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

A review of the Geothermal Resources of Saudi Arabia: 2015-2020

Lashin A.[1,2], Chandrasekharam, D.[3], Al Bassam, A.[4], Al Arifi, N[5]. Rehman, S.[6] and Al Faifi, H.[5]

[1] King Saud University, College of Engineering-Petroleum and Natural Gas Engineering Department, Riyadh 11421-Saudi Arabia.

[2] K.A.CARE Energy Research and Innovation Center in Riyadh.

[3] Department of Civil Engineering, Indian Institute of Technology Hyderabad, India 5502285.

[4] National Center for Water Research and Studies (NCWRS), MEWA, Saudi Arabia.

[5] King Saud University, College of Science -Geology and Geophysics Department, Riyadh 11451 - Saudi Arabia.

[6] Center for Engineering Research, King Fahd University of Petroleum and Minerals, KFUPM BOX # 767, Dhahran – 31261, Saudi Arabia.

arlashin@ksu.edu.sa

Keywords: Geothermal Resources, Direct Utilization, Power Generation, Saudi Arabia.

ABSTRACT

The renewable energy, including geothermal resources, occupies a very advanced rank in the priorities of the Saudi 2030 promised vision document. Some aspect of power generation based on wind and solar renewable resources are now in use, however, the geothermal power plants are not yet installed in Saudi Arabia. It is planned to add 30 gigawatts of generating capacity to the electricity grid and to accommodate all types of energy generations by the end of 2020. According to the 2030 vision of the Saudi Arabia, the country is going to move gradually from depending mainly on fuel energy to renewable and low-carbon forms of energy by the end of the year 2030. So it has become clear that the KSA is moving ahead with investments in renewable energy, nuclear power and other alternatives to fossil fuels so that it could use its vast oil reserves for other goods, such as plastics and polymers. Saudi Arabia is enriched by several types of hydrothermal geothermal resources especially at the western and southwestern parts along the Red Sea coast. Some aspects of low geothermal applications are economically viable in KSA and already in use i.e. swimming pools, refreshment places, and medical purposes. The geothermal potential of the volcanic eruptions at the western of the Saudi Arabian shield 'or what is called Harrat' is considered a sizeable opportunity for developing geothermal power as it covers more than 80,000 km^2. The high enthalpy resources of Harrat areas can be used for power generation if a good location is selected and more accurate geothermal resource assessment is done. A good occurrence of the high generating granites (Midyan granites) is encountered NW of the Saudi Arabian shield. It is estimated to yield a heat production in the range from 15 to 134 $\mu W/m^3$. Geothermal energy can be used also for desalination at Saudi Arabia since the current cost of desalinated water, processed through conventional energy source, with subsidy is 0.03 US$/$m^3$ which is less than the average cost in many places in the world (i.e. US$ 6/m^3). In general, the future of geothermal renewable energy in Saudi Arabia is promised, however a more detailed geological/geophysical exploration work and resource assessment is needed to better investigating these resources.

1. INTRODUCTION

At present, the Kingdom of Saudi Arabia (KSA) relies largely on hydrocarbons to fuel power generation, burning up to 680,000 barrels of oil per day, which prevents the resources from being used for export or downstream processing. The accelerated drive into renewable energy is part of the government's broader plan to boost the economy by freeing up more hydrocarbons for export. As the largest oil producer in the world, KSA has plans to become completely powered by renewable and low-carbon forms of energy. Thus, in the past few years, it has become clear that KSA is moving ahead with investments in renewable energy, nuclear power and other alternatives to fossil fuels so that it could use its vast oil reserves for other goods, such as plastics and polymers. Although there is no impending energy problem for KSA in the near future, there has been a strategic tendency in the past few years to substitute hydrocarbon-related energy resources (oil and natural gas) with other renewable sources to free up additional crude oil for export. Renewable energy has several unique characteristics that should be considered when comparing these resources to oil-based alternatives (Hussein et al. 2014, Lashin and Al Arifi 2014; Chandrasekharam et al. 2016a).

Saudi officials believe that oil is more precious underground than as a fuel source. In their promised vision of 2030, they put a long term strategic plan to replace fossil fuels and to use alternative energy sources. This reflects the goal of future energy planning for the KSA and the current policy shift from dependence on fossil fuels to using alternative renewable and sustainable energy resources. Therefore the investment in renewable energy generating capacity is a key to this process, particularly given the Kingdom's rising energy demand; in 2017 energy consumption stood at 298,000 GWh, according to the General Authority for Statistics, with the government expecting this figure to treble by 2030. This is also being supported by a 2018 government decision to raise prices of petrol and electricity, a measure that lowered petrol consumption by 8% last year compared to 2017. Khalid Al Falih, the minister of energy, industry and mineral resources, says these price reforms, combined with the inclusion of more renewables, should see domestic hydrocarbons energy consumption fall by 1.5-2m barrels of oil equivalent per day by 2030 (Oxford Business Group, 2019).

Currently, there is no specific regulation or policies on renewable energy technologies (RETs) usage in Saudi Arabia, but the government have set an ambitious strategy plan to adopt RETs on a wide scale (Mosly and Makki, 2018). On April 17, 2010, King Abdullah City of Atomic and Renewable Energy (KACARE) was established by a Royal order with a mandate to contribute to sustainable development in the KSA in industries related to renewable energy (wind, biomass, solar, tidal and geothermal) and to atomic energy for peaceful purposes. All initiatives are developed on a sustainable economic framework that ensures efficiency and maximize impact on the energy value chain in Saudi Arabia. Among the different types of renewable resources, geothermal power has a unique role in terms of power energy owing to its high conversion coefficient (>95%) compared to other renewable resources (Chandrasekharam et al. 2016a).

The western coastal parts of the Arabia Shield of the KSA encounter a complex system of geothermal resources due to the tectonic or volcanic activity associated with the opening of the Red Sea/Gulf of the Suez Rift in this area (Boulos, 1990, Lashin, 2007, 2012; Chandrasekharam et al. 2014, 2015a,b, 2016a). The thermal waters reach the surface through a complicated grid of structural elements, which follow the main tectonic elements associated with the regional Red Sea tectonics. Over the past few years, many investigators believed that the cost of the initial investment of geothermal energy for generating geothermal-based plants would be comparatively high relative to those of other renewable resources.

In the last ten years a comprehensive academic research has been done to investigate the geothermal resources of Saudi Arabia. Most of this work was funded by King Saud University (KSU) through the National Plan of Science and Technology (NPST) projects and Deanship of the scientific research (DSR)-Visiting Professor Program (VPP). Although this is the current case, still the potential of geothermal resources is largely unknown and needs more detailed and comprehensive work to study these resources, especially in the volcanic eruption regions, and to evaluate the country's economic reserves for possible energy production and domestic applications. With the exception of some direct low-grade geothermal applications, the utilization of geothermal energy in KSA, especially in terms of power generation, is still far from the economic scale.

2. GEOLOGIC SETTING & CLASSIFICATION

The western continental margin of Saudi Arabia experienced series of volcanic and tectonic events since 27 Ma, the period when the Arabia continent started drifting away from the main African continent due to the activation of the Red Sea rift. This phase was followed by extensive volcanic and plutonic activity along the western margin of SA. The volcanic activity is represented by volcanic centres with large volumes of basaltic and basaltic andesitic (Harrats). Most of the geothermal resources of Saudi Arabia are encountered along the western and south-western coast of the Red Sea (Fig. 1). It is represented by hydrothermal resources encountered mainly at Jizan & Al-Lith areas and the hot dry rocks of the Harrats. The geothermal resources of the KSA can be categorized as low, medium and high enthalpy resources.

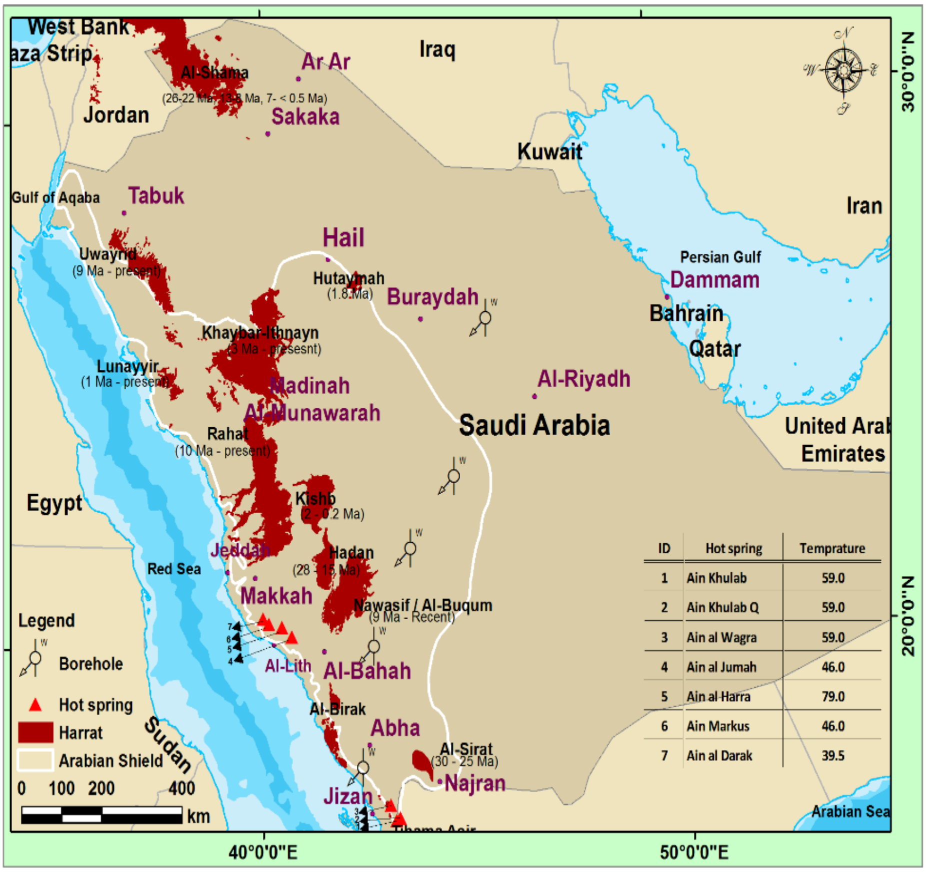

Figure 1: Major geothermal features in Saudi Arabia. Volcanic fields (filled red polygons), hot springs (filled red triangles), heat flow measurements (Gettings 1982).

2.1 Low-Enthalpy Resources

Sedimentary aquifers represented by deep-seated aquifers encountered in thick sedimentary basins in the eastern part of the KSA. Low-enthalpy resources are confined, and their geothermal potential is represented by the normal geothermal gradient. They can only be accessed through deep oil wells and access temperature up to 70^{o}C.

2.2 Medium-Enthalpy Resources

Hydrothermal systems - hot springs encountered along the western and southwestern coast and represented by shallow hot springs of hot surface water (Al-Lith and Jizan areas). Medium-enthalpy resources are unconfined targets with direct access to hot subsurface anomalies through an open network of active faults and fractures. The hydrothermal fluid circulation appears to have started during the onset of subduction process along the coast together with the volcanic episodes. Examples of these geothermal manifestations are found around Al Ardah, Al Khouba, Bani Malik, Ain Khulab and Al-Lith areas, as thermal springs with surface temperatures varying from 31 to 96 °C and a flow rate of 5 to 20 L/m. Preliminary assessment was made on the geothermal potential of Jizan and Al-Lith geothermal sites (Chandrasekharam et al. 2015a).

2.3 High-Enthalpy Resources

Basaltic lavas, Harrats and granites that constitute approximately 80,000 km² of lava fields, known as Harrats. They consist of volcanic eruptions, largely basaltic in composition, that extend along the coastal part of the Red Sea in the Western of Saudi Arabia. These harrats covered a large part of the paleo-channels along the west coast giving rise to hot aquifers below the Harrats. Steam from the host aquifers and steam from the hot lavas resulted in the occurrence of fumaroles at several places within Harrats along the western margin. The geothermal gradient recorded in the Harrats is >90 °C/km (Coleman et al. 1983; Chandrasekharam et al. 2016a). The Harrats of Khaybar and Rahat are believed to have the highest heat flow and enthalpy. Fumarole activity is also observed in Harrat Khaybar. Harrats are composed of alkaline olivinitic basalts with a partially solid surface; they are exposed at both the surface and the subsurface, forming naturally roofed feeder channels of lava flows, known as “lava tubes". Local collapses of the roof along its length provide access. Inside, lava stalactites, stalagmites, lava levees and channels may be preserved. Most lava tubes occur in basaltic matrix, which is the most fluid type of molten volcanic rock (Roobol et al. 2002).

2.4 High Heat Generating Granite

It includes the high production radioactive granite (pre- and post-orogenic granites) that is enriched with high uranium, thorium and potassium concentrations and is located in the north and north-western parts of Saudi Arabia (Midyan and Haal granites). The heat generating capacity of this granite as estimated from the U, Th and K contents varies from 15 to 134 µW/m^3. The highest value is recorded by the Midyan granites which is located NW of the shield and occupying an area of 375 km^2 (Chandrasekharam et al. 2015b) (Fig. 2).

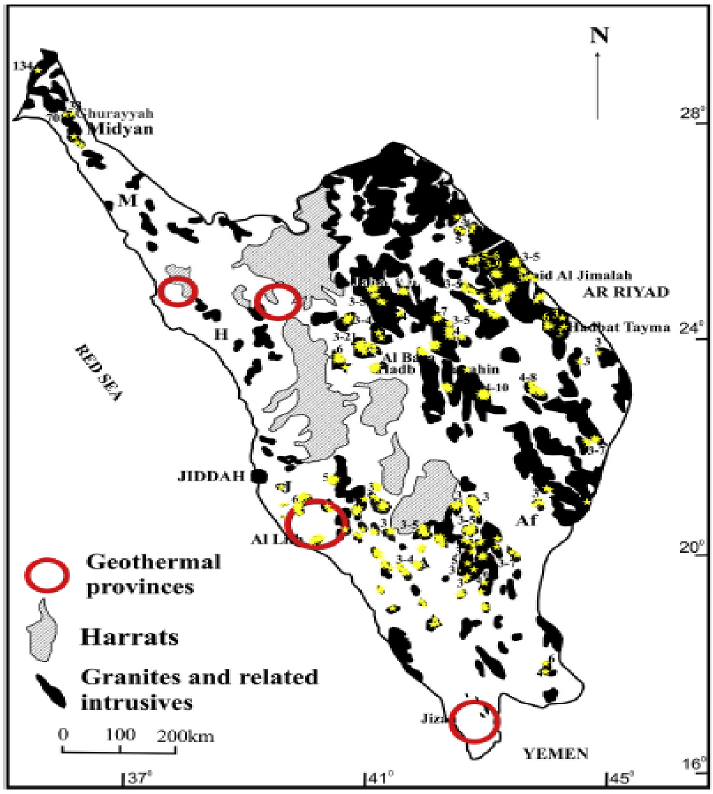

Figure 2: Geological map showing the different locations of the geothermal provinces, Harrats, high production granites (yellow stars with heat production values) in the Arabian Shield of Kingdom of Saudi Arabia (after Chandrasekharam et al. 2015b).

3. PAST/PRESENT DAY ACTIVITY

El Dayel (1988) investigated the hydro-chemical characteristics of the hot springs in the Jizan and Al-Lith regions by analyzing water samples from the hot springs. From 1992 to 2004 a more detailed work on the petrography, petrochemical composition and mineralogy of the Harrats was conducted by Roobol and Camp, 1991a,b & Roobol et al., 1995 & 2002, Pint 2006 and Pint et al. 2004). It is indicated that the Harrats of Ithnayn, Khaybar and Rahat, where some steam fumaroles were observed, are good 'high-enthalpy' locations that would be suitable for geothermal power production (Roobel at al. 2002). From 2005 to 2010, Rehman compiled all the geothermal information and activity as reported in the proceedings of the WGC 2005 and 2010 (Rehman & Shash 2005 and Rehman 2010). A more detailed geophysical survey, including seismic reflection and MT methods, was done by Lashin et al. 2013 at Wadi Al-Lith area. The first results are presented in the proceedings of WGC 2015. The analysis of seismic data indicated the Red Sea rift (NW-SE) and the transform faults (ENE-WSW) as the main structural players that control the movement of geothermal water. The MT survey showed that geothermal source is located deep at a depth of 2500 m (Lashin et al. 2015b).

From 2010 to 2014, a new academic era of geothermal projects was lunched by KSU to study the geothermal resources encountered in the western and southwestern regions of the KSA based on Landsat images and chemical and geophysical analyses (Lashin and Al Arifi 2010; 2012; Hussein e t al. 2013). A more detailed work with done by Prof. Chandrasekharam (Indian Institute of Earth Sciences-Bombay) with a group of scientists from KSU under the VPP program in the period from 2014-2019. The different geothermal systems along the western coastal parts of the Saudi Arabia and the high production granites, as well as the evolution of geothermal systems along the Red Sea in relation to the east African systems were investigated (Lashin et al. 2014; Chandrasekharam et al. 2015a,b, 2016a,b, and 2018).

More recently, Aboud et al. (2018) carried a more detailed geophysical survey on the Harrats area, with special emphasis to the volcanic field of Harrat Rahat, using magneto telluric method. The gathered data were analyzed using 3D inversion technique in order to image the subsurface resistivity setting. Figure 3 A-D shows the resistivity distribution in northern Rahat volcanic field at different depths of 1 km, 6 km, 15 km and 20 km where four major resistivity structures are indicated. A thick high resistive peak (red-color zone) began to appear at depth of 15 km and continue to a depth of 20 km at the northern-western part of Harrat Rahat (Fig. 3C). Since this peak is located approximately underneath the historical eruption, it can be considered good signature of a good geothermal reservoir of partial melting zones (Aboud et al. 2018).

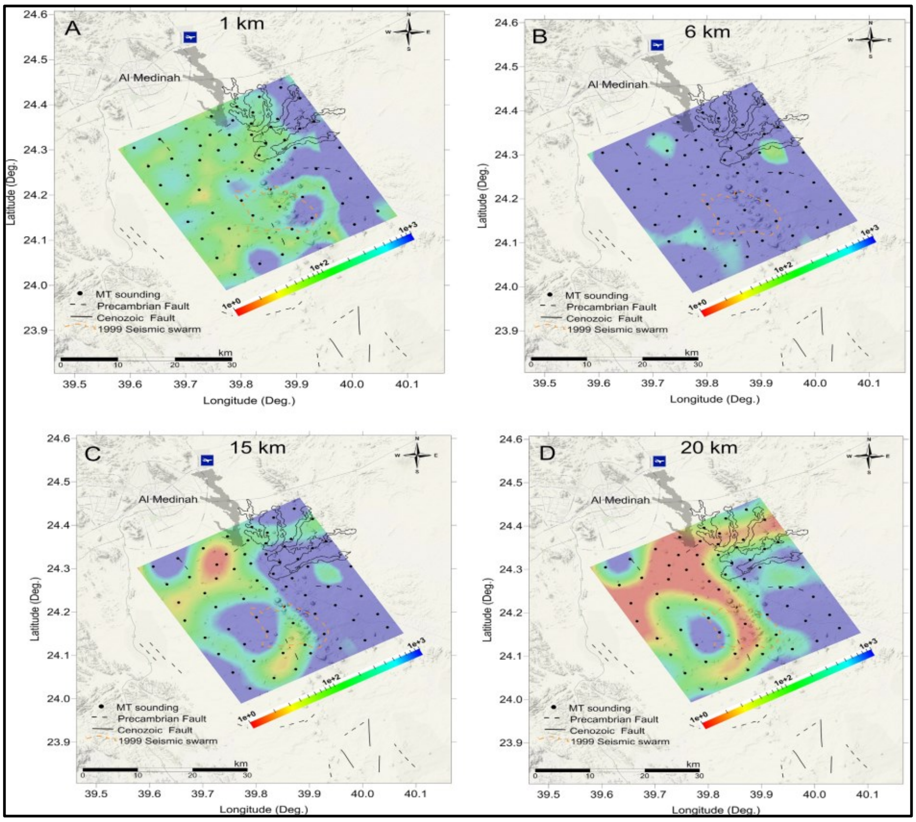

Figure 3: Resistivity distribution in northern Rahat volcanic field at different depths of A. 1 km, B. 6 km, C. 15 km and D. 20 km (after Aboud et al. 2018).

4. UTILIZATION OF GEOTHERMAL RESOURCES

If a good geothermal resource assessment is done, the geothermal resources of Saudi Arabia can be utilized in an industrial scale. It can be used for desalination, energy production, besides other low-grade direct applications.

4.1 Desalination

Saudi Arabia covers an area of 2.15 million km^2 and is the largest country in the Arabian Peninsula. Major part of the country is arid while a part of the coastal strip along the Red Sea enjoys semi-arid climate. Large part of the population lives in urban areas with access to water and sanitation. So for arid countries like Saudi Arabia the most efficient and cost effective method to obtain fresh water through desalination process is to adopt technology based on solar or geothermal energy sources (Ghaffour et al., 2014). Although the desalination plants generate electricity, the unit cost of the power is not cost effective compared to other energy sources that generate electricity (Ahmad and Ramana, 2014). Currently 33 desalination plants are in operation in Saudi Arabia under a governmental subsidy. The cost of this desalinated water is 0.03 US$/$m^3$ which is far less than the average cost of US$ 6/m3 that is being charged by countries across the world (Taleb and Sharples 2011, Chandrasekharam et al. 2016b).

4.2 High Heat Generating Granite (Enhanced Geothermal Systems)

The western Saudi Arabian shield hosts two distinct geothermal systems: the hydrothermal systems represented by hot springs and the Enhanced Geothermal Systems (EGS) represented by radiogenic granites that generate high heat due to the high concentration of radioactive minerals. 1 km3 of these peralkaline granite plutons that contain the highest content of uranium, thorium and potassium, can generate 79- 106 kWh of electricity for a period of 30 years (Somerville et al., 1994). Good example of high production KSA granite is that exposed in/around Midyan with a registered heat production value up to 134 $\mu W/m^3$. The power that can be generated from such granites using the established EGS technology is about 120 x 106 terawatt hour (Chandrasekharam et al. 2015b).

4.3 Energy Production

According to previous geothermal studies in other geothermal areas the available geothermal resources are sufficient for utilization on an economic industrial scale. In the case of high temperature geothermal systems, where the temperatures of the geothermal fluids exceed 150 °C, electricity can be generated using binary technology that is common in several parts of the world. It is anticipated that the fractured, Precambrian rocks are best suited for power applications due to their high temperature (Lashin and Al Arifi, 2010, 2014; Lashin et al. 2014, 2015; Chandrasekharam et al. 2015b, 2016). The large volcanic systems of the KSA Harrats should be a favourable candidate for geothermal power provided that the hosting crustal rift system is reasonably fractured and of dyke intensity sufficiently large to provide a classical high-enthalpy reservoir. Being close to the coastal parts of the Red Sea provides a continuous water supply and enables fast recharging for the geothermal reservoirs through structurally controlled subsurface feed zones.

At the regions of plate boundaries and rifting, where volcanic eruptions are located, the vertical permeability and magma intrusions allow the convective flow of heat and mass and thus the depths are relatively accessible and the temperatures are favorable for power generation (150-300°C). There are also on-land escarpment faults of the Red Sea coast, which host geothermal potential in fractures and can also be viable for power development. Thus, the entire coast of the Red Sea in the KSA may have good anomalies of geothermal potential, with additional potential in a wider area extending inland towards the Harrats and beyond (Grimur Bjornson, RG personal communication). Selecting an appropriate location for power development at the Harrat area should primarily be based on datasets obtained from surface exploration. Harrat Khaybar is the most interesting due to its wide range of extension and its proximity to a very densely populated area (Al Madinah Al Munwarah).

Figure 3: The partially solid surface of a molten lava at the Harrtas area (Roobol, 2002).

Harrat Khaybar is located north of Al Madinah Al Munwarah between 39° and 41° longitude E and 25° and 26° latitude N. It covers an area of 12,000 km^2, and its surface is mildly alkaline, with low sodium (Na) and potassium (K) content. The surface is composed of alkaline olivine basalt (AOB), hawaiite, mugearite, benmoreite, trachyte and comendite. The Khaybar lavas range in age from approximately 5 million years old to post-Neolithic and historic (Pint, 2006). Many lava tubes and caves are found in Harrat Khaybar. The most important of these is Dahl Rumahah, which is 208 m long. This cave is a flat, northwest-trending passage ranging from 1.5 to 7 m wide and 2.5 m high. A high level of radon gas is found in this cave, entering the cave through cracks in the floor (Fig. 3).

4.4 Low-Grade Applications

The most common low-grade applications are district heating (in winter) and cooling (in summer), various agricultural applications, medical and touristic purposes. Actually some direct low-grade geothermal applications are now in use is Saudi Arabia. A number of swimming pools, medical therapy, Spa and refreshment places are constructed at Bani Malik and Al Khouba-Jizan areas (Fig. 4). A figure of 44 MWt is given for the installed capacity for direct geothermal use as of 31 December 2019, with annual energy use of 152.89TJ/yr and capacity factor of 0.31 (Table 5).

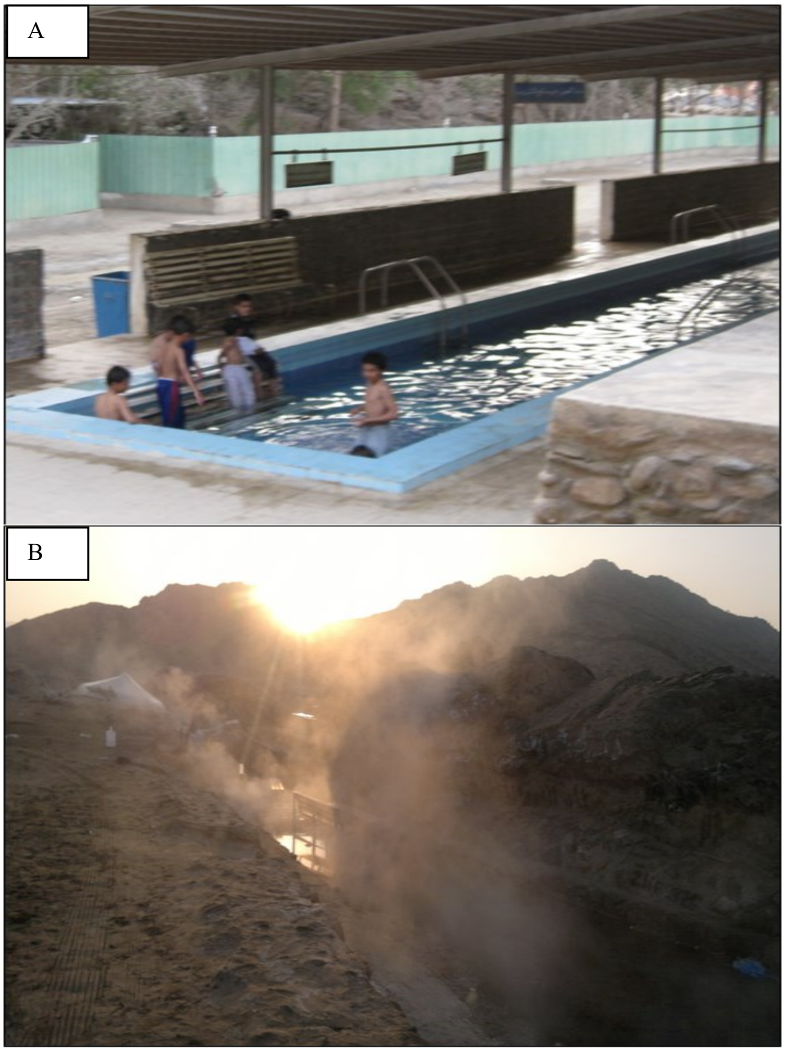

Figure 4 A and B: Direct application of geothermal energy at Saudi Arabia as represented by some swimming pools and medical therapy refreshment areas (Bani Malik and Ain Al-Harrah thermal waters).

5. DISCUSSION

Saudi Arabia total electricity generating capacity from the fossil oil is currently around 66 gigawatts (GW), split forty-sixty between oil and gas. While projections suggest slower growth in the future, peak electricity demand may still double by 2030. Saudi Arabia expects this year to launch several renewable energy projects, especially solar power plants, worth $7 billion. Turki Mohammed al-Shihri, director of the Saudi Renewable Energy Development Project Office, has claimed that bids will be issued for eight projects with a total capacity of 4.125 GW this year. The cost of these projects will be between five and seven billion dollars (Table 1). In addition, at the end of 2017, the Saudi Arabian government announced plans to construct two large nuclear power reactors. The original projections included 17 GW of nuclear capacity by 2040 to provide 15 percent of the power generated in Saudi Arabia. Plans for small reactors for desalination are well advanced on two fronts (Table 1).

The geothermal power plants are not yet installed in Saudi Arabia. The Saudi electric ministry has designed more advanced optimization and control technology system that could improve overall plant reliability and deliver operational and maintenance efficiency over the generating life of the facility. It is planned to add 30 gigawatts of generating capacity to the electricity grid and to accommodate all types of energy generations by the end of 2020, including the renewable ones; i.e. geothermal, solar, wind, etc. (Lashin et al. 2015a).

The geothermal potential of the Harrat is considered a sizeable opportunity for developing geothermal power. By using the global energy statistics for active volcanoes and by assuming that the fractured Precambrian crust is of similar geothermal quality to that of the state of Nevada, a 3- to 5-GW power-generating capacity is proposed for the western coast of the KSA (RG, personal communication). This figure should be put into the perspective recent goal of King Abdullah City for Atomic and Renewable Energy (KACARE) of using 54 GW of renewable energy. Geological datasets indicate that the geothermal reservoirs at the Harrat area, where some fumaroles are observed, may host geothermal systems between 150 and 300°C, which could be confirmed by surface exploration and deep drilling (Fig. 5). Thus, both binary-type power generation and condensing steam turbines may be used to convert geothermal heat to power.

Figure 5: Observed fumaroles and vapor at the Harrat area (Roobol, 1995).

For desalination and other direct applications, the geothermal resources of Saudi Arabia are quite suitable and economically viable. For example, Saudi Arabia uses energy intensive conventional desalination process while the world uses reverse osmosis process. The conventional desalination methods consume 12 x 109 kWh to generate 1 m^3 of fresh water (Ghaffour et al. 2014). Once fresh water is available at affordable cost (with same cost without subsidy) and with abundant fossil fuel reserves, Saudi Arabia can have strong control over energy and food security and help other Gulf countries and countries surrounding the Red Sea to improve their fresh water demand (Chandrasekharam et al. 2016b).

6. FUTURE DEVELOPMENT AND INSTALLATIONS

The Kingdom of Saudi Arabia is the largest oil producer in the world. According to the new vision of the country (Vision of 2030), KSA is going to be completely powered by renewable and low-carbon forms of energy by the end of the year 2030. So the Kingdom seeks to introduce nuclear energy and renewable energy into the national energy mix to generate some of its future electricity needs, conserve natural resources, increase exports and seek to develop a mix of renewable energy sources. Saudi Arabia and other Middle Eastern oil producers are looking for renewable energy to grow domestic demand so that they can export more oil to receive higher oil revenues. Saudi Arabia is looking to install 9.5 GW of solar and wind capacity by 2023. Manufacturers have lowered their solar pricing offerings in recent years. Saudi projects this year include 3.3 GW of solar photovoltaic and 800 megawatts of wind (Table 1). This will contribute to preserving the Kingdom's oil and gas resources for future generations by establishing an attractive investment environment, where the Kingdom is keen to form a new national industry integrated with the vision of the Kingdom 2030.
Till now no actual geothermal governmental application or running projects are active in KSA. Most of the past activities are lunched by non-governmental private companies and as academic projects and separate research done by researchers from universities. However, in the last 4 year more attention is paid to the geothermal renewable energy to be included on the main core with other renewable energy sources in the protocols that have been assigned between the first governmental organization at KSA (KACARE) and some private sectors and public universities.

One of these promised protocols is that lunched between KACARE and KSU at the 27^{th} of May 2019. The agreement aims to enhance cooperation between the two sides in the fields of research and innovation, education and training, and provide advisory services to support scientific research in the fields of atomic energy and renewable energy development. Exploration of geothermal resources and geothermal resource assessment are among the main issues that will be funded under this protocol (Table 7).

As mentioned earlier, the future development of geothermal energy is Saudi Arabia has different aspects and applications. The geothermal energy can be used for desalination since the current cost of subsidized desalinated water is 0.03 US$/$m^3$ which is less than the average cost in many places in the world. The high enthalpy potential of the Harrats is a good source of power generation, supposing that a good location with detailed geothermal resource assessment is selected (i.e. Khaybar). The high generating granites encountered at the NW of the shield of Saudi Arabia can yield a heat production up to 134 µW/m^3. Another good aspect of the hydrothermal geothermal resources (low and medium) is that encountered at the western part of Saudi Arabia. In some locations at KSA (i.e. Bani Malik and Al Khouba-Jizan), these resources are already in use for low-grade and direct applications (swimming pools, refreshment places, medical purposes, etc.).

In general, the market of renewable energy applications and utilizations in Saudi Arabia 'more specifically the geothermal energy is promised. Among the gulf countries, Saudi Arabia can become the leader in controlling CO2 emissions and mitigating the impact on climate change and agricultural production through geothermal energy (Chandrasekharam et al. 2016a). This will enable the country to support food and energy for the growing population for several decades and stop importing food products. However a more detailed geological and geophysical exploration work in needed to better investigates these resources, besides a more detailed resource assessment.

ACKNOWLEDGMENTS

The authors extend their appreciations to King Saud University, Deanship of Scientific Research (DSR), NSTIP strategic technologies program, Visiting Professor Program (VPP) and K.A.CARE Energy Research and Innovation Center in Riyadh.

REFERENCES

Aboud, E., Wameyo, P., Alqahtani, F., and Moufti, M.R. : Aging Subsurface Northern Rahat Volcanic Field, Madinah City, Saudi Arabia, Using Magnetotelluric Study. *Journal of Applied Geophysics,* **159**, (2018), 64–572.

Ahmad, A., and Ramana M.V.: Too costly to matter: economics of nuclear power for Saudi Arabia. *Energy,* **69**, (2014), 682–694.

Boulos, F.: Some aspects of the geophysical regime of Egypt in relation to heat flow, ground water and micro-earthquakes, chapter, 6 in: Said, R.,: The geology of Egypt, (1990), 61-89.

Chandrasekharam, D., Lashin, A., Al Arifi, N., Al Bassam, A.A., and Varun, C. : Evolution of Geothermal Systems Around the Red Sea. *Environmental Earth Sciences*, (2015a) DOI 10.1007/s12665-014-3710-y.

Chandrasekharam, D., Lashin, A., Al Arifi, N., Al Bassam, A., El Alfy M., Ranjith, P.G., Varun, C., and Singh, H.K. : The Potential of High Heat Generating Granites as EGS Source to Generate Power And Reduce CO2 Emissions, Western Arabian Shield. Saudi Arabia. *Jour Afr Earth Sci*. **112**, (2015b), 213–233.

Chandrasekharam, D., Lashin, A., Al Arifi, N., and Al Bassam, A. : Red Sea Geothermal Provinces. *CRC Press*, (2016a), 217p.

Chandrasekharam, D., Lashin, A., Al Arifi, N., Al Bassam, A., and Varun, C. : Desalination of Seawater Using Geothermal Energy to Meet Future Fresh Water Demand of Saudi Arabia. Water Resources Management. (2016b), DOI 10.1007/s11269-016-1419-2.

Chandrasekharam, D., Lashin, A., Al Arifi, N., Al-Bassam, A.M. and Varun, C. : Geochemical Evolution of Geothermal Fluids Around the Western Red Sea and East African Rift Geothermal Provinces. *Journal of Asian Earth Sciences,* **164**, (2018), 292-306.

Coleman, R.g., Gregory, R.T., and Brown, G.F. : Cenozoic Volcanic Rocks Of Saudi Arabia. Mistery Of Petroleum And Mineral Resources, Open-File Report 83-788, (1983), 86p.

Demange, J. : Exploration for High Enthalapy Geothermal Resources at Harrat Khayber. Jeddah, Saudi Arabia: Ministry of petroleum and mineral resources, Deputy ministry for mineral resources (1982).

Gettings, M., E. 1982. Heat-Flow Measurmenst at Shot Points Along the 1978 Saudi Arabian Seismci Deep-Refraction Line. In Part 2: Discussion and interpretation. U. S Geological Survey.

Ghaffour, N., Lattemann ,S., Missimer, T., N, Sinha, S., and Amy, G.: Renewable energy-driven innovative energy-efficient desalination technologies. *App. Energy,* **136,** (2014), 1155–1165.

Hussein, M.T., Lashin, A., Al Bassam, A., Al Arifi, N., and Al Zahrani, I. : Geothermal Power Potential at the Western Coastal Part of Saudi Arabia. *Renewable and Sustainable Energy Reviews,* **26,** (2013), 668-684.

Karytsas, C., Mendrinosa, D., and Radoglou G.: The current geothermal exploration and development of the geothermal field of Milos island in Greece. *GHC Bull,* **25**, (2004), 17–21.

Lashin, A.: Evaluation of the Geothermal Potential Around the Coastal Parts of the Gulf of Suez, Egypt, Using Well Logging And The Geo-Thermometer Data. *Egypt. J. Appl. Geophys*., **6 (2),** (2007), 215-248.

Lashin, A.: A Preliminary Study on the Potential of the Geothermal Resources Around the Gulf of Suez, Egypt. *Arabian Journal of Geosciences*, **6 (8),** (2012), 2807-2828.

Lashin, A., and Al Arifi, N.: Some Aspects of the Geothermal Potential of Egypt. Case Study: Gulf of Suez-Egypt. World geothermal congress, Bali, Indonesia, 25-29 April, (2010).

Lashin, A., and Al-Arifi, N.: The geothermal potential of Jizan area, Southwestern parts of Saudi Arabia. *Int. J Physical Sciences*, **7(4),** (2012), 664 - 675.

Lashin, A. and Al Arifi, N.: Geothermal Energy Potential of Southwestern of Saudi Arabia "Exploration and Possible Power Generation. A Case Study at Al Khouba Area – Jizan. *Renewable and Sustainable Energy Reviews,* **30,** (2014), 771-789.

Lashin, A., D. Chandrasekharam, D., Al Arifi, N., Al Bassam, A., and Varun, C.: Geothermal Energy Resources of Wadi Al-Lith, Saudi Arabia. *Journal of African Earth Sciences,* **97**, (2014), 357–367.

Lashin. A., Al Arifi, N., Chandrasekharam, D., Al Bassam, A., Rehman, S., and Pipan, M.: Geothermal Energy Resources Of Saudi Arabia: Country Update. Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April (2015).

Lashin, A., Pipan, M., Al Arifi, N., Al Bassam, A., Mocni, A., [and] Forte, E.: Geophysical exploration of the western Saudi Arabian geothermal province: First results from the Al-Lith area. Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April, (2015b).

Mosly, I., and Makki, A.A.: Current Status and Willingness to Adopt Renewable Energy Technologies in Saudi Arabia. *Sustainability*, **10,** 4269, (2018), 20p.

Oxford Business Group: The plan to turn Saudi Arabia into a renewable energy leader, https://oxfordbusinessgroup.com, (2019).

Pint J. : Prospects For Lava-Cave Studies In Harrat Khaybar, Saudi Arabia. Saudi Geological Survey, (2006).

Pint, J., Al Shanti, M., Al Amoudi, S., and Forti, P. : Ghar Al Hibashi, Harrat Nawasif / Al Bukim, Kingdom Saudi Arabia. Open-File Report, Saudi Geological Survey, (2004), 74p.

Rehman, S.: Saudi Arabian geothermal energy resources - An update. Proceedings World Geothermal Congress, Bali-Indonesia, (2010).

Rehman, S., and Shash, A.: Geothermal resources of Saudi Arabia – Country update report. Proceedings World Geothermal Congress, Antalya-Turkey, (2005).

Roobol M. J., and Camp V. E.: Geologic map of the Cenozoic lava field of Harrats Khaybar, Ithnayn, and Kura, Kingdom of Saudi Arabia: Saudi Directorate General of Mineral Resources Geoscience Map GM-131, with explanatory text (1991a).

Roobol M. J, and Camp V. E. : Geologic Map of the Cenozoic Lava Field of Harrat Kishb, Kingdom Of Saudi Arabia. Saudi Arabian Directorate General of Mineral Resources Geoscience Map GM-132, with explanatory text, (1991b), 34p.

Roobol M. J, Bankher K, and Bamufleh S., Geothermal anomalies along the MMN Volcanic Line including the cities of Al Madinah al Munawwarah and Makkah al Mukarramah: Saudi Arabian Deputy Ministry for Mineral Resources Confidential Report DMMR-MADINAH-CR-15-2, (1995).

Roobol M.J., Pint, J., Al-Shanti, M.A., Al-Juaid, A.J., Al-Amoudi, S.A. and Pint, S.: Preliminary survey for lava-tube caves on Harrat Kishb, (2002).

Somerville, M., Wyborn, D., Chopra, P., and Rahman, S.: Don Estrella, Theo Van der Meulen, Hot dry rock feasibility study. Energy Research and Development Corporation, unpublished report, (1994).

Taleb, H.M., Sharples, S.: Developing sustainable residential building in Saudi Arabia: a case study. *App Energy,* **88**, (2011), 383–391.

STANDARD TABLES

Table 1. Present and planned production of electricity.

	Geothermal		Fossil Fuels		Hydro+Wind		Nuclear		Other Renewables (Solar + Solar CSP)		Total	
	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. Wh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/ yr
In operation in December 2019	Nil	Nil	60,000	-	850	-	Nil	Nil	3,000	-	63,850	-
Under construction in December 2019	Nil	Nil	6,000		800	-	Nil	Nil	4,147	-	10,947	-
Funds committed, but not yet under construction in December 2019	250	-	-	-	400	-	-	-	3,300	-	3,700	-
Estimated total projected use by 2020	1,000	-	120,000	-	6,450	-	17,000	-	26,147	-	170,597	-

Table 3: Utilization of geothermal energy for direct heat as of 31 December 2019 (other than heat pumps).

Locality	Type[1)]	Maximum Utilization					Capacity[3)] (MWt)	Annual Utilization		
		Flow Rate	Temperature (°C)		Enthalpy[2)] (kJ/kg)			Ave. Flow	Energy[4)]	Capacity
		(kg/s)	Inlet (Reservoir T)	Outlet (Surface T)	Inlet	Outlet (Discharge)		(kg/s)	(TJ/yr)	Factor[5)]
Ain Al Harrah (Al Lith area)	B	-	185	96	-	219	26.99	6.3	78.94	0.34
Bani Hilal (Al Lith area)	K	-	120	45	-	120	-	0.35	-	-
Wadi Markoub (Al Lith area)	K	-	120	56	-	120	-	0.4		-
Al Darakah (Al Lith area)	K	-	105	41	-	105	-	0.1	-	-
Ain Al Waghrah-1 (Jizan)	B	-	129	44	-	184	-	-	-	-
Ain Al Waghrah-2 (Jizan)	B	-	152	45	-	188	-	-	-	-
Ain Al Waghrah-3 (Jizan)	B	-	120	57	-	239	-	-	-	-
Ain Al Waghrah-4 (Jizan)	B	-	120	57	-	239	-	-	-	-
Ain Al Waghrah-5 (Jizan)	B	-	123	45	-	188	-	-	-	-
Ain Al Waghrah-6 (Jizan)	B	-	125	61	-	255	-	-	-	-
Ain Al Waghrah-7 (Jizan)	B	-	96	57	-	239	-	-	-	-
Al Khouba (Jizan)	B	-	133	76	-	318	17.84	6	73.95	0.27
Bani Malik (Jizan)	B	-	105	45	-	188	-	-	-	-
TOTAL										

Table 5. Summary table of geothermal direct heat uses as of 31 December 2019.

Use	Installed Capacity[1] (MWt)	Annual Energy Use[2] (TJ/yr = 10^{12} J/yr)	Capacity Factor[3]
Individual Space Heating[4]	Nill	Nill	Nill
District Heating [4]	-	-	-
Air Conditioning (Cooling)	-	-	-
Greenhouse Heating	-	-	-
Fish Farming	-	-	-
Animal Farming	-	-	-
Agricultural Drying[5]	-	-	-
Industrial Process Heat[6]	-	-	-
Snow Melting	-	-	-
Bathing and Swimming[7]	44	152.89	0.31
Other Uses	-	-	-
Subtotal			
Geothermal Heat Pumps	-	-	-
TOTAL	44.0	152.89	0.31

[4] Other than heat pumps

[5] Includes drying or dehydration of grains, fruits and vegetables

[6] Excludes agricultural drying and dehydration

[7] Includes balneology

Table 6. Wells drilled for electrical, direct and combined use of geothermal resources.

Purpose	Wellhead Temperature	Number of Wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration[1]	(all)	-	1 (Jizan)	-	-	-
Production	>150° C		-	-	-	-
	150-100° C	-	-	-	-	-
	<100° C	-	1	-	-	46 m
Injection	(all)	-	-	-	-	-
Total			1			46 m

[1] Include thermal gradient wells, but not ones less than 100 m deep

Table 7. Allocation Of Professional Personnel To Geothermal Activities (Restricted to personnel with University degrees)

(1) Government (4) Paid Foreign Consultants
(2) Public Utilities (5) Contributed Through Foreign Aid Programs
(3) Universities (6) Private Industry

Year	Professional Person-Years of Effort					
	(1)	(2)	(3)	(4)	(5)	(6)
2014-2015	KACare	-	King Saud University (8 persons)	1	-	Meahona/ ACWA (3 persons)
2016	-	-	King Saud University (4 persons)	1	-	-
2017	-	-	King Saud University (4 persons)	1	-	-
2018	KACare	-	King Saud University (4 persons)	1	-	-
2019	KACare	-	King Saud University (4 persons)	1	-	-
Total	4 Years	-	8 persons /5 Years	1 person /5 Years	-	3 persons /5 Years

Table 8. Total investments in geothermal in (2019) US$.

Period	Research & Development Incl. Surface Explor. & Exploration Drilling	Field Development Including Production Drilling & Surface Equipment	Utilization		Funding Type	
			Direct	Electrical	Private	Public
	Million US$	Million US$	Million US$	Million US$	%	%
1995-1999	Nil	Nil	Nil	Nil	Nil	Nil
2000-2004	-	-	-	-	-	-
2005-2009	-	-	-	-	-	-
2010-2014	1.25 M	0.20	0.36 M	-	-	100 %
2015-2019	1.15 M	0.30	0.45 M	-	70%	30 %