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The Future Role of Geothermal Resources in Reducing Greenhouse Gas Emissions in California and Beyond

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ABSTRACT

The State of California has enacted legislation requiring a transition by 2045 to use 100% renewable energy for electrical power generation. California is already the world leader in production of electricity from geothermal resources, with an installed capacity of nearly 3,200 MWe, but in future geothermal energy should play an even greater role. However, the rapid growth of solar and wind electrical generation is making it difficult for geothermal developers to get new power purchase agreements. We suggest that enhancing the contribution of geothermal resources to California's energy mix should be buttressed by its role in reducing greenhouse gas (GHG) emissions. A recent development in Iceland suggests a way to do so. The successful drilling of a 4.5 km deep geothermal well that penetrated supercritical conditions (bottom hole temperature of ~600ºC, fluid pressure ~34 MPa), has opened new possibilities for improving economics of geothermal energy. Because of the higher enthalpy and more favorable flow characteristics of supercritical water, supercritical geothermal wells should produce up to ten times more power than conventional high-temperature geothermal wells. However, producing much higher temperature working fluids creates other possibilities to improve geothermal economics by making downstream processes more efficient, and by using a fully integrated approach. Existing geothermal generation provides baseload electricity, but in California it could become even more valuable by contributing to balancing the grid. This would be done by selling electricity when demand is high, and at times of lower demand using electricity to produce hydrogen by electrolysis of hot water. Electrolysis is more efficient at high temperatures, but electrolytic cells require clean water, so heat exchangers and/or desalination would be necessary. Advanced electrolytic cells can be switched on and off quickly, permitting rapid balancing of the electric grid. Similarly, when the chemistry of geothermal brine is suitable, valuable products such as lithium, manganese and other metals should be extracted from the brines. Development of supercritical and superhot geothermal generation would reduce GHG emissions by (1) replacing the use of the hydrocarbons that would be used to produce that electricity, (2) using electrolysis to produce hydrogen as a transportation fuel or as a form of energy storage, (3) producing methanol, using the geothermal CO_2 and hydrogen, to use as a gasoline additive, (4) producing lithium (reducing the price of batteries needed for pollution free transportation), (5) and extracting other metals like zinc, silver, lead, manganese, etc. (without the GHG produced by transport and smelting of ores). The Salton Sea Geothermal Field, in Southern California, is an ideal site to test this approach, and where we suggest a test facility should be built to develop the necessary technology.

1. INTRODUCTION

This paper discusses the implications for the future development of the geothermal industry by using supercritical or superhot resources for production of hydrogen, methanol, metals, especially lithium, desalinated water, and various direct uses, and the contribution that this would make to reducing emissions of greenhouse gases (GHG). We are using the term "superhot" for fluids that are above supercritical temperature but below supercritical pressure. The critical point for pure water occurs at 374ºC and 22.1 MPa, but it is higher for solutions that contain dissolved salts. For example, the critical point for seawater is 407°C and 29.8 MPa (Bischoff and Rosenbauer, 1988). Not only do such fluids have higher enthalpy than conventional geothermal reservoir fluids, but they also exhibit extremely high rates of mass transport due to the greatly enhanced ratios of buoyancy forces to viscous forces in the supercritical state (Hashida et al., 2001; Fournier, 1999; Friðleifsson, Elders, and Albertsson, 2014). Previous presentations have discussed these concepts and the relevant newer technologies that could be employed applied in their utilization (Elders et al., 2018; Shnell et al., 2018). This paper focuses on the theme of how adopting this approach would also reduce emissions of GHG in California, and elsewhere.

2. RENEWABLE POWER PRODUCTION IN CALIFORNIA

Unlike the intermittent generation from solar and wind power, geothermal generation has the advantage of being a source of baseload power. However, in certain circumstances this is not an advantage. For example, in California, USA, the rapid development of solar power is causing problems in balancing the grid. In the early evening, when the sun goes down, the demand for electricity remains high ("The Duck Curve", see Figure 1). In this environment any large new sources of electrical generation should be flexible with respect to time of day, for example by incorporating battery or pumped storage, or by other means that respond to the daily changes in the ratio of supply to demand.

Recent cost comparisons between various types of renewable power generation indicate that, under the appropriate circumstances and without subsidies for renewable energy, geothermal electric power can be cost competitive. For example, the unsubsidized cost of community PV generation is estimated to be between \$76/MWh and \$150/MWh, while geothermal generation is estimated to cost between \$77/MWh to \$117/MWh (Lazard, 2017). However, development of geothermal resources has the disadvantage of requiring large front-end investments before building a plant for generation of electric power.

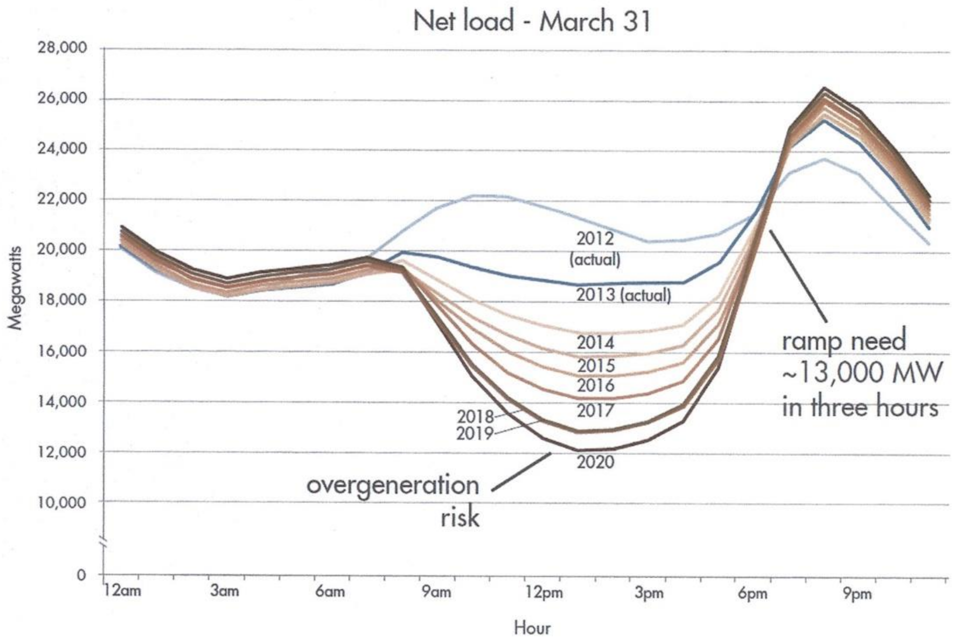

Figure 1: Projected daily electricity demand, minus wind, and solar generation, on a typical spring day in California. There is a risk of overgeneration in the middle of the day and early afternoon, followed by a steep ramp where an additional 13 GWe

Lazard (2017) estimates that the capital cost per installed megawatt for geothermal power lie in the range of $4,000 to $6,000/kWh whereas the capital costs for installing community solar PV are only $1,550/kWh to $3,100/kWh. Furthermore, where land and permitting are available, solar PV can be installed rapidly, whereas a "greenfield" geothermal development involves risks and can take eight to ten years to begin producing revenue. Obviously, reducing costs and improving the reliability of exploration and drilling would directly address this problem. However, an international consortium, the Iceland Deep Drilling Project (IDDP), is taking a different approach, that is to produce supercritical geothermal resources to increase the power output per well. Currently interest in developing supercritical geothermal resources is increasing worldwide (Reinsch et al., 2017).

3. THE ICELAND DEEP DRILLING PROJECT (IDDP)

The IDDP is a long-term project by a consortium of Icelandic energy companies aimed at drilling deep enough to reach the supercritical conditions believed to exist beneath existing high-temperature geothermal fields in Iceland (Friðleifsson and Elders, 2005; Friðleifsson, Elders, and Albertsson, 2014). Modeling indicates that a well penetrating a supercritical geothermal reservoir could produce an order of magnitude more usable energy than that produced by a conventional high-temperature (~300°C) geothermal well 2 to 3 km deep. Thus, fewer wells are needed for a given power output, resulting in both lower costs and a smaller environmental footprint. The first attempt to drill into a supercritical reservoir was made in 2009 in the Krafla caldera, in NE Iceland. However, the well (IDDP-1) did not reach supercritical fluid pressures because drilling had to be suspended when 900°C rhyolite magma flowed into the well at only 2,100 m depth (Elders et al., 2009**).** When the well was tested, it produced superheated steam at 452°C at a flow rate and pressure sufficient to generate about 35 MWe. While flowing, this was the worlds' hottest production well, but after two years of flow testing repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves leading to premature abandonment of the well. The results of the IDDP-1 well were described in 14 papers in a special issue of Geothermics, 2014, volume 49 (http://iddp.is/2014/01/15/geothermics-special-issue-on-iddp-january-2014/).

The second well in the series, IDDP-2, was drilled to a vertical depth of 4.5 km in the Reykjanes high-temperature geothermal field in SW Iceland, on the landward extension of the Mid-Atlantic Ridge (Friðleifsson et al., 2017). This was done by taking over an existing 2.5 km deep well and deepening it directionally towards the main up flow zone of the system. The Reykjanes field is unique among Icelandic geothermal systems in being recharged by seawater. In January 2017, following only six days of heating, a temperature of 426°C at 34.0 MPa pressure was logged, confirming that supercritical conditions exist at depth. Inflection points in the temperature log occurred at ~3,400 m due to cooling at a major loss of circulation zone and at smaller loss zones at ~4,375 m and ~4,500 m. Whatever the fluid composition at 4.5 km depth, it is hard to argue that the measured temperatures and pressures are not supercritical. A long-term program of injecting cold water at 50 l/s was then begun to enhance the permeability of these deeper loss zones. A second series of temperature/pressure logs run from May 23-29, 2017 indicated that the permeability of the deepest loss zone had increased and yielded an estimated bottom hole temperature of 536ºC. Unfortunately, a constriction subsequently developed in the production casing at a depth of ~2400 m that now prevents deployment of logging tools deeper than that depth.

Applying petrological geothermometry to the alteration minerals in these cores indicates that alteration was progressive with depth but occurred under varying conditions (Zierenberg et al. 2017; Friðleifsson, et al., 2017). Samples from the currently producing reservoir (<3,000 m) give temperature estimates that lie on the boiling point to depth curve for seawater, as might be expected. The hydrothermal mineral pairs in the deepest cores indicate that hydrothermal alteration involved seawater-derived fluids at supercritical conditions above 600ºC. In these rocks fluid inclusions are sparse and consist only vapor, or vapor plus daughter crystals. Careful study of these fluid inclusions confirms that alteration near the bottom of the well involved a >600ºC, CO_2 -rich vapor and a concentrated Fe-K chloride brine (Bali, 2018).

The more than year-long experiment of injecting cold water to stimulate the deep permeable zones in the IDDP-2 ended in May 2018, and the well began to heat up, concurrent with design and construction of the surface installations necessary for a long-term flow test, planned to begin in the March-April of 2019. Whatever the outcome of these planned flow tests, it is evident that the IDDP-2 has achieved its primary objectives of demonstrating, for the first time anywhere, that it is possible to drill into supercritical conditions and that permeability exists even approaching the transition from brittle to ductile behavior. It is also evident that, if the flow tests are successful, IDDP-2 should be the world's hottest producing geothermal well.

4. IMPLICATIONS FOR THE GLOBAL ENERGY MARKET

Supercritical conditions are not restricted to Iceland, but should occur deep in any young, volcanic-hosted geothermal system. Recent numerical simulations of magma-heated, saline, hydrothermal systems indicate that phase separation is the first-order control on the dynamics and efficiency of heat and mass transfer near intrusions (Scott et al., 2017). Above deep intrusions emplaced at >4 km depth, where fluid pressure is >30 MPa, phase separation occurs by condensation of hypersaline brine from a saline intermediate-density fluid. The fraction of brine remains small, and advective and vapor-dominated mass and heat fluxes are therefore maximized for exploitation of supercritical geothermal resources.

The potential advantages of the approach of accessing hotter and deeper supercritical and superhot geothermal resources include: (1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this would be offset by much higher power output per well. (2) Improvement in the power output of existing geothermal fields without increasing their environmental footprints. (3) Improvement in the lifetime of existing geothermal fields by increasing the size of the producible resource by extending production downward. (4) Accessing deeper, hotter, environments for fluid injection. (5) Improvement in the economics of geothermal power production. Higher-enthalpy aqueous working fluids in a turbine have a higher heat-to-power efficiency and therefore should potentially yield more favorable economics. Higher temperatures of the working fluid result in higher exergy (availability of maximum electrical power production potential for a given flow rate). (6) Improvement in the downstream uses of hotter geothermal brines.

5. COMBINED USE OF SUPERCRITICAL AND SUPERHOT GEOTHERMAL ENERGY

The marketability of new electrical power generation capacity from more efficient supercritical (or superhot) geothermal resources depends upon both the local geology and the prevailing economics of electricity production and distribution. However, one thing they have in common is that pricing needs to be competitive. The unique feature of geothermal resources compared to other kinds of alternative energy is that geothermal wells produce combinations of heat, water and flashed steam. In this regard, the very high enthalpy of supercritical and superhot systems creates new opportunities to add value by (1) allowing flexibility in sales of electricity depending on time of day, and more importantly (2) adding revenue from downstream use of the hot fluids by, for example, making hydrogen and methanol, extracting dissolved metals and minerals, desalinating water, and finally direct use of the spent fluids. Such plants could sell electricity to the grid when demand is high, and when demand is lower could use all or part of the electricity on site to make storable and salable products.

5.1 Electrolysis and Desalination

At appropriate times of day, all or part of the electricity produced can be used for electrolysis to make hydrogen and oxygen from clean water. Hydrogen is mainly used in industrial chemical and refining processes, in metallurgy, glass production and electronics, but it should have an even greater future as a transportation fuel. Currently, production by electrolysis of water is only a minor source of hydrogen, as the dominant source of commercial hydrogen production uses industrial steam to reform natural gas. The availability of supercritical water would improve the economics of electrolysis relative to using natural gas. This could also be helped by carbon credits as reforming fossil methane releases CO_2, whereas hydrogen fuel from electrolysis using geothermal energy will have a near zero GHG footprint in addition to zero vehicle tailpipe emissions. But the main point is that, at supercritical conditions, electrolysis is much more efficient, and so the electricity needed is much less. Similarly, the use of very high enthalpy geothermal fluids in heat exchangers should make desalination more cost effective. New technical developments in electrolysis and desalination that promise to improve the economics even more have been described by Shnell et al. (2018).

5.2 Renewable Methanol

Another concept included in our comprehensive scheme is the production of renewable methanol. The carbon footprint of generating electricity from geothermal flashed steam is small compared to generation using fossil fuels. For example, geothermal plants produce an amount of CO_2 that is typically less than 30% of that produced by combined cycle gas turbines generating the same amount of electricity. IDDP-2 was drilled in the Reykjanes geothermal field, which currently has an installed capacity of 100 MWe. This plant provides the

CO_2 from its gas extractors to a methanol plant, built and operated by an independent company, Carbon Recycling International, where 5 MWe of power is used to purify the CO_2 and combine it with hydrogen (produced by electrolysis) in a catalytic reaction to make more than 5 million liters of methanol a year. This renewable methanol is sold to be blended with gasoline and used in the production of biodiesel in Iceland and abroad (see: Carbon Cycling International at www.cri.is.-info@cri.is).

5.3 Mineral and Metal Extraction

An additional source of revenue from supercritical and superheated brines would be extraction and refinement of metals and salable minerals from supercritical and superhot geothermal fluids. Many geothermal brines contain high concentrations of such potential products. Unusually high concentrations of metals occur in the brines of the Salton Sea Geothermal Field (SSGF) in southern California, which, among currently producing geothermal systems, has the most concentrated brines (up to 25 weight % TDS - more than eight times the salinity of seawater). The SSGF currently has an installed generating capacity of ~400 MWe, but the latest published estimate of its geothermal reserves to 2 km depth, indicated that it could generate 2,950 MWe for 30 years (Kaspereit et al., 2016). Most of this large geothermal resource is undeveloped, largely because of the difficulties in getting power purchase agreements, due to competition from solar power. The undeveloped northern part of the SSGF is probably the largest known undeveloped resource in the world. The resource estimate by Kaspereit et al. (2016) was based on production from depths of less than 2 km, which is the current industry practice in the USA. Following the example of the Iceland Deep Drilling Project (IDDP), this estimate for the SSGF is much too conservative if production from depths of 4 to 5 km were considered.

Although the SSGF brines contain unusually high concentrations of metals (Table 1), previous attempts by the principal operator of the SSGF (Berkshire Hathaway Renewables), using solid-liquid ion exchange to extract zinc proved to be uneconomic at that time.

Table 1. Some metal concentrations (mg/kg) in the brine of well State 2-14, in the SSGF, calculated to reservoir conditions at >300ºC (data from the Salton Sea Scientific Drilling Project, Elders and Sass, 1988)

Li	Rb	Cs	Mn	Fe	Zn	Cu	Pb	Cd	As
209	132	142	1500	1710	507	6.8	102	2.3	5

As battery grade lithium carbonate is currently selling at about 12,000 USD/tonne, the concentration of lithium in the SSGF, ranging up to 250 mg/kg, is of particular interest. The value of lithium reserves in solution at drillable depths in the SSGF exceeds tens of billions USD. The geothermal plants *currently* operating at the SSGF have the potential to extract an impressive 2.5 billion USD/year of lithium. If the entire known Salton Sea geothermal resource area were to come into production, these quantities scale to over 14 billion USD/year.

5.4 Integration and Synergism

There are hundreds of geothermal plants around the world that in total currently generate a total of 30 times as much power as the SSGF, suggesting an enormous potential impact if combined hydrogen production and metal extraction were developed globally. The overarching principle of developing such a comprehensive scheme is the synergism of integrating different technologies that use supercritical, or superhot, fluids to improve the economics of geothermal resources. Figure 2 presents one configuration of how this integration could occur for a scenario where the supercritical or superhot geothermal fluid is not suitable for direct introduction in a turbine and so heat exchangers are used to heat a clean water as the working fluid. Many other combinations would be possible, depending on the specific local conditions.

6. THE POTENTIAL FOR GEOTHERMAL RESOURCES TO REDUCE GHG EMISSIONS IN CALIFORNIA

Reducing GHG emissions produced by electricity generation is clearly desirable, as is making hydrogen by electrolysis. However, as Figure 3 shows, electricity generation, both generated in state and imported, contributes only 16 % of the GHG emissions in California. By far the largest source of emissions is transportation, which contributed 41% of the GHG emissions in the state in 2016, therefore, the biggest potential for reducing GHG emissions would come from using hydrogen as a transportation fuel. Increased use of electric vehicles will play an important role in reducing GHG emissions, particularly in urban environments in California. However, hydrogen powered vehicles have a greater range and flexibility, particularly for ships, trains, and medium and heavy-duty transportation, including trucks and buses.

Schemes like those illustrated in Figure 2 have the potential to reduce GHG emissions from all the sources shown in Figure 3, for example, in industries could use geothermal sources for process heat and use electrolytic hydrogen instead of producing it from natural gas. In Iceland, 97% of buildings use geothermal hot water for space heating. In California, while there is a lesser need for space heating, air conditioning is a large energy consumer. The Imperial Valley of Southern California has a climate with more than 100 days in the year when the temperature exceeds 100ºF (38ºC).

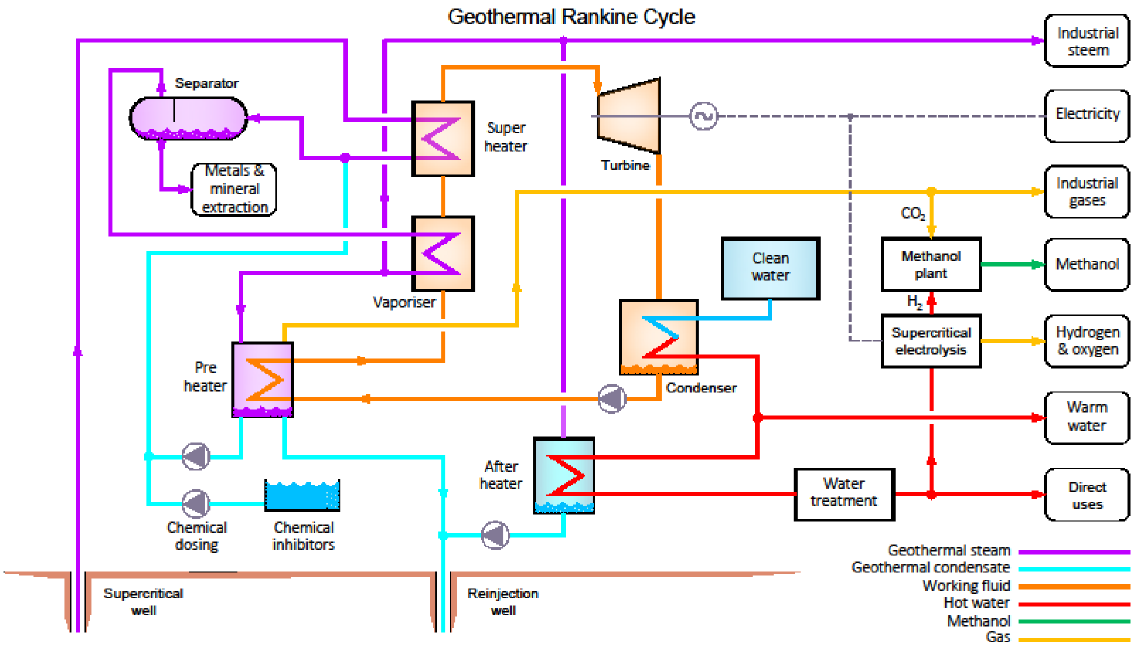

Figure 2. A possible comprehensive scheme for using supercritical or superheated fluids with integrated and flexible production of industrial steam, electricity, industrial gases, methanol, hydrogen, hot water and desalinated water for direct uses. This configuration uses clean water, heated by supercritical or superhot fluids, as the working fluid in a turbine.

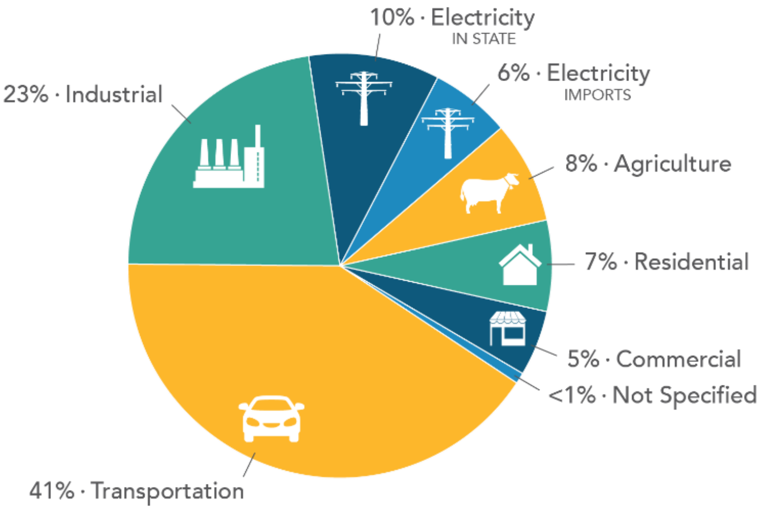

Figure 3. The relative contributions to California's 429.4 million metric tons of GHG emissions in 2016 according to the data of the California Energy Commission (CEC Annual report, 2017).

This area currently has installed ~900 MWe of geothermal electric power at power plants at SSGF, Heber, East Mesa, and Brawley. Downstream of these plants the hot water from both flashed steam and binary plants is injected for disposal, without using any of the heat remaining after electrical power generation. This wasted energy might be applied for district heating and cooling for domestic and industrial users, and by agricultural users such as refrigeration of farm products, sugar refining, and meat packing plants, that currently rely on natural gas. This would reduce GHG emissions from both domestic and agricultural emitters.

As in Iceland, geothermal district heating schemes are common in colder climates but operating “district cooling” schemes are virtually unknown, although there are some individual buildings that use geothermal water for cooling. More than 20 years ago studies were carried out that examined the feasibility, design, and economics of geothermal heating/cooling in the Mexicali Valley in Baja California, immediately south of the Imperial valley (Campbell-Ramirez et al, 1993; Elders et al., 1996). They showed that by using geothermal hot water the capital cost of three 310-ton absorption units, with production, distribution, and transmission systems, enough to service Mexicali Airport, would be 1.8 million USD with an annual O&M cost of 35,000 USD (in 1996 US dollars). This scheme was never implemented, as the geothermal division of the Federal Electricity Commission of Mexico was focused only on generating electricity. We suggest that similar investigations of geothermal direct-use for heating and cooling in the Imperial Valley could help meet the energy needs of the agricultural processing industry.

The actual size of the reduction in GHG emissions in California by using schemes like those illustrated in Figures 2 is hard to quantify as it depends on the degree of adoption by the geothermal industry, but it would be large and furthermore replicable at geothermal plants worldwide. We envision that ultimately, depending on local conditions, fully integrated geothermal plants will become factories producing hydrogen, metals, and water for heating and cooling, while producing electricity, with much of it consumed internally. The reductions in GHG emissions will come from keeping CO_2 out of the atmosphere by: 1) displacing hydrocarbon fuels used for the electricity generated, 2) making hydrogen for energy storage, 3) making hydrogen for transportation and for syngas, 4) creating a domestic supply of lithium for batteries used in Zero Emission Vehicles, 5) producing metals such as lithium, manganese and zinc without transporting or smelting ores, and 6) replacing electricity and natural gas used for air-conditioning and space heating.

7. DISCUSSION

7.1 Suitable Geothermal Fields Elsewhere

Superhot fluids at less that supercritical pressures have been encountered in wells in numerous volcanic geothermal fields, including the SSGF (Kaspereit et al., 2016) and elsewhere in California at The Geysers (Lutz et al., 2012). Deep wells drilled in Kakkonda in NE Japan (Muraoka et al., 1998), Laderello in Italy (Bertini et al., 1980), Los Humeros in Mexico (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010), Menengai in Kenya (Mbai et al., 2015), and Puna, Hawaii, USA (Teplow et al., 2009) have all encountered temperatures above 374°C. By drilling deeper to reach higher pressures, development of supercritical geothermal resources could be possible at these locations and in many other volcanic areas worldwide. For example, in Japan the Japanese Beyond Brittle Project (JBBP) is an ambitious EGS project to extract geothermal energy from >500°C neogranites (Muraoka et al., 2014). Another future possibility, when the technology and economics permit, is to produce useful energy directly from the worldwide submarine mid-ocean ridge systems (Elders, 2015). Vents discharging supercritical water on the sea floor have been directly observed at 5ºS on the Mid-Atlantic Ridge (Koshchinsky et al., 2010). Similarly, if the technology can be developed, very high temperature energy could be extracted directly from magmas (Eichelberger et al., 2018).

7.2 Economic Implications

The economics of utilizing such supercritical and superhot geothermal fluids could be greatly enhanced by using a flexible and integrated approach. Using superhot water and electricity on site to make hydrogen fuel obviates the need to use electricity storage such as batteries or pumped storage at times when electricity demand is low, while keeping flow rates from the wells constant. Similarly, the higher enthalpy should improve the economics of extracting metals and minerals from the brines and making renewable methanol and desalinated water. Of course, not all these techniques will be applicable in any given case and a great deal of technological development will be necessary. This integrated approach will likely evolve in a step-wise fashion at different sites and we suggest that the Salton Sea Geothermal Field is the ideal site in the USA to begin.

7.3. A Plan to Begin Implementation

As a first step we suggest construction and operation of a testbed, a Geothermal Demonstration Facility (GDF), at the SSGF. The GDF would bring together several innovative and synergistic systems, including state of the art electrolysis to produce hydrogen, forward or reverse osmosis to produce deionized water for electrolysis, extraction of lithium and other metals, and cascading the thermal effluent to produce hot and chilled water appropriate for district heating or cooling. This demonstration would use a doublet of an existing production well and an injection well that delivers fluids to the testbed at temperatures >250°C. The two-phase (brine and steam) produced from the well would be separated in a double-flash cycle, producing hot water and steam at two distinct temperatures. The two brine streams, at temperatures of 250°C and 100°C, would be delivered continuously to the GDF (Figure 4) and the residual brine would be re-injected into the geothermal reservoir.

The GDF would use shallow brackish groundwater or local irrigation water for process water in the field tests to make deionized water necessary for electrolysis. Heat exchangers would transfer heat from geothermal fluids to the deionized water. This hot, deionized water would be used in the best available commercial electrolytic equipment to produce hydrogen that would be stored on site and could be used in a demonstration of a hydrogen-fueled vehicle at the site. The aggressive chemistry of the geothermal brine will require design and fabrication of a high alloy heat exchangers and related piping, valves, and instrumentation. While current lithium extraction techniques are carried out at 100°C (atmospheric flash temperature), the heat exchanger would provide the opportunity to use brine at temperatures intermediate between 250°C and 100°C, potentially eliminating some of the chemical supersaturation challenges, especially with silica, that occur at lower temperatures.

The intent would be to operate the GDF as an open testbed made available for approved "Best Available Technology" offered by public and private developers of relevant technologies. Each technology provider would be expected to design, construct, and operate any additional specific components necessary for a short-term demonstration of the efficacy of their specific system. The test data produced would be released to the public domain, while respecting rights of the technological developer to their proprietary intellectual property.

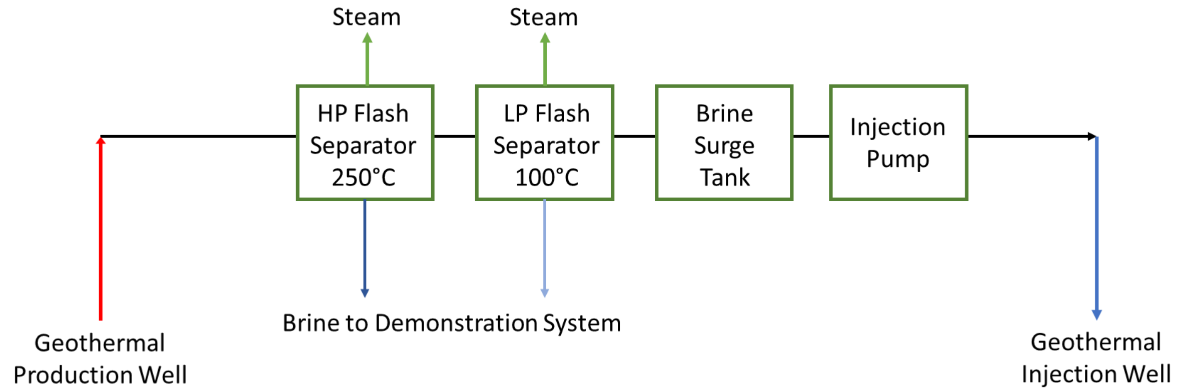

Figure 4A. Conceptual design of geothermal fluid production supplied to the GDF.

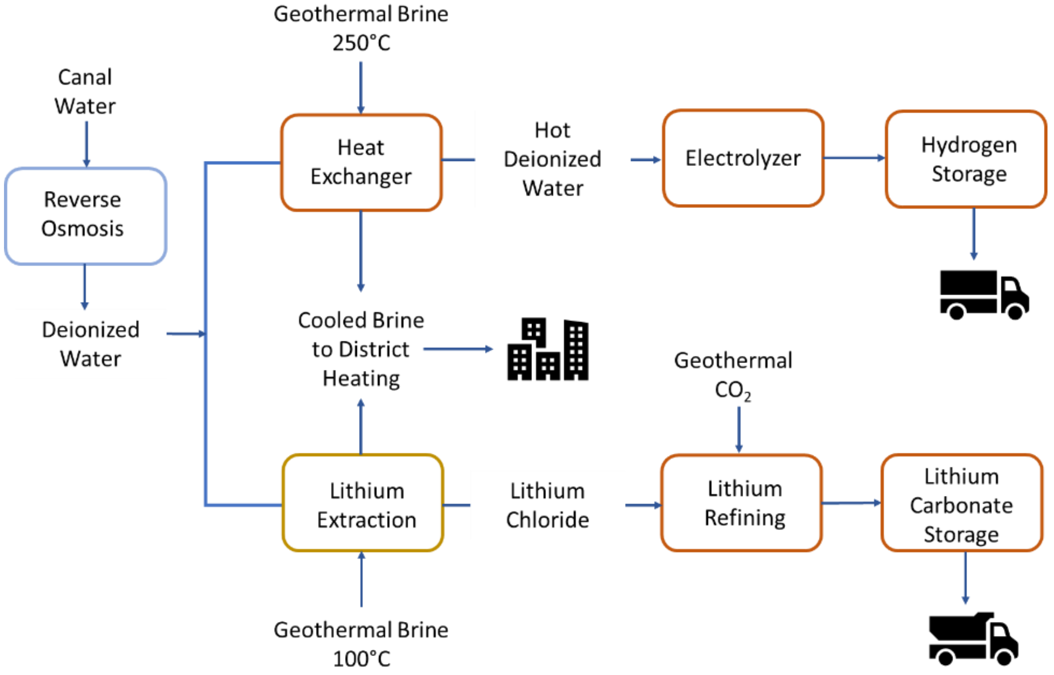

Figure 4B. Conceptual design of the GDF using geothermal brine at temperatures of 250° and 100°C.

Our preliminary estimates for design, construction, and operation of this testbed, with continuous supervision and monitoring by a small operations and maintenance team for a period of two months, would cost less than 2 million USD (not including drilling and completing the necessary wells). If successful, this pilot system could easily be replicated and scaled up to an industrial size wherever the economics are justified. Similarly, when deeper, superhot, or supercritical wells become available it could be redesigned to handle those conditions. This would be a first step towards our ultimate aim of developing systems like that shown schematically in Figure 2.

8. CONCLUSIONS

We believe that the next big steps forward for the worldwide geothermal industry should be (1) development of supercritical and superhot systems, (2) development of advanced systems for electrolysis, and mineral extraction, etc., and (3) building and operating fully integrated power plants with hydrogen and metal production incorporated at the beginning rather than being "add-ons". Implementation of this plan will require cooperation of the geothermal industry, electrical utilities, and consumers, with participation at the outset by international, federal, state, and regulatory agencies, and with appropriate community involvement.

A major incentive for such cooperation, especially in California, is the goal of reducing GHG emissions. The reduction in GHG will come from keeping CO_2 out of the atmosphere by: 1) displacing hydrocarbon fuels used for the electricity generated, 2) making hydrogen for energy storage, 3) making hydrogen for transportation and for syngas, 4) creating a domestic supply of lithium for batteries used in Zero Emission Vehicles, 5) producing metals such as lithium, manganese and zinc without transporting or smelting ores, and 6) replacing electricity and natural gas used for air-conditioning and space heating.

Our ambitious long-term goal is to have USA's geothermal industry recognize and adopt the concept that reducing GHG emissions is not only necessary in view of climate change, but should also be profitable. The transition will be difficult, but we must begin. Our proposal for a Geothermal Demonstration Facility at the Salton Sea Geothermal Field is a first step.

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REFERENCES

Albertsson, A., J.Ó. Bjarnason, T. Gunnarsson, C. Ballzus and K. Ingason. In: "Iceland Deep Drilling Project, Feasibility Report", (Ed.) G.Ó. Friðleifsson. "Part III: Fluid Handling and Evaluation", Orkustofnun Report OS-2003-007 (2003), 1-33.

Albertsson, A. and Jonsson, J. "The Svartsengi Resource Park". Proceedings if the World Geothermal Congress. (2010) Bali, April (2010)

Bali, E. "Fluid inclusion study from the IDDP/2/DEEPEGS borehole". Proceedings of the GEORG Geothermal Workshop, Reykjavik, November 14-15th 2018 (2018).

Bertini, G., Giovannoni, A., Stefani, G.C., Gianelli, G., Puxeddu, M., and Squarci, P. "Deep Exploration in Larderello Field: Sasso 22 Drilling Venture Advances in European Geothermal Research". (Strub, A.S. and Ungemach, P., Eds.): Proceedings of the Second International Seminar on the Results of EC Geothermal Energy Research, Springer Netherlands, (1980) 303-311.

Bischoff J.L. and R.J. Rosenbauer, "Liquid-vapor relations in the critical region of the system $NaCl-H_2O$ from 380°C to 414°C: A refined determination of the critical point of seawater". Geochimica et Cosmochimica Acta, 52, (1988) 2121-2126.

California Energy Commission, "2017 Integrated Energy Policy Report", CEC-100-2017-0010-CMF, 592 pages (2017).

Campbell-Ramirez, H., Elders, W.A., Reyes-Lopez, J. A., Ramirez-Hernandez, J., Vega-Aquilar, M., and Carreon-Diazconti. "Potential for Direct-Use of Geothermal Energy for the Mexicali Valley, Baja California, Mexico". *Geothermal Resources Council Transactions,* 17 (1993) 3-9.

Eichelberger J. Ingolfsson, H.P., Carrigan, C., Lavallee,Y., J. W., Marksson, S. H.. "Krafla Magma Testbed (KMT): Understanding and Using the Magma-Hydrothermal Connection." Transactions, Geothermal Resources Council 42 (2018) 2596-2406.

Elders, W. A. and Sass, J. H., "The Salton Sea Scientific Drilling Project". Journal of Geophysical Research, 93, (1988) 12953-12968.

Elders, W.A., Campbell-Ramirez, H., and Carreon-Diazconti, C. "Direct-use potential of the Tulechek geothermal area, B.C., Mexico." Geothermal Resources Council Transactions, 20 (1996), 73-80.Elders, W.A., G.Ó. Friðleifsson, G.Ó., and Saito, S. "The Iceland Deep Drilling Project: A search for supercritical fluids". Transactions Geothermal Resources. Council, 21, (2001) 297-300.

Elders, W.A. "The potential for on-shore and off-shore high-enthalpy geothermal systems in the USA". Proceedings of the Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, January 26-28, (2015), Paper SGP-TR-204, 1-6.

Elders, W.A., Friðleifsson, G.Ó., Zierenberg, R. A., Pope, E. C., Mortensen, A. K., Guðmundsson, Á., Lowenstern, J. B., Marks, N. E., Owens, L., Bird, D. K., Reed, M., Olsen, N. J. and Schiffman, P. "Origin of a rhyolite that intruded a geothermal well while drilling in a basaltic volcano, at Krafla, Iceland". Geology, 39, No. 3, (2011) 231-234

Elders, W.A., Friðleifsson, G.Ó. and Albertsson. A., "Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide". Geothermics, 49 (2014) 111-118.

Elders, W.A., Shnell, J., Friðleifsson, G.Ó., Albertsson, A. and Zierenberg, R.A. "Improving Economics by utilizing supercritical and superhot systems to produce flexible and integrated combinations of electricity, hydrogen, and minerals." Transactions Geothermal Resources. Council, 42, (2018) 1914-1927.

Fournier, R.O., “Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment.” Economic Geology 94 (8), (1999)1193–1211.

Fournier, R.O., “Hydrothermal systems and volcano geochemistry”. In Durzin, D. (Ed.), “Volcano Deformation: Geodetic Monitoring Techniques”. Springer-Praxis, Berlin, New York, Chichester, UK, Chapter 10 (2007) 323–341.

Friðleifsson, G.Ó. and Elders, W.A., "The Iceland Deep Drilling Project: A Search for Deep Unconventional Geothermal Resources”. Geothermics, 34, (2005) 269-285.

Friðleifsson, G.Ó., Elders,W.A., and_Albertsson, A., “The concept of the Iceland Deep Drilling Project”. *Geothermics*, 49 (2014) 2-8.

Friðleifsson, G.Ó., Elders, W.A., and Albertsson, A., “The concept of the Iceland Deep Drilling Project”. *Geothermics*, 49 (2014) 2-8.

Friðleifsson, G.Ó., Elders, W.A., Zierenberg, R.A., Stefánsson, A., Fowler, A.P.G., Weisenberger, T.B., Harðarson,. B.S., Mesfin, K.G. “The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the sea-water recharged Reykjanes geothermal field in SW Iceland has successful reached its supercritical target”. Scientific Drilling, No. 23, (2017) 1-12.

Friðleifsson, G.Ó., Elders, W.A., Zierenberg, R.A., Fowler, A.P.G., Weisenberger, T.B., Mesfin, K.G., Sigurðsson Ó , Níelsson, S., Einarsson G., Óskarsson, F., Guðnason, E. A., Tulinius, H., Hokstad, K., Benoit, G., Frank Nono, F., Loggia, D., Parat, F., Cichy, S. B., Escobedo, D., Mainprice, D., “The Iceland Deep Drilling Project at Reykjanes: Drilling into the Root Zone of a Black Smoker Analog.” Journal of Volcanology and Geothermal Research. Article VOLGEO_6435 (2018) 60 MS pages.

Gutiérrez-Negrín, L.C.A., Izquierdo-Montalvo, G., 2010. “Review and update of the main features of the Los Humeros geothermal field, Mexico”. *Proceedings World Geothermal.Congress, Bali Indonesia* 25-29 April (2010), 1-5.

Hashida, T., Bignall, G., Tsuchiya, N., Takahashi, T., Tanifuji, K., “Fracture Generation and water rock interaction processes in supercritical deep seated geothermal reservoirs”. *Transactions Geothermal Resources Council* 25, (2001) 225–229.

Kaspereit D., Mann, M., Sanyal, S., Rickard, B., Osborn, W.L., and Hulen J. 2016. “Updated Conceptual Model and Reserve Estimate for the Salton Sea Geothermal Field, Imperial Valley, California”. *Transactions Geothermal Resources Council* 40, (2016) 11.

Koshchinsky, A., Garbe-Schonberg, D., Sander, S., Schmidt, K., Gennerich, H.-H., Strauss,H., . “Hydrothermal venting at pressure-temperature conditions above the critical point of seawater, 5oS on the Mid-Atlantic Ridge". *Geology* 30 (8), (2008) 615-618.

Lazard, “Lazard’s Levelized Cost of Energy Analysis - Version 11.0”. (2017). See: https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf.

Lutz, S.J., Walters, M., Moore, J.N. and Pistone, S. “New insights into the high-temperature reservoir, north-western Geysers**.”** *Transactions Geothermal Resources Council* **36**, (20**12**) **907-16.**

Mbia, P.K., Mortensen, A.K., Oskarsson, N., Hardarson, B.S., Sub-surface geology, petrology, and hydrothermal alteration, of the Menengai Geothermal Field, Kenya: Case study of Wells MW-02, MW-04, MW-06, and MW-07, Proceedings of World Geothermal Congress 2015, 20p., Melbourne, (2015).

Muraoka, H., Asanuma, H., Tsuchiya, N., Ito, T., and the participants of the ICDP/JBBP Workshop: “The Japan Beyond-Brittle Project”. *Scientific Drilling*, 17, (2014) 51-59.

Muraoka, H., Uchida, T., Sasada, M., Yasukawa, K., Miyazaki, S.I., Doi, N., Saito, S., Sato, K., and Tanaka, S. “Deep geothermal resources survey program: Igneous, metamorphic and hydrothermal processes in a well encountering 500^{o}C at 3729 m depth, Kakkonda, Japan”. *Geothermics*, 27, (1998) 507-534.

Reinsch, R., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., and Sanjuan, B., “Utilizing Supercritical Geothermal Systems: A Review of Past Ventures and Ongoing Research Activities.” *Geothermal Energy*, 5, (2017).

REN21. “Renewables 2018 Global Status Report.” Renewable Energy Policy Network for the 21st Century, gsr@ren21.net.

Shnell, J., Newman, J.S., Raju, A., Nichols, K., Elders, W.A., Osborn W.L., and Hiriart,, G. “Combining High-Enthalpy Geothermal Generation and Hydrogen Production by Electrolysis Could Both Balance the Transmission Grid and Produce Non-Polluting Fuel for Transportation,” *Proceedings, 41st Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California (2016).

Shnell, J., Elders, W.A., Kostecki, R., Nichols, K., Osborn, W.L., Tucker, M.C., Urban, J.J. and Wachsman, E. D. “Supercritical Geothermal Cogeneration: Combining Leading-Edge, Highly-Efficient Energy and Materials Technologies in a Load-Following Renewable Power Generation Facility.” *Transactions, Geothermal Resources Council* 42 (2018) 2043-2054.

Scott, S., Driesner, T. and Weis, P. 2017. “Boiling and condensation of saline geothermal fluids above magmatic intrusions”, Geophysics Research Letters, 44, (2017) 1696-1705.

Teplow, W., Marsh, B., Hulen, J., Spielman, P., Kaleikini, M., Fitch, D., Rickard, W., “Dacite melt at the Geothermal Venture Wellfield, Big Island of Hawaii”, *Transactions Geothermal Resources Council,* 33, (2009) 989-1005.

Zierenberg, R.A., Fowler, A.P.G., Friðleifsson, G.Ó., Elders, W.A. and Weisenberger, T.B., “Preliminary Description of Rocks and Alteration in IDDP-2 Drill Core Samples Recovered from the Reykjanes Geothermal System, Iceland”. *Transactions Geothermal Resources Council*, 41, (2017) 1599-1615.