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Energy from Ocean Floor Geothermal Resources

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ABSTRACT

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, 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 base-load electricity even more important in the future. A solution to the global need for baseload 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 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 below the levels of other forms of generation. Such generation, being both bountiful and inexpensive, 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. Geothermal resources are accessible in the ocean floor all around the globe. Abundant resources are easily available near Iceland and the West Coast of North America, but such resources in fact wrap around the globe. This paper will describe the conceptual design for the ocean-floor geothermal system and provide the well drilling cost analysis, manufacturing cost analysis and life cycle cost analysis of the system.

1. INTRODUCTION

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 provides the design and projected costs of a self-contained, submersible, remote-controlled electricity 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%. Additional efficiency is gained due to the use of the surrounding ocean water, which is generally at a temperature of 3°C at such depths, for cooling. The target is a capacity of 100 MW_e per station, using four production wells accessing supercritical fluids to produce 50 MW_t of energy each, with plant efficiency at 50% and maintaining plant availability at 90% for a period of 30 years. The generating station is projected to have a capital cost (including financing) of $1.365 billion and operating costs of $215 million over thirty years. Assuming a life span of thirty years and average availability of ninety percent (90%) and adding $0.006 per kWh for transmission, the levelized cost of electricity is projected to be $0.073 per kWh. In some circumstances, the foregoing economic model would need to be adjusted to reflect the potential additional net revenues resulting from the recovery of valuable metals and minerals from the supercritical geothermal brine. A major effect of this system is the ability, by combining the off-peak baseload electricity of this system with the direct use of the supercritical geothermal resource to produce low-cost hydrogen, creating a unified, renewable energy industry that balances wind and solar generation of electricity with 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. Professor Jefferson Tester (then of the Massachusetts Institute of Technology, now at Cornell University) has estimated that 100 million quads of usable geothermal energy could be harvested per year, thousands of times the total global primary energy consumption of 472 quads in 2006. (Bullis, 2006; *see also* Tester *et al*., 2006, hereinafter, the "MIT Study".). The innovation proposed here uses a large part of these vast geothermal resources, 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. One response to this limitation is the current focus on enhanced (or engineered) geothermal systems ("EGS"). EGS is expected to access a greater volume of resources, but will do so by drilling wells to depths of 5,000 meters or more, which would raise the cost of the energy substantially. Another problem with EGS is the induced seismicity that concerns people living near such facilities, and their governments. Moreover, EGS will use substantial amounts of stimulation water in many areas where water is a dwindling resource. Unfortunately, the resources that EGS is expected to reach are still limited to 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 national governments and energy companies 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 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 than a hydrothermal liquid water geofluid at 225°C." (Tester, *et al*., 2006.). A few 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.)

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 on a rift zone (although areas that are so located, such as the area around the Salton Sea in California, 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 5,000 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 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. One embodiment of the innovation would use the flows from existing geothermal vents. (*See* Hiriart *et al.*, 2010a; Hiriart and Hernandez, 2010b.). The present approach, however, would drill wells in 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 super-critical 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 geothermal resources that are much more extensive than the conventional geothermal resources currently used.

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, or to create such reservoirs using ocean water and EGS technologies. This approach contemplates the drilling of vertical injection wells, whether EGS wells or wells drilled into existing reservoirs, in areas near oceanic rift zones where the crust is approximately 2,000 meters thick and the mantle beneath the crust is at a temperature of 700°C. Each injection well would then be surrounded by four production wells, each directionally drilled to points approximately 500 meters laterally distant from the injection well and 1,600 meters below the ocean floor, so that (assuming that the crust conducts heat uniformly) the resource temperature should be 525°C. The four production wells should produce 50 MW_t each, supporting a generating station with a capacity of 100 MW_e (assuming a supercritical power plant efficiency of 50%).

The technology for offshore drilling to the depths contemplated by this approach has already been developed in drilling for the oil and gas industry. The largest oil field in the Gulf of Mexico is approximately 150 miles from shore. Recently, oil companies have drilled wells that reach as much as 8,000 meters beneath the ocean floor, and have drilled wells in water as deep as 2,800 meters. Drilling for geothermal resources will, however, be conducted in rock formations that do not contain any oil or natural gas deposits, but that present an unusual challenge. The rock to be drilled is basalt, rather than sedimentary, and it is harder. Geothermal wells in Iceland are drilled in basalt; drilling geothermal wells 2,000 meters deep in Iceland has been estimated to cost about $5,000,000 per well. (Fridleifsson, 2013.).

A significant advantage to drilling offshore is the much higher temperatures at which the 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 are necessary, or to help to recharge existing reservoirs.

Direct current is significantly more effective than alternating current for the underwater transmission of electricity, so the generating stations in the rift zones 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 gigawatts of direct current at 500 kV from the Oregon-Washington border to Los Angeles, a distance of approximately 846 miles (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 closely together in clusters. For example, if generating stations, generating an average of 100 MW_e each, are constructed at one-kilometer intervals along two lines, one on the each side of the rift zone, for the 150 kilometer distance that the rift zone parallels the coast of California, then a total of 300 such stations can be built, with a total capacity of 30 gigawatts, 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 the standardization of aspects of the stations, thus saving costs and speeding up the manufacturing and placement of the stations.

The proposed geothermal approach uses a heat exchanger and separates the supercritical turbine from the minerals in the resource, which would otherwise build up in the turbine. The build-up of minerals can be cleaned from the heat exchanger using current geothermal techniques, more easily than it can be cleaned from the turbine. The turbine then operates like a standard supercritical turbine without the complications of geothermal brine scaling inside the turbine. Standardized turbines, rather than turbines that have been designed for the conditions of a specific well, are less expensive to build and maintain, and a turbine can be replaced with another turbine when maintenance is required.

4. INNOVATIONS

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 innovation uses a self-contained, submersible, remote-controlled geothermal-powered electric generating station that uses a supercritical CO_2 turbine coupled to a generator to convert geothermal energy to electricity. The station can be built on a barge, which can be towed by a tug to the ocean surface above the geothermal wells, then submerged and lowered by winches on the installation vessel to the site on the ocean floor prepared for the station. There, by remote control, with the assistance (to the extent needed) of a remotely operable submersible vehicle operated from the tug, the station is coupled to the wellheads for the geothermal production wells and to the wellhead for the injection well. The station uses the production from more than one well, each of which is in close proximity to the others at the crustal surface but accesses different geothermal reservoirs, or 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 is detachable from the wellheads and the cables by remote control, so that the station can be retrieved by a tug, raised to the surface and towed to shore every three to five years for maintenance and overhaul. These regular overhauls, combined with the very cold water and the low levels of oxygen in the water at such depths, prevent corrosion from being a problem for the station. 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. The station will be constructed with enough variable buoyancy to permit the station to be lifted to the surface with relatively little work. A submersible remotely operable vehicle, operated from a ship on the ocean surface, can handle minor repairs and adjustments that may be necessary between overhauls, to the extent that they can't be handled with the remote controls built into the station. Placing the station on the ocean floor, at a depth of 2,000 meters or more, conserves the pressure that would otherwise be lost if the station were at sea level, and avoids the loss of temperature (and consequent loss of efficiency) that would result from being farther from the wellhead.

Another innovation will reclaim and refine metals and strategic minerals, creating an additional source of revenue. A number of studies have been performed regarding the recovery of various minerals and metals from geothermal fluids, depending on the circumstances and characteristics of the reservoirs and the rock in which they reside, and many of the studies are summarized in the literature on the topic. (*See* Bourcier *et al*., 2005; Bakane, P. A., 2013.). A number of attempts have been made at commercializing such recovery; for examples of conventional geothermal approaches that have been commercially unsuccessful, *see* Bloomquist, 2006 (discussing extraction of silica, which facilitates subsequent extraction of lithium, zinc, manganese and other elements); Kagel, 2008 (discussing various studies and attempts at mineral and metal recovery from geothermal brine); and Skinner, 1997 (stating that precipitation of metals and minerals from hydrothermal fluids results from at least four factors: change in temperature, change in pressure, chemical reactions between the fluid and the surrounding lining, and mixing of the fluid with another solution). One approach to commercialization appears to be successful, using technologies developed to recover minerals and metals from resources in the Salton Sea area similar in many respects to ocean geothermal resources. (Harrison, 2010.). It is anticipated that the ocean geothermal system will be able to collect significant metals and minerals because seafloor hydrothermal fluids are particularly rich in metals and minerals, which vary depending on the location and circumstances of the resources (Tivey, 2007; Koski), and the supercritical temperature of the ocean geothermal brine renders it particularly effective at leaching such metals and minerals out of the rock. The proposed ocean geothermal system will remove metals and minerals from the geothermal brine while it is in the heat exchanger.

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 the third 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 of the first innovation above. The nuclear industry has promoted the development of solid oxide electrolysis 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 in 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 (by microfiltration or reverse osmosis) to 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. Very recently, scientists at Lawrence Berkeley National Laboratory and Argonne National Laboratory have worked together to develop hollow nanoscale frameworks of platinum and nickel, which use 85% less platinum and provides more than 30 times as much catalytic activity as existing catalyst structures. This new technology has already demonstrated high durability, showing no decrease in activity after 10,000 cycles of operation. (Matulka, 2014.). 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). 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 petroleum. This change will create a unified energy industry in which geothermal energy, with an availability factor of over 90%, will provide inventories of transportation energy (as petroleum does in current industry practice) and become 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 needing to build the massive amounts of bulk electricity storage that would otherwise be required and that is currently being considered, although massive amount of bulk storage may have unexpected and detrimental consequences. (Carson and Novan, 2012.).

5. IMPACT ON ENERGY PROBLEMS

The ocean-floor geothermal generating station, capable of generating 100 MW_e, is projected to have, once the technology matures, a capital cost (including financing) of $1.365 billion and an operating cost of $7.16 million per year. Assuming a life span of thirty years and an average availability of ninety percent (90%), the levelized cost of electricity from the station is projected to be $0.067 per kilowatt-hour. These projections were calculated in large part on the basis of data provided for the Renewable Energy Policy Project ("REPP"), which in turn relies on World Bank Group data from 1999. (Shibaki, 2003.). The cost of the power plant was projected by calculating the mid-point of the cost of power plants as reported by REPP for large plants using high-quality resources ($925 per kilowatt), increasing that amount by fifty percent to provide for the added cost involved in modifying the power plant for operation on the ocean floor, and then adding an additional ten percent to reflect inflation in costs for a total of $153,000,000 for the 100 MW_e power plant. The capital cost of the reservoir, however, was calculated on the basis of an estimate by Fridleifsson. To support a capacity of 100 MW_e, it was projected that four production wells, with a production of 50 MW_t each (assuming a supercritical power plant efficiency of 50%), and one injection well are required. Fridleifsson has estimated that the cost of drilling a conventional well to a depth of 2,000 meters in Iceland is currently $5,000,000. It is commonly assumed that a well drilled offshore can cost up to ten times as much as an equivalent well drilled onshore. On that basis the offshore wells would cost up to $50,000,000 each, for a total well cost of $250,000,000. The cost of exploration was projected by comparing the mid-point of the cost of exploration as reported by REPP for large plants using high-quality resources ($250 per kilowatt) to the mid-point of the cost of the reservoir reported by REPP for such plants ($375 per kilowatt) and multiplying the ratio thus established (*i.e*., two-thirds) times the $250,000,000 projected above to estimate exploration costs of $167,000,000. Thirty-year financing for all of the above costs at an after-tax seven percent cost of capital is projected to cost $795,000,000. Operating and maintenance costs were projected by calculating the mid-point of operating and maintenance costs as reported by REPP for large plants ($0.0055 per kilowatt-hour), increasing that amount by fifty percent to provide for the added costs involved in operating the power plant on the ocean floor, and then adding an additional ten percent to reflect inflation in costs for a total of $215,000,000, assuming that the power plant operates for thirty years at an availability of ninety percent. If the power plant operates for thirty years at an availability of ninety percent, 23,668,200,000 kilowatt-hours of electricity is produced and dividing that number into the total of $1,580,000,000 for the above capital and operating costs yields a levelized cost of $0.0666 per kilowatt-hour. Such a cost is competitive with the projected levelized cost for conventional combined cycle gas-fired plants and advanced combined cycle plants, and lower than the projected levelized cost for conventional coal-fired plants, advanced coal plants, conventional combustion turbine gas-fired plants, advanced combustion turbine plants, advanced nuclear plants, wind plants, solar photovoltaic plants, solar thermal plants or hydroelectric plants estimated for generating technologies to be brought on line in 2016. (*See* U.S. Energy Information Agency, 2011.) This projected cost rises from $0.067 to $0.073 per kilowatt-hour if $0.0059 is added for "transmission investment" (which is the amount estimated by the EIA for transmission investment, in the Outlook cited above, for off-shore wind energy). It should be noted that the capital and operating costs of the initial stations are likely to be higher than the foregoing projected costs, and that the projected costs are expected to be characteristic of the stations after the learning achieved from building and operating the initial stations.

The economics of the proposed system described above would be improved by the potential additional revenues resulting from the recovery of valuable metals and minerals from the supercritical geothermal brine.

The systems described above can create a unified energy industry that provides the energy required for the grid and the energy needed for transportation entirely from renewable resources, on a balanced and sustainable basis.

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