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A new assessment of combined geothermal electric generation and desalination in western Saudi Arabia: targeted hot spot development

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ABSTRACT

High heat flow associated with the tectonic spreading of the Red Sea make western Saudi Arabia a region with high potential for geothermal energy development. The hydraulic properties of the Precambrian-age rocks occurring in this region are not conducive to direct production of hot water for heat exchange, which will necessitate use of the hot dry rock (HDR) heat harvesting method. This would require the construction of coupled deep wells; one for water injection and the other for steam recovery. There are some technological challenges in the design, construction, and operation of HDR geothermal energy systems. Careful geotechnical evaluation of the heat reservoir must be conducted to ascertain the geothermal gradient at the chosen site to allow pre-design modeling of the system for assessment of operational heat flow maintenance. Also, naturally occurring fractures or faults must be carefully evaluated to make an assessment of the potential for induced seismicity. It is anticipated that the flow heat exchange capacity of the system will require enhancement by the use of horizontal drilling and hydraulic fracturing in the injection well with the production well drilled into the fracture zone to maximum water recovery efficiency and reduce operating pressure. The heated water must be maintained under pressure and flashed to steam at surface to produce to the most effective energy recovery. Most past evaluations of geothermal energy development in this region have been focused on the potential for solely electricity generation, but direct use of produced steam could be coupled with thermally driven desalination technologies such as multi-effect distillation, adsorption desalination, and/or membrane distillation to provide a continuous source of heat to allow very efficient operation of the plants.

Keywords: Renewable energy desalination; Geothermal energy; Electricity generation; Hot dry rock thermal energy harvesting; Saudi Arabia

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1. Introduction

Development of renewable energy resources is becoming more attractive even in energy-rich countries, such as Saudi Arabia, Oman, and Algeria as the price of oil becomes greater. While Saudi Arabia is considered to be energy independent and is a major exporter of oil, replacement of conventional oil-fired power plants (with associated desalination facilities) with renewable energy sources of generation is attractive based on lost opportunity cost and environmental considerations. Current Saudi oil production is roughly 10 million barrels/d. Domestic use of oil for power generation could rise to 3 million barrels/d of oil equivalent within the near future [1]. Therefore, Saudi Arabia has set a goal of obtaining half of it power needs using renewable energy sources by 2020. Also, the current lost sales opportunity cost is staggering. For example, a simple savings of 1 million barrels/d of oil would generate a revenue stream of at least $80/barrel net of the production cost which would contribute $80 million/d or $29 billion/year to income. A recent publication has suggested that the current Saudi Arabia system of granting subsidies for internal use of electricity and power will create financial discord in the Kingdom within 12 years [2].

Geothermal energy development in Saudi Arabia has been discussed in a number of assessments, but primarily within the context of electricity generation without considering potential efficiency links with desalination [3–7]. An assessment of power consumption conducted by the International Energy Agency in 2005 suggested that 10% of the total power consumption in Saudi Arabia was used for desalination and power generation [7]. Stand-alone geothermal powered desalination has also been considered at a number of locations and a few low-enthalpy systems have been constructed and are operating [8–16]. Another concept using combined cycled solar and geothermal powered adsorption desalination (AD) has also been proposed [17]. A new concept developed by Missimer et al. [18] links electricity generation and multiple desalination processes to produce greater joint efficiency by conserving latent heat extracted from a geothermal source. This new concept has direct application to Saudi Arabia which contains a region exhibiting high heat flow rates and great potential for geothermal energy harvesting.

It is the purpose of this research to explore the potential for combined geothermal electricity generation and desalination in western Saudi Arabia where the Red Sea rift zone contains the necessary heat flows to allow economic development of geothermal energy. Heat flow is not evenly distributed in this region and will require a targeted approach to provide the most cost-effective development scheme.

2. Methods

Information on the geothermal resources of Saudi Arabia has been compiled from the literature to assess the potential for high-temperature generation of electricity coupled with desalination. Also, the potential development of lower temperature geothermal energy was assessed for potential to power thermal desalination systems that require lower operating temperatures, such as an AD and membrane distillation (MD).

An assessment of the heat and energy requirements of various desalination processes was made to develop various hybrids that would increase the overall efficiency of heat and electric utilization. The desalination system type was matched to the potential temperature of the heat that could be harvested within Saudi Arabia.

3. Background

The Red Sea is an active tectonic region that contains a spreading center (rifting) where oceanic crust is being created with associated areas of high heat flow (Fig. 1). Active rifting of the continental crust along the central axis of the Red Sea began in the early Miocene at about 20 Ma followed by active oceanic crustal spreading beginning at about 5 Ma [19,20]. The tectonic activity in the region was accompanied by volcanism in Ethiopia, Sudan, and Saudi Arabia beginning in 31 Ma [21] and continuing to 1256 AD at Al Madinah [22].

Very recent upward movement of the molten rock caused the intrusion of a dyke at Harrat Lunayyir in northwest Saudi Arabia in 2009 [23]. A number of volcanic vents occur in the Harrat region of western Saudi Arabia, many containing fumaroles venting hot gas.

Despite the fact that the Red Sea and its margins are an area of relativity high heat flow which exceeds the world mean (about 50 mW/m^2) value by 2–10 times, the heat flow rates extending from the Red Sea rift zone rapidly decline away from the axis and inland away from the shoreline. Makris et al. [24] report that heat flow density ranges from as high as 500 mW/m^2 along the central rift of the Red Sea to about 140 mW/m^2 about 65 km to the east of the rift near the shoreline in Saudi Arabia (data from a northern transect). A measurement made in a well located within the coastal plain of the southern Red Sea near the Saudi Arabia–Yemen border showed a heat flow

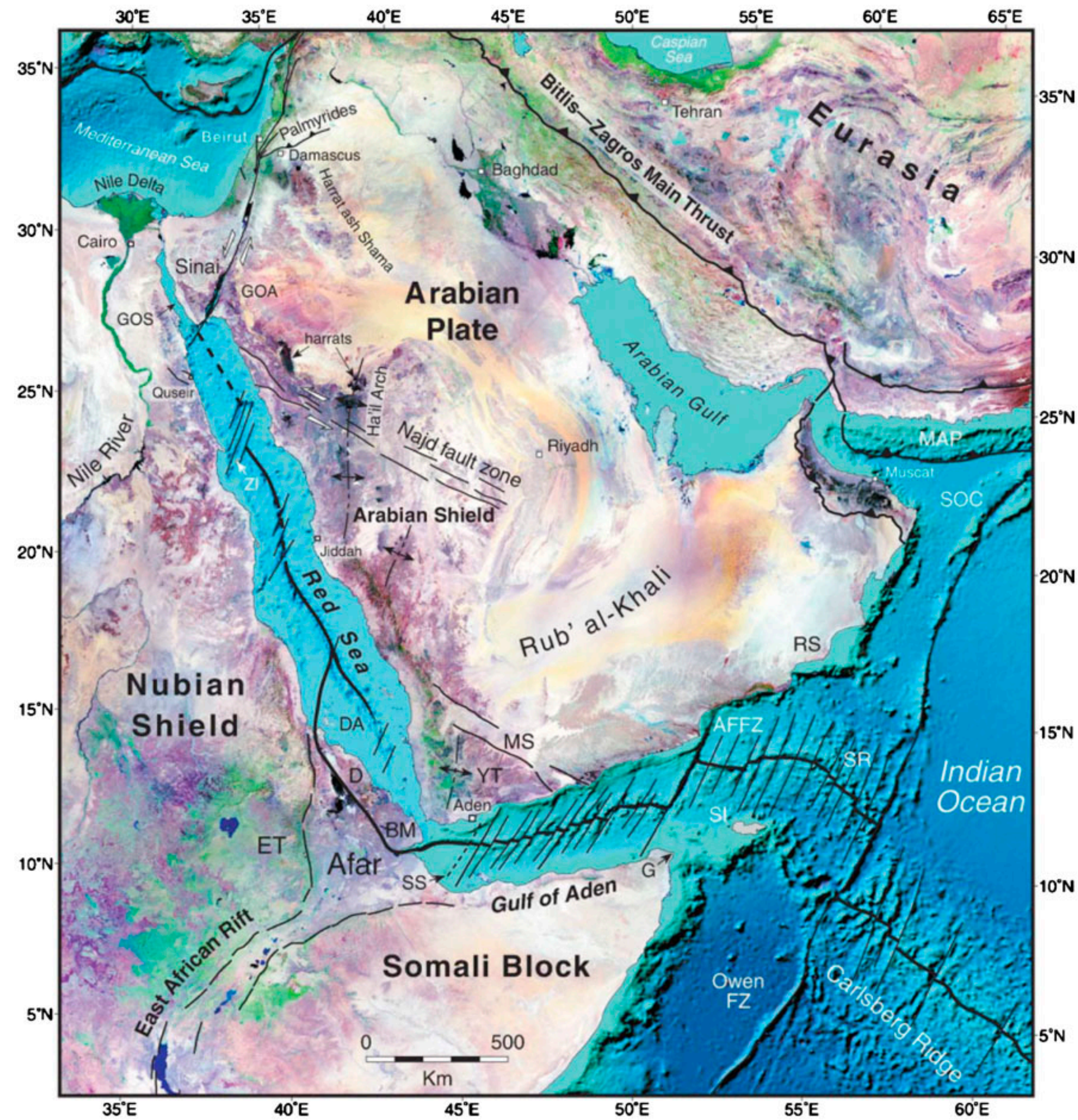

Fig. 1. Map showing the regional tectonic features involving the Red Sea. The heat flow maximum in the Arabian Peninsula lies along the east coast of the Red Sea (from Bosworth et al. [19]).

density of 111 mW/m^2 [25]. A heat flow density profile from the Red Sea rift at a location seaward of Ad Darb (17.7°W, 42.3°N), located south of Jeddah, to Riyadh (24.3°W, 45.6°N) showed three heat flow density zones with an average of 168 mK/m^2 in the rift region, 113–126 mW/m^2 on the Red Sea shelf and coastal plain, and 33–42 mW/m^2 within the Precambrian Shield [26]. Barnard et al. [27] reported heat flow values at two on land locations in coastal Saudi Arabia near Shoaiba and Yanbu. The estimated heat flow values at those site were >126 mWm^2 and between 84 and 105 mWm^2, respectively. Gettings [26] also estimated that the temperature at the base of the continental crust at a depth of 40 km to be about 450°C. Since the crust is thinner closer to the spreading center, the depth to base of continent crust is less and the temperature is likely to be much higher.

The geothermal gradient in the coastal plain of the Red Sea of Saudi Arabia and Egypt can be estimated from bottom-hole temperatures of oil wells and test wells. Based on the literature, the estimated range of the geothermal gradient in the coastal plain of Saudi

Arabia is 27–46˚C/km [27–29]. Barnard et al. [27] reported high flow ranges onshore at Shoaiba and Yanbo at between 45.6–54.7˚C/km and 36.4–45.6˚C/km, respectively. The measured shallow groundwater temperature along the Red Sea coastal area is about 28˚C and using the mid-point of the heat flow range, the estimated bottom-hole temperature at 3 and 5 km below surface would be between 178 and 278˚C at Shoaiba and 151 and 233˚C at Yanbu. However, there are areas where the shallow subsurface is much hotter based on recent volcanic activity, such as the region near Al Medinah (e.g. Harrat Lunayyir) [17].

Most of the "high temperature" geothermal areas are located within the coastal plain and active volcanic region of western Saudi Arabia [30–35]. Some thermal springs associated with the rift-relation geothermal activity produce moderate temperature water in a range from 31.4 to 75.5˚C [4]. These springs are located at Gizan and Al Lith in southwestern Saudi Arabia. However, some interior cratonic "hot spots" produce hot water from aquifers. An example occurs at Riyadh, where at a depth of about 1,200 m hot water is produced from a large number of wells that feed a series of brackish water reverse osmosis plants [36,37]. The water temperature from the aquifer ranges from 60 to 70˚C.

4. Results

4.1. Geothermal energy development method (high-temperature steam production)

Coastal plain sediments and the Precambrian shield rocks of western Saudi Arabia generally have an overall low hydraulic conductivity, and are not water bearing. So, geothermal heat harvesting using a hot groundwater system is not feasible. However, the high heat flow and temperature of the deep rock types can be used to develop a variety of hot dry rock (HDR) geothermal heat harvesting systems [38–41].

All HDR geothermal systems require the construction of an injection well and a recovery well. In some HDR systems, the thermal reservoir rock contains a natural fracturing pattern, so that cool water pumped under high pressure will migrate through the natural fractures, become heated, and travel into a recovery well as superheated water (Fig. 2). To increase the surface area of fractures and the hydraulic conductivity of the thermal reservoir rock, a horizontal offset well can be drilled that connects either directly or indirectly with a recovery well. The horizontal offset segment of the well can be hydraulically fractured and the vertical open zone of the recovery well would also be hydraulically fractured (Fig. 2). Hydraulic

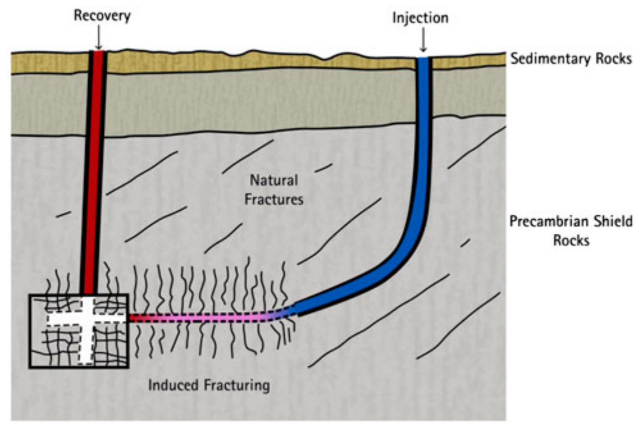

Fig. 2. Schematic of a HDR geothermal energy collection system (Missimer et al. [18]).

fracturing collapses the open borehole and fills it with rock rubble. The artificial fracturing of the boreholes causes the injected water to follow a tortuous path, therefore promoting heat transfer from the rock to the water and allowing the water to move through the fractured rock with reduced resistance compared with using natural fractures. A careful balance must be achieved between the hydraulic conductivity of the fracture zone, the heat exchange rate, and the vertical thermal conductivity of the reservoir rock. If the heat is removed too quickly, then the reservoir rock surrounding the heat exchange area would cool and eventually the system would fail. If properly designed, the heat collection system can be sustainable if the heat removal is less than the heat replenishment.

An important issue in the use of HDR geothermal technology is the cost of the wells used for harvesting heat which is primarily dependent on their depth and the heat reservoir properties. Obviously, having high heat flow, a high natural geothermal gradient, and a high thermal conductivity of the rock are all desirable properties. Therefore, a key issue is locating HDR geothermal systems in the proper areas which in the case of Saudi Arabia would be in the western provinces near the Red Sea and possibly near to recent volcanic activity (Harrat areas) where rock at shallow depths is quite hot. If the desired bottom-hole temperature is 300˚C, the estimated depth of the wells in the Saudi Arabia coastal plain based on an average surface temperature of 25˚C would range from about 6 to 10 km using the estimated normal range in the geothermal gradient.

Locations near the lava flows (Harrats) in western Saudi Arabia are the most likely "hot spots" that could have the most desirable properties. For example, the intrusion of molten rock to form a dyke at between 5 and 10 km below surface produced an area with very high heat flow with the fluid rock having a likely temperature of about 1,200˚C based on typical temperatures of alkali olivine basaltic magmas [42]. An HDR system located near a high-temperature intrusion could be constructed to a very shallow depth, perhaps <1 km. However, the location of proposed HDR geothermal systems must be carefully evaluated to assess the potential for induced seismicity that occur due to high-pressure injection of water into natural fractures that could begin to actively slip, resulting in minor earthquake generation [43]. Also, there is a limit concerning the ability to construct wells in rocks that have a temperature above 374˚C which is the supercritical temperature for water. Geothermal wells have been drilled in Japan and Italy to depths ranging from 4 to 5 km with bottom-hole temperatures well above supercritical [44]. However, water above the supercritical temperature is highly reactive and tends to dissolve silica and other minerals which could create scaling problems in surface facilities. Therefore, Missimer et al. [18] suggested a steam temperature of 180˚C from the recovery well which would not require a borehole being constructed below a bottom-hole temperature of 300˚C. Many deep oil wells have been drilled into rock systems having this temperature or a higher one and geothermal wells have been drilled to depths ranging from 4 to 5 km with temperatures above supercritical or 374˚C [14].

A map showing the potentially most productive locations for high-temperature geothermal energy development in Saudi Arabia is given in Fig. 3. The area near Al Madinah is well suited for geothermal development that could be used for electricity generation. However, to achieve an optimal link between geothermal energy development, electricity development, and desalination, the facility would be most effectively located near the Red Sea shoreline. Some type of test drilling program to measure geothermal gradients would be quite useful is determining the optimum location of the site.

Fig. 3. Locations of the harrats in Saudi Arabia that have high potential for geothermal energy development (modified from the Saudi Geological Survey).

4.2. *Linking electricity generation with thermal desalination*

Typical geothermal powered power generation plant harvest steam with a single or perhaps two passages through the turbine system with subsequent venting "cool" steam to ambient. It has been suggested that the integration of thermal desalination processes with electric generation could be accomplished by taking the waste steam and using it as the heat sources for multi-effect distillation (MED) and AD based on conservation of latent heat with a downstream reducing temperature [18]. The thermal desalination processes would be designed to use progressive lower temperature steam.

Choice of the downstream desalination process arrangement would be dependent on the stable temperature of the produced steam. For example, if a very hot thermal reservoir would be the heat source with a temperature near supercritical (374˚C), then an arrangement could be a single pass through the electric turbine with the first thermal desalination process being multi-stage flash desalination coupled downstream with MED, AD, or perhaps MD. A moderate temperature steam, such as 180˚C proposed by Missimer et al. [18], could be used in a single- or dual-pass system of electric generation coupled to MED, AD, and or MD. A "low" temperature steam could be used to do a single-pass electric generation system coupled to AD and MD. The design of the system would be based on system energy balance modeling and on optimization of the process steam to maximize usage of latent heat. Another consideration is the capacity of the overall system to provide a scale that creates economic benefit competitive with more conventional electric/desalination systems.

4.3. Low-temperature geothermal energy development and brackish water desalination

Coupled electric generation and desalination of low-temperature spring water in Saudi Arabia cannot be accomplished based on the springs studied [4]. However, the temperature range of the spring water is 31.4–79.5˚C with an average of 54.9˚C with a discharge rate of 20 L/min.

Low-temperature seawater desalination could be coupled with a shallow HDR geothermal harvesting system to produce recovered water temperatures in the range of 60–90˚C. These systems could operate in a stand-alone mode not coupled with power generation. The desalination process of choice may be AD or MD. Feasibility of operating high-capacity desalination systems (100,000 m^3/d) using these technologies would have to be assessed based on well construction costs and scale factors. A combined-cycle solar-geothermal system linked with AD has been proposed previously [17]. Low-enthalpy geothermal powered desalination systems have been designed, operated, and evaluated in the past, but mostly for low-capacity facilities [11,12,45–50].

5. Discussion

5.1. Development of high-temperature HRD systems

Western Saudi Arabia contains an abundant supply of high-grade geothermal energy based on natural heat flow rates 2–10 times higher than the global average. The key issue is how to most economically develop these resources to meet all current and future power requirements of western Saudi Arabia, and with transmission, power most of the country. Geothermal electricity generation is a base-load source and is not interruptible compared with other renewable energy sources, such as solar or wind. Electric power generation at a large scale can be accomplished using HDR heat harvesting systems located in appropriate areas. Also, since a significant quantity of electricity in Saudi Arabia is used to desalinate seawater, it is logical to co-locate and integrate desalination systems with electrical generation facilities to achieve improved overall efficiency and two revenue streams from HDR installations.

5.2. Geothermal energy exploration

HDR heat harvesting systems for electric generation could be located at "hot spots" within the coastal plain of Saudi Arabia to produce the least costly systems with lower well construction costs. Generation of electrical energy can be accomplished in virtually any area based on the ability to transmit the power. However, there are a number of other considerations, especially cooling, that require careful planning and design. Water cooling is much more effective compared with air cooling, so there may be an advantage of locating a facility near the sea to obtain water for cooling. Also, co-location with desalination plants will require additional cost-benefit analyses based on transmission considerations for the produced electricity, the raw seawater, and the product water.

Various remote sensing methods could be used to assess heat flow along the coast of western Saudi Arabia to locate true "hot spots" where natural heat flow is higher than background. These methods would include satellite imaging and perhaps some ground-based instrument readings. The bottom-hole temperature of existing water wells could be measured in certain cases. Seismic wave behavior monitored during earthquakes could be used to some degree to search for any liquid magma. A goal would be to create a heat flow map of the coastal zone.

Once a heat flow map has been made of the coastal zone of Saudi Arabia, it is proposed that some theoretical modeling be completed. Then, geothermal energy exploration should be conducted using geophysical measurements, such as gravity surveys, deep resistivity surveys, and magnetotelluric measurements. A first phase would be to construct deep exploratory wells adjacent to existing power and desalination facilities to assess the geothermal gradients and to estimate the cost of system development. Detailed heat flow and petrophysical data should be collected from these test holes. On sites where there appears to be high potential for HDR heat harvesting, the test hole should be enlarged and converted to a possible recovery well for future use. Flexibility in the design of the testing program would allow this option to occur (e.g. construct and case the upper part of the borehole with a large casing diameter to the top of the hard rock section, perhaps 100–300 m). This would save considerable cost as systems are designed and constructed. A second phase of exploration could be focused on high heat flow locations in the coastal zone located closest to urban areas that have combined electric and potable water requirements.

5.3. Full integration of HDR geothermal energy harvesting systems with electric generation and desalination

Full integration of geothermal powered electricity generation and desalination should be accomplished using the conservation of latent heat concept developed by Missimer et al. [18]. The linked desalination processes should consider only the most energy efficient or combinations of processes allowing downstream heat usage and recycling. Seawater reverse osmosis facilities could be co-located with thermal processes to further improve overall combined electric–water production efficiency [50].

6. Conclusions

Western Saudi Arabia is an ideal location for the development of HDR geothermal energy harvesting systems with natural heat flows 2–10 times greater than average on the Earth's surface. HDR geothermal energy harvesting has been evaluated for primarily electricity generation in the past and is relativity expensive based on a pure cost/kilowatt-hour (kWh) basis. However, when linked with desalination, the overall economics of the combined revenue streams makes geothermal energy development more attractive. Also, past cost analyses of geothermal electricity generation have focused on strictly the cost/kWh and not on issues such as greenhouse gas emissions and carbon footprint. A life-cycle cost analysis on the total system using a geothermal energy source, including electricity generation and desalination would be quite competitive and would be lower than use of conventional hydrocarbon powered generation systems. The true cost of environmental protection and lowering of greenhouse gas emissions is difficult to assess, but would add to the fundamental economic viability of the system.

Based on the existing data found from on-land sites in western Saudi Arabia, the area near Shoaiba shows a high potential for geothermal energy development near an existing combined electric generation and desalination facility. With a possible bottom-hole temperature of 278°C at a depth of 5 km, combined with high heat flow, this area appears to be ideal for future geothermal exploration.

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