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Improving Geothermal Economics by Utilizing Supercritical and Superhot Systems to Produce Flexible and Integrated Combinations of Electricity, Hydrogen, and Minerals

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ABSTRACT

In 2017, a 4.5 km-deep well in SW Iceland reached supercritical conditions with a bottom hole temperature probably >600°C) and a pressure of 35MPa. This paper discusses the potential significance of this achievement. Supercritical wells could produce up to ten times more power than normal high-temperature geothermal wells. Although the cost of drilling supercritical wells is greater than the cost of drilling conventional wells, this should be offset by the much higher power output per well, yielding more favorable economics. Producing higher temperature working fluids creates other possibilities to improve economics by making downstream processes more efficient. To improve earnings, the geothermal industry could improve returns on investments by taking a fully integrated and flexible approach that uses the electricity generated to extract value from supercritical and superhot fluids (i.e., above supercritical temperatures but at pressures below supercritical). Where the conditions permit, this can be done by selling electricity when demand is high, and at times of lower demand using electricity to produce hydrogen as a fuel by electrolysis of hot or supercritical water. Electrolysis is more efficient at high temperatures, but electrolytic cells require clean water, so heat exchangers and/or desalination would be necessary. Similarly, when the chemistry of geothermal brine is suitable, salable products such as lithium, base metals and other mineral products could be extracted from the brines. Shnell et al. (2018) discuss new technological approaches to these processes in an accompanying paper. The future of utilizing supercritical and superhot geothermal systems lies in CUSGER (Combined Use of Supercritical Geothermal Energy Resources), the name suggested for flexible integration of the production of electric power, hydrogen, minerals,

renewable methanol, and desalinated water. A new chapter in the development of alternative energy could be about to begin.

1. Introduction

Compared to the phenomenally fast growth of electricity generation by carbon-free sources such as solar and wind, the worldwide rate of growth of installed geothermal generating capacity is very modest. According to a recent global status report on electric power generation, renewable power generation reached 70% of the net additions to installed capacity in 2017 (Ren21, 2018). An estimated 0.7 GW of new geothermal power came online in 2017, bringing the global total to an estimated 12.8 GW. However, this represents only ~1% the worldwide renewable power capacity (excluding hydro) of 1,081 GW, whereas solar PV capacity was 402 GW or 37% of this renewable power capacity. 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 such an environment it is clearly desirable that 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 other means of flexibility that respond to the daily changes in the ratio of supply to demand.

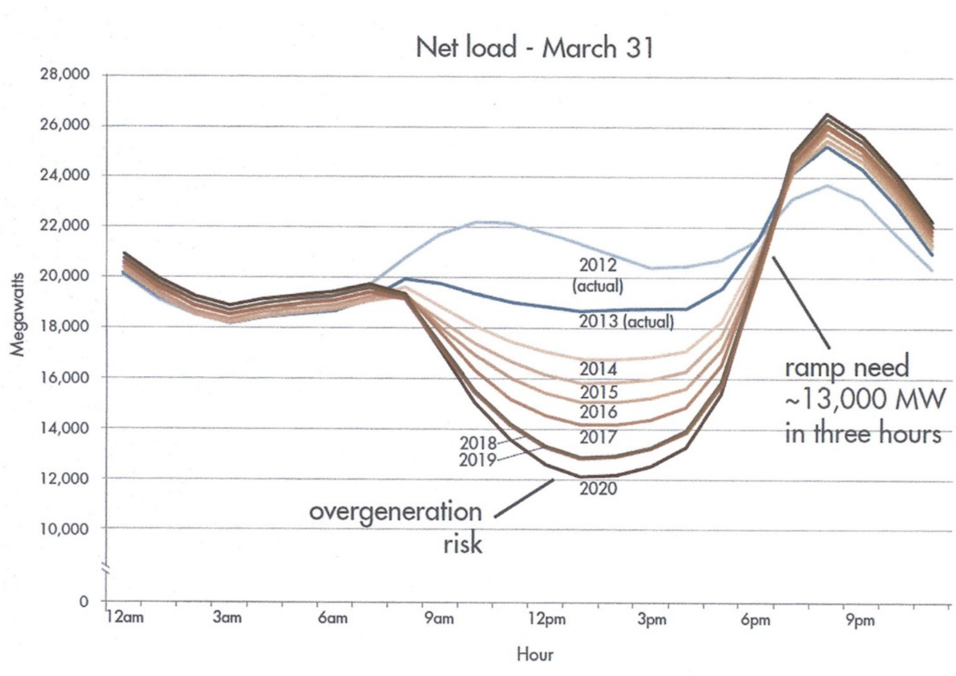

Figure 1: Projected daily electricity demand, minus wind, and solar generation, on a typical spring day in California. There is a risk of overgeneration in the middle of the day and early afternoon, followed by a steep ramp where an additional 13 GWe is needed (Source: California Energy Commission, Annual Report 2017, Figure ES-4).

Recent cost comparisons between various types of renewable power generation indicate that, even without subsidies for renewable energy, in the appropriate circumstances 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, including surveys to select drilling sites, drilling exploration wells, and if the exploration phase is successful, drilling production and injection wells, before building a plant for generation of electric power. 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 can take eight to ten years to produce revenue. Obviously, reducing costs and improving the reliability of exploration and drilling would directly address this problem. However, with the Iceland Deep Drilling Project (IDDP), an international consortium is taking a different approach, that is to produce supercritical geothermal resources that should greatly increase the power output per well. Currently interest in developing supercritical geothermal resources is increasing worldwide (Reinsch et al., 2017).

This paper discusses the implications of the IDDP for the future development of the geothermal industry and the potential it creates for enhancing revenues by downstream use of supercritical or superhot resources for production of hydrogen, methanol, metals and minerals, desalinated water, and various direct uses. We are using the term “superhot” for fluids that are above supercritical temperature but below supercritical pressure. An accompanying paper submitted to this meeting discusses promising newer technologies that could be applied to these downstream processes (Shnell et al., 2018).

2. Supercritical Geothermal Resources

The main motivation of the IDDP is to investigate the power potential and economics of the temperature-pressure regime of supercritical geothermal fluids (Elders et al., 2001). The critical point for pure water occurs at 374°C and 22.1 MPa, but it is higher for solutions that contain dissolved salts (Figure 2). 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 (Fournier, 1999; Fournier, 2007; Hashida et al., 2001; Friðleifsson, Elders, and Albertsson, 2014).

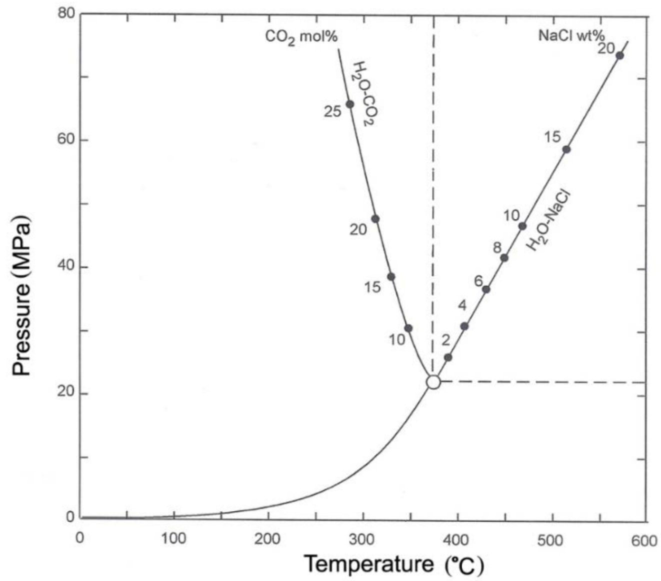

Figure 2. The boiling point curve and critical point curves for water. The critical point for pure water is indicated by the open circle at 374°C and 22.1 MPa. As shown by the relevant critical point curves for H_2O-NaCl and H_2O-CO_2, dissolved salt increases the temperature and pressure of the critical point whereas dissolved gas reduces the temperature and elevates the pressure of the critical point (Hashida et al., 2001).

3. The Iceland Deep Drilling Project (IDDP)

The IDDP is a long-term project by a consortium of Icelandic energy companies aimed at greatly increasing the production of usable geothermal energy by 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. The fewer wells needed for a given power output result in a smaller environmental footprint. When the IDDP consortium was formed in 2003, three geothermal fields in Iceland were chosen as suitable to search for supercritical resources, Krafla in the northeast of Iceland, and Hellisheidi and Reykjanes in the southwest. The first attempt to drill into a supercritical reservoir was made in 2009 in the Krafla caldera, but the well (IDDP-1) did not reach supercritical fluid pressures because drilling had to be suspended at a shallow depth (Elders et al., 2009). This was because 900°C rhyolite magma flowed into the well at only 2,100 m depth. However, the IDDP-1 well was completed with a liner set above the rhyolite intrusion. 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. This caused collapse of the well casing and premature abandonment of the well. The IDDP-1 well is 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/).

IDDP-2, the second well in the series, 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 and directionally drilling 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 4,560 m measured 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 several months-long 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 536^{o}C, which is consistent with other estimated formation temperatures based on extrapolation of a joint geophysical inversion of earlier wireline logs obtained at shallower depths (Hokstad and Täniavsuu-Milkeviciene, 2017). Unfortunately, a constriction subsequently developed in the production casing at a depth of ~2400 m that at present is preventing deployment of logging tools deeper.

Additional information on the downhole conditions of the IDDP-2 comes from the drill cores obtained. These sampled a series of dolerites (diabases) with chilled margins that are interpreted to come from a sheeted dike complex (Zierenberg et al., 2017; Friðleifsson et al., 2017). Alteration mineral assemblages indicate a complex history of response to dike emplacement and variable hydrothermal conditions. The shallowest IDDP-2 rocks are extensively altered to greenschist facies mineral assemblages that include epidote, actinolite, plagioclase, quartz, and chlorite. Deeper than 3,825 m, igneous clinopyroxene is pervasively altered to hornblende, and amphibolite facies mineralogy prevails that includes, in addition to hornblende, calcic plagioclase, hydrothermal olivine, orthopyroxene, clinopyroxene and biotite. Such assemblages require a minimum of 400°C to form. Unfortunately, fluid inclusions are sparse in the amphibolite facies rocks and difficult to work with as they consist of only vapor, or vapor plus daughter crystals. Study of these inclusions is still under way, and the results will be published elsewhere. Despite the extensive hydrothermal alteration, primary igneous textures are usually quite well preserved. As these dolerites lack microscopic porosity, the textures and minerals observed are consistent with alteration by high-temperature, very low viscosity, supercritical fluids (Zierenberg et al., 2017).

Another study of these cores to estimate downhole temperatures is also underway that when concluded will also be published elsewhere (R. A. Zierenberg and P. Shiffman, personal communication, April 2018). It applies petrological geothermometry to the alteration by measuring the partitioning of specific elements between pairs of minerals that appear to have equilibrated together under hydrothermal conditions. The mineral pairs being analyzed are hydrothermal clinopyroxene-orthopyroxene, the Fe-Ti oxides magnetite and ilmenite, and the feldspars plagioclase and orthoclase (Davidson and Lindsey, 1989; Ghiorso and Evans, 2008; Putirka, 2008). Titanium contents of biotite and quartz provide an additional constraint on these temperatures. Samples from the currently producing reservoir (<3,000 m) have 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 occurred over a range extending from ~1,000^{o}C down to 600^{o}C. The minerals are recording hydrothermal alteration by seawater-derived fluids at supercritical conditions above 600^{o}C. However, the actual present-day temperatures deep in the IDDP-2 still require to be determined by direct measurements.

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. In the summer of 2018 the plan is to attempt to insert a 4-inch drill pipe past the constriction to allow deployment of a downhole fluid sampler at the bottom of the well, concurrent with design and construction of the surface installations necessary for a long-term flow test, planned to begin in the first quarter 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 Energy Market in Iceland and Beyond

If the flow tests planned for the IDDP-2 live up to expectations and lead to development of supercritical resources in the principal geothermal fields in Iceland, how would this new electricity be used in Iceland and elsewhere?

Iceland has the highest electricity production per capita in the world, (19,000 GWh/year for a population of ~300,000) and is in the unique position of producing entirely "green" electricity. Approximately 73% comes from hydroelectricity (1,986 MWe) and 27% (655 MWe) is produced by conventional flashed steam geothermal plants. The geothermal companies also provide hot water to heat 97% of the buildings in Iceland, and for other uses such as drying fish, greenhouses, and bathing (Albertsson and Jonsson, 2010). Favorable electricity prices have attracted energy-intensive industries, such as aluminum smelting and production of ferro-silicon, that together use 77% of the electricity produced. The cost is between 25-30 USD/MWh for contracts negotiated 10 to 15 years ago. For future contracts, Landsvirkjun, the Icelandic National Power Company, is proposing long-term contracts at a fixed price of 43 USD/MWh for 12 years, with discounts in the first 5-7 years for "greenfield" projects (source: http://askjaenergy.com//iceland-introduction/energy-data/).

In addition to developing new energy intensive industries, Iceland has an even larger potential electricity market that could be developed within the next few years. "IceLink" is a plan to build a 1,200 km long, submarine, high-voltage DC cable to Scotland to interconnect Iceland's electric grid to those of the UK and beyond. The additional annual generation required is estimated to be 5,000 to 6,000 GWh. Landsvirkjun estimates that 3,900 GWh of this would require construction of new hydroelectric, geothermal, or wind power plants, an increase of >20% in the total installed generating capacity (Askja Energy - Report posted April 18, 2018). There is clearly a market in Iceland for electricity generated by more efficient superhot and supercritical geothermal resources. A first step could be to decarbonize Iceland's fishing fleet by converting to use hydrogen as a fuel.

However, if Iceland is successful in developing supercritical geothermal energy it could impact high-temperature geothermal resources worldwide. The potential advantages of the approach of accessing hotter and deeper geothermal resources include:

(1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this should 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).

5. CUSGER (Combined Use of Supercritical Geothermal Energy)

The marketability of new electrical 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 and water. The flashed steam passes to a turbine-generator, but the still hot separated brine goes to a disposal well. 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 (2) more importantly 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. The CUSGER scheme proposed here begins with negotiating contracts for power sales that have prices depending on the time of day. A CUSGER plant 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 salable products.

5.1 Electrolysis and Desalination

The key part of the proposed CUSGER scheme is, at suitable times of day, to use all or part of the electricity produced for electrolysis to separate hydrogen and oxygen from clean water. Hydrogen is mainly used in industrial chemical and refining processes, in metallurgy, glass production and electronics, and more recently 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 methane or natural gas. The availability of supercritical water would improve the economics of electrolysis relative to reforming natural gas. This could also be helped by carbon credits as reforming methane releases CO_2, whereas hydrogen fuel releases only water. But the main point is that, at supercritical conditions, electrolysis is much more efficient, and so the electricity needed is much less (Shnell et al., 2018). Similarly, the use of very high enthalpy geothermal fluids in heat exchangers should make desalination more cost effective. The accompanying paper by Shnell at al. (2018) describes new technical developments in electrolysis and desalination that promise to improve the economics even more.

5.2 Renewable Methanol

Another proposal included in CUSGER is 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). As hydrogen production by electrolysis is an integral part of CUSGER, capturing the CO_2 for methanol production should be even more efficient.

5.3 Mineral and Metal Extraction

An additional source of revenue included in the CUSGER concept is the extraction and refinement of metals and salable minerals from supercritical and superhot geothermal fluids. Many geothermal brines contain high concentrations of such potential products. For example, historically Laderello in Italy was first developed as a source of borax, but today the worldwide geothermal industry has very little commercial production of metals and minerals.

Table 1. Some metal concentrations (mg/kg) in the well State 2-14, in the SSGF, calculated to reservoir conditions at >300°C (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

This is true even for 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 3 km depth, indicated that it could generate 2,950 MWe for 30 years (Kaspereit et al., 2016). Despite its huge heat content, development of the SSGF resource was slow because of its very high salinity. This problem was overcome by creative chemical engineering in designing the power plants operating today. Although these brines contain unusually high concentrations of metals (Table 1), previous attempts by the principal operator of the SSGF

CalEnergy), using solid-liquid ion exchange to extract zinc from ZnCl, proved to be uneconomic at that time.

A simple calculation indicates that the lithium in solution in the SSGF, at current prices (recent reported to be >$13,000 USD/tonne) in this large geothermal system to a depth of 4 km could be worth several billion USD (not considering costs of extraction and price elasticity). The accompanying paper, by Shnell et al. (2018), describes some of newer technology that could be applied to this hitherto intractable problem by using supercritical or superhot geothermal fluids. In appropriate circumstances in the CUSGER scenario, along with power production, part of future developments would be extraction of valuable metals, such as lithium, providing an additional revenue stream, that, in favorable cases, could possibly exceed the revenues from power sales.

5.4 Combination and Integration

The overarching principle of the CUSGER scheme is the synergism of integrating different technologies that use supercritical fluids to improve the economics of geothermal resources. Figure 3A and 3B present diagrams of how this integration could occur for two different scenarios: (1) where the chemistry allows using the supercritical or superhot geothermal fluid directly in turbines with minimal treatment such as removing condensate, non-condensable and acid gases, and (2) 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 working fluid, most likely water (but Shnell et al., 2018 discuss using CO_2 turbines). Many other combinations are possible, depending on the local conditions.

6. Conclusions

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 technology development will be necessary. The CUSGER approach will likely evolve in a step-wise fashion at different sites.

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.

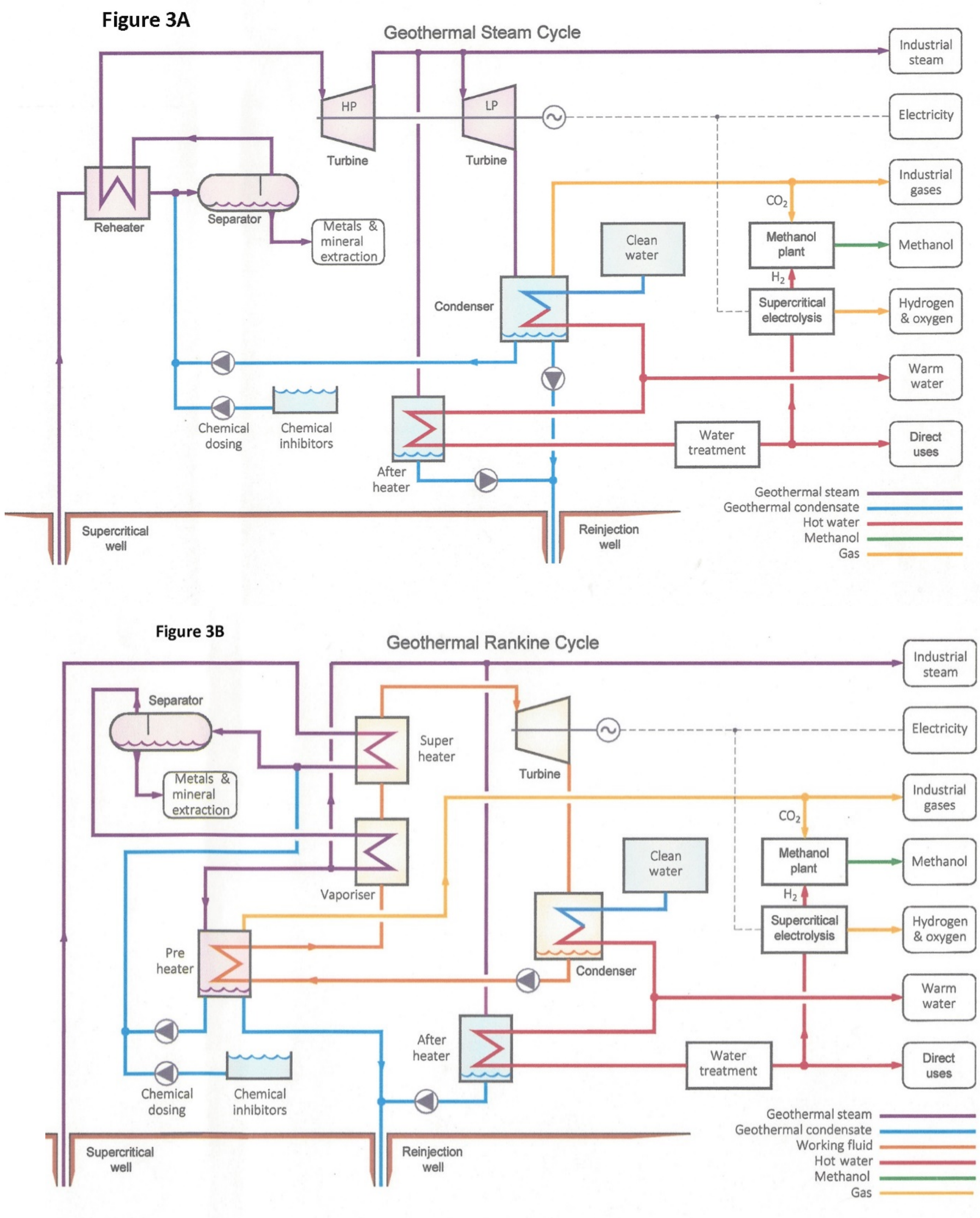

Figure 3: Possible schemes for CUSGER processes using supercritical or superheated fluids with integrated and flexible production of industrial steam, electricity, industrial gases, methanol, hydrogen and hot water and desalinated water for direct uses. Figure 3A: using supercritical or superhot fluids directly in turbines in two stages. Figure 3B: Using clean water, heated by supercritical or superhot fluids, as the working fluid in the turbine.

Similarly, superhot fluids at less that supercritical pressures have been encountered in wells in several volcanic geothermal fields. 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), Puna, Hawaii, USA (Teplow et al., 2009) and Salton Sea in USA (Kaspereit et al., 2016) have all encountered temperatures above 374°C. By drilling deeper to reach higher pressures, development of supercritical geothermal resources could be possible there 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 5^{o}S 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).

Until the series of flow tests are concluded we will not know the economic potential of the IDDP-2 experiment. However, despite all the problems encountered, we are encouraged by the results of the IDDP-1 and IDDP-2 so far. We know where to drill at Krafla and Reykjanes and have learned much about drilling and completing very hot wells. This knowledge will be applied in planning and drilling the IDDP-3 at Hellisheidi in the next few years. Having drilled what appears to be the world's hottest geothermal well, and by demonstrating that it is possible to drill into supercritical conditions, we believe that we are on the threshold of a new era of geothermal development with the potential to yield very large new sources of environmentally friendly, alternative energy.

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