COMBINING HIGH-ENTHALPY GEOTHERMAL GENERATION AND HYDROGEN PRODUCTION BY ELECTROLYSIS COULD BOTH BALANCE THE TRANSMISSION GRID AND PRODUCE NON-POLLUTING FUEL FOR TRANSPORTATION

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ABSTRACT Although base-load electricity generated from geothermal resources is cost competitive compared to electricity generated from solar and wind resources, it is less attractive to utilities compared to natural gas because gas-fired generation can be ramped up or down quickly to respond to the problem of balancing the grid due to daily and seasonal variation in the ratio of wind and solar generated electricity to demand. One approach to adding value to geothermally generated electricity is to address the problem of flexibility by creating electrical storage capacity. We suggest, however, that load following could, under appropriate conditions, be achieved more economically and effectively by using geothermal resources both (A) to generate electricity both for sale and for electrolysis to produce hydrogen as a non-polluting transportation fuel, and (B) to preheat the feedwater for such electrolysis. As both power generation and electrolysis of water are more efficient at high temperature conditions, the best environment to test this concept is in very high temperature, preferably supercritical, geothermal reservoirs. In Iceland, the Iceland Deep Drilling Project (IDDP) aims to investigate such supercritical geothermal conditions. In 2009 Phase 1 of the IDDP created the hottest geothermal well in the world (450oC) but it was too shallow to reach supercritical pressures. Phase 2, beginning in May 2016, will drill to greater depth to reach the appropriate pressure and temperature conditions. In California the Salton Sea and the Geysers geothermal fields both offer high temperatures at drillable depths. In fact, in some parts of the Salton Sea geothermal field temperatures exceeding the critical temperature are likely at ~3.5 km depth. This creates the possibility of large-scale production of hydrogen to alleviate the serious levels of greenhouse gas and air pollution produced by combustion of fossil fuels in Southern California. However, the greatest potential world-wide for such systems is along oceanic spreading centers, which produce supercritical geothermal resources for 65,000 kilometers around the world. High temperature geothermal wells could produce at a constant flow rate, generating electricity for the grid when needed for balancing, and otherwise generating electricity and heating feedwater to supercritical temperatures for electrolysis to produce hydrogen as a fuel for transportation and oxygen for industrial purposes. Electrolysis can be ramped down in seconds so that balancing power can be provided to the grid immediately, more responsively than gas-fired generation. By providing standby capacity to utilities, we can avoid wasting capital on stand-by gas fired plants (which create greenhouse gases) or batteries or other forms of storage that do not create any additional clean power. That money can, instead, be invested in a flexible form of generation that runs in baseload mode, cleanly, and can supply both balancing capacity and fuels, as needed. Implementation of such systems will require deep drilling of the high temperature geothermal fields, development of technology for water treatment and supercritical electrolysis, and the negotiation of flexible forms of capacity and pricing for electricity sales that respond to supply and demand at any given time.

INTRODUCTION

Most of the renewable resources that have been developed in recent years are intermittent, and therefore can contribute to imbalances in the electricity grid in balancing supply and demand of electricity. A recent study reported that California, one of the leading states in using renewable power, will still be using natural gas to generate electricity in 2050, and because California uses a lot of intermittent renewable energy, it will require huge amounts of storage to balance its grid (Mahone, 2015). Germany, one of the countries with the highest usage of renewables, is also encountering the balancing problem and is reverting to burning more coal. As other states and nations follow the examples of California and Germany, they too will have to deal with these issues. Balancing grids requires standby capacity that is always available. Geothermal energy provides baseload generation of electricity with a capacity factor of 92%, which is higher than any other form of generation but as presently used it is best suited for baseload generation rather than balancing. In addition, geothermal energy is little affected by climate change, so its capacity will be increasingly important for balancing the grid as climate change intensifies and intermittent renewables become less reliable.

Fossil fuels are currently the main sources of energy for transportation and for heating. Their use as transportation and heating fuels creates more greenhouse gases in California than the generation of electricity releases. Hydrogen could be used to substitute for fossil fuels. Most hydrogen is, however, currently produced by reforming natural gas and other fossil fuels, thereby still creating greenhouse gases. This problem can be mitigated by generating electricity from renewable resources to produce hydrogen by electrolysis if current methods of electrolysis are made more efficient and less expensive. Electrolysis of water becomes more efficient when done at supercritical temperatures and pressures, in part because at high temperatures the additional heat replaces some of the electricity that is otherwise required for electrolysis, as shown in Figure 1 (from Mougin, 2015).

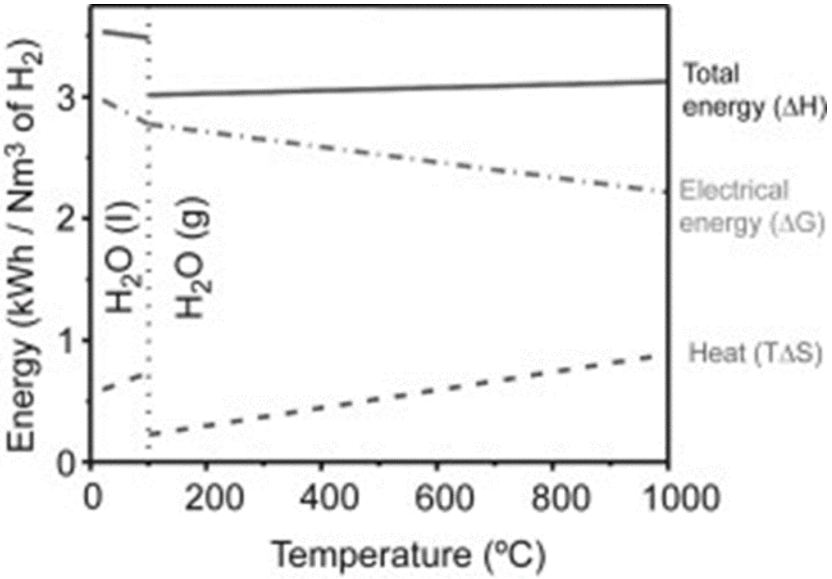

Figure 1 Effect on temperature on the thermodynamic parameters of water electrolysis

The efficiency of electrolysis is also affected by overpotential, which is the excess voltage needed, due to inefficiencies, to decompose water through electrolysis. The overpotential has three components: the activation overpotential caused by rate limiting steps, the concentration overpotential caused by a drop in concentration at the electrode surface relative to the bulk phase due to mass transport limitations, and the ohmic overpotential caused by the resistivity of the electrolyte (Kelly, 2014). These overpotential issues that may be alleviated to some extent by certain changes in several of the properties of water as it goes from a liquid to a supercritical state, including that the viscosity of supercritical water is lower than that of liquid water by a factor of 10 or 20, that the dielectric constant of supercritical water is about an order of magnitude lower than that of water at standard conditions, that the specific conductance of supercritical water is several orders of magnitude higher than that of liquid water, that supercritical water has virtually no surface tension and that the density of supercritical water is much higher than that of steam. When electricity generated from geothermal energy is not contributing to balancing the electricity grid, it could be used for electrolysis to create inventories of hydrogen for the transportation sector. When electricity is needed for balancing the grid, the amount used for electrolysis could be reduced in seconds and the power sent directly to the grid (Eichman, Harrison, and Peters, 2014). The flexibility to respond to both the need for balancing and the need for hydrogen fuel would be accomplished by a combination of electrical generators that use high-temperature geothermal resources with electrolysis of water heated by additional such high-temperature geothermal resources to produce hydrogen.

California has suitable high-temperature geothermal resources, for example, in the Salton Sea geothermal area that could provide the electrical capacity to help balance its transmission grid. In addition, these geothermal fields could provide the additional renewable energy to produce hydrogen for transportation and heating, which are the biggest producers of greenhouse gases in California (CARB, 2015). In the future, high-temperature geothermal resources in Iceland, and ultimately other new high-enthalpy resources, including the mid-ocean rift zone (which stretches for 65,000 kilometers around the world) and other geothermal resources in the ocean floor, will enable the balancing of the grid and the use of electrolysis to replace carbon-based fuels globally. Geothermal energy could have, in the future, a lower levelized cost of electricity than any other form of generation (EIA 2015), thus helping to solve both the need for grid balancing and the need for clean transportation fuels. With a foundation of baseload, high-enthalpy geothermal energy and supercritical electrolysis, all renewable resources can work together to advance, and replace fossil fuels in transportation as well as in electricity, more quickly and flexibly.

THE CURRENT STATE OF AFFAIRS.

In a number of states, one of the biggest concerns of electric utilities, and therefore of the developers of power plants, is the renewable portfolio standard, if any, set by the applicable government. Nevada's renewable portfolio standard, for example, is one of the most stringent in the United States, with a requirement that at least 25 percent of the utility's retail energy sales be derived from renewable energy resources by 2025. California, one of the few states with an even higher standard, requires that all retail sellers of electricity must service 33 percent of their load with renewable energy by 2020. Given that geothermal energy is one of the cleanest of renewable resources, one might expect that developers of geothermal energy projects in California and Nevada would be in a very favorable position.

Unfortunately for geothermal developers, that is not necessarily the case. California utilities have accelerated their achievement of the renewable standards by signing "take or pay" agreements with a number of developers of wind or solar projects because such projects can be developed and constructed much more quickly than geothermal projects. As the wind and solar projects approach the 33% renewable portfolio standard, there are times that they supply the grid with so much power that the utilities do not need the baseload power generated by geothermal energy (CAISO, 2013). The utilities therefore are not contracting for new geothermal power, which is a source of baseload electricity. It is projected that wind and solar will continue to dominate future construction of new renewable plants, exacerbating this problem.

Unfortunately for California, the wind and solar projects from which the utilities are purchasing their renewable requirements provide intermittent power rather than baseload power. As the intermittent power in the system approaches the 33% requirement, the grid at certain times of day could become unstable, and it becomes necessary to adjust the supply of electricity to "balance" the demand by making expensive spot purchases, and to acquire the related "ancillary services" by which the security and quality of the electricity supply is ensured. (The Federal Energy Regulatory Commission defines ancillary services as "those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.") Nevertheless, California and Nevada are continuing to raise and accelerate their renewable portfolio standards, and some countries around the world are considering adopting, or have already adopted, a 100% renewable portfolio standard in their desire to fight climate change. Indeed, as mentioned above, the leaders of the "G-7" recently announced that their countries would adopt 100% renewable portfolio standards.

One possible solution to providing balancing and other ancillary services, and the solution that is favored by California, is the storage of large amounts of electricity that are generated when they are not needed, to be used when ancillary services are needed. Such storage is, however, expensive; the least expensive form of storage, which is pumped storage, has been available for many years, but it is expensive and only possible where favorable topography exists. An innovative proposal has been made, however, to combine pumped storage with geothermal generation (Hiriart, 2015). Utilities usually prefer to keep a standby plant running, rather than store the electricity. Another possible solution is described in a recent study which notes that some geothermal facilities have contracted to operate, and others could operate to some extent, in "flexible mode" rather than in "baseload mode." They would do so under modified contracts and/or by making retrofits to their plants (Matek, 2015). That study also notes, however, that operating in flexible mode can often be less efficient and more expensive than baseload operation, and that certain of the flexible geothermal facilities ceased operating in flexible mode because of low demand for their ancillary services and/or price competition from other forms of power.

The expenses of those possible solutions are, moreover, compounded because there is a second problem that must also be solved. As the world seeks to achieve the 100% renewable standard, it will have to cease using fossil fuels for transportation and heating and replace them with clean fuels. One possible form of such replacement is electricity, but storage will not increase the amount of electricity available; instead, it will actually decrease the amount of electricity, because storage is not 100% efficient. If California pursues the storage approach, much more electricity must be produced by wind and solar projects, which have a higher levelized cost of electricity than geothermal has (U.S. Energy Information Agency, 2015), and then the cost of storing such electricity must be added to its already higher cost of production. In a recent study, the National Renewable Energy Laboratory assessed reductions in capacity and energy values of prospective wind and solar facilities as they penetrate further into the market for generation. This reduction reflects the increasing need for balancing in the future, which will impede the development of wind and solar. (Brown et al., 2015) Furthermore, such an approach will become even more difficult and expensive in the future, because solar and wind power will become more intermittent and unpredictable as climate change continues to worsen. Another possible replacement for fossil transportation fuels is hydrogen, but over 90% of the hydrogen used today is provided by steam reformation of methane or other methods using fossil fuels, all of which actually produce additional greenhouse gases.

HYDROGEN PRODUCTION BY ELECTROLYSIS.

A partial solution to both of these problems relies on high-enthalpy geothermal energy. Geothermal energy provides baseload generation of electricity with a capacity factor of 92%, which is higher than any other form of generation. (U.S. Energy Information Agency, 2015). In addition, geothermal energy is largely immune to the effects of climate change. It therefore has the capacity to provide the balancing and other ancillary services needed by the grid. Precisely because it provides baseload electric power, however, the utilities will not contract for it alone to balance the electric grid. Furthermore, its current installed capacity is small compared to wind and solar energy. However, producing electricity from high-enthalpy systems, both from existing resources such as the Salton Sea and from new high-enthalpy resources, and combining electricity generation with hydrogen production by electrolysis, could provide the additional renewable energy needed to replace fossil fuels used for transportation and for heating. Moreover, in a recent study that forecast energy costs for the periods from 2015 to 2020 and from 2035 to 2040, geothermal energy was projected for both periods to have a lower levelized cost of electricity than any other form of generation. (U.S. Energy Information Agency 2015). If this proves to be the case, geothermal will be less expensive than fossil fuels, and less expensive than the other forms of renewable energy, thus solving both the need for ancillary services as well as providing a fuel for clean transportation and heating purposes, all at a lower overall cost to society.

A number of the major automakers are beginning to design and build cars that will run on hydrogen rather than batteries, and California has announced plans to build more hydrogen service stations around the state in order to expand the use of hydrogen to replace gasoline. Transportation and heating fuels create more greenhouse gases in California than are caused by the generation of electricity. Hydrogen could solve that problem but, as noted above, most hydrogen is currently produced by methods that consume fossil fuels and release greenhouse gases.

We are proposing that hydrogen could be produced by electrolysis of geothermally heated water, using off-peak geothermal electricity that would otherwise be stored in batteries. As mentioned above, geothermal power plants operate at a constant rate, so the electrolysis can run all the time, justifying the higher capital investment needed for the most efficient cells. If the necessary associated technical problems are overcome in an economically viable manner, it should be possible to produce the least-expensive hydrogen. In contrast, current proposals for electrolysis using renewable energy would occasionally use excess power from intermittent resources that have a higher levelized cost of electricity than geothermal and, because they only run occasionally, will support only less-efficient electrolytic cells producing more-expensive hydrogen. The higher capital costs of highly efficient electrolysis, and the volume of hydrogen that will be needed to replace carbon-based transportation and heating fuels, will require baseload geothermal energy, not intermittent renewables. This use of geothermal will not only increase the contribution of geothermal to the overall portfolio of renewable resources, it will also, by providing the capacity to balance the grid, avoid the decrease in capacity and energy values of wind and solar power discussed above and enable those renewables to expand more rapidly as well. Moreover, because the hydrogen will go into the kind of inventories that the economy has always used for transportation and heating fuels, hydrogen is a form of storage that does not impose an additional expense or burden on the economy.

In the past, electrolysis has been too inefficient and expensive a means of producing hydrogen as an economical transportation fuel. Research has, however, found that electrolysis is more efficient when conducted at supercritical temperatures. (Byrd, 2011; Franck, 1970; Flarsheim *et al*., 1986.) The concept proposed here is to use, where available, geothermal brine resources above the critical temperature of water to heat the clean feedwater, after its pressure is raised above the critical level, to a temperature above critical temperature. Electrolysis is more efficient when the pressure of the feedwater is raised to the desired pressure for the hydrogen prior to the electrolysis, rather than pressurizing the gas following the electrolysis. Current systems for transporting and dispensing hydrogen are designed to operate at 700 bar, which is much more that the critical pressure of water, so pressurization of the feedwater for electrolysis is not a waste of energy, but simply an efficient step toward reaching the standard operating pressure for the gas. Such pressurization of the feedwater would be less expensive because it is more efficient to pressurize liquid water than gaseous hydrogen, given the presence of inexpensive electricity when geothermal generation and electrolysis are combined. Moreover, electrolysis can be cut back to operate at less than 10% of capacity without a significant loss of efficiency, and such cut backs can be performed in less than 2 seconds. (Eichman, 2014). The electricity that would otherwise power the electrolysis can therefore be switched to provide electricity or other ancillary services to the grid immediately. Other research has found ways to decrease the cost of the electrodes that are needed, which will further reduce the cost of electrolysis. Thus, geothermal wells can run in baseload fashion, as they should, while the electricity is used to balance the grid and/or to produce hydrogen, as the circumstances dictate, by using the geothermal energy for the generation of electricity and/or the electrolytic production of hydrogen. Hydrogen inventories will be analogous to storage, from the perspective of electricity generation. On the other hand, as a replacement for fossil fuels for transportation and heating, which has always been produced for and drawn from inventory, (and, if the economics permit, for the generation of electricity at the peak of demand, in place of natural gas) hydrogen will open a whole new market for the geothermal industry, and one that can be expected to grow rapidly for the foreseeable future in favorable locations where high enthalpy fluids can be produced.

The nuclear industry has promoted the development of solid oxide electrolytic cells for high-temperature electrolysis, but they require temperatures of 800°C to 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 rates are too high to be acceptable. (O'Brien, 2010; Zhang, *et al*., 2012.) The largest source of supercritical geothermal fields is likely to be found on mid-ocean ridges (Shnell, 2015; Elders, 2015A; Elders, 2015B). In the future, remote control electrolysis stations on the ocean floor would be able to take feedwater that has been desalinated from the ocean (by microfiltration or reverse osmosis) and raised above critical pressure, and make direct use of supercritical geothermal resources to heat the feedwater up above the critical temperature. Such electrolysis requires less than half the extremely high temperatures required by solid oxide electrolysis cells, and can achieve efficiency through using a platinum catalyst. Recent advances in proton exchange membranes for electrolytic cells make it possible to design, construct and operate electrolytic cells that use supercritical water. (Yamazaki, 2013; Wei, 2011; Yates, 2011)

The high-enthalpy geothermal plants could sell capacity to the utilities that need to be able to balance the grid, and also sell the utilities the electricity generated using that capacity when the utilities need it. When the utilities do not need the electricity, the electrolysis cells could use the electricity to produce hydrogen. The electrolyzer cells can be turned down and back up, as needed, in seconds with no loss of efficiency. The capacity can be used for ancillary services, although most of the electricity will be used to produce hydrogen, and the geothermal plants would have two sources of revenue, one from capacity charges and one from energy prices.

MOVING FORWARD

Current geothermal technologies do not produce enough geothermal energy to fulfill these roles except to a minor extent. Despite the cost advantages of geothermal, the EIA has projected only 200 MW per year of new capacity. (U.S. Energy Information Agency, 2015). It has been noted by experts that we need to develop more high-enthalpy geothermal energy. (Elders, 2015a; Elders 2015b; Hiriart, 2010a; Hiriart, 2010b). In fact, the geothermal industry should in the future harness supercritical resources, first in Iceland and the Salton Sea area in California, and thereafter those which are accessible in the ocean floor (Shnell, 2009). Progress towards this goal could get a quick start by adding electrolytic cells to existing high-enthalpy geothermal facilities that are operating at the Salton Sea today. In the future, research should focus on utilizing standardized models of high-enthalpy and supercritical generators and supercritical electrolytic cells, thereby enabling it to construct new geothermal facilities quickly, as wind and solar facilities are constructed today. (Shnell, 2015). This approach will optimize the production of hydrogen by (a) using waste heat from such generators and electrolysers, in addition to the heat from the geothermal resource, and allocating such heat optimally between the working fluid of the turbine and the feedwater for the electrolyzer, and (b) allocating the electricity from the generator optimally among the functions of (i) pressurizing the feedwater in order to achieve higher pressure in the hydrogen produced, (ii) heating the feedwater in order to increase the efficiency of the electrolysis, and (iii) providing power to the electrodes to increase the rate of the electrolysis.

In addition, the flexibility provided by this system should increase in the future because the specifications and characteristics of the turbines and of the electrolytic cells, such as the preferred electrodes and the preferred membranes, will evolve. In the longer term, flexibility will be needed by the entire energy industry as the energy needs of countries change, the climate changes and technologies change. With such flexibility, all of the major forms of renewable energy can be built more rapidly to replace fossil fuels more quickly. The utility can sign a power purchase agreement with a wind or solar facility and not have to worry about that facility being intermittent as long as enough geothermal capacity is committed to balance it; on the other hand, the developer of a geothermal facility will not have to worry about too many wind or solar facilities being built as long as the geothermal facility can convert its energy to hydrogen. If the technology and economics of this approach are favorable, hydrogen could also be used in place of fossil fuels in existing power plants, if such plants are retrofitted for the new fuel, with no need for new electricity plants or transmission lines; most of the plant and infrastructure might continue to be useful in many cases, and such changes could greatly accelerate the move away from fossil fuels. The owner of a concentrating solar facility could use electrolytic cells as well, but such a facility is likely to be too intermittent to work well in support of an electrolyzer. On the other hand, if the grid has a surplus of electricity, the excess could be transmitted to geothermal facilities, where it could be used for short periods to create overpotential in the electrolytic cells and provide even more hydrogen.

CONCLUSION

Geothermal energy can be increasingly effective in the future. While California and other well-developed energy markets face the issues of occasional overcapacity of intermittent renewables and the increased need for balancing, other markets around the world have completely different issues and characteristics. In addition, each market will continue to change as the global energy industry continues to change and evolve. Geothermal energy needs to develop the flexibility to respond to the full range of issues and changes. By developing the ability to produce and provide both electricity and hydrogen, and to balance between the two almost instantly, the geothermal industry will gain a larger role in a new, unified energy industry.

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