Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Supercritical Geothermal Cogeneration on the Threshold

Jim Shnell, John Orcutt, William L. Osborn, Michael C. Tucker and Eric Wachsman

1371 Smokewood Drive, Santa Ana, California 92705

jhshnell@cox.net

Keywords: supercritical, ocean floor, rift zone, baseload, dispatchable, electrolysis, hydrogen

ABSTRACT

The Accord signed by 177 nations at COP 21 in Paris in 2015 demonstrated the breadth of the consensus around the world that the problems of global warming and climate change must be solved. At the same time, it reflected a lack of consensus on the best means and methods to achieve the solution. It left the choices of means and methods to the discretion of each of the various countries. Variations in the relevant conditions and circumstances in different countries led to various approaches to their solutions. In the same year, the World Geothermal Congress 2015 convened a large conference in Melbourne to consider new research and developments in geothermal science and industry, many of which have led to progress over the past five years. A global solution of the global problems, however, will require a new foundation to replace the coal, oil and natural gas that provided the foundation in 2015, and still do today.

Some of the solutions that were proposed in 2015 have lost support, while some innovative new solutions have gained support. High-enthalpy geothermal resources from around the world is one of the solutions that is gaining support. Massive amounts of supercritical geothermal resources exist in the ocean floor all around the world and science and engineering are already developing the innovations in core fields like geophysics, exploration and power generation that will enable supercritical geothermal generation and electrolysis to balance the other renewable resources. Together, they will power the grids in various countries while, at the same time, supercritical geothermal energy will provide the clean hydrogen to replace fossil fuels for transportation, industrial and other uses around the world. These steps will not only transform the geothermal industry but will unify the entire energy industry.

Making the science and engineering innovations effective will require the development of accompanying innovations in cross-cutting and general fields such as advanced technologies (like electrolysis and desalination), minerals extraction and processing, integrated energy systems (like cogeneration), software for geothermal applications, new business strategies (like hydrogen transportation) and new financing, policy, legal and regulatory aspects. These innovations will support the science and engineering developments in the new, supercritical geothermal industry to enable it to work economically and achieve the efficiency and provide the power needed to solve global warming and climate change and become the cornerstone of the new, unified, clean energy industry.

1. INTRODUCTION

Much of the world has already switched to wind and solar power to curtail significantly the burning of coal to generate electricity for the grid, and the need for further, large increments of new, renewable electric generating capacity to replace fossil fuels will increase as the world replaces petroleum with electricity and/or hydrogen to fuel transportation, whether to charge the batteries of electric cars or to provide hydrogen through electrolysis. Such replacement transportation energy, by consuming off-peak electricity, will make baseload electricity even more important in the future. A solution to the global need for baseload and dispatchable renewable power can be achieved through several inter-related innovations, which adapt and use existing technologies to access geothermal resources in the deep-sea floor. 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 transportation energy and of electricity to balance the grid. 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 resources in a supercritical state can, however, be gained through the ocean floors. Not long ago, the ocean floors were almost entirely unknown but, in recent years, there has been rapid growth in research about the ocean floors, particularly in the study of the ocean rift zones. The continuing development of this knowledge will alleviate the historically high costs, risks and delays of geothermal development. 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 balancing 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 Brayton-cycle turbines powered by supercritical CO_2 as the working fluid, which are now in the research and development stage of commercialization. These advancements in geothermal technology, developing a very high-temperature and therefore very efficient form of geothermal generation, will make geothermal energy (already highly reliable, with availability factors over 95%, 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. Such generation, being both bountiful and inexpensive, will form the foundation for a further innovation, the direct use of additional supercritical geothermal resources in a form of cogeneration to provide hydrogen by electrolysis without greenhouse gases or other pollution. 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. Geothermal resources are accessible in the ocean floor around the globe. Abundant resources are readily available near Iceland and the West Coast of North America, but such resources in fact wrap around the world. Also, the increasing need for potable water in many areas of the world is strongly linked to the issues and future demands of the climate change and the energy industry in general. To the extent that the solutions for the energy industry come from the production of hydrogen, electrolysis will increase the demand for pure water, and an increasing demand for and development of desalination. The solutions for the issues confronting the energy industry, and a variety of other technologies as well, are increasing the demand for strategic metals and minerals. In recent years, those increasing needs have driven increased research and development for the production of such metals and minerals, a number of which can be extracted from geothermal brine.

2. CURRENT STATE OF THE ART

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; hereafter the "MIT Study") estimated that 100 million quads of usable geothermal energy could be harvested per year, which is thousands of times the total global primary energy consumption of 472 quads in 2006. (Bullis, 2006).

An instructive exception to the typical 200°-300°C temperature range of geothermal resources for power generation 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 national governments and energy companies is seeking to use these exceptional resources by drilling to a depth of approximately 5,000 meters to tap supercritical geothermal resources. The engineers working on the Iceland Deep Drilling Project have calculated that supercritical geothermal fluids could provide up to ten times as much power, at the same volumetric flow rate, as a well producing two phase flow at 250°C. (Friðleifsson, 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 than a hydrothermal liquid water geofluid at 225°C." (Tester, *et al*., 2006).

3 ADVANCEMENTS IN EXPLORATION AND DEVELOPMENT

Recently, the potential advantages of supercritical geothermal resources in the United States has stimulated considerable research in the geothermal areas around The Geysers, Salton Sea and Coso geothermal fields in California (Stimac et al., 2017). Similar interest in supercritical geothermal systems has also grown in other countries, including Italy, Iceland, Japan, Mexico and Kenya (Reinsch et al., 2017). Several years ago, the Iceland Deep Drilling Project, in seeking to drill a deeper geothermal well, drilled into magma at a depth of approximately 2,000 meters, and a temperature of 900°C. (Elders, *et al*., 2014) The geothermal resources accessible in Iceland are very unusual, however, because it is situated in a mid-oceanic rift zone. The difficulty and cost of drilling through a large amount of rock can be avoided by drilling offshore. 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 ocean averages about 5,000 meters, well within the accessible depths of current drilling and completion technology. The most promising area on the ocean floor is the oceanic rift zone, which wraps around the world "like the seams on a baseball." (Nicholls and Coules, 2009.) The geothermal resources under the ocean floor are vast enough to supply all future energy requirements. The question is how to access those resources.

Exploration for and the development of geothermal resources, and the risks, delays and costs thereof, have long been major impediments to the advancement of the geothermal industry. Worse, in the case of exploration in the ocean floor, until recently very little was known about the ocean floor and drilling wells in it was presumed in geothermal operations to present a daunting challenge, although the oil and gas industries have drilled wells in the ocean floors for decades.

Recently, however, the United States has created the Ocean Observatories Initiative ("OOI"), a network of technologically advanced cabled and uncabled platforms that measure physical, chemical, geological and biological properties and make the data freely available online to a global audience; during the third quarter of 2018, the OOI data portal received 6,100 visits from 56 countries with a total data download of 45.64 GB. (Smith et al., 2018) The OOI works with the Global Ocean Observing System, (an international framework under the United Nations) to support the collection of ocean observations to benefit science and society, making the data available freely to all users. (Lindstrom, 2018)

Such ocean observatories increasingly use nodes with arrays attached and autonomous underwater vehicles for gathering particular types of information, including crustal and deep earth data. An early cable system on the Juan de Fuca ridge, off the coast of the State of Washington, gathered data in an extreme environment of volcanoes, hot vents and related igneous features. Such corrosive and challenging conditions are likely to limit future cabled ocean observatory systems mostly to international and multinational projects, which could provide global coverage at a fraction of the cost of dedicated systems. The Smart Cables Joint Task Force is a partnership of three United Nations entities (the Intergovernmental Oceanographic Commission of UNESCO, the International Telecommunication Union and the World Meteorological Organization) who are working with scientific, telecommunications and governmental parties worldwide to develop geophysical and other types of prototype sensor suites. Seafloor geodetic measurements associated with plate tectonics can be measured without drift, and accurate seismic measurements on the sea floor can be made over a broad spectral band. (Baggeroer et al., 2018)

The innovations described in this paper will be further supported by ongoing developments in oceanography and geophysics. 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 was driven primarily by slab-pull forces had been the predominant view of experts for the past forty years. It is, however, now being replaced by the realization that half of the energy driving plate tectonics arise from the deep mantle. The former 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, indicating 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 can show dynamic upwelling under the Juan de Fuca Ridge from a depth of 200 kilometers below the crust (Eilon and Abers, 2017). Such information would be useful in determining where and how to drill geothermal wells not only under the Juan de Fuca Ridge, but also under the Gorda Ridge to the south of it, under the Explorer Rift Zone and the Souvanco Fracture Zone near the Pacific coast of British Columbia, and numerous other such oceanic locations around the world.

4 SUPERCRITICAL GENERATION OF ELECTRICITY

The geothermal energy under the ocean floor, a vast, high-temperature resource which has never before been accessed to generate electricity, could provide baseload energy to balance wind and solar power and, combined with them, to reverse climate change. This system will use 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 supercritical CO_2 turbine to convert geothermal energy to electricity. This approach will access much more extensive geothermal resources than the conventional geothermal resources currently used. Supercritical geothermal fluids can provide five to ten times as much power, at the same volumetric flow rate, as a well producing two phase flow at 250°C. (Friðleifsson, et al., 2003; Tester et al., 2006).

In addition to the foregoing advantages of supercritical resources in terms of the amount of energy that is accessible and the ability of such resources to transport more energy, the theoretical advantages of the Brayton cycle have been recognized for some time. In recent years increased research and development of the Brayton cycle using supercritical CO_2 as the working fluid has been pursued. The U.S. Department of Energy has combined the efforts of several of its own offices with the resources and talents of Sandia National Laboratories and Argonne National Laboratory, in cooperation with industrial companies and other interested entities, to advance the commercialization of the Brayton cycle, in large part because it can achieve a conversion efficiency at a temperature of 750°C that is up to sixty percent (60%) higher than that of the Rankine cycle. Also, the Brayton cycle is highly flexible and can be used in connection with a large variety of energy sources. For example, the Office of Energy Efficiency and Renewable Energy (EERE) has shown an interest in developing the use of the Brayton cycle with geothermal energy and with concentrated solar power. The EERE focuses on the ability of concentrated solar power to reach temperatures of 600°C because they approach the optimal temperature of 750°C for the Brayton cycle. Unfortunately, the EERE considers geothermal energy to have a temperature range of only 100°C to 300°C, notwithstanding the demonstration in recent years that geothermal resources can be found at temperatures above 600°C. Moreover, geothermal resources are ideal for baseload operation and there are many other ways in which the characteristics of supercritical geothermal resources match up very well with the capabilities of the Brayton cycle. The current roadmap to commercialization calls for commercial interests to be ready to apply the Brayton cycle technology over the full range of expected conditions by 2025. The roadmap calls for the EERE to support the Supercritical Transformational Electric Production program (the "STEP Program") through the incremental development and testing of the components that comprise the sCO_2 Recompression Closed Brayton Cycle ("RCBC") energy conversion system. The power conversion advantages of the Brayton cycle are its (1) broad applicability to a variety of heat sources, (2) up to fifty percent (50%) higher conversion efficiency, (3) reduced capital costs due to its smaller size compared to a Rankine cycle system, (4) reduction in greenhouse gas emissions, (5) reduced water consumption, and (6) ability to make more effective use of dry cooling. In addition, the operational flexibility of the Brayton cycle may provide greater ease of operation of cogeneration or otherwise combined functions such as the balancing of intermittent power on the grid and the production of inventories of hydrogen, thus providing storage of energy, or the ability to provide power to microgrids. In general, the supercritical closed Brayton cycle has the following benefits over the steam Rankine cycle: up to fifty percent (50%) higher cycle efficiency (potentially up to 60% higher with a recompression closed-loop cycle); good load following capabilities (especially important for balancing the grid); a wide array of designs to meet varying requirements; excellent scalability while maintaining efficiency; ability to incorporate air cooling; ease of building, installing and operating; compact turbomachinery; ability to interface with high temperatures at smaller scale; potential to reduce the cost of the power block; and operational simplicity to reduce operating and maintenance costs. The greater efficiency and lower costs of the Brayton cycle will flow through the SGC system to provide lower cost hydrogen. Other important benefits of the Brayton cycle include a smaller footprint (particularly important for a plant operating on the ocean floor) and reduced production of greenhouse gases. (Mendez and Rochau, 2018).

5 SUPERCRITICAL ELECTROLYSIS USING SOLID OXIDE PROTON-CONDUCTING MEMBRANES

Supercritical generation of electricity on the ocean floor 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. (Shnell et al., 2015).

Supercritical 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 electrolysis, which can be performed on the ocean floor by making direct use of additional supercritical geothermal resources together with the excess off-peak electricity from the baseload geothermal generation of the supercritical CO_2 turbine generator discussed above. 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 considered unacceptable (O'Brien, 2010; Zhang et al., 2012). Supercritical water has properties that render electrolysis significantly more efficient than at standard temperature and pressure (Franck, 1970; Flarsheim et al., 1986). Electrolysis stations can make direct use of supercritical geothermal resources to heat water above critical temperature.

Electrolysis of water becomes less expensive when done at supercritical temperatures, in part because at high temperatures the additional heat replaces some of the electricity (which is more expensive than heat) that is otherwise required for electrolysis, as shown in Figure 1 (from Mougin, 2015).

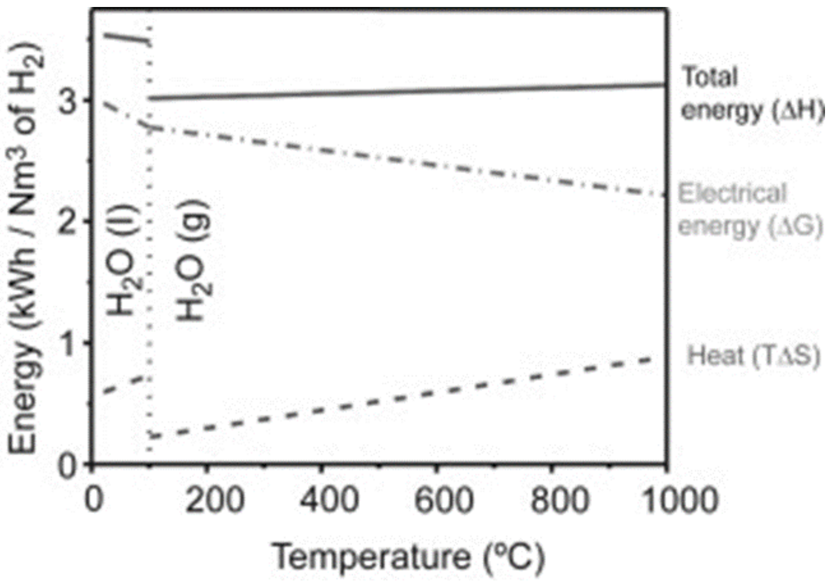

Figure 1- Effect of temperature on thermodynamic parameters of electrolysis

Much of the new power replacing baseload coal and nuclear power is wind and solar power, which require load following to achieve grid balancing. Such balancing is provided in large part by natural gas-fueled generation that produces greenhouse gases, and more recently, in high value situations, using battery storage. Geothermal energy is baseload, but geothermal power generation using current technology is not sufficient to balance the grid; supercritical resources are needed. Also, further curtailment of greenhouse gases will require renewable energy to replace the fossil fuels now used for transportation fuels. Hydrogen could replace fossil fuels, but over 90% of hydrogen is now produced from fossil fuels, thereby producing greenhouse gases. This can be avoided by generating electricity from supercritical geothermal resources and using the electricity in combination with additional geothermal resources raising the feedwater to supercritical temperature to produce hydrogen by electrolysis in a form of Supercritical Geothermal Cogeneration (SGC). SGC will produce large amounts of clean electricity cheaply and will perform electrolysis efficiently and on a large scale using a solid oxide proton conducting membrane.

SGC is transformational because the properties of water under supercritical conditions change in unique ways that make both electricity generation and electrolysis more efficient. The supercritical temperature is sufficient to achieve high proton conductivity in the CPCM so that the protons are conducted more easily and efficiently, changes which may be further advanced by the effects of the supercritical pressure. Further, the properties of water change to make both electricity generation and electrolysis more efficient. It is anticipated that this approach will use electrolysis, and its flexibility, to expand greatly the scope and effect of virtually unlimited geothermal resources by opening major markets for geothermal and other renewable energy relating to balancing the electrical grid and to replacing current transportation fuels with hydrogen. To the extent that the grid needs balancing, baseload geothermal can do so without disruption of the grid, but it will disrupt the providers of coal, nuclear, natural gas and battery power that are otherwise needed for balancing. To the extent that electricity is not needed to balance the electricity grid, it can be used in electrolysis to create hydrogen for the transportation sector, disrupting and ultimately replacing oil, natural gas and other polluting fuels. When electricity is needed for balancing the grid, the amount used for solid oxide proton conducting membrane electrolysis can be reduced accordingly in two seconds, and the electricity sent to the grid.

SGC makes dual use of geothermal resources at temperatures above the critical temperature of water to power both electricity generation and electrolysis, as shown in Figure 2 (from Shnell et al., 2018). The feedstock for the electrolysis can be water that is purified (as discussed in the following section, on desalination) using excess low-grade geothermal heat (which would otherwise require "heat sinks" for disposal) and pressurized above 221 bar before being heated above 374°C in a heat exchanger using additional heat from the supercritical resource. SGC will use geothermal resources at supercritical temperatures and pressures, more efficiently than the current technology, so some of the costs of electricity from the proposed approach are projected to decrease. Other factors, however, such as the materials that are required to withstand more corrosive brines that may be encountered at such temperatures, may raise the costs unless other materials or approaches are developed through further research. This approach will use supercritical energy resources from the geothermal fields, with potential to cogenerate with solar and onshore 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 fuel to balance microgrids and backup power. It will enable utility-scale production of hydrogen for grid resiliency, energy storage and energy security around the world.

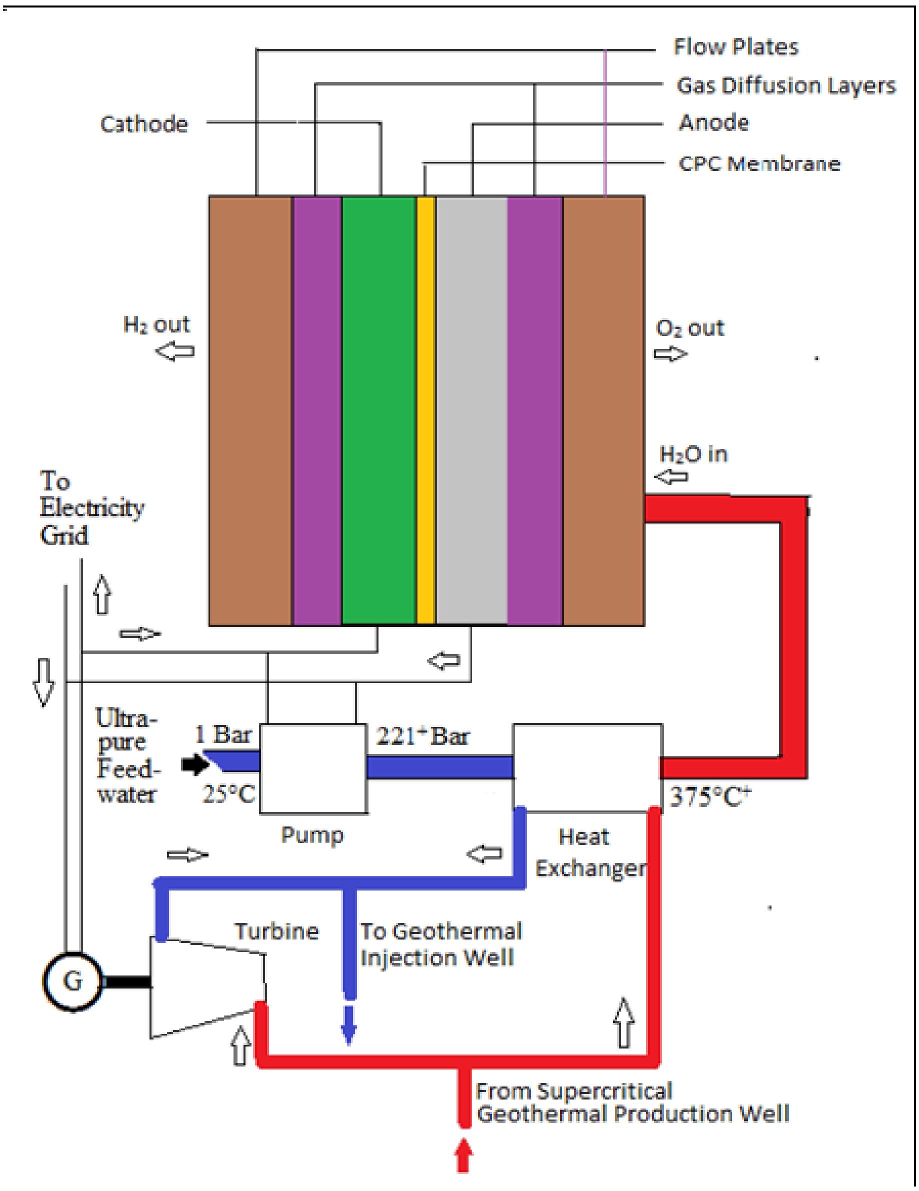

Figure 2 – CPCM in Supercritical Geothermal Cogeneration System (not to scale)

In addition to the foregoing factors, supercritical water changes properties in electrolysis. 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, 1970; McDonald et al., 1986) Some of the changes that are important to electrolysis are related to the loss of polarity in supercritical water. These changes include the loss of surface tension and drop in viscosity by a factor of 10 to 20 (depending on pressure), increase in diffusivity and self-ionization, lower relative permittivity by an order of magnitude and higher specific conductance by an order of magnitude or more (Table 1).

Table 1 – Changes in Properties of Supercritical Water

PROPERTY	LIQUID WATER	SUPERCRITICAL
Self-Ionization (pK_w)	14 @ 25°C	15 @ 400°C
Dynamic Viscosity	890µPa	41.79µPa
Surface Tension	72mNm^2 @ 25°C	0
Relative Permittivity	78.54 @ 25°C	5.9 @ 400°C
Specific Conductance	0.055 µS/cm	1.17 µS/cm

Moreover, this approach combines supercritical electrolysis with recent developments in proton exchange electrolysis using a CPCM, instead of a polymer membrane. The CPCM will withstand the higher temperature and produce purer hydrogen. If the costs of electrolysis cell stacks follow those of equivalent fuel cell stacks, the operating temperature of the CPCM, lower than that of the solid oxide fuel cell ("SOFC"), may enable it to mimic the costs of the protonic ceramic fuel cell (PCFC): (a) PCFC production costs are 27% to 37% lower than SOFC production costs; (b) PCFC balance-of-plant hardware costs are lower than SOFC balance-of-plant hardware costs; and (c) PCFCs are more durable than SOFCs (Dubois et al., 2017). The lower costs and higher durability of the CPCM due to its comparatively lower temperatures than the SOFCs are not lost because of the supercritical pressure of SGC; current "ultra-supercritical" power plants, which operate at pressures of 292 bar and at temperatures of 623°C, use ferritic and austenitic stainless steel, which are in the same class of materials now used in PCFCs (Marion et al., 2014).

The foregoing analysis may combine a ceramic proton conducting membrane with metal-supported proton conducting electrolysis cells (collectively, MS-SOECs). Such MS-SOESs are similar to metal supported solid-oxide fuel cells ("MS-SOFCs") which have gained substantial recognition on the basis of their relatively low cost and robust structure. MS-SOFCs enable very fast start-ups and are primarily comprised of low-cost stainless steel as the metal support. These characteristics are also inherent to MS-SOECs. The early form of MS-SOECs were primarily oxide-conducting and predominantly engaged in steam electrolysis. As a result, these SOECs provide predominantly moist hydrogen, and the electrolysis is operated at a temperature range of 650° to 900°C, and the early MS-SOECs have a tendency to operate at temperatures up to be solid oxide conducting. Recent research has focused more on proton-conducting electrolysis, which produces dry hydrogen, and much purer hydrogen with no mixture of oxygen. It operates at a temperature range of 500° to 700°C and the dryness and coolness of the hydrogen reduces or eliminates the oxidation of the metal (Tucker, 2020).

6. DESALINATION

The production of hydrogen by electrolysis will require a source of water. So far, renewable energy has played only a minor role in desalination (NRC, 2008). 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). Recent development of thermally driven FO technologies described in this paper have the potential to recover more water while using less electricity than is used for RO (Shnell et al., 2018).

The usefulness 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. The geothermal resources produced will add economic value to the geothermal facility by providing pure water to produce hydrogen.

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 research and development work remains in order for this method to compete with RO and traditional thermal desalination techniques.

The foregoing includes a novel approach being developed by the Water-Energy Resilience Research Institute at Lawrence Berkeley National Laboratory to FO water purification, using the ionic liquids class of thermally sensitive draw solutes (WERRI, 2019). Phase separation between ionic liquid (IL) and water has been of great interest for fundamental research as well as potential industrial applications (Kohno and Ohno, 2012). SGC will use the dynamic shifts of IL/water mixtures between a homogeneous mixture and separate IL and water phases for FO desalination applications. Most IL/water mixtures exhibit an upper critical solution temperature phase change (i.e., miscibility of IL with water generally increases upon heating). Interestingly, some ILs undergo a lower critical solution temperature phase transition with water in which the separated IL and water phases become miscible upon cooling. As the phase transition of IL/water mixtures can occur at ambient conditions within a few degrees, ILs can be used as solvents in a highly energy efficient FO desalination process (Cai et al., 2015).

SGC can utilize lower temperature geothermal resources to provide the energy necessary for FO water treatment. SGC can provide all the thermal energy necessary for the FO treatment using geothermal fluids having temperatures of 150°C or less, while recovering more water from the feed stream than could be accomplished using RO technologies.

ILs are expected to be effective draw solutes for FO given their ability to reach high concentrations. The driving force for this separation is the natural osmotic pressure gradient between IL draw solution and saline water feed solution, which will force a net flow of water through the membrane, thus effectively separating the feed water from its solutes at temperatures that correspond to formation of a homogeneous IL/water phase. A small amount of the waste heat can be used to split the homogeneous IL/water phase into an IL phase and an aqueous phase. The rate of phase change between the homogeneous mixture and the separated IL/water biphasic mixture upon heating or cooling should be rapid but may require facilitation. This scheme could radically reduce the energy-intensity of water purification.

The miscibility of ILs with water depends strongly on the character of the ionic species. Physico-chemical analysis of hydrophobic ILs that undergo a phase separation after mixing with water showed that there is a particular range of "hydrophilicity" of the amphiphilic ILs within which the phase transition is possible. IL/water phase changes can undergo phase separation upon heating from 20° to 25°C. Since the hydrophilicity of ILs depends on the chemical structure and composition of the ion species, the phase behavior of the IL-water systems can be controlled by specific molecular design of IL ions.

WERRI is also pursuing research, development and demonstration of other new approaches. The Water Technology Innovation Program at the Idaho National Laboratory is also researching numerous new approaches to desalination, including FO (INL, 2019).

7. EXTRACTION OF METALS AND MINERALS

In instances where a supercritical geothermal resource is associated with hypersaline, metal-rich brines, such as those found in Mid-Ocean Ridge and arc/back-arc basins vent fluids (Shnell et al., 2018), the SGC will provide an opportunity to extract metals and other valuable compounds from the brine, creating an additional source of revenue. Historical efforts to extract valuable minerals from the hot, hypersaline brines of the Salton Sea Geothermal Field were reviewed in Shnell et al. (2018). The current high market price of lithium and the elevated concentrations of lithium in the SSGF brine have encouraged continued development of extraction methods.

In June 2017, EnergySource Minerals LLC (EnergySource) received a $2.5 million grant from the California Energy Commission to produce an engineering package and capital budget for a facility to extract lithium and mineral co-products from geothermal brines using existing processes and equipment from the water treatment, metal processing and chemical processing industries, and demonstrate that process in an existing pilot test facility (CEC, 2017). In June 2018, EnergySource filed a U.S. Patent Application describing a process to remove various minerals from geothermal brine (Featherstone, 2018). In this process, the geothermal brine undergoes oxidation and precipitation to remove iron and silica, and further processing to precipitate manganese and zinc. The polished brine is then subjected to solid-liquid ion exchange (IX) to extract and concentrate lithium chloride, followed by conversion of the lithium chloride to lithium carbonate or lithium hydroxide. The precipitated manganese and zinc are processed using solvent extraction to produce manganese sulfate and zinc sulfate.

In December 2018, Lilac Solutions Inc. (Lilac) was granted a patent for the use of coated ion exchange particles for lithium extraction from brines (Snydecker, 2018). Their novel coating of the IX particles will prevent degradation of the material, and better control of molecular transport in and out of the IX particles during loading and elution. In October 2019, Lilac was granted a patent for an integrated system for lithium extraction and conversion, which incorporates their coated IX material in various embodiments of a complete lithium extraction and production process, including IX, pH modification, suspended solids control, purification and precipitation (Snydecker et al., 2019).

Efforts to develop improved methods to extract lithium from concentrated brines are also being applied in areas where lithium is produced from salars, or evaporite basins. Historically, lithium is produced from these areas, such as the Salar de Atacama in Chile, by solar evaporation. This relatively slow process results in the depletion of groundwater in the typically arid regions where these resources are located. Developers of these resources have more recently come under scrutiny for excessive water consumption. Thus, processes to rapidly extract lithium without relying primarily on evaporation are being developed. At Clayton Valley, Nevada, the site of the only current lithium production in the U.S., Pure Energy Minerals proposed using the Tenova process[1], wherein pretreatment is applied to remove calcium and magnesium, followed by solvent extraction to remove lithium as lithium sulfate, and conversion of lithium sulfate to lithium hydroxide.

Although current efforts are currently focused primarily on lithium extraction, continued development of these multi-step processes to remove the valuable components of concentrated brines will allow more efficient recovery of metals from brines, including salars, conventional geothermal fluids or fluids associated with supercritical geothermal fluids.

8. CONCLUSIONS

The demonstration by the Iceland Deep Drilling Project of developing supercritical geothermal resources in the Atlantic Mid-Ocean Rift Zone (Elders et al., 2018), points to the need for development of supercritical geothermal generation of electricity, supercritical electrolysis of hydrogen, desalination by forward osmosis, and extraction of metals and minerals from the geothermal brine using reactions over a broad range of temperatures and other conditions. These developments will enable the combination of supercritical geothermal resources with wind and solar power to resolve both environmental and economic issues and unify the energy sector on a foundation of 100% renewable resources around the world. 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 a more productive 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. The organization and continued growth and operation of the Ocean Observatories Initiative and the Global Ocean Observing System will lead to continuing advances in the global knowledge of the ocean floors around the world. The observational 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 via 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 worldwide entirely from renewable resources, on a balanced and sustainable basis.

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