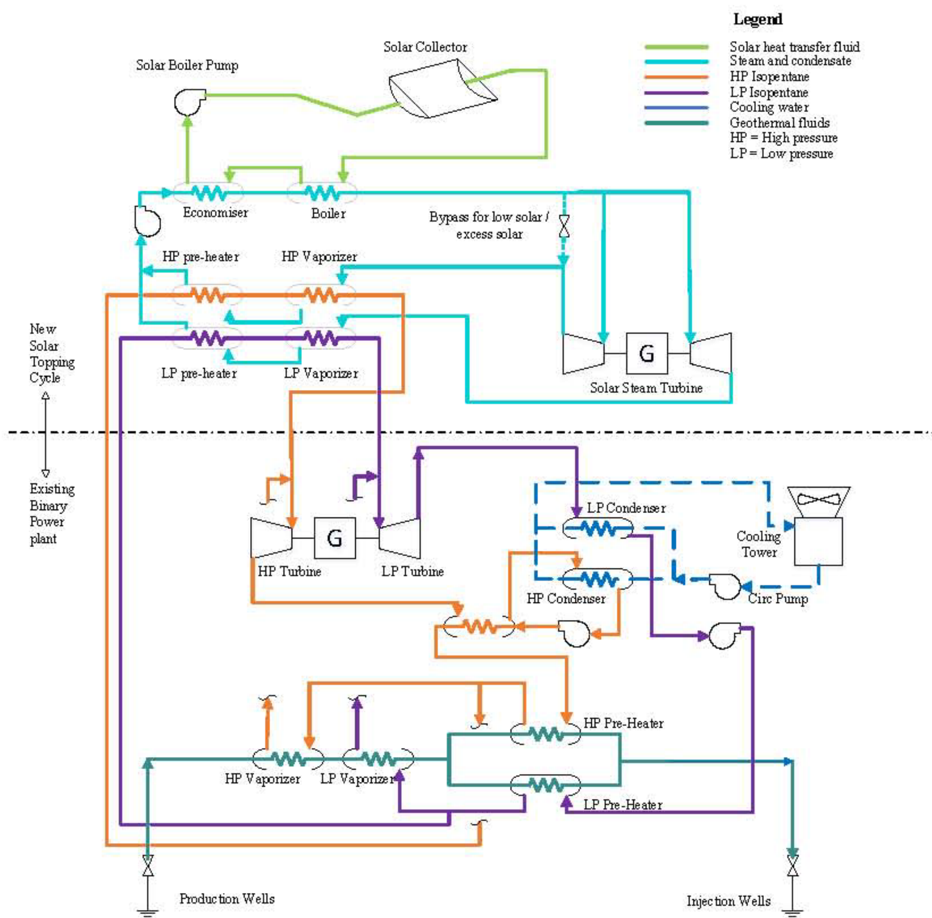

Figure 5: Process flow diagram for a hybrid geothermal-CSP project with two steam topping turbines (McTigue *et al.*, 2018)

This work was undertaken in a comprehensive way, including modeling of different configurations, meteorological conditions and irradiance levels, CSP designs and sizes of the CSP array, including those that could accommodate thermal energy storage (TES) as a way to maximize generation. Analyses were undertaken for the various scenarios to compare the annual power generation levels, the levelized cost of electricity (LCOE) and the resulting conversion efficiency (focusing particularly on the incremental efficiency added by the CSP-supplied topping cycle). As the demand for clean energy continues to increase, integrated projects such as that described in McTigue *et al.* (2018) will become the norm.

4. Geothermal + Wind

The examples in Section 3 above describe how geothermal operators can use solar energy to maximize power generation and revenue in two ways:

1) solar PV to make up for less efficient geothermal generation due to high ambient temperatures, thus “leveling out” the delivery of power on a daily and/or seasonal basis; and
2) CSP to add an increment of generation to a geothermal plant that has an inadequate resource supply.

The operators of wind energy projects could benefit from associating with geothermal in a similar way: by adding geothermal power to their projects, wind operators could “level out” the delivery of renewable power, particularly during the night but also and at other times when wind speed are low. The extensive study of wind energy has resulted in numerous representations of wind speeds and more importantly wind power density (Watts/m^2), including the Global Wind Atlas (2021). It is well understood that the highest wind power densities exist in coastal areas, including some around the Pacific Ring of Fire, which hosts many geothermal projects and has significantly more geothermal potential. Working clockwise from the west side of the Ring of Fire, areas with potential for high-temperature geothermal power (volcanic domains) and wind exist in the Kuril islands, Kamchatka, the Aleutian islands and the volcanic regions that extend into SW Alaska. Wind power density is also high in areas of high elevation, such as the Cascade Range in Washington, Oregon and northern California. Further south, some of the areas along the Andean volcanic chain have high winds (particularly at high elevation).

However, there is also significant wind potential in non-geothermal areas, such as the central wind belt in the United States, which extends from Texas to the Canadian border (Figure 6). The windy mid-continent has many deep basins that have been developed for oil & gas that coincide with areas of favorable wind speeds. Figure 7 (developed with the interactive mapping tool on the website of the Energy Information Agency, 2021) shows existing wind projects in Texas and Oklahoma and the locations of deep basins that produce hydrocarbons. Such basins are also found in other parts of this wind belt, including northeastern Colorado, western Wyoming, eastern Kansas, northwestern Missouri, much of southern Iowa, and western North Dakota, including part of the Williston Basin. Researchers at the University of North Dakota (see Gosnold *et al.*, 2017 and other papers for which Dr. Gosnold is the lead author) have undertaken numerous analyses of the Williston Basin’s geothermal potential, and a geothermal project is currently under development in the northern sector of the Basin in Saskatchewan. Wind power operators in this region could find opportunities to maximize power delivery with a geothermal component, contributing to and stabilizing project revenues. In addition, even in lower-quality wind regions, the coupling of wind and geothermal power production could take advantage of transmission infrastructure, together yielding more attractive “packaged” power pricing than might be possible from stand-alone resources.

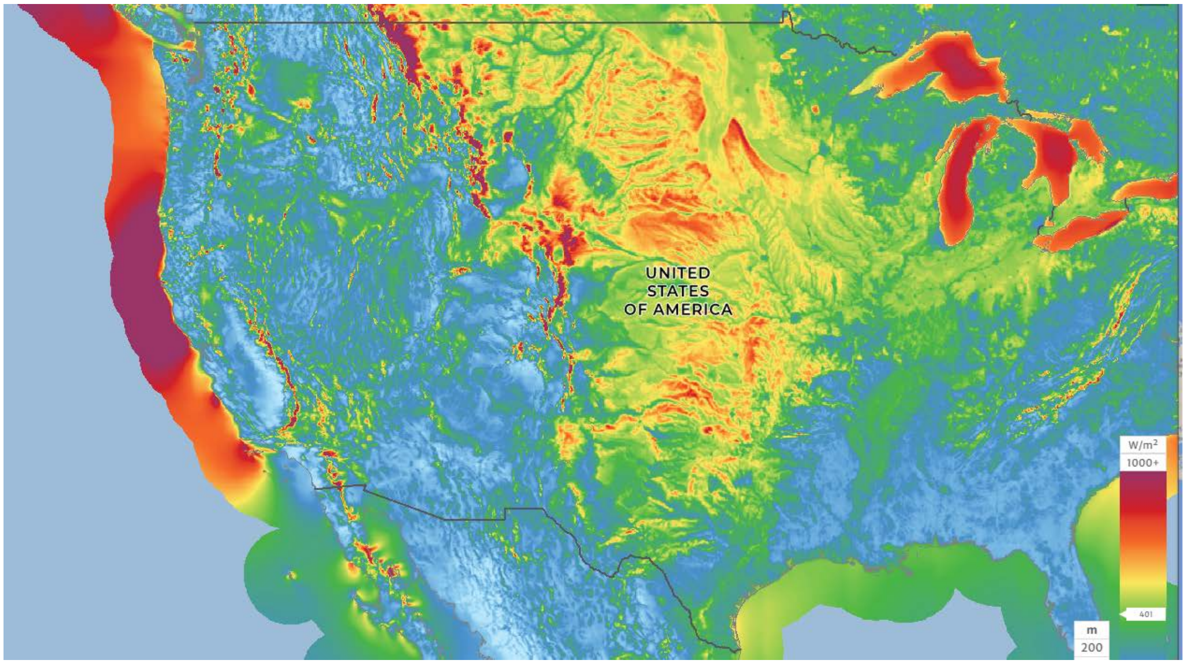

Figure 6: Wind power density in the central wind belt of the United States (from the interactive map at Global Wind Atlas, 2021).

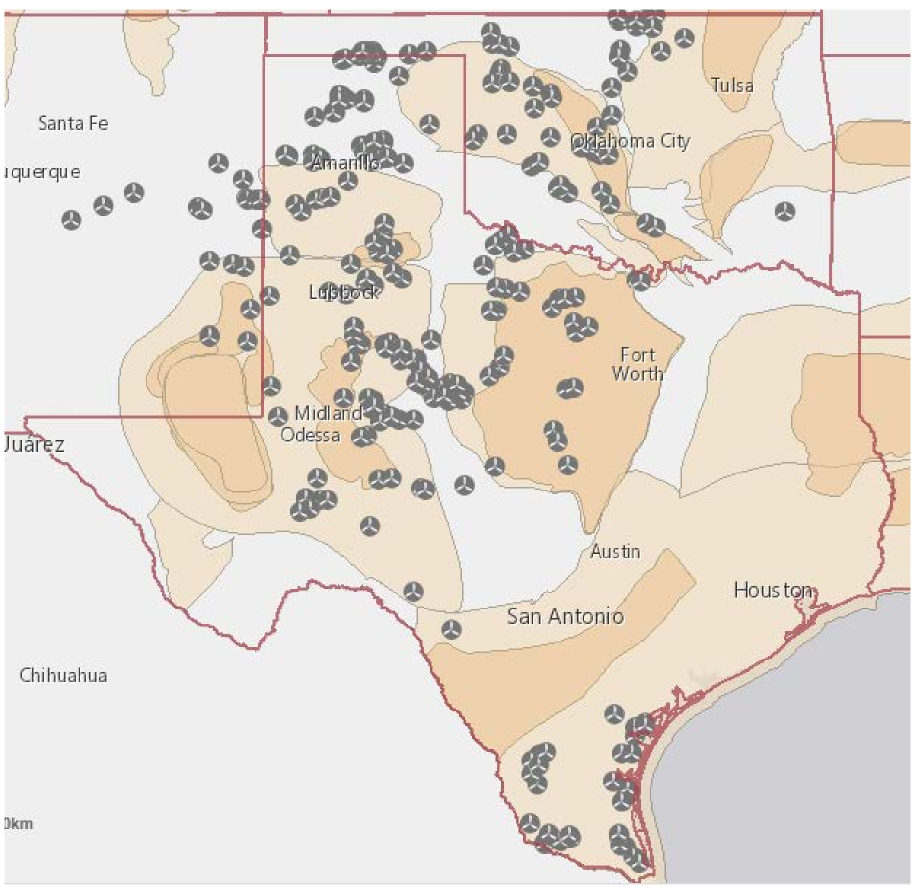

Figure 7: Wind power projects, sedimentary basins (light tan) and tight shale plays (darker tan) in Texas and Oklahoma (from the interactive map at U.S. Energy Information Administration, 2021).

5. Geothermal + Green Hydrogen

Hydrogen – most commonly created through electrolysis of water – is a critical element of the energy transformation underway today. Depending on the source of energy used for electrolysis, the produced hydrogen is classified as gray (produced with fossil fuel), blue (produced with fossil fuel in a process that include carbon capture, utilization and storage) or green (produced using clean power). Most hydrogen produced today is gray hydrogen, although there is a growing demand for blue hydrogen, which – like gray hydrogen – is mainly produced using natural gas. Several major blue hydrogen projects are underway. As one example, oil major BP (2021) announced in March that it is planning a large blue hydrogen facility in the UK that could generate up to 1 GW of blue hydrogen by 2030. Green hydrogen is more costly and will therefore have a slower uptake, but the production of green hydrogen using solar energy is already beginning to gain traction.

Considering the baseload characteristic of geothermal power, geothermal + green hydrogen is an active area of investigation and planning, particularly in traditional geothermal domains. Further, since cost-effective hydrogen is a foundation for most advanced clean fuel processes – and for CO2 conversion – geothermal has the potential to be pivotal in the energy transformation. Below we discuss two options for using geothermal power to produce green hydrogen.

5.1 Excess Geothermal Capacity in Island Arcs

One innovative geothermal + green hydrogen hybrid opportunity exists in volcanic island arcs. In the eastern Caribbean, most countries rely on imported fossil fuels that tend to have high volatility, contributing to very high electricity prices. However, there at least seven islands with geothermal potential. From north to south, these are Saint Kitts and Nevis, Montserrat, Guadeloupe (the only Caribbean island with a geothermal power plant today), Dominica, Saint Lucia, Saint Vincent and the Grenadines, and Grenada. The capacity of these islands is at least 160 MW (Gischler *et al.*, 2016) and potentially as much as 250 MW. Martinique may also have some potential (see Gadalia *et al.*, 2015 and Genter *et al.*, 2002). Geothermal energy provides an opportunity for all of these islands to diversify their energy portfolios and support their commitments to climate change mitigation and adaptation goals. However, the electricity demands of most of these islands is relatively low (the peak demand ranges from a few MW to 10-20 MW in most cases). Because of their size, small geothermal power plants have higher per-MW costs to develop, which is one of the factors that has held back geothermal development compared to traditional alternatives with high CO2 emissions. However, the capacities of some Caribbean geothermal resources significantly exceed the local demand.

This situation provides opportunities to use the excess power in creative ways that promote the energy transformation underway today; for example, excess geothermal power could be exported to nearby islands, or it could be used for electrolysis to create green hydrogen. There is also potential to couple with agricultural waste or available biomass to create renewable natural gas (RNG), a biogas that 1) has been "conditioned" to remove water, CO2, H2S and other trace elements; and 2) is a pipeline-quality gas that is fully interchangeable with conventional natural gas and thus can be used in natural gas vehicles (Alternative Fuels Data Center, 2021).

The Inter-American Development Bank and the Caribbean Development Bank have a common interest in producing green hydrogen and are collaborating on a new initiative to:

- assess the size of the green hydrogen opportunity in the eastern Caribbean;
- evaluate the needed technologies and estimate the costs to develop the green hydrogen supply from treated seawater and electrolysis using geothermal power; and
- develop business models that will enable green hydrogen to be used within in and beyond the Caribbean region:
    1. locally (on the island of production and on neighboring islands);
    2. regionally (to supply green hydrogen for industrial uses in Trinidad and Tobago); and
    3. for export to locations in the Latin America-Caribbean region.

Other island arcs (such as the Aleutian chain in Alaska, South Pacific Islands, the Indonesian archipelago, etc.) may have some or all of the same conditions and aspirations, so the IDB initiative is timely and topical.

5.2 Stranded/Unused Geothermal Capacity

Similar to the situation with excess or unused geothermal capacity in island arcs, there is a significant amount of untapped geothermal resources in remote locations without transmission access to load centers. Chile is a good example of this situation. The Universidad de Chile estimates the potential is 16 MW; a more conservative estimate is between 3-4 GW. The high Andes hosts most of the high-enthalpy geothermal resources in Chile. Nearly all of these geothermal resources are "stranded" by distance to the grid, lack of a local off-taker, the need to compete for uncertain least-cost market pricing, project development costs, environmental/social challenges or a combination of these factors. The opportunity to develop green hydrogen from unused or under-utilized geothermal resources provides an excellent opportunity for new businesses that can take advantage of the baseload characteristic of geothermal power. In such a scheme, it would be possible to use the separated brine from geothermal power plants in the high Andes to provide heating to local towns, replacing other fuels that emit significant CO2 and create air pollution. Thus, the synergistic use of geothermal for green hydrogen, particularly when combined with direct use will enable meaningful reductions in carbon emissions.

6. Conclusions

Geothermal hybrid solutions offer a wide range of benefits and opportunities in a wide range of places, demonstrating the value of geothermal energy within and beyond the traditional geothermal domains, and particularly as an important element of the energy transformation that is currently underway. Pre-existing data from oil & gas wells in deep sedimentary basins can be leveraged to assess the potential for geothermal power, heating or both. Wellbore and numerical modeling can enable oil & gas companies to make informed decisions about investing in re-completion; doing the work "on paper" (through modeling) helps identify which wells would be worth investing in for re-completion and re-purposing as geothermal wells. Geothermal hybrids with solar and wind can maximize the output of clean energy and increase the consistency of power delivery. The production of green hydrogen from geothermal is a natural fit, and one that "doubles down" by creating one clean energy source from another. It is clear that hydrogen will be a game-changer in the future, and there are places around the world where unused geothermal resources with significant capacity for power production could be used today for the production of green hydrogen. We mention two such situations herein: 1) excess capacity on islands, where ships, ferries and cars could run on hydrogen; and 2) good geothermal resources that are remote from load centers and transmission, where green hydrogen produced from geothermal energy can be sent to load centers by pipelines or trucks that run on hydrogen.

The geothermal hybrids mentioned herein are only a few examples of how opportunities and new business models can be developed by combining geothermal with other energy technologies, creating something better - together.

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