Geothermal energy resources in Oman

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Oman's oil and gas reserves are comparatively low relative to those of other Gulf Co-operation Council member countries. This article explores the potential of using geothermal energy resources for electricity generation in Oman. Geothermal energy is counted as a type of renewable energy, which means its availability is not affected by the lack of source and the increasing price of fossil oil. The review of geothermal energy shows that the cost of electricity generation and the emission of greenhouses gases are comparatively lower than for other forms of renewable energy resources. Different types of geothermal plants are discussed with reference to the required temperature for operation of these plants. Binary cycle geothermal power plants are used for low-temperature applications (85–175°C). The temperature of 53 boreholes in Oman is more than 100°C, meaning they can be used in binary geothermal plants for electricity generation. The maximum temperature (173–68°C) is at Petroleum Development Oman well 'Makarem-I' located in the northern part of Oman. There is opportunity for Oman to adopt renewable energy resources and explore the potential of geothermal in more detail. This will help the country to reduce its dependency on oil and gas and compete in the region towards adopting renewable energy.

1. Introduction

Oman's economy is heavily reliant on oil and gas revenues, which in 2014 accounted for about 84% of the country's export earnings and 47.2% of its gross domestic product (CBO, 2015; NCSI, 2015). All of Oman's domestic energy consumption is supplied by natural gas and oil, reflecting the country's relative abundance of oil and natural gas reserves. In 2011, oil accounted for 71% of Oman's total primary energy consumption, and natural gas made up the remaining 29%. With the exception of 2009, Oman's petroleum consumption rose steadily over the past decade, reaching 154 000 barrels/d in 2013. This makes a further significant contribution towards emissions of greenhouse gases.

Oman, like other Arab gulf countries, depends on oil and gas to produce electricity. However, these resources are not guaranteed to last forever, and are thus one of the energy security issues in the country. Some of the gulf countries have diversified their energy resources; for example, the United Arab Emirates has considered nuclear and renewable energy as part of its electricity generation and Qatar aims to generate 20% of its energy from renewables by 2024 with 1800 MW of installed green capacity by 2020. As for Oman, the progress of renewable energy development is at a slow pace as currently the electricity generation is

still dependent on oil and gas. The Oman Vision 2020 economic development programme seeks to reduce dependence on oil, diversify the economy and create new employment opportunities for all citizens. Oman Vision 2020 also stresses the promotion of technology transfer and the increased use of natural and renewable resources, with due regard to the social and natural environment, which gives priority to the main key aspects (NCSI, 2008).

In the last two decades, energy consumption in the Gulf Cooperation Council (GCC) member countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates) has increased rapidly. In 2013, the average electricity consumption in GCC countries was ~12370.91 kWh/year/capita, while in China this value was 3762.07 (WB, 2016). GCC countries' electricity consumption is more than double the consumption per capita in the UK, which is 5407.29 kWh. In 2013, the electricity consumption per capita in Oman was 5981.45 kWh. The main reason for the high consumption rate of electricity in GCC countries is the high temperature during summer; second, the cost of electricity is very low compared with other countries. The low cost of electricity for both domestic and industrial users in GCC countries does not encourage them to avoid the excessive use of electricity. In Oman, the electricity consumption is comparatively lower than other

GCC countries as Oman is ahead in terms of infrastructure development and industrialisation.

Umar and Wamuziri (2016) explored the potential of wind and solar energy in Oman and found that there is a huge opportunity to use these resources. This paper provides a review of the geothermal energy resources in Oman by considering the temperature data from Petroleum Development Oman (PDO). Geothermal is derived from the Greek: ‘geo’ means earth and ‘thermal’ means heat, and it can be interpreted as geothermal heat or energy produced from the earth. There are 53 boreholes in Oman with temperatures greater than 100°C, which can be used for electricity generation by way of a binary geothermal energy power plant.

1.1 Geothermal energy

Geothermal energy is counted as a type of renewable energy, which means availability is not affected by the lack of source and the increasing price of fossil oil. The energy contained in the geothermal fluid is water, which can be in vapour phase, liquid or as a mixture. The fluid is usually located at a depth of more than 1 km below the earth’s surface. The energy (hot water) comes from the radioactive decay energy from the centre of the earth, where the temperature can reach up to 6650°C, and this energy moves to the earth’s surface by

conduction and convection (DiPippo, 2012; Gehringer and Loksha, 2012). It is estimated that the energy flowed from these activities reaches up to 42 million MW. Geothermal energy occurs due to three important elements in a specific location within the earth: source of heat, water and permeable layer (Dickson and Fanelli, 2013). The water comes into the earth from rain or melting snow, is trapped in an impermeable layer and forms the geothermal source, as shown in Figure 1 (Muffler and Cataldi, 1978). Geothermal energy, it is estimated, can supply the need of the world’s energy consumption for 100 000 years (Sofyan, 2012).

Considering the fluid temperature, the enthalpy of geothermal energy can be classified into low, medium and high. Although sometimes classification can be confusing, at least two variables can be used to determine the thermodynamic state of the water (Lee, 2001). Geothermal classification is still not standardised; some classifications separate geothermal into five categories based on the characteristics of the reservoir. Table 1 lists the characteristics of five geothermal categories: hot water systems; two-phase, liquid-dominated systems with low, medium and high enthalpy; and two-phase, vapour-dominated systems (Kaya *et al.*, 2011). Lower temperatures (120–200°C) require pumping; they are common in extensional terrains, where heating takes place by way of deep circulation along faults, such as in the western USA and Turkey.

Figure 1. Schematic diagram of the geothermal reservoir (Ngangkham *et al.*, 2012)

In a Rankine cycle binary plant, water passes through a heat exchanger. The water vapourises an organic working fluid that drives a turbine. These binary plants originated in the Soviet Union in the late 1960s and predominate in new US plants. Binary plants have no emissions. Heat pumps extract energy from shallow sources at 10–20°C in 43 countries for use in space heating and cooling. Home heating is the fastest growing means of exploiting geothermal energy, with a global annual growth rate of 30% in 2005 and 20% in 2012.

1.2 Geothermal power plants

According to Younas *et al.* (2016) geothermal resources are available in three temperature ranges: (a) low temperature, (b) moderate temperature and (c) high temperature. Above 150°C is considered high temperature, while between 90°C and 150°C is considered moderate and below 90°C is considered as low temperature. For different ranges of temperature,

Table 1. Categories of geothermal systems (Kaya *et al.*, 2011)

Category		Temperature, T : °C	Production enthalpy, h : kJ/kg
Hot water		$T < 220$	$h < 943$
Two-phase, liquid-dominated	Low enthalpy	$220 < T < 250$	$943 < h < 1100$
	Medium enthalpy	$250 < T < 300$	$1100 < h < 1500$
	High enthalpy	$250 < T < 330$	$1500 < h < 2600$
Two-phase, vapour dominated		$250 < T < 330$	$2600 < h < 2800$

separate geothermal power plants are used for electric power generation. Geothermal power plants are environmentally friendly, renewable and sustainable due to the characteristics of the energy source (Duffield and Sass, 2003; Holm *et al.*, 2012). The carbon dioxide emission from coal-fired power plants is 12 times more than that from a geothermal power plant, while the carbon dioxide emission from gas power plants is six times more than that from a geothermal power plant (Alhamid *et al.*, 2016). In addition, the area required for a geothermal power plant is smaller than the area required by conventional power plants (Risch and Eastham, 2012). Another advantage of a geothermal power plant is the ability to sustain base load electricity: since the energy produced does not fluctuate with the weather or season, uninterrupted electricity production is possible (Edrisi and Michaelides, 2013; EPRI, 2010).

There are three types of geothermal power plants in use today, namely dry steam, flash steam and binary cycle. The dry type or direct steam power plant (Figure 2) is the typical geothermal plant with a steam vapour-dominated system (dry steam). Dry steam generated from several production wells are circulated by pipes to the turbine. The high-temperature and -pressure steam is used to rotate the turbine. This approach to utilising geothermal energy is restricted because dry-steam hydrothermal resources are very rare.

In a flash steam power plant – also referred to as a wet steam power plant – hydrothermal fluids above 182°C can be used to make electricity. Fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to

vapourise rapidly, or ‘flash’. The vapour then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy. Flash power plants can be categorised into single-flash and multiple-flash plants. Hot water is collected in a vessel and as water pumps to the generator, water is released from the hot geothermal reservoir and the abrupt change in pressure forces some water to be converted into steam. The steam rotates the turbine and the electrical output is received by generator as presented in Figure 3.

Binary cycle geothermal power plants are used for low-temperature applications. The hot water heats up another fluid with a low boiling point (BP) – often these are organic compounds, such as butane (BP = −0.5°C) – by way of a heat exchanger. The steam from this fluid is used to rotate the turbine, which results in electrical output through the generator. The two fluids used in a binary cycle power plant are

- geothermal fluid (extracted from a geothermal reservoir)
- working fluid (low BP).

The geothermal fluid transfers its energy to the working fluid using a heat exchanger and the working fluid is converted into steam. The steam operates the turbine; steam is then condensed and prepared for the next cycle. The geothermal fluid is sent back to the reservoir for maintaining the internal temperature of the geothermal reservoir. Furthermore, a binary cycle plant operates at temperatures of 85–175°C. At such temperatures (85–175°C), substantially less carbon dioxide is

Figure 2. Dry or direct steam power plant (GSE, 2011; Kagel, 2009; Lund, 2009)

emitted (Kose, 2007). The typical structure of a binary cycle geothermal power plant is shown in Figure 4.

The research conducted by Shevenell (2012) on Nevada geothermal wells reported that a geothermal project's costs might be expected to range from US\$835 000 to US \$3.4 million/MW if the drilling of the well is successful. Similarly, drilling costs per MW were estimated using all drilled wells (successful or not) and the indicated costs could

range from US\$341 000 to US\$1.1 million/MW. A typical breakdown of costs for the completion of a geothermal power production facility from beginning to end is presented by the Geothermal Energy Association (GEA, 2005) and Hance (2005), and is shown in Figure 5. Although the data presented here are more than 10 years old, it helps to understand the cost of different stages of a geothermal power project. It should be noted that the percentage of such costs may vary from country to country.

Figure 3. Flash steam geothermal power plant (GSE, 2011; Kagel, 2009; Lund, 2009)

Figure 4. Binary cycle geothermal power plant (GSE, 2011; Kagel, 2009; Lund, 2009)

Figure 5. Typical cost breakdown of geothermal power projects (Hance, 2005)

2. Geothermal resources in Oman

The underground fluid temperature is the key element to be considered when evaluating the potential of geothermal energy for electricity generation and other uses. Knowing the temperature will further help to use the appropriate geothermal plant for energy generation. The temperature of Oman hot water springs is one of the main indicators that suggest that the temperature of underground fluid could be comparatively higher. According to the Oman Water Society (OWS, 2016), there are more than 360 water springs; most of which are in the Musandam, Muscat and Dhofar governorates and are non-traditional sources for fresh water. Of these, 23 springs are classified as hot water springs which are very famous for tourism and natural therapy. For instance, the temperature of the spring at Al Kasfah (Figure 6), located in Wilayat Ar Rustaq in the Al Batinah South governorate, is 45°C (MOT, 2016). In order to explore further the potential of underground temperature and to investigate the possibility of using geothermal energy in Oman, it was necessary to examine the fluid temperature at a certain depth in Oman. Such exploration required boring to obtain samples from the earth's interior and

Figure 6. Al Kasfah Spring in Oman (MOT, 2016)

to examine the temperature, and involved huge cost. The geothermal gradient can be used to estimate the depth of the desired temperature; however, as the thickness of the crust varies around the world, using an average value of geothermal gradient (25°C/km) would not give accurate results.

The only organisation which conducts underground exploration in Oman is the PDO. The main purpose of PDO exploration is to search for new oil and gas reserves; however, the measurement of sample temperature at a certain depth is part of such exploration. PDO operates more than 5000 well drillings in more than 120 oil fields in Oman. PDO is producing 7 barrels of well water per barrel of crude oil (5–6 million barrels of water a day). Most of the produced well water is reinjected into the same or new wells. The average temperature of the well water was estimated to be 86°C (AERO, 2008). The latest data obtained from PDO show significant temperatures (Table 2) at different locations in Oman, which could be used for energy generation. The 53 boreholes which have a temperature of more than 100°C are located in block 6 as shown in Figure 7.

Considering the temperature data of different boreholes in Table 2, the binary cycle geothermal power plant, which operates at a temperature of 85–175°C, can be used for power generation. According to Monroy Parada (2013), binary power plants constitute 44% of total geothermal power plants in the world. A comparison of cost for electricity generation using different renewable sources is shown in Figure 8. It is clear that the cost of electricity generation from a geothermal binary plant is comparatively lower than that from solar, hydro, wind or nuclear plants. Electricity generation costs for a 50 MW geothermal binary plant is US\$92/MWh (GEA, 2016). Such comparison provides a guideline to adopt an appropriate source of renewable energy in Oman. The maintenance of binary cycle power plants is highly influenced by different factors such as the nature of the geothermal fluid used in the primary loop, the nature of the working fluid, the technology and location of the plant, and the climate and weather. Corrosion and scaling are the most common problems in binary power plants (Monroy Parada, 2013).

3. Conclusion

The temperature data obtained from PDO for 53 boreholes indicate that there is potential for the utilisation of geothermal energy resources in Oman. Considering the temperature of these boreholes, the binary geothermal plant can be used to produce electricity. The cost of energy production of a binary geothermal plant is low compared with solar and wind. The initial cost of the geothermal project is high while the success of drilling is the main contributing factor. The maintenance of binary cycle power plants is highly influenced by different factors such as the nature of the geothermal fluid, the technology and the location

Table 2. Temperature of 53 boreholes (temperature above 100°C)

Well name	Temperature: °C
Abu Thaylah	102-70
Al Bashair	157-00
Al Faisal	116-51
Al Noor	101-40
Ambrah	100-92
Aseel	100-48
Asfoor	117-74
Barik	124-38
Dafiq	103-00
Faal	120-74
Fahud South East	163-00
Fahud South	106-60
Fayrouz	101-63
Inaam	153-84
Khazzan I	157-65
Khazzan II	145-74
Lahan	129-64
Mabrouk I	121-10
Mabrouk II	114-40
Makarem I	173-68
Makarem II	170-00
Musallim	147-54
Nibras	142-84
Qarn Nihayda	110-00
Qashoob	115-40
Rabab	117-00
Sabeel	114-00
Sakhiya	107-33
Suwaihat	106-40
Tibr	140-13
Yibal I	137-20
Yibal II	123-00
Yibal III	111-00
Yibal IV	131-10
Zalzala	107-10
Al Husain	125-00
Al Huwaisah I	126-40
Al Huwaisah II	110-00
Al Huwaisah III	114-00
Al Huwaisah IV	124-00
Dhulaima I	104-00
Dhulaima II	157-80
Fahud	130-00
Fushaigha	110-00
Hasira I	103-30
Hasira II	103-00
Lekhwair I	101-70
Lekhwair II	160-00
Lekhwair III	147-00
Saih Nihayda	111-00
Saih Rawl I	100-60
Saih Rawl II	133-00
Shuwaiq I	118-90

of the plant, and the climate and weather. Other issues with binary geothermal plants are corrosion and scaling. In the GCC region, the United Arab Emirates has set a target to produce

Figure 7. Location of boreholes with temperatures more than 100°C

Figure 8. Electricity generation cost in US\$/MWh from different renewable energy resources (GEA, 2016); PV, photovoltaic

25% of power by renewable sources by 2030 and Qatar aims to generate 20% of its energy from renewables by 2024. The United Arab Emirates has recently started a feasibility study on the use of geothermal resources. There is an opportunity for Oman to consider geothermal energy resources and to reduce its dependency on oil and gas. This research is exploratory in nature and considers the temperature data for the potential use of geothermal resources in Oman. The data presented in this paper are from the PDO, keeping in mind that the focus of PDO is on oil and gas resources. The depth of the required temperature to use the geothermal resources will be a factor that will contribute towards the cost and needs to be considered during the feasibility study. While planning for using geothermal resources, Lund (2009) suggests that several associated

environmental impacts such as emission of harmful gases, noise pollution, water use and quality, land use, and impacts on natural phenomena, wildlife and vegetation need to be considered.

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