

Al-Douri, Y.; Waheeb, S. A.; Johan, Mohd Rafie

Article

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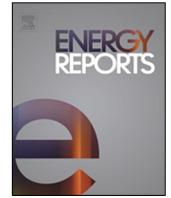
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Research paper

Exploiting of geothermal energy reserve and potential in Saudi Arabia: A case study at Ain Al Harrah



Y. Al-Douri^{a,b,c,*}, S.A. Waheeb^d, Mohd Rafie Johan^b

^a University Research Center, Cihan University, Sulaimaniya - 46002, Iraq

^b Nanotechnology and Catalysis Research Center (NANOCAT), University of Malaya, 50603, Kuala Lumpur, Malaysia

^c Department of Mechatronics Engineering, Faculty of Engineering and Natural Sciences, Bahcesehir University, 34349, Besiktas, Istanbul, Turkey

^d Department of Engineering Sciences, Community College, Umm Al-Qura University, PO Box 715, Makkah 21955, Saudi Arabia

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ABSTRACT

Saudi Arabia is enriched by geothermal resources and related to the tectonic activity of Red Sea, volcanic rocks and ridges. The geothermal energy reserve, potential and their reserve for possible energy production are investigated. Nowadays, production process of crude oil accompanied with flaring of gases result in excessive CO₂ emissions. If the growth rate of national oil consumption continues, local demand will be doubled within a decade. The study of geothermal energy is covered. A selection of possible applications of geothermal futures is discussed. Furthermore, the study has focused on necessity of maintaining green and clean environment as well as climate of lowest dust content.

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1. Introduction

The geothermal production of heat and power depends on the depth of reservoirs (Islam and Dincer, 2017). Hydrothermal systems with temperature more than 179.85 °C are found near the boundaries of plate tectonic (Anon, 2014). Geothermal energy sources can be categorized as, low-temperatures below 89.85 °C, moderate temperatures between 89.85–149.85 °C and high temperatures above 149.85 °C (Coskun et al., 2011). The geothermal fields can be exploited for both power generations and direct use of heat under appropriate conditions. It is known that geothermal energy has a minimum emission of CO₂ and regards a clean energy. Its generation of electricity via geothermal energy touches 11000 MWe (Bertani, 2010) and reflects the geothermal benefits to power generation. The geothermal energy looks environmental friendly, its plants emit 0.893 kg CO₂/MWh, while oil-based power plants emit 817 kg CO₂/MWh and gas-based power plants emit 193 kg CO₂/MWh (Chandrasekharam and Bundschuh, 2008).

Taleb (2009) has reviewed a geothermal resource that represents a clean and renewable source of energy, it has been used to generate electricity since 1904. Despite availability of some resources-rich geothermal locations, Kingdom of Saudi Arabia (KSA) has not undertaken any serious geothermal projects.

It is aimed to identify the real barriers hindering the utilization of geothermal resources in KSA. While, Alshehry and Belloumi (Alshehry and Belloumi, 2015) have investigated dynamic causal relationships between energy consumption, energy price and economic activities in KSA using Johansen multivariate cointegration approach with CO₂ emissions as the control variable. The results have showed there is a long-term relationship between economic growth, energy consumption, CO₂ emission and energy price. And, Alrashed and Asif (Alrashed and Asif, 2012) have indicated that almost 70% of total projects in KSA's construction sector are related to residential buildings. It is further estimated that 2.32 million new homes are to be built by 2020 in order to meet the demand of growing population. They have detailed account of energy profile of KSA. In this respect, they have investigated the potential of various renewable energy options to provide green energy and provided recommendations to promote the use of renewable energy sources in the KSA.

This work aims to research the geothermal energy reserve estimation and potential of KSA to offset predicted its abundance and shortages in the upcoming decades concerned with detecting sources of arising geothermal water, detecting feed zones, effecting structural elements and possible condition system, followed by geothermal parameters of subsurface formation temperature, discharge enthalpy and heat flow with a focus on Ain Al Harrah hot spring site and advantageous analysis of technical feasibility of assessment and development of Ain Al Harrah. To best of our knowledge, this is a first serious study will be added to the literature of geothermal energy, resources, geologic setting and

* Corresponding author at: Nanotechnology and Catalysis Research Center (NANOCAT), University of Malaya, 50603, Kuala Lumpur, Malaysia.

E-mail address: yaldouri@yahoo.com (Y. Al-Douri).

Nomenclature

GCC	Gulf Cooperation Council
KSA	Kingdom of Saudi Arabia
p.u.	Porosity Units
RE	Renewable Energy

geophysical survey potential in KSA. This study is divided into followings: Section 2 studies the geothermal energy, followed by geothermal resources, geologic setting, geophysical surveys and geothermal reserve estimation and potential in Sections 3–6, respectively. The conclusions are summarized in Section 7.

2. Geothermal energy

Power reaches highest points for a couple of hours per day and couple of months per year. Fig. 1 shows latest growth in number of consumers in KSA for the last two decades, where it is predicted that energy requirements reach 60 GW/year by 2020. It is evident that generation and transmission capacities will not be able to meet demand in near future, causing overloads for the electricity company (Arouri et al., 2012). The present per-capita energy consumption in KSA is already higher than those of most industrial and developed nations. Fig. 2 explores various categories of consumption in percentage of distribution for different sectors. The costs of utility are escalating along with drop-in oil prices, more escalation is expected to be there with growing demand on oil. The concept of conserving energy is increasingly into important issue (Arouri et al., 2012; Waqas et al., 2018).

Geothermal energy is a natural energy resource that has not been well explored in KSA due to lack of supportive infrastructure, specialized professionals, awareness and technical information (Taher and Hajar, 2014; Chandrasekharam et al., 2014). Since the geothermal well is the deeper, there is a possibility of accessing both steam and/or hot water through a pipe connection to use its latent heat for energy exploitation, given that such wells' depths range between 1–2 miles. Geothermal wells can offer alternate forms of applications. The following preview lists the percentages of major direct applications related to geothermal energy projects; heat pumps geothermal: 54.4%, balneology/bathing: 19.1%, green houses: 5%, interiors heating of buildings: 15.4, aquaculture: 2.2%, industrial: 1.7%, snow melting: 1.3%, agricultural: 1.6% and miscellaneous: 0.3% (Lund et al., 2005). There is also a heat exchange unit of pipes to be buried down within the ground to the relevant building that is intended to use. In cold seasons, heat is taken from the heat exchanger by virtue of installed heat pump and delivered to the indoor air intake. A warming action is obtained for the inner space. While, in hot seasons, the process is reversed within the heat pump itself and the rest of system components resulting into a cooling action for the building inner space (Dell and Rand, 2004).

In geothermal practice and stations, superheated steam is needed for generating electrical power. Fig. 3 illustrates the three types of geothermal stations and cycles. The first type is called the “Dry Steam” plant where pipes carry the steam available in a geothermal well or reservoir to reach the turbine rotor's blades. In the second type, the boiling water of geothermal well (which is under high pressure too) is taken out and made to evaporate into steam and the rest is same as in the first type. This is called “Flash Steam” plant. Being a sustainable process, the water condensed next to rotating turbine's rotor is injected back to geothermal well. The third type uses another medium to transfer the heat from hot geothermal water to medium producing hot steam that

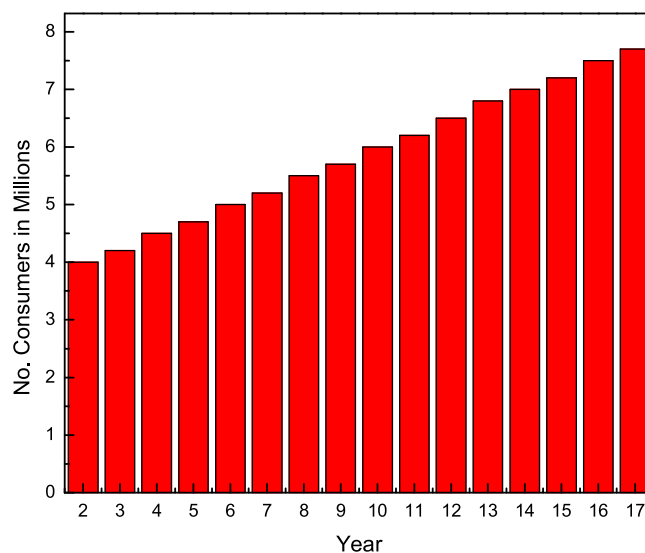


Fig. 1. Consumer growth over the first two decades of third millennium.

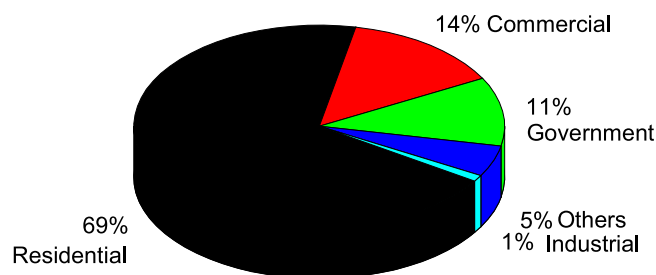


Fig. 2. Percentage distribution of consumption categories in KSA.

is carried out the action of rotating turbine's rotor. This type is called “Binary”.

There is neither harmful concentration of gases nor carbon dioxide emissions go against the regulations followed for the global warming phenomena. Additionally, no carbon dioxide is emitted by geothermal facilities, while steam and flash plants' emission of carbon dioxide are much lesser than plants using fossil fuels, based on each MWh produced, hence the “sustainable and clean” allotted to geothermal stations and technology (DIP-ippo, 2008).

The interpretation of electric resistivity data resulted in a number of pseudoelectrics and geoelectrics. These are mainly concerned with detecting sources of arising geothermal water, detecting feed zones, effecting structural elements and possible condition system. It is indicated that Ain Al Harrah (Latitude: 20°29N and longitude: 40°28E as presented in Table 1) has interpreted geoelectric profile. Generally, the geothermal fluids/systems are indicated by the low resistivity in the interpreted resistivity profile. A good geothermal reservoir volume with a thickness, 23 m (depths 9.20–32 m) is found at middle of resistivity profile. It represents a good geothermal reservoir that extends more than 80 min the NE direction. A high resistivity uplift (216–1866 ohm.m) is indicated. It exhibits NW–SE trending resistivity profile and shows one of the major subsurface structural elements that control the movement and ascending of geothermal water in Ain Al Harrah area (Waqas et al., 2018; Chandrasekharam et al., 2014).

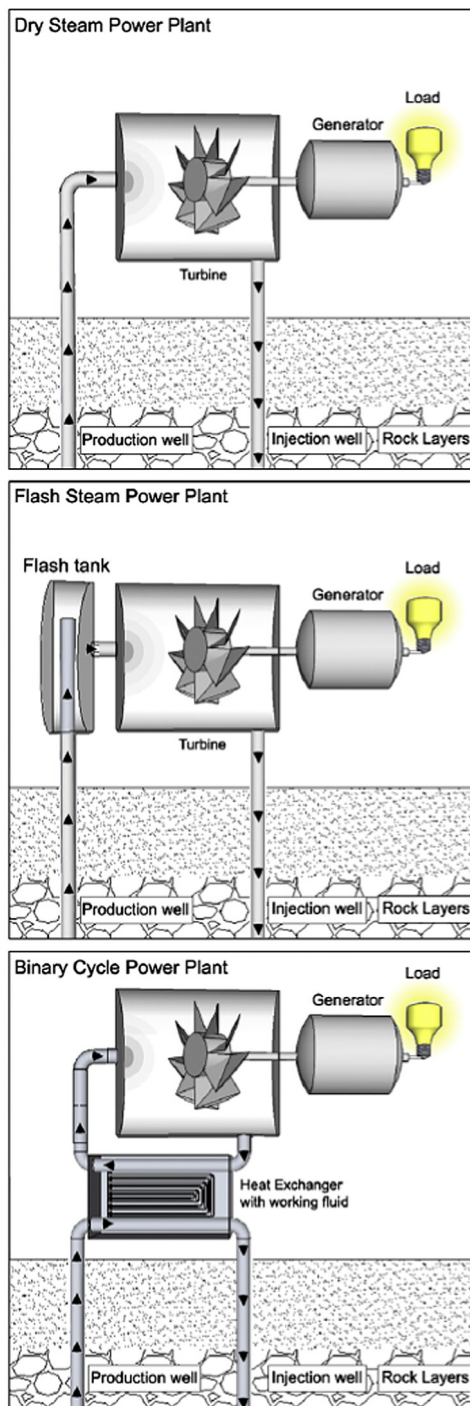


Fig. 3. The main types of geothermal plant technologies.

3. Geothermal resources

Due to prevailing global energy issues and recurring crises, it may be agreed that each country would better pursue its own resources of renewable energy patterns whether solar, wind or geothermal. For KSA, there are both geothermal and solar energies may be harnessed to produce both water and electrical power to meet the KSA's demands (Oktun and Sayigh, 1976). The status of geothermal resources of KSA is "untapped", while report has talked about ten locations of hot springs found in Al-Lith region. Furthermore, there is a vast volcanic zone found in

Table 1

The physical properties of thermal springs in KSA.

	Latitude	Longitude	Temp. (°C)	Flow rate (kg/s)
Ain Khulab (Jizan)	16°45'N	43°07'E	75.5	0.016–0.32
Ain Khulab Quwa (Jizan)	16°48'N	43°12'E	59.0	0.32
Ain Al Wagrah (Jizan)	17°03'N	42°59'E	55.0	0.24
Ain Al Wagrah Dam (Jizan)	17°03'N	42°59'E	59.0	0.32
Ain Al Harra (Al-Lith)	20°29'N	40°28'E	79.0	0.064–0.08
Ain Al Jumrah (Al-Lith)	20°18'N	40°42'E	46.0	0.0048
Ain Markus (Al-Lith)	20°33'N	40°09'E	46.0	0.0048
Ain Al Darakah (Al-Lith)	20°39'N	40°01'E	39.5	0.0016

western part of KSA (Rehman and Shash, 2005). Eight of KSA distinguished hot springs has been listed in Table 1 with their properties along with temperature and flow rate representing the amount of heat flow from depth and up to surface.

Rehan et al. (2018) have presented an assessment of renewable energy production from sources available in KSA for energy generation and solution. However, there are challenges in commercialization of natural resources to renewable facilities including geothermal, waste collection, impurities and others.

While, renewable energy (RE) sources could be used to serve centralized systems in urban centers and thus provide an opportunity to make greener, they are mostly used to serve rural communities off the grid. In 1256 A.D. a volcanic eruption was recorded in the city of Al Madina eventually leaving what locals call "Harrats" or fields of settled volcanic lava (Fig. 4). These "Harrats" exhibit activities of geothermal nature in the form of hot springs with prominent steam emission and shallow wells of considerably hot waters (Roobol et al., 2007). All geothermal resources are easily accessible (Alnatheer, 2005). Al-Saleh et al. (2008) have developed a few scenarios for renewable energy. Their study has considered geothermal prospects and offered hopeful approach of understanding the hardships that create barriers hindering the utilization of KSA's resources of geothermal energy (Al-Saleh, 2007).

Geothermal parameters of subsurface formation temperature, discharge enthalpy and heat flow are interpreted based on results of geothermometer data. The subsurface temperature shows regular distribution of subsurface temperature for Ain Al Harrah hot spring. A much higher range of subsurface temperature, 95–152 °C is indicated for the hot spring. This is clearly indicated by the areas occupied by Ain Al Harrah hot spring. The maximum value of subsurface temperature, 151.4 °C is exhibited by Ain Al Harrah hot spring. The discharge enthalpy assigns high enthalpy values for hot spring, 180–255 kJ/kg and low enthalpy values for surrounding water wells, with a general trend of decreasing towards the shore line, 100–160 kJ/kg. The heat flow distribution ensures the same concluded results from the discharge enthalpy and subsurface temperature data. Good and high heat flow values are recognized in the area of Ain Al Harrah hot spring. The recorded heat flow values as high as 210 mW/M² (Roobol et al., 2007; Al-Saleh et al., 2008).

4. Geologic setting

KSA is divided into two geological provinces. The western area consists of crystalline igneous and metamorphic rocks, of presumed Pre-Cambrian age, topographically and structurally sloping to the northeast, east and southeast. The eastern area has easterly dipping sedimentary rocks overlying the basal igneous and metamorphic complex. These sediments consist of Paleozoic, Mesozoic (nearly complete section), Tertiary and recent deposits. The area is subdivided into Nejd and Hassa (Arabian Gulf) sub-provinces. The eastern parts of Nejd subprovince consist of sedimentary rocks, ranging in age from early Paleozoic to

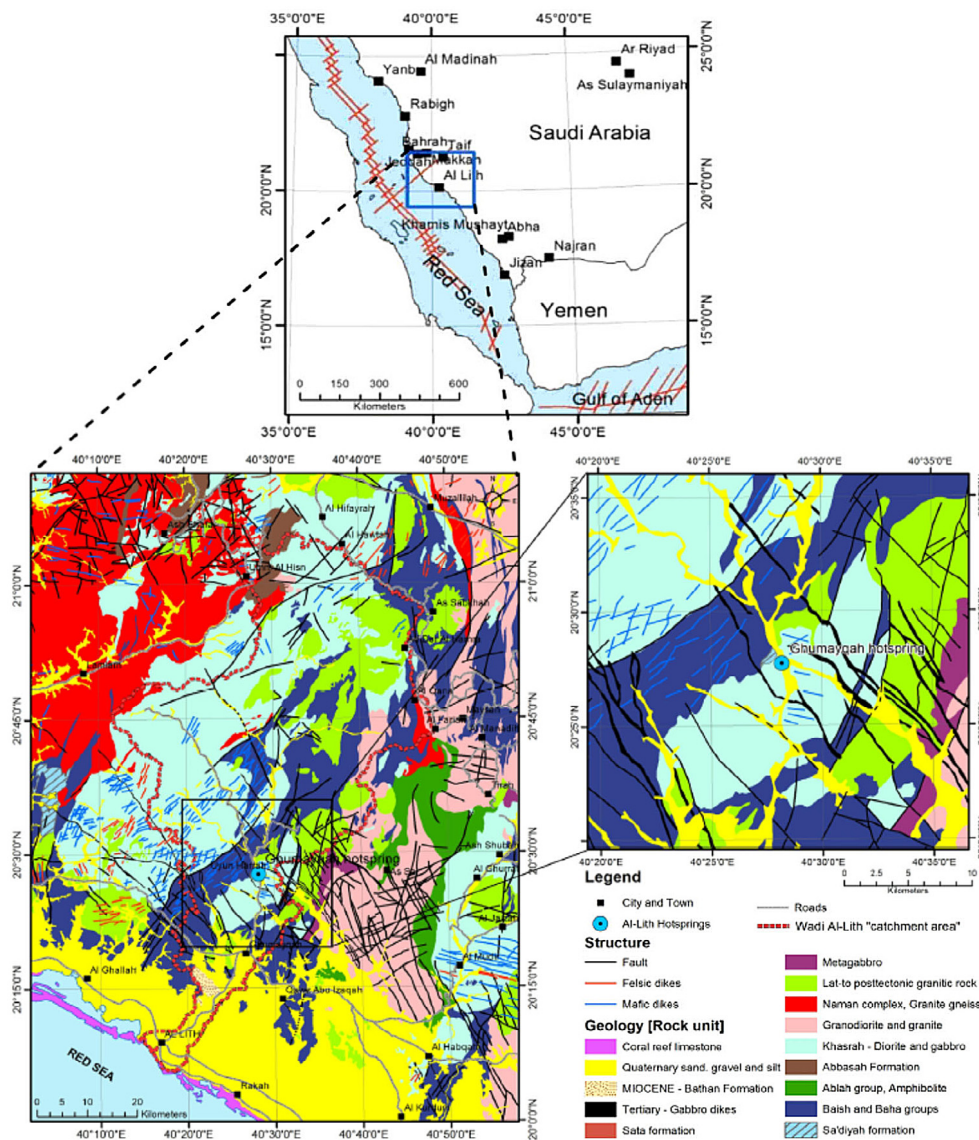


Fig. 5. Geologic maps of Wadi Al-Lith area showing Ain Al Harrah hot spring (Muffler, 1978).

5. Geophysical surveys

The geophysics is to study gravitational, magnetic, electrical and seismic-velocity properties of earth's surface and interior. Geothermal potential can be explored using variety of geophysical and geochemical (geo-thermometer) techniques which are normally used in geo-technical and geological investigations as well as in the exploration of hydrocarbons in the oil industry (Al-Arifi et al., 2012). These techniques provide the necessary information for constructing a realistic model of geothermal system and assessing the potential of resource. Electric resistivity is related to various geological parameters such as mineral and fluid content, porosity and degree of water saturation in the rock (Loke, 0000).

A number of two-dimensional electric profiles was performed at the location of hot springs in Wadi Al-Lith area. The syscal-R1 system (IRIS instruments) with 72 multi-electrodes system, with 4 x 18 electrode cables was used for conducting the field surveys via different electrode spacing (1 m, 3 m, 5 m and 10 m) (Loke, 0000). Geophysical surveying is one of the important functions of Saudi geological survey and has applications in many aspects of

work by the Saudi geologic survey. It is used to locate small physical targets such as pipe-lines and concentrations of metallic ores; to locate more subtle targets like zones of clay alteration around mineral deposits or boundaries and thicknesses of underground water reservoirs; and to investigate large-scale phenomena as potential movement of magma in the Earth's crust. The drift of the Arabian Peninsula moves away from Africa, and the sources and intensities of earthquakes affect the region (Geophysics in Saudi Arabia, 2010).

The main objective of exploration geophysics is to map the structures that are of potential economic importance, to control the location of ore deposits and petroleum reservoirs. In geologic mapping, geophysics is commonly used to differentiate rock types and characterize their contacts. In field of geohazards and environment, geophysics is used to measure features such as magnitude and location of earthquakes and earthquake epicenters, and levels of naturally occurring radiation. Geophysical methods are contributed significantly to geologic mapping and exploration for hydrocarbons, minerals and aquifers in KSA, and aided the discovery of several ore deposits of economic significance in the Arabian shield. For geothermal resource availability,

it is mentioned for comparison in some of GCC countries (Kazem, 2011; Youssef et al., 2012) and has put the abundance for KSA.

A technical feasibility analysis for the possible assessment and development of Ain Al Harrah is made. This analysis is preliminary in nature because it is based solely on surface exploration. A more specific project feasibility study that considers power plant and field design and operation will be conducted when the results of the exploratory drilling and testing program are completed (Geophysics in Saudi Arabia, 2010). The appropriate technology for Ain Al Harrah can be determined once the resource is better constrained. Furthermore, there are three major technologies commonly used to generate electricity from Ain Al Harrah. The three types are:

- Dry steam: uses geothermal steam directly from a geothermal reservoir that has a fracture system that is entirely steam, 220–245 °C.

- Flash: geothermal steam is separated from hot water at the surface. The steam is delivered to a steam turbine, while water phase is re-injected into geothermal reservoir, 200–330 °C.

- Binary cycle: uses a secondary 'working' fluid (binary fluid) with a lower boiling temperature than water, such as ammonia (Kalina cycle). Heat from geothermal fluid causes binary fluid to flash to vapor via a heat exchanger, and binary vapor is sent through the turbine to generate power.

Regarding Ain Al Harrah, the hot spring is located topographically in a low to medium accessible area that has good fracture system and good thermal gradients that allow heat to flow and be extracted more easily to the surface. Since the minimum temperature for binary plants is 120 °C, Kalina cycle seems to be the most appropriate design for energy production from Ain Al Harrah (Kazem, 2011).

6. Geothermal reserve estimation and potential

Geothermal reserves are defined as quantities of thermal energy which are expected to be recovered from known reservoirs of a given date forward. The reserve is part of the resources which is currently known and characterized by drilling, geochemical, geophysical and geological evidence and could be legally extracted (Muffler and Cataldi, 1978). The most common approach for geothermal reserve estimation is the volumetric method. This method is mainly utilized in the last stages of geothermal exploration as well as the early stages of field development to justify drilling and commitment for a specified power plant size. It may be used if good surface indications and geophysical surveys are available (Clotworthy et al., 2006). It can be applied better than numerical modeling, which requires a significant number of wells and production history to be considered reliably (Sarmiento and Steingrimsson, 2008). In general, the reservoir parameters for geothermal-reserve estimation are gathered from analyses of temperature data and other geophysical and geochemical interpretations.

Geothermal-reserve estimation was carried out for evaluating the possible geothermal capacities of Ain Al Harrah hot spring based on the following equations;

$$E_t = E_r + E_f = V(1 - \Phi)\rho_r C_r(T_i - T_0) + V\Phi\rho_w C_w(T_i - T_0) \quad (1)$$

where E_t is total thermal, energy unit (J) in the rock (E_r) and fluid (E_f), Φ is reservoir porosity (%), V is reservoir volume (m^3), $\rho_{r,w}$ is densities of rock and water (kg/m^3), respectively, $T_{i,0}$ is initial reservoir and reference temperatures (°C), respectively. This stored thermal energy can be converted into power potential using (Muffler and Cataldi, 1978):

$$PowerPotential (MWt) = \frac{E_t RF CE}{PL LF} \quad (2)$$

Table 2
Reservoir parameters used for geothermal reserve estimation.

Property		Unit	Value
Reservoir	Volume	km^3	1.28
	Porosity	%	4
Density	Rock	kg/m^3	2800
	Water	kg/m^3	980
Heat capacity	Rock	$J/kg \text{ } ^\circ C$	1000
	Water	$J/kg \text{ } ^\circ C$	4200
Temperature	Initial	$^\circ C$	95
	Reference	$^\circ C$	45

where RF is recovery factor, CE is conversion efficiency, PL is geothermal plant life in years and LF is load factor. Assuming the following parameters;

- A reservoir area, 4.8 km^2 ($1.2 \times 4.0 \text{ km}^2$) and volume, 1.28 km^3 are providing a reservoir thickness of 250 m as concluded from the interpretation of resistivity data.

- An initial temperature, $95 \text{ } ^\circ C$ was recorded for the geothermal reservoir.

- A reference temperature, $45 \text{ } ^\circ C$ was suggested (due to higher average annual surface temperature in KSA).

- The pore volume range was 3–5 p.u. (porosity units) for the fractured granitic rocks (average value of 4 p.u. (porosity units)).

- The density range was $0.0027\text{--}0.0029 \text{ kg/m}^3$ (average value of 2.80 g/cc).

The different reservoir parameters were derived from analyses of temperature and geo-thermometer data that can be used in thermal energy estimation as given in Table 2. According to these parameters and by utilizing in Eq. (1), the total stored heat energy of Ain Al Harrah geothermal area is found to be $1.713 \times 10^{17} \text{ J}$ ($1.34 \times 10^{16} \text{ J}$ for thermal fluids and $1.57 \times 10^{17} \text{ J}$ for reservoir rock) (Clotworthy et al., 2006).

The total stored heat energy of Ain Al Harrah hot spring can be converted into power energy units (megawatt thermal using Eq. (2)) for possible energy production and other low-geothermal utilizations (Muffler and Cataldi, 1978). Assuming a recovery factor of 0.2, which is factual (normal factor for geothermal reservoirs), turbine conversion efficiency of 0.47 that is realistic (initial temperature/reservoir temperature) plant life of 20 years and load factor of 0.95, the thermal power potential of Ain Al Harrah geothermal reservoir is 26.99 MWt. This geothermal reserve is considered promising and can be used for providing Al-Lith area with electricity (clean energy) on a long-term basis (Lashin et al., 2015). We strongly recommend exploiting geothermal system to generate electricity for the first time in KSA using a power plant that processes thermal fluid and boils at low temperature (Lashin, 2012). Surface geology and geophysical data could provide information compatible with a circulation of fluids in a complex system of fracture related to at least two principal directions. This is well to demonstrate the prevailing structural elements that may control the whole geothermal system in the area. The outputs show a clear high resistivity anomaly located around 2000 m from topographic surface, which is most likely linked to the geothermal anomaly at the site. The anomaly is oriented along a northwest-southeast direction, which is the main structural trend of the Red Sea rift. Several fractures are further observed in the imaged volume up to an approximate depth of 500 m. At that shallower depth, the geothermal anomaly changes gradually rotating towards a north-south trend. This means that the main fracture zones control the geothermal system and exhibit variations in azimuth and dip at different depths. Such variations may be related to the combination of principal stresses and fault systems linked to the Red Sea rift (Lashin, 2012). The identification of areas of potential geothermal interest (Al-Dayel, 1988) and

improved estimates of geothermal resource base and recoverable resources (Muffler, 1978) are in accordance with our assessment of geothermal energy reserve and potential.

7. Conclusions

The geothermal potential of available geothermal resources in KSA has been re-evaluated and investigated. Alternative methods to meet KSA requirements for energy have been explored. The consumer growth rate increasing is associated with lifestyle changes. It has been demonstrated that other types of technologies such as thermal systems are appropriate, with overall cost considered reasonable. It is recommended for direct investment towards the development of infrastructure of renewable energy in terms of localized or shared plants with ample storage capacities to serve the escalating demands. All the processes have the potential to contribute for fulfilling the country's demands for being a part of an effective plan for reducing CO₂ emissions.

References

- Al-Arifi, N., Lashin, A., Al-Humidan, S., 2012. Migration of local earthquakes in the Gulf of Aqaba, Saudi Arabia. *Earth Sci. Res.* 16, 35–40.
- Al-Dayel, M., 1988. Geothermal resources in Saudi Arabia. *Geothermics* 17, 465–476.
- Al-Saleh, Y.M., 2007. A glimpse into the status and prospect of renewables in oil-producing countries; with a special reference to the Kingdom of Saudi Arabia. *Geopolit. Energy* 29, 2–13.
- Al-Saleh, Y.M., Upham, P., Malik, K., 2008. Renewable Energy scenarios for the Kingdom of Saudi Arabia. Tyndall Centre for Climate Change Research, Working Paper 125, http://www.tyndall.ac.uk/publications/working_papers/twp125.pdf.
- Alnatheer, O., 2005. The potential contribution of renewable energy to electricity supply in Saudi Arabia. *Energy Policy* 33, 298–312.
- Alrashed, F., Asif, M., 2012. Prospects of renewable energy to promote zero-energy residential buildings in the KSA. *Energy Procedia* 18, 1096–1105.
- Alshehry, A.S., Belloumi, M., 2015. Energy consumption carbon dioxide emissions and economic growth: The case of Saudi Arabia. *Renew. Sustain. Energy Rev.* 41, 237–247.
- Anon, 2014. Geothermal electricity, Available at: <http://www.geoelec.eu/about-geothermal-electricity/>.
- Arouri, M.E., Youssef, A.B., M'henni, H., Rault, C., 2012. Energy consumption economic growth and CO₂ emissions in Middle East and North African countries. *Energy Policy* 45, 342–349.
- Bertani, R., 2010. Geothermal power generation in the world-2005–2010 update report. In: *Proceedings of the World Geothermal Congress*. Bali.
- Chandrasekharam, D., Bundschuh, J., 2008. *Low Enthalpy Geothermal Resources for Power Generation*. Taylor and Francis Pub. UK, p. 169.
- Chandrasekharam, D., Lashin, Aref, Arifi, Nassir Al, 2014. The potential contribution of geothermal energy to electricity supply in Saudi Arabia. *Int. J. Sustain. Energy* 33, 1–10.
- Clotworthy, A.W., Ussher, G.N.H., Lawless, J.V., Randle, J.B., 2006. Towards an industry for geothermal reserves determination. *GRC Trans.* 30, 9–16.
- Coskun, C., Oktay, Z., Dincer, I., 2011. Investigation of some renewable energy and exergy parameters for two geothermal district heating systems. *Int. J. Exergy* 8, 1–15.
- Dell, R., Rand, D.A.J., 2004. *Clean Energy*. Royal Society of Chemistry, London.
- DiPippo, R., 2008. *Geothermal Power Plants: Principles, Applications, Case Studies, and Environmental Impact*. Butterworth-Heinemann, Amsterdam.
- Geophysics in Saudi Arabia, Saudi Geological Survey, 10/21/2010. <http://www.sgs.org.sa/English/earth/Pages/Geophysics.aspx>.
- Islam, S., Dincer, I., 2017. Development, analysis and performance assessment of a combined solar and geothermal energy-based integrated system for multigeneration. *Sol. Energy* 147, 328–343.
- Kazem, H.A., 2011. Renewable energy in Oman: Status and future prospects. *Renew. Sustain. Energy Rev.* 15, 3465–3469.
- Lashin, A., 2012. Assessment of geothermal resources at the Al-Lith area, Kingdom of Saudi Arabia. In: *New Zealand Geothermal Workshop Proceedings*. Auckland, New Zealand.
- Lashin, A., Al Arifi, N., Chandrasekharam, D., Al Bassam, A., Rehman, S., Pipan, M., 2015. Geothermal Energy Resources of Saudi Arabia: Country Update Proceedings World Geothermal Congress. Melbourne, Australia.
- Loke, M.H., 0000. *Electrical imaging surveys for environmental and engineering studies: A practical guide to 2-D and 3-D surveys*, Copyright (1997, 1999, 2000) by Dr. M. H. Loke, 11700 Penang, Malaysia.
- Lund, J.W., Freestone, D.H., Boyd, T.L., 2005. Direct application of geothermal energy: 2005 worldwide review. *Geothermics* 34 (2005), 691–727.
- Muffler, L.J.P., 1978. R. cataldi methods for regional assessment of geothermal resources. *Geothermics* 7, 53–89.
- Muffler, P., Cataldi, R., 1978. Methods for regional assessment of geothermal resources. *Geothermics* 7, 53–89.
- Oktun, G., Sayigh, A.M., 1976. Geothermal energy in Saudi Arabia and its use in connection with solar energy. In: *Proceedings of the International Conference*. Saudi Arabia, Dhahran, pp. 583–595.
- Rehan, M., Demirbas, A., Rashid, U., Budzianowski, W.M., Pant, Deepak, Nizami, A.S., 2018. Waste to biodiesel: A preliminary assessment for Saudi Arabia. *Bioresour. Technol.* 250, 17–25.
- Rehman, S., Shash, A.A., 2005. Geothermal resources of Saudi Arabia—country update report. In: *Proceedings of the World Geothermal Congress*. Turkey, Antalya, p. 7.
- Roobol, M.J., Bankher, K., Bamufleh, S., 2007. Geothermal Anomalies Along the MMN Volcanic Line Including the Cities of Al Madinah Al Munnawwarah and Makkah Al Mukkarramah. Jeddah. Saudi Geological Survey.
- Sarmiento, Z.F., Steingrimsson, B., 2008. Computer Program for Resource Assessment and Risk Evaluation Using Monte Carlo Simulation. Short Course on Geothermal Project Management and Development. UNU-GTP, KenGen and MEMD-DGSM, Entebbe, Uganda.
- Taher, N., Hajar, B., 2014. *Energy and Environment in Saudi Arabia: Concerns and Opportunities*. Springer, Berlin.
- Taleb, H.M., 2009. Barriers hindering the utilization of geothermal resources in KSA. *Energy Sustain. Dev.* 13, 183–188.
- Teriki, Abdulla Homoud, 1947. *Geology of Saudi Arabia* (M. A. thesis). University of Texas at Austin, USA.
- Waqas, M., Nizami, A.S., Aburizaiza, A.S., Barakat, M.A., Rashid, M.I., Ismail, I.M.I., 2018. Optimizing the process of food waste compost and valorizing its applications: A case study of Saudi Arabia. *J. Cleaner Prod.* 176, 426–438.
- Youssef, Ahmed M., El-Kaliouby, Hesham M., Zabramawi, Yasser A., 2012. Integration of remote sensing and electrical resistivity methods in sinkhole investigation in Saudi Arabia. *J. Appl. Geophys.* 87, 28–39.