PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

EXPLORATION AND DEVELOPMENT OF SUPERCRITICAL GEOTHERMAL RESOURCES ON THE OCEAN FLOOR

Jim SHNELL, Wilfred A. ELDERS, John ORCUTT and William L. OSBORN
Mailing Address: 17602 17th Street, Suite 102, PMB135, Tustin, CA 92780
E-mail address: OceanGeothermal@gmail.com

Keywords: geothermal, ocean floor, supercritical, rift zone, baseload, hydrogen

ABSTRACT

The demand for clean, renewable energy is continuing to increase around the world. Much of that demand is being met with wind and solar power, but these resources are intermittent and therefore require balancing. Presently, developed geothermal resources are not adequate to provide the balancing that will be needed in the future. Attention is turning to supercritical geothermal resources. Although such resources on land are still limited, the most significant geothermal resources on earth are the supercritical reservoirs under the ocean floor. To prevail in the struggle against global warming and climate change, we must proceed to develop these resources as quickly as possible.

The early steps in finding and developing geothermal resources are difficult. We will need to adopt and adapt all the tools and learning we have developed about geothermal exploration on land, in geology, geophysics and geochemistry. Further, we will need to apply tools such as "play fairway analysis," which was developed in oil and gas exploration, but should prove very helpful in finding the ocean rift zones which contain so much (but not all) of the supercritical geothermal resources in the ocean floor. We will also need to apply the lessons that oceanographers have learned about the ocean rift zones and other supercritical features on the ocean floor. Such tools will be essential to find and develop the ocean geothermal energy that will provide much of the additional renewable power, and much of the balancing needed for wind and solar power to grow even faster. By combining these renewable resources we will increase our ability to stop, and eventually reverse, climate change.

1. INTRODUCTION

The United Nations' Intergovernmental Panel on Climate Change ("IPCC") recently approved the Special Report on Global Warming of 1.5°C (the "Special Report"). The Special Report found that limiting global warming to 1.5°C will require "unprecedented actions" and "rapid and far-reaching" transitions in land, energy, industry, buildings, transport and cities and that emissions of carbon dioxide caused by humans would need to decrease by 45% by 2030. The Special Report also found that limiting global warming to 1.5°C would require deep reductions in the use of natural gas (as a result of a recent change in the understanding of the GHG effect of methane, which has a Global Warming Potential that is 86 times as high as the GWP of CO_2; note that such reductions can be achieved by replacing the use of natural gas for energy purposes by the use of hydrogen from electrolysis, as described below). Thereafter, the United States government released its Fourth National Climate Assessment (NCA4), completed in November 2018, co-written by hundreds of scientists and finding that climate change is already causing increasing damage in the United States. Most nations are still committed to attacking climate change, but many of them are not meeting their pledges under the Paris Agreement of 2015, and emissions are still rising rather than falling. The current administration in the United States has been curtailing environmental regulations, and it plans to quit the Paris Agreement in 2020.

The need for large increments of new electric generating capacity to replace fossil fuels will increase as the world replaces petroleum with either electricity or hydrogen to fuel transportation. Such replacement transportation energy, by consuming off-peak electricity, will make base-load electricity even more important in the future. A solution to the global need for baseload renewable power can be achieved through the following four inter-related fields of innovations which adapt and develop existing technologies to utilize supercritical properties of geothermal resources in the deep-sea floor:

1. Supercritical generation of baseload electricity that is flexibly curtailable;
2. Supercritical water electrolysis for hydrogen;
3. Desalination; and
4. Extraction of minerals from the geothermal resource.

Geothermal energy is the only form of clean, renewable energy that can provide enough baseload electricity to replace coal, petroleum, natural gas and nuclear power as the primary sources of electricity and transportation power. The use of geothermal energy is currently limited in scope and location to a relatively few areas on land that provide limited resources. Access to vast amounts of geothermal energy can, however, be gained through the ocean floors, under which abundant geothermal resources can be found in a supercritical state. Supercritical geothermal resources will enable the generation of electricity on an efficient, economical and highly reliable basis through the first innovation, the use of remote-controlled turbine generators on the ocean floor that will supply both the grid's demand for electricity and, by operating during off-peak hours, the power needed to replace existing transportation fuels. These stations will incorporate a further innovation, the use of turbines powered by supercritical CO2 as the working fluid, which is still in the research and development stage for nuclear power plants and has not previously been considered for geothermal plants. These advancements in geothermal technology, to develop a very high-temperature and therefore very efficient form of geothermal generation, will make geothermal energy (already highly reliable, with availability factors over 90%, and very friendly to the environment, with no negative effect on the land surface or the atmosphere) more affordable, by reducing the levelized cost of geothermal power generation.

The innovations described in this paper will be further supported by ongoing developments in oceanography and geophysics. The development of geothermal resources is often challenged by expenses and difficulties of exploration and similar expenses and difficulties can be anticipated in the pursuit of new resources in the ocean floor. New opportunities, however, will also arise in this new context. For example, the plumes created by geothermal vents in the ocean can be detected across thousands of kilometers of ocean in exploring for active vent fields (Searle, 2013). The belief that plate tectonics is driven primarily by slab-pull forces has been the predominant view of experts for the past forty years. It is, however, now being replaced by the perception that half of the forces driving plate tectonics arise from the deep mantle. The earlier perception was the result of early estimates that the heat flux in the core-mantle boundary was no more than 4 TW. More recent estimates of the heat flux at the core-mantle boundary range from 14 to 20 TW, indicate that there may be much greater geothermal resources under the ocean crust than previously anticipated (Rowley et al., 2016). More recently, researchers have developed an analytical approach to using data from the Amphibious Array deployment of the Cascadia Initiative to show unusually high attenuation of teleseismic P and S waves and at the same time measuring P and S wave differential travel times across the array. This approach enables the gathering of significant information. For example, it shows dynamic upwelling under the Juan de Fuca Ridge from a depth of 200 kilometers below the crust (Eilon and Abers, 2017). Such information could be a useful tool in determining where and how to drill geothermal wells.

Geothermal generation, being both bountiful and more efficient, will form the foundation for a further innovation, the direct use of supercritical geothermal resources to provide hydrogen by electrolysis. This advance will enable the restructuring of the transportation and electrical energy industries so that the provision of inventories of transportation energy (in accordance with current industry practice) serves as a buffer for the load following demands of the grid for electricity. In addition, the ocean geothermal system can be operated in coordination with other energy sources such as wind and solar power, or on a stand-alone basis, to transform the energy generation and delivery industries. Unlike electricity, which is generally transported via transmission lines, hydrogen (like oil and natural gas) can be transported around the world by tanker, or shorter distances by rail cars or trucks as well as by transmission pipelines, enabling hydrogen to replace oil, natural gas and coal.

The geothermal energy under the ocean floor, a vast, high-temperature resource which has never before been accessed to generate electricity, could provide enough baseload energy to reverse climate change. This paper contemplates a self-contained, submersible, remote-controlled electric generating station that will sit on the ocean floor at depths of 2,000 meters or more, where it can access geothermal resources at supercritical temperatures and pressures and use a highly efficient super-critical CO_2 turbine to convert the energy to electricity. This approach will access more extensive geothermal resources than the conventional geothermal resources currently used. Supercritical geothermal fluids can provide six times as much power per liter as geothermal fluids used in current geothermal systems. In addition, supercritical turbines are more efficient than steam turbines, and resource temperatures of 500°C will enable the use of supercritical CO_2 turbines, which are much smaller (which is particularly beneficial under the pressures at the ocean floor) and even more efficient. Supercritical CO_2 in a closed-loop recompression Brayton cycle could have a plant efficiency of 50% (Shnell, J., et al., 2018). This system combines the off-peak baseload electricity of this system with the direct use of the supercritical geothermal resource in a new style of cogeneration to produce low-cost hydrogen. Hydrogen will be the basis for a unified energy industry that balances the demands of the grid for electricity by the storage of energy that is inherent in the transportation industry.

2. CURRENT STATE OF THE ART

The current state of the art in geothermal production of electricity uses the heat in geothermal reservoirs of hot water or steam found under the land. However, the accessible geothermal resource base that is useable in existing geothermal technology is not sufficient to solve the current major issues in the electric generating industry such as climate change, pollution, and the costs and risks inherent in the reliance on fossil fuels or in the disposal of nuclear wastes. Satisfying the increasing demand for electricity while enabling the retirement of less desirable modes of generating electricity, such as the burning of coal, will require much more geothermal energy than is available using existing geothermal technology. Fortunately, the amount of geothermal heat available is far greater than the geothermal resource base that is accessible using current methods. Tester et al. (2006, hereinafter, the "MIT Study") has estimated that 100 million quads of usable geothermal energy could be harvested per year, many orders of magnitude greater than total global primary energy consumption of 472 quads in 2006 (Bullis, 2006.). The innovation proposed here relies on these vast geothermal resources to operate efficiently and effectively.

One way to provide more geothermal power currently is to drill deeper into the Earth's crust for heat, because geothermal temperatures increase with depth. Increased depth of drilling, however, increases the difficulty of drilling and the cost per meter of drilling. The difficulty and cost have prevented the use of deeper wells to provide more energy. The land areas where geothermal heat rises close enough to the surface to be economically accessible are limited, and few of those resources reach a temperature of 250°C. An instructive exception to the temperature limitation of 250°C is Iceland, which has very productive geothermal resources because it is located on the mid-ocean rift zone of the Atlantic Ocean. As a result, Iceland has comparatively easy access to large, very high-quality geothermal resources. A consortium of energy companies and the national government of Iceland is seeking to use these exceptional resources by drilling to a depth of approximately 5,000 meters in order to tap supercritical geothermal resources. It is estimated that beneath three of the developed geothermal fields in Iceland, temperatures should exceed 550°C to 650°C, and the occurrence of frequent seismic activity below 5 km, indicates that the rocks are brittle and therefore likely to be permeable (Fridleifsson, et al., 2007.) The engineers working on this Iceland Deep Drilling Project ("IDDP") have calculated that supercritical geothermal fluids could provide up to ten times as much power, per unit of volume, as the geothermal fluids used in the conventional technology. "A conventional well that produces dry steam only, at a wellhead pressure of 25 bar_a and a downhole pressure of 30 bar_a can yield approximately 5 MW of electric power if the volumetric rate of inflow to the well is 0.67 m^3s^{-1}. An IDDP well tapping a supercritical reservoir with temperatures of 430 – 550 °C and pressures of 230 - 260 bar may be expected to yield 50 MW of electric power given the same volumetric inflow rate, 0.67 m^3s^{-1}. An IDDP well may thus afford a tenfold improvement in power output over a typical conventional well" (Albertsson, et al., 2003.). The MIT Study indicated that a liter of supercritical water at a temperature of 400°C and a pressure of 250 bars has more than five times the power producing potential of a hydrothermal liquid at 225°C (Tester et al., 2006). Such supercritical fluids have not only higher enthalpy than conventional geothermal reservoir fluids, they also exhibit extremely high rates of mass transport due to their enhanced ratio of buoyancy force to viscous force (Friðleifsson and Elders, 2017). In 2017, the Iceland Deep Drilling Project reached a vertical depth of over 4,500 meters and a temperature of 426°C with IDDP-2, thus confirming supercritical conditions in the Reykjanes field, which is recharged by seawater (Elders, *et al*., 2018).

3. THE SOLUTION

The geothermal resources accessible in Iceland are very unusual, however, because it is situated in a mid-oceanic rift zone. Very few areas on land lie in a rift zone (although areas that are so located, such as the Salton Trough of California, which is the northern extension of te Gulf of California rift system, often present significant geothermal resources). In other areas on land, it is necessary to drill much deeper to access such temperatures. The difficulty and cost of drilling through a large amount of rock can be avoided by drilling offshore. According to the USGS, the Earth's crust in continental landmasses averages approximately 30,000 meters in thickness, and can be as thick as 100,000 meters, but the thickness of the Earth's crust under the oceans averages about 6,000 meters and is less in some areas. The most promising area on the ocean floor is the oceanic rift zone, which wraps around the world "like the seams on a baseball", as described in a recent National Geographic production, "Drain the Ocean" (Nicholls and Coules, 2009). The hydrothermal vents in the ocean floor carry approximately twenty-five percent of the global crustal heat flux and, to do so, about 5 x 10^{14} kilograms of seawater pass through hydrothermal systems in the midocean rift zones every year (Searle, 2013). The geothermal resources under the ocean floor are vast enough to supply all future energy requirements. The question is how to access those resources.

One innovation is a self-contained, submersible, remote-controlled electric generating station that will sit on the ocean floor. (This step would reduce the amount of drilling by 2,000 to 2,500 meters per well, which is the usual range of depth of the mid-ocean ridge, thus decreasing the cost and risk of drilling.) The proposed approach would drill wells in the ocean floor to depths of 2,000 meters or more to access geothermal resources at supercritical temperatures and pressures. The station will use a supercritical turbine coupled to a generator for converting geothermal energy to electricity (Shnell, 2009). These improvements will enable geothermal energy to compete with fossil-fueled power plants on a cost basis. This approach will also access much more extensive geothermal resources than the currently used land-based geothermal resources.

The objective is to discover and develop areas under the rift zone having temperatures of 500°C or more and to drill into reservoirs of geothermal fluid at such temperatures. Offshore drilling to the depths contemplated by this approach is currently practiced in the oil and gas industry. The largest oil field in the Gulf of Mexico is approximately 250 kilometers from shore. Recently, oil companies have drilled wells as deep as 8,000 meters beneath the ocean floor in water as deep as 2,800 meters. Drilling for geothermal resources will, however, be conducted in basalt, rather than sedimentary rock, a harder formation that is more difficult to drill. Nevertheless, geothermal wells in Iceland are drilled in basalt; wells 2,000 meters deep are estimated to cost about $5,000,000 per well (Fridleifsson, 2013).

A significant advantage to drilling offshore is the shallower drilling depth at which supercritical geothermal resources can be accessed. Another major advantage is that the reservoirs are more sustainable, because the heat flow through the ocean floor is much higher, as shown in the *Geothermal Map of North America* (Blackwell and Richards, 2004). Also, there is a virtually unlimited supply of saline water with which to create or enlarge geothermal reservoirs, if Enhanced Geothermal Systems (EGS) are necessary, or to recharge existing reservoirs.

4. DC TRANSMISSION

Direct current is significantly more efficient than alternating current for the underwater transmission of electricity, so the subsea generating stations will be built to generate direct current, which will be transmitted to the continental coastlines by high-voltage direct current ("HVDC") transmission lines, similar to the transmission line from Norway under the North Sea to the Netherlands. In the United States, the Pacific DC Intertie ("Path 65") transmits up to 3.1 GW DC at 500 kV from the Oregon-Washington border to Los Angeles, a distance of approximately 1,410 kilometers (Eriksson, 2005). Siemens and ABB are currently developing transmission technology for ultra-high voltage direct current lines, which will transmit up to 10 gigawatts of power efficiently over distances of 3,000 kilometers or more (Callavik et al., 2014).

The potential effect of the proposed system is particularly great because the comparatively uniform characteristics and consistency of the crust over large areas of the ocean rift zone, which is largely composed of basalt and related rock, and the thinness of the crust in the rift zone should enable the placement of many geothermal generation stations in close proximity. Thus, many such stations can be built close together and connected by short HVDC lines. Such clusters would decrease the risk and expense of exploration for geothermal resources because information gathered in the drilling of wells for one plant could be used in drilling the wells for its neighbors. In addition, the similarities of the conditions from one station to the others in the cluster would enable economies of scale, thus saving costs and speeding up the manufacturing and placement of the stations.

5. INNOVATIONS

As discussed in the Introduction to this paper, the innovations described in this paper will be further supported by ongoing developments in oceanography and geophysics. The development of geothermal resources is often challenged by expenses and difficulties of exploration and similar expenses and difficulties can be anticipated in the pursuit of new resources in the ocean floor. New opportunities, however, will also arise in this new context. For example, the plumes created by geothermal vents in the ocean can be detected across thousands of kilometers of ocean in exploring for active vent fields (Searle, 2013). The belief that plate tectonics is driven primarily by slab-pull forces has been the predominant view of experts for the past forty years. It is, however, now being replaced by the perception that half of the forces driving plate tectonics arise from the deep mantle. The earlier perception was the result of early estimates that the heat flux in the core-mantle boundary was no more than 4 TW. More recent estimates of the heat flux at the core-mantle boundary range from 14 to 20 TW, indicate that there may be much greater geothermal resources under the ocean crust than previously anticipated. This study supports the idea of an ongoing source of magma and hot rock along the mid-ocean ridges, and analyzes the spreading data to argue for upwelling in the rift zones. (Rowley et al., 2016). More recently, researchers have developed an analytical approach to using data from the Amphibious Array deployment of the Cascadia Initiative to show unusually high attenuation of teleseismic P and S waves and at the same time measuring P- and S-wave differential travel times across the array. This approach enables the gathering of significant information. For example, it shows dynamic upwelling under the Juan de Fuca Ridge from a depth of 200 kilometers below the crust (Eilon and Abers, 2017). It, too, supports the idea of an ongoing source of magma and hot rock along the mid-ocean ridges. Such information could be a useful tool in planning and developing geothermal wells.

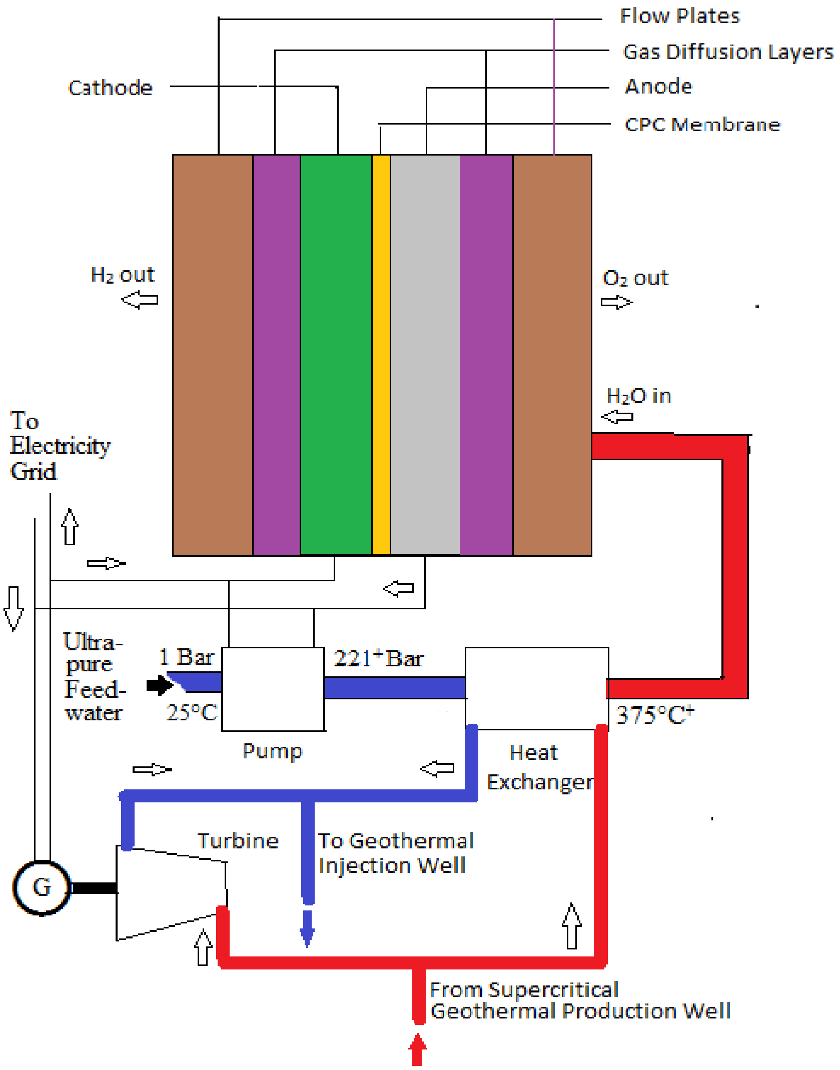
5.1 Supercritical Generation of Electricity

To use the geothermal energy under the ocean floor, a new approach will be needed to generate electricity. Too much energy would be lost by bringing the resource to the surface of the ocean through a pipe surrounded and cooled, for two thousand meters or more of its length, by ocean water. This proposed innovation uses a self-contained, submersible, remote-controlled geothermal-powered electric generating station that incorporates a supercritical CO_2 turbine coupled to a generator to convert geothermal energy to electricity. The generating station would be coupled to the geothermal production and injection wells. The station uses the production from multiple production wells located on the same drilling location, but accessing different areas of the same reservoir using directional drilling. The station is also connected to a remote control cable that enables control of the station from a facility on land, and to an undersea transmission cable that delivers the electricity to the electrical grid on land. The station would be detachable from the wellheads and the cables by remote control, so that the station could be retrieved by a tug, raised to the surface and towed to shore every three to five years for maintenance and overhaul. The stations will, as far as practical, be constructed in a standardized model, so that an equivalent station can promptly replace a station that is retrieved.

Supercritical geothermal resources will enable the generation of electricity on an efficient, economical and highly reliable basis through the use of turbine generators that will supply both the grid's demand for electricity and, by operating during off-peak hours, the power needed to replace existing transportation fuels. These stations will incorporate a further innovation, the use of turbines powered by supercritical CO_2 (sCO_2) as the working fluid, which is still in the development stage for nuclear power plants and has not previously been considered for geothermal plants. These advancements in geothermal technology will develop a very high-temperature and therefore very efficient form of geothermal generation. Supercritical CO_2 in a closed-loop recompression Brayton cycle can achieve a plant efficiency of 50%. This advance will make geothermal energy (already highly reliable, with availability factors over 90%, and very friendly to the environment, with negligible impacts on the land surface or the atmosphere) more affordable, by reducing the levelized cost of geothermal power.

5.2 Supercritical Water Electrolysis for Hydrogen

Supercritical ocean floor geothermal resources will, by operating during off-peak hours, supply the power needed to replace existing transportation fuels, whether by charging the batteries of electric cars or by providing hydrogen through the second innovation, electrolysis, which can be performed advantageously on the ocean floor by making direct use of the supercritical geothermal resources together with the excess off-peak electricity from the baseload geothermal generation. The nuclear industry has promoted the development of solid oxide electrolysis cells for high-temperature electrolysis, but they require temperatures of 800°-900°C to achieve maximum efficiency, and recent tests have observed long-term performance degradation rates of 3.2% to 4.6% per thousand hours of operation, which is too high to be acceptable (O'Brien, 2010; Zhang et al., 2012). It was noted, however, even before the development of solid oxide electrolysis cells, that supercritical water has properties that render electrolysis of supercritical water significantly more efficient than electrolysis of water at standard temperature and pressure (Franck, 1970; Flarsheim et al., 1986). Remote control electrolysis stations on the ocean floor will make direct use of supercritical geothermal resources to heat desalinated ocean water to critical temperature. Such electrolysis requires less than half the extremely high temperatures required by solid oxide electrolysis cells. This new approach will add the direct use of supercritical ocean geothermal resources for high-temperature, high-pressure electrolysis to the use of supercritical geothermal resources to generate direct current electricity (which is more efficient than alternating current for electrolysis) in a form of supercritical geothermal cogeneration (“SGC”). The generation of sufficient baseload energy to provide electricity for charging plug-in electric vehicles and/or generating hydrogen by electrolysis enables the replacement of fossil fuels as transportation fuels. This change will create a unified energy industry in which geothermal energy (which, with an availability factor of over 95%, will provide inventories of transportation energy (as petroleum does in current industry practice) and becomes the buffer for the variable but immediate demand for electricity, solving the load control and balance issues that arise from heavy reliance on solar and wind energy, without requiring the construction of massive amounts of bulk electricity storage that will otherwise be required.



CPCM in Supercritical Geothermal Cogeneration System (*not to scale*)

SGC makes dual use of geothermal resources at temperatures above the critical temperature of water to power both electricity generation and electrolysis. The feedstock for the electrolysis can be water that is purified using excess low-grade geothermal heat (which would otherwise require "heat sinks" to dispose of it) and pressurized above 221 bar before being heated above 374°C in a heat exchanger using the supercritical resource. Electricity from geothermal power using current technologies, recently estimated by the Energy Information Agency to cost $50 per MWh, is cost competitive with other forms of generation. (U.S. Energy Information Administration, 2015) SGC will use geothermal resources at supercritical temperatures and pressures, more efficient than the current technology, so the cost of electricity from the proposed approach is projected to be 20% lower. This approach will use stranded energy resources such as Salton Sea and ocean rift zone geothermal, with potential to cogenerate with solar and offshore wind resources, and reduce the use of coal, petroleum, natural gas and nuclear energy while providing hydrogen (without producing greenhouse gas or other pollution) as a flexible, balancing fuel for micrograids and other backup power. It will enable utility-scale production of hydrogen for grid resiliency, energy storage and energy security around the world.

The efficiency of standard electrolysis is decreased by activation, ohmic, and concentration overpotential, which is alleviated by changes in the properties of water as it goes from a liquid to a supercritical state. (Franck, E. U., 1970; McDonald, A. C., et al., 1986)

5.3 Desalination

So far, renewable energy has played only a minor part in desalination (NRC 2008). The earth is a huge reservoir of geothermal energy, that when accessible can be used in many applications. When collocated with saline or brackish water sources, geothermal energy can enable new and/or alternative desalination technologies such as multistage flash distillation, multi-effect distillation, and forward osmosis (FO) (Chung et al., 2012; Zhao et al., 2012). Prior work has utilized lower temperature geothermal fluids as the thermal energy source for multi-effect distillation, and multistage flash distillation (Goosen, 2010), as well as other distillation systems (Bourouni and Chaibi, 2005). The amount of treated water recovered from saline waters using these technologies was low relative to reverse osmosis (RO). The thermally driven FO technologies described in this proposal have the potential to recover more water while using less electricity than is accomplished with RO.

The use of geothermal energy to desalt saline water depends on its competitiveness with other sources of energy. SGC will be competitive by using an innovative, energy-efficient FO desalination technique that will be powered using geothermal heat that, having initially been supercritical, has expended some of that thermal energy in SGC but still retains a comparatively high temperature. This innovation will add economic value to the geothermal facility by producing potable water. (Shnell. J., et al., 2018).

Forward osmosis (FO) is a membrane-based separation process that uses the osmotic pressure gradient between a concentrated draw solution and a feed stream to drive water flux across a semi-permeable membrane (i.e., passively with the gradient, as opposed to RO which requires energy to pump against the gradient; Cath et al., 2006; Shaffer et al., 2015). The primary requirement for draw solutions is to find a mixture with enough osmotic potential to power the trans-membrane transfer. Other challenges include selecting a draw solute that may be easily and economically removed and re-generated. While FO has achieved some market success, substantial R&D work remains in order for this method to compete with RO and traditional thermal desalination techniques.

5.4 Extraction of Minerals

One of the most intriguing features of Mid-Ocean Ridges (MORs) and arc/back-arc basins is the occurrence of hydrothermal vents known as “black smokers” and their associated deposits of ore minerals and unusual biologic communities. Studies have shown that these hydrothermal vents are often composed of and flanked by assemblages of sulfide, sulfate, carbonate and other minerals compositions (Rona et al., 1986; Pederson, 2010). Sulfides of iron, copper, manganese, zinc and lead are most common. These metal sulfides precipitate from reduced, low pH (1-5) hydrothermal vent fluids with discharge temperatures sometimes exceeding 350°C. These metal-rich fluids are produced by the reaction of seawater infiltrating seafloor rock assemblages and mixing with magmatic fluids. (Figure 2) These reactions deplete the seawater with respect to magnesium and sulfate through formation of smectites, chlorites and anhydrite. This results in decreasing fluid pH and enrichment in sulfide and metals (e.g., Fe, Cu, Mn, Pb, Zn). The magmatic fluids that fuel the hydrothermal system also contribute CO_2, CH_4, H_2 and He to the vent fluids (Tivey, 2007).

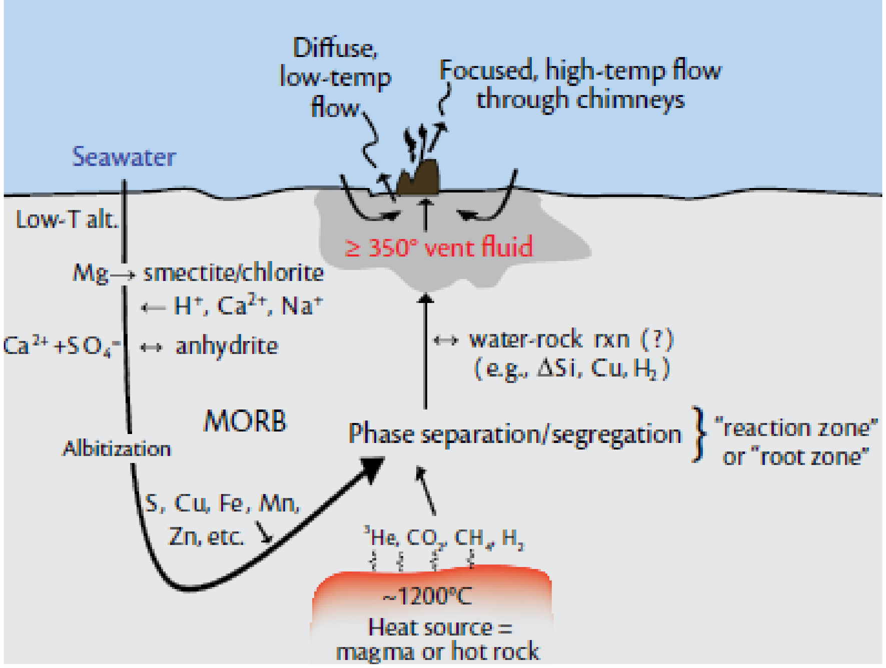


Figure 2. A generic mid-ocean ridge vent system, detailing the water/rock reactions of seawater with seafloor basalt and magmatic gas to produce metal-rich 350°C vent fluids (from Tivey, 2007).

The conditions described above, with the exception of low pH, are similar to fluid chemistry and production conditions at the Salton Sea Geothermal Field (SSGF). The SSGF occurs in a continental rift environment, and local geographic conditions have allowed a saline lake basin to persist for millions of years, with high salinity lake water infiltrating the underlying high temperature rift environment. This has resulted in extensive water/rock reaction, amphibolite facies metamorphism of the rift basin sediments and liberation of metals to the geothermal brine (Osborn, 1989). The result is a high-temperature (389°C at 2 km depth), hypersaline (25 wt.% TDS) geothermal fluid rich in dissolved metals (Hulen et al., 2002; Gallup et al., 1995; Table 1).

Table 1. Comparison of Mid-Ocean Ridge and Back-Arc hydrothermal fluids maximum concentrations (mg/kg) to fluids produced at the Salton Sea Geothermal Field. MOR and Back-arc compositions from Tivey (2007) and SSGF compositions from Gallup (1995).

Environment	Temperature (°C)	pH	Cl	Fe	Mn	Zn	Cu
MOR	≤405	2.8-4.5	44,138	1,004	181	51	10
Back-Arc	278-334	<0.1 - 5	28,007	140	390	196	2
SSGF	389	5.5	128,400	700	760	280	4

Discharges from seafloor hydrothermal vents often occur at pressure and temperature conditions approaching or exceeding supercritical conditions, and at ocean depths of 1500-3500 meters (Tivey, 2007). Thus, although the depth to the seafloor can be quite deep, the drilling depth of about 1500 meters to supercritical conditions is relatively shallow. This decreases drilling cost and risk. The hydrothermal fluids often exhibit low pH, which would be corrosive to typical carbon steel well casing. Therefore, wells would need to be completed with more robust nickel- or titanium-alloys. These drilling depths and materials of construction are also similar to conditions at the SSGF, where production wells are drilled to depths of about 2 km and are completed with titanium alloy casings (Roger, 2003) to mitigate the corrosive effects of hypersaline brine at high temperature; downstream piping, pumps and vessels also rely on nickel alloys and duplex stainless steel materials of construction.

Although the high salinity and acidic conditions of seafloor hydrothermal systems would similarly require alloy materials of construction, the acidic brine composition would be beneficial with respect to silica chemistry; low pH delays precipitation of amorphous silica and metal silicates from solutions supersaturated with respect to dissolved silica, extending the time available for brine processing to remove heat and dissolved metals before silica deposition on process materials occurs (Gallup, 1996).

The proposed facility will extract metals and other valuable compounds from geothermal brine, creating an additional source of revenue. For example, assume a supercritical production well producing 50 MW of electrical power at a flow rate of 0.67 kg/s, and that the geothermal resource contains the mineral concentrations shown in Table 1. If 90% of the manganese is extracted as electrolytic manganese dioxide (EMD), and the market value of EMD is US$2000 per metric ton, the value of extracted manganese would be US$8.2-$17.7 million annually. In comparison, if the 50 MW output of the well produces revenue at US$100/MW, and operates 90% of the time, the annual value is US$39.4 million. Thus, the extraction of only manganese increases annual revenue by 15-27%. Concurrent extraction of other metals would contribute to this benefit.

Extensive research has been conducted regarding mineral recovery from land-based geothermal fluids, and numerous attempts have been made to commercialize an extraction process (Christopher et al., 1975; Harrar and Reber, 1983; Clutter, 2000; Harrison, 2014; Ventura, 2016). At the Salton Sea, metals extraction has primarily focused on silica, zinc, manganese and lithium. Amorphous silica is currently extracted from the brine at all Salton Sea power plants to prevent scaling in injection pipelines and wells but is disposed as waste due to low purity. BHP Billiton Ltd. investigated zinc, lead and silver extraction at the Salton Sea (U.S. Patent 5,229,003), but later ceded efforts to CalEnergy (U.S. Patent 6,458,184). From 2000-2004, CalEnergy extracted and produced commercial quantities of High Grade (99.95%) zinc from Salton Sea geothermal brine using solid-liquid ion exchange (Clutter, 2000); the plant was decommissioned due to a combination of technical difficulties and poor market conditions. CalEnergy also produced manganese at the pilot scale using liquid-liquid solvent extraction but did not attempt to commercialize the process (U.S. Patent 6,682,644). Recent efforts have focused on lithium extraction due to rising market conditions related to electric vehicles and battery storage, and because power plants currently in operation at the Salton Sea process brine with an annual lithium flux valued in excess of $2billion. Various methods for selectively extracting lithium that have been proposed or attempted include: (1) solid-liquid ion exchange, (2) liquid-liquid solvent extraction, (3) high temperature membrane filtration, and (4) wholesale brine salt precipitation followed by off-site purification.

The viability of metals extraction from geothermal fluids will be improved in the proposed commercial facility. The proposed geothermal approach uses a heat exchanger and separates both the supercritical turbine and the supercritical electrolyzer from the minerals in the resource, which would otherwise build up in the turbine and the electrolyzer. The build-up of minerals can be cleaned from the heat exchanger using current geothermal maintenance techniques, more easily than it can be cleaned from the turbine or the electrolyzer. The turbine and electrolyzer then operate like a standard supercritical turbine or electrolyzer, respectively, without the complications of geothermal brine scaling inside the turbine or the electrolyzer. Standardized turbines and electrolyzers, rather than turbines and electrolyzers that have been designed for the conditions of a specific well, will be less expensive to build and maintain, and can be rapidly replaced with a standardized turbine or electrolyzer when maintenance is required. Whereas the currently operating geothermal plants are optimized for power generation, the proposed facility will include metals extraction in the heat exchanger part of the integrated process design, allowing the heat exchanger's staged cooling of the geothermal resource to improve mitigation of unwanted amorphous silica precipitation, and extraction of the target metals at optimum temperature, pressure and other physico-chemical conditions..

6. CONCLUSION

Recent innovations described above relate to exploring for and developing supercritical geothermal resources, including the tracing of plumes from geothermal vents for thousands of kilometers across the ocean, the realization that a much greater heat flux at the core-mantle boundary creates an ongoing source of magma and hot rock to drive upwelling along the mid-ocean ridges, and the use of a more sophisticated analysis of seismic wave data to gather data on upwelling and other activity in the rift zones to a depth of 200 kilometers. These innovations confirm the existence of and aid in the development of the supercritical geothermal resources to power supercritical Brayton-cycle turbine generators and supercritical electrolysis in cogeneration to provide electricity to balance intermittent power and hydrogen to replace fossil fuels, with energy left over to drive innovative desalination and mineral extraction processes. Together, these innovations will create a unified energy industry that operates entirely from renewable resources, on a balanced and sustainable basis.

REFERENCES

Albertsson, A., J. Bjarnason, T. Gunnarsson, C. Ballzus and K. Ingason, "The Iceland Deep Drilling Project: Fluid Handling, Evaluation, and Utilization," in International Geothermal Conference, Reykjavik, September 2003.

Bakane, P.A., "Overview of Extraction of Mineral/Metals with the Help of Geothermal Fluid," *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2013).

Blackwell, D. D., and Richards, M. 2004. *Geothermal Map of North America*. American Assoc'n Petroleum Geologist (AAPG), at http://www.smu.edu/geothermal/2004NAMap/2004Namap.htm.

Blackwell, D., Z. Frone and M. Richards, "The Future of Geothermal Energy: The Shale Gas Analogy," 37 *Transactions* 117-122, Geothermal Resources Council (2013).

Bloomquist, R. G., Ph.D., "Economic Benefits of Mineral Extraction from Geothermal Brines," Washington State University Extension Energy Program, 2006, at http://bcsmain.com/mlists/files/megb/Papers//20Bloomquist.pdf

Bourouni, K., Chaibi, M.T., (2005). “Application of geothermal energy for brackish water desalination in the South of Tunisia,” *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, 24-29 April 2005.

Bullis, K., “Abundant Power from Universal Geothermal Energy,” MIT Technology Review, August 1, 2006.

Buongiorno, J., Idaho National Engineering and Environmental Laboratory, “The Supercritical-Water-Cooled Reactor,” ANS, 2002 Winter Meeting, *at* http://gif.inel.gov/roadmap/pdfs/supercritcal-water-cooled_reactor.pdf.

Callavik, M., Boden, M., Corbett, J., Kuljaca, N., MacLeod, N., Schettler, F. and Sonerud, B., "roadmap of the Supergrid Technologies," European Sustainable Energy Week, Brussels, June 25, 2014, at http://www.dii-eumena.com/fileadmin/Daten/Downloads/EUSEW2014/EUSEW%202014%20Speakers%20Presentations_%20Magnus%20Callavik_FOSG.pdf

Cath, T.Y., Childress, A.E., Elimelech, M., (2006). Forward osmosis: Principles, applications, and recent developments. *Journal of Membrane Science* 281, 70–87.

Chung, T. S., S. Zhang, et al., "Forward osmosis processes: Yesterday, today and tomorrow", *Desalination* **287**, 78-81 (2012).

Christopher, D. H., et al., “The Recovery and Separation of Mineral Values from Geothermal Brines”, Bureau of Mines, PB-245 686, 12 June 1975.

Clutter, T., “Mining Economic Benefits From Geothermal Brine”, *Geothermal Resources Council Bulletin*, Vol. 29 No. 1 (2000).

DiPippo, R., University of Massachusetts, Dartmouth, private correspondence dated September 24, 2007.

Elders, W. A., J. Shnell, G. Ó. Friðleifsson, A. Albertsson, R. Zierenberg, “Improving Geothermal Economics by Utilizing Supercritical and Superhot Systems to Produce Flexible and Integrated Combinations of Electricity, Hydrogen and Materials,” *Geothermal Resources Council Transactions,* Vol. 42, 2018.

Elders, W. A., G. Ó. Friðleifsson, A. Albertsson, 2012 "Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide," *Geothermics*, v. 49, p. 111-118 (2014).

Elders, W. A., G. Ó. Friðleifsson, 2010, " Implications of the Iceland Deep Drilling Project for Improving Understanding of Hydrothermal Processes at Slow-spreading Mid-ocean Ridges." *in* Rona, P.A., Dewey, C.W., Dyment, J. and Murton, B.J. (*Eds)* American Geophysical Union, Geophysical Monograph 118, pp. 91-112 (2010).

Office of Energy Efficiency and Renewable Energy ("EERE"), U.S. Department of Energy, "Geothermal Power Plants - Minimizing Land Use and Impact," at http://energy.gov/eere/geothermal/geothermal-power-plants-minimizing-land-use-and-impact (2014).

Eilon, Z., and Abers, G., “High Seismic Attenuation at a Mid-Ocean Ridge Reveals the Distribution of Deep Melt”) Science Advances, May 2017, in https://www.researchgate.net/publication/317155367_High_seismic_attenuation_at_a_mid-ocean_ridge_reveals_the_distribution_of_deep_melt

Energy Information Administration ("EIA") *International Energy Annual 2006.*

Eriksson, C., "Critical Intertie," *Power Engineering International*, January 9, 2005, at www.powerengineeringint.com/articles/print/volume-13/issue-9/features/hvdc-systems/critical-intertie.html.

Featherstone, J. L., R. H. Van Note and B. S. Pawlowski, “Cost-Effective Treatment System for the Stabilization of Spent Geothermal Brines,” *Geothermal Resources Council Transactions,* Vol. 3, 1979.

Flarsheim, W. M., Y. M. Tsou, I. Trachtenberg, K. P. Johnston and A. J. Bard, "Electrochemistry in Near-Critical and Supercritical Fluids," *The Journal of Physical Chemistry*, Volume 90, Number 16, 1986.

Franck, E. U., "Water and Aqueous Solutions at High Pressures and Temperatures," at pac.iupac.org/publications/pac/24/1/0013/pdf/ (1970).

Friðleifsson, G. Ó., and W. A. Elders, "Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland," *Geothermal Resources Council Transactions,* Vol.41 (2017).

Friðleifsson, G. Ó., A. Albertsson, B. Stefansson, and E. Gunnlaugsson, "Iceland Deep Drilling Project: Deep vision and future plans," International Geothermal Conference, Reykjavik, September 2003, at http://www.jardhitafelag.is/PDF/S06Paper122.pdf.

Friðleifsson, G. Ó., A. Albertsson, B. Stefansson, E. Gunnlaugsson, and H. Adalsteinsson, “Deep Unconventional Geothermal Resources: a major opportunity to harness new sources of sustainable energy,” 20th World Energy Conference, Rome, November 2007. World Energy Council, December 30, 2006.

Friðleifsson, G. Ó., O. Sigurdsson, D. Þorbjornsson, R. Karlsdottir, P. Gislason, A. Albertsson and W. A. Elders, "Preparation for Drilling Well IDDP-2 at Reykjanes," 49 *Geothermics* 119-126 (2014).

Friðleifsson, G. Ó., Iceland Deep Drilling Project, private conversation on October 1, 2013.

Gallup, Darrell L.; Featherstone, John L.; Reverente, Jessie P.; Messer, Philip H.. Line Mine: A Process for Mitigating Injection Well Damage at the Salton Sea, California (USA) Geothermal Field. World Geothermal Congress, 1995.

Gallup, Darrell L. Brine pH Modification Scale Control Technology. Geothermal Resources Council Transactions, 1996.

Goosen, M., Mahmoudi, H., and Ghaffour, N. (2010) “Water desalination using geothermal energy.” *Energies*, v. 3, p. 1423-1442.

Harrar, J.E. and Raber, E., 1983. Chemical Analyses of Geothermal Waters and Strategic Petroleum Reserve Brines for Strategic and Precious Metals. J. Geochemical Exploration, June 1983.

Harrison, S. (Principal Investigator), “Technologies for Extracting Valuable Metals and Compounds from Geothermal Fluids,” Final Report for Department of Energy Geothermal Technologies Program Grant DE-EE0002790 (Simbol Materials) 2014.

Hiriart, G., R. Prol-Ledesma, S. Alcocer and S. Espindola, "Submarine Geothermics; Hydrothermal Vents and Electricity Generation" *in* Proceedings of the World Geothermal Congress, April 25-29, 2010.

Hornburg, C.D., “Possibilities for a Geothermal Energy and Mineral Industrial Complex in the Salton Sea Area,” *Third Geopressured-Geothermal Energy Conference, Volume II*,

Hiriart, G. and I. Hernandez, "Electricity Generation from Hydrothermal Vents," 34 *Transactions* 137-142, Geothermal Resources Transactions (2010).

Hoffman, M.R., “Brine Chemistry - Scaling and Corrosion Geothermal Research Study in the Salton Sea Region of California,” EQL Memorandum No. 14, *California Institute of Technology Environmental Quality Laboratory* (1975).

Hulen, J.B., Kaspereit, D., Norton, D.L., Osborn, W. and Pulka, F.S., “Refined Conceptual Modeling and a New Resource Estimate for the Salton Sea Geothermal Field, Imperial Valley, California,” *Geothermal Resources Council Transactions*, Vol. 26, pp. 29-36 (2002).

Intergovernmental Panel on Climate Change ("IPCC"), Working Group II, *Fifth Assessment Report*, "Summary for Policymakers," March 31, 2014.

Kagel, A., The State of Geothermal Technology, Part II: Surface Technology, Geothermal Energy Association, 2008, "Mineral Recovery," pp 49-52.

Koschinsky, A., D. Garbe-Schonberg, S. Sander, Katja Schmidt, H. Gennerich, and H. Strauss, “Hydrothermal Venting at Pressure-Temperature Conditions above the Critical Point of Seawater, 5°S on the Mid-Atlantic Ridge,”

Geology, August 2008, v. 36, no. 8, pp 615-618.

Koski, R., 1996. "The Escanaba Trough of Gorda Ridge: A Laboratory for Mineral-forming Processes," Coastal and Marine Geology Program, US Geological Survey.

Masson, D.G., D.A. Cacchione and D.E. Drake, "Tectonic Evolution of Gorda Ridge Inferred from Sidescan Sonar Images," 10 *Marine Geophysical Researches* 191-204, February 2, 1988.

Matulka, R., "Small Catalyst Finding Could Lead to Big Breakthrough for Fuel Cell Deployment," Office of Public Affairs, U.S. Department of Energy, April 29, 2014.

McDonald, A. C., F. F. Fan and A. J. Bard, "Electrochemistry in Near-Critical and Supercritical Fluids. 2Water." *The Journal of Physical Chemistry*, Volume 90, pp. 196-202 (1986).

McKibben, M. A., A. E. Williams, and G. E. M. Hall, “Precious Metals in the Salton Sea Geothermal Brine,” *Geothermal Resources Council, Transactions*, Vol. 13 (1989).

Nicholls, S. and Coules, V., "Drain the Ocean," National Geographic Channel, August 9, 2009.

NRC, “Desalination: A National Perspective,” National Research Council, Washington, DC 255 (2008).

O'Brien, J. E., "Large-Scale Hydrogen Production from Nuclear Energy Using High Temperature Electrolysis," *Proceedings of the 14th International Heat Transfer Conference*, Washington, D. C., August 2010.

Osborn, W. L., “Formation, diagenesis, and metamorphism of sulfate minerals in the Salton Sea Geothermal System, California, U.S.A.”, W. L. Osborn. Thesis (M.S.), University of California at Riverside (1989).

Rolf B. Pedersen, Hans Tore Rapp, Ingunn H. Thorseth, Marvin D. Lilley, Fernando J. A. S. Barriga, Tamara Baumberger, Kristin Flesland, Rita Fonseca, Gretchen L. Früh-Green & Steffen L. Jorgensen. Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge. Nature Communications volume 1, Article number: 126 (2010).

Pierce, K.G., B. J. Livesay and J. T. Finger, "Advanced Drilling System Study," Geothermal Research Department, Sandia National Laboratories (1996).

Roger, Thomas. Titanium in the Geothermal Industry. Proceedings of the European Geothermal Conference, 2003.

P. A. Rona, G. Klinkhammer, T. A. Nelsen, J. H. Trefry & H. Elderfield. Black smokers, massive sulphides and vent biota at the Mid-Atlantic Ridge. Nature volume 321, pages 33–37 (01 May 1986).

Rowley, D. B., A. Forte, C. Rowan, P. Glišović, R. Moucha, S. Grand and N. Simmons, "Kinematics and dynamics of the East Pacific Rise linked to a stable, deep-mantle upwelling," Science Advances, December 2016, in http://advances.sciencemag.org/content/2/12/e1601107

Searle, R., Mid-Ocean Ridges, published by Cambridge University Press, 2013.

Shaffer, D.L., Werber, J.R., Jaramillo, H., Lin, S., Elimelech, M., "Forward osmosis: Where are we now?" *Desalination* **356**, 271–284. doi:10.1016/j.desal.2014.10.031 (2015).

Shibaki, M., "Geothermal Energy for Electric Power," report to the Renewable Energy Policy Project, 2003, found at http://www.repp.org/geothermal/geothermal_brief_economics.html

Shimko, M., President, Avalence LLC, private conversation on June 10, 2009.

Shnell, J., W. A. Elders, R. Kostecki,[3] K. Nichols,[4] W.L. Osborn ,[5] M.C. Tucker ,[3] J.J. Urban,[3] and E.D. Wachsman, "Supercritical Geothermal Cogeneration: Combining Leading-Edge, Highly-Efficient Energy and Materials Technologies in a Load-Following Renewable Power Generation Facility," *Geothermal Resources Council Transactions,* Vol. 42, 2018.

Shnell, J, "Global Supply of Clean Energy from Deep Sea Geothermal Resources," 33 *Transactions* 137-142, Geothermal Resources Transactions (2009).

Sigurvinsson, J., C. Mansilla, P. Lovera, and F. Werkoff, "*Can High Temperature Steam Electrolysis Function With Geothermal Heat?*" 32 International Journal of Hydrogen Energy, 2007 (pp. 1174-1182).

Skinner, B. J., "Hydrothermal Mineral Deposits: What We Do and Don't Know," in H.L. Barnes, ed., Hydrothermal Ore Deposits, 3rd edition, 1997.

Smith, J. W., "Babcock & Wilcox Company Supercritical (Once Through) Boiler Technology," May, 1998.

Tester, J. W., B. J. Anderson, A. S. Batchelor, D. D. Blackwell, R. DiPippo, E. M. Drake, J. Garnish, B. Livesay, M. C. Moore, K. Nichols, S. Petty, M. N. Toksoz and R. W. Veatch, Jr., "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century," © Massachusetts Institute of Technology, November 1, 2006.

Tingting Wang, Jian Lin, B. Tucholke and Yongshun John Chen, "Crustal Thickness Anomalies in the North Atlantic Ocean Basin from Gravity Analysis," *Geochemistry, Geophysics, Geosystems* (published by AGU and the Geochemical Society), Volume 12, Number 3, March 31, 2012.

Tivey, M. K., "Generation of Seafloor Hydrothermal Vent Fluids and Associated Mineral Deposits," *Oceanography*, Volume 20, Number 1, March 2007.

U.S. Energy Information Agency, "Levelized Cost of New Generating Resources in the Annual Energy Outlook 2011" at http://205.254.135.24/oiaf/aeo/electricity_generation.html.

Ventura, S., Selective Recovery of Metals from Geothermal Brines, SRI International report to U.S.DOE, December, 2016.

Werner, H.H., "Contribution to the mineral extraction from supersaturated geothermal brines Salton Sea Area, California," *Geothermics*, Volume 2, Part 2, Pages 1651-1655 (1970).

Wise, J. L., T. Roberts, A. Schen, O. Matthews, W. A. Pritchard, G. Mensa-Wilmot, S. Ernst, R. Radtke, R. Riedel and J. Hanaway, "Hard-Rock Drilling Performance of Advanced Drag Bits," 28 Geothermal Resources Council Transactions, 2004 (pp. 177-184).

Zhang, X., J. E. O'Brien, R. C. O'Brien, J. J. Hartvigsen, G. Tao and N. Petigny, "Recent Advances in High Temperature Electrolysis at Idaho National Laboratory: Stack Tests," *Proceedings of the ASME 2012 6th International Conference on Energy Sustainability & 10th Fuel Cell Science, Engineering and Technology Conference*, San Diego, California, July 2012.

Zhao, S. F., L. Zou, et al., "Recent developments in forward osmosis: Opportunities and challenges," *Journal of Membrane Science* 396, 1-21 (2012)>