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Classification of the Geothermal Resources and Reserves of HS Orka, SW-Iceland

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ABSTRACT

HS Orka is the largest privately held geothermal company in Iceland. HS Orka is developing four high temperature geothermal fields located on the Reykjanes peninsula SW-Iceland, named Reykjanes, Svartsengi, Eldvorp and Krysuvik, and operating two power plants at Reykjanes (100 MW_e) and Svartsengi (75 MW_e). Expansions are planned that will increase HS Orka's geothermal power production from the current output of 175 MW_e by an additional 230 MW_e, thus bringing total production capacity to 405 MW_e by 2015. In 2009, Magma Energy Corp. acquired 43% stake in HS Orka. Mannvit Engineering prepared an independent technical report on the resources and properties of HS Orka on behalf of Magma as a part of Magma's due diligence exercise. In the independent technical report the geothermal resources and reserves of HS Orka were classified according to the Australian Geothermal Reporting code (2008). The results indicate that HS Orka has sufficient producing reserves and early stage development resources within its current operational and exploration portfolio in order to support its expansion plans of adding an additional 230 MW_e to its current operational output of 175 MW_e. The geothermal fields of HS Orka contain 175 MW_e ***Proven Reserves*** and additional ***Indicated*** and ***Inferred Resources*** of 130 MW_e and 500 MW_e, respectively. This paper discusses the results of the classifications according to the Australian Geothermal Reporting Code and the methods used to assess the geothermal resources and reserves of HS Orka.

1. Introduction

HS Orka is the largest privately held geothermal energy company in Iceland and operates on the Reykjanes peninsula, SW-Iceland. HS Orka is currently owned 98% by Magma Energy Corp., a Canadian pure play global geothermal power company actively engaged in operating, developing, exploring and acquiring geothermal energy projects.

HS Orka's operates two geothermal power plants: the Reykjanes (100 MW_e) and Svartsengi (75 MW_e) geothermal power plants in the Reykjanes and Svartsengi geothermal fields, respectively. Furthermore, HS Orka has two geothermal fields under development, named Eldvorp and Krysuvik. All of the power plants and properties of HS Orka are located on the Reykjanes peninsula, southwest of Reykjavík, the capital of Iceland (Figure 1). The Reykjanes, Svartsengi, Eldvorp and Krysuvik geothermal fields contain all high temperature geothermal resources, which are all located within two active fissure swarms associated with the volcanic rift zone along the Reykjanes peninsula, where the sub-marine Mid-Atlantic Ridge connects to the volcanic rift zone of Iceland.

Hitaveita Suðurnesja (HS), a predecessor of HS Orka, was founded in 1974 with the original objective of providing hot water for district heating. Electricity production commenced in 1978 with two 1 MW_e backpressure units and gradually the electrical production increased in stages with the final stage commissioned in

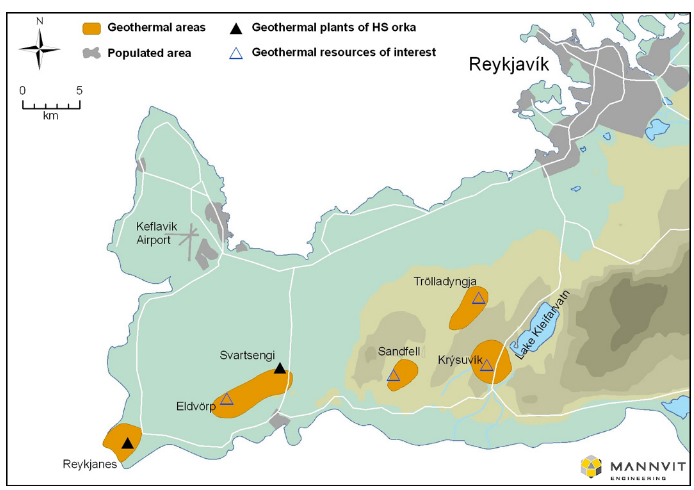

Figure 1. Location of HS Orka's power plants and geothermal resources on the Reykjanes peninsula, SW-Iceland.

late 2007. The current installed capacity of the Svartsengi geothermal power plant is about 75 MW_e. HS Orka generates 150 MW_{th} of thermal energy at Svartsengi for district heating (Thorolfsson, 2005). The Reykjanes power plant started commercial operation in May 2006 and has installed capacity of 100 MW_e. The plant consists of two 50 MW_e Fuji double flow condensing units. The condensing unit of the power plant is cooled with seawater, which is unique for geothermal power plants.

Expansions are planned that will increase HS Orka's geothermal power production from the current output of 175 MW_e by an additional 230 MW_e, thus bringing total production capacity to 405 MW_e by 2015. HS Orka plans to expand the Reykjanes power plant with one 50 MW_e Fuji unit and a 30 MW_e secondary flash unit. HS Orka further plans to develop the Eldvorp geothermal field up to 50 MW_e and the Krysuvik field up to 100 MW_e.

In 2009, Magma Energy engaged Mannvit Engineering, an Icelandic engineering and consulting company, to conduct an independent technical assessment on the resources and power plants of HS Orka, as a part of Magma's due diligence exercise before acquiring 43% stake in HS Orka. The geothermal resources and reserves of HS Orka were assessed and classified in a technical report (Hjartarson and Einarsson, 2009) according to the Australian Geothermal Reporting Code (Australian Geothermal Code Committee (AGCC), 2008), the one officially available at the time.

This paper discussed the four geothermal systems HS Orka has under utilization and development and the level of knowledge available on the separate fields, which forms the base for the resource assessment and classification. The paper also briefs the methods used to classify and assess the geothermal resources and reserves of HS Orka according to the Australian Geothermal Reporting Code.

2. Geothermal Reporting Codes

The geothermal industries in Australia and North-America have recognized the importance of consistent reporting of geothermal resources and reserves as the number of listed geothermal companies increases and more capital for geothermal project development comes from the equity markets. Codes for public reporting provide a minimum set of requirements for the public reporting of exploration results, geothermal resources and geothermal reserves. Reporting codes will provide a basis for transparency, consistency and confidence in the public reporting of geothermal information. The purpose of reporting codes is to provide a reporting basis that will be satisfactory to investors, stakeholders and capital markets, and to increase investor confidence and interest in the geothermal energy sector through the standardization of geothermal reporting.

The Australian Geothermal Energy Association (AGEA) and the Australian Geothermal Energy Group (AGEG) jointly developed the first Geothermal Reporting Code which was released in 2008 (AGCC, 2008). The Canadian Geothermal Energy Association (CanGEA) followed in 2010 with a separate reporting code, which adopted the Australian code and used it as the base for the Canadian Geothermal Reporting Code (Canadian Geothermal Code Committee (CGCC), 2010). The codes have the same structure, basic definitions and, therefore, are very similar.

Magma Energy reported the resources and reserves of HS Orka on voluntary compliance basis according to the Australian Geothermal Reporting Code, the only one officially available at the time. Magma Energy is publicly traded on the Toronto Stock Exchange and as an active CanGEA corporate member, Magma will use the Canadian Code on a voluntary compliance basis until 2011 when Code compliance will be a mandatory requirement for CanGEA membership. Mannvit Engineering is a corporate member of the CanGEA and is in the Registrar of Qualified Persons under the Canadian Geothermal Code for Public Reporting.

During the work of the independent technical report described in this paper, the Australian Geothermal Reporting Code had only been official for about one year. Except for the Code itself little information was available in the public domain on the experience working according to the Code. Papers describing other Competent Persons experience were not available and could not be drawn upon.

2.1 Classifications of Geothermal Resources and Reserves

The classification regime for ***Exploration Results***, ***Geothermal Resources*** and ***Geothermal Reserves*** under the Geothermal Reporting Code are explained in Figure 2. The Geothermal Reporting Code distinguishes between three levels of Geothermal Resources (***Inferred***, ***Indicated*** and ***Measured***) based on increasing geological knowledge and confidence. Geothermal Reserves are evaluated from the Geothermal Resources by the consideration and application of Modifying Factors. The term ***Modifying Factors*** is defined to include energy recovery and conversion, production, economic marketing, environmental, social, legal, land access and regulatory factor. These factors need to be considered and applied to a specific geothermal development project where geothermal resource is being or believed to be utilized. Two categories of Geothermal Reserves are distinguished (***Probable*** and ***Proven***). Inferred Geothermal Resources are defined with low level of confidence and they can never be directly converted into Geothermal Reserves. The classification of Geothermal Resources and/or Reserves must be done by a Competent Person and the role of the Competent Person is a vital aspect in any Public Geothermal Reporting.

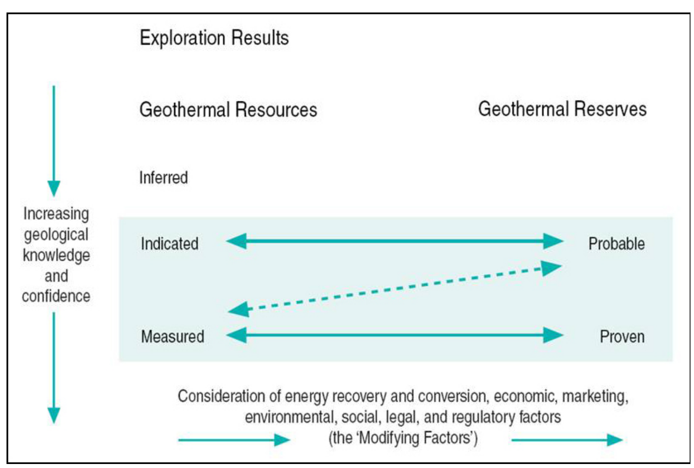

Figure 2. The relationship between exploration results, geothermal resources and geothermal reserves (AGCC, 2008).

More information on the Australian Geothermal Reporting Code, its development and current status within the Australian geothermal industry can be found in two papers presented at WGC 2010 (Williams et al., 2010; Lawless et al., 2010).

3. Geothermal Fields and Classification

3.1 Reykjanes

Systematic exploration in the Reykjanes geothermal field started in the late sixties and several exploration wells were drilled. Drilling for power production commenced in 1998 to supply high-pressure steam for the Reykjanes power plant. Today, a total of 28 wells have been drilled in the field. Most of the current production wells are directionally drilled and the average depth of the wells is about 2,200 m. Substantial research and exploration data has been collected during the research history of Reykjanes, spanning over 40 years, especially in the recent 7 years, with field development and the construction of the Reykjanes power plant. The data collected is sufficient to get quite a good knowledge on the geological structure, the nature and the characteristics of the geothermal system.

The Reykjanes geothermal system is a liquid dominated high-temperature geothermal system with sea water as the reservoir fluid. The highest temperature in the system has been measured above 320°C, but the dominating reservoir temperature is around 295°C. The mass extraction from the field has created a steam zone in the depth range of 800-1,200 m. This has resulted in increased fluid enthalpy and lower mass extraction needed to supply the power plant. In 2008, the average enthalpy was about 1,400 kJ/kg and the annual average mass extraction 614 kg/s (Vatnaskil Consulting Engineers, 2009). Reinjection is not yet an integral part of the reservoir management, but reinjection experiment started in July 2009 and is ongoing. Currently, about 50 kg/s is being reinjected into the geothermal reservoir.

HS Orka plans to expand the Reykjanes plant to 180 MW_e in two phases. The phase 1 expansion will consist of the addition of one 50 MW_e Fuji condensing unit and is expected to be operational by 2012. The phase 2 expansion will consist of a 30 MW_e secondary flash turbine and does not require drilling of new production wells as it will use secondary energy from the existing primary flash turbines. This second phase of expansion is expected to be on line by 2014.

The list below provides insight to the information and data available on the Reykjanes geothermal system and was used as a base for the geothermal reservoir assessment and the resource and reserve classification according to the Australian Geothermal Reporting Code.

- Geological investigation, geochemical analysis and geophysical surface exploration campaigns (Rosenkjær and Karlsdóttir, 2009; Karlsdóttir, 2005; Karlsdóttir 1997; Franzson, 2002) along with the analysis of information from 28 wells drilled.
- Hundreds of temperature and pressure measurements have been performed in the wells in the field, during completion warm-up and in the utilization phase (Jónsson, 2008).
- The monitoring program implemented at Reykjanes gives information on the mass extraction, reinjection and enthalpy changes. Well head pressures and control valve positions are monitored automatically and displayed on a website (Vatnaskil Consulting Engineers, 2009).
- Land subsidence monitoring and satellite imaging (Jónsson, 2009).

The natural state and the response to the 40 year production history of the Reykjanes geothermal system has been simulated in details with two different detailed numerical models. Several future production scenarios have been calculated with the models to evaluate the response of the geothermal system for the next 30 years (Vatnaskil Consulting Engineers, 2009; Björnsson et al., 2008; Hjartarson and Júlíusson, 2007).

The resource and reserves of the Reykjanes geothermal system were estimated by considering future forecasts of reservoir pressure response and well-head pressure decline made with numerical models and calculations. The models were calibrated by simulating both reservoir data and historical monitoring data. The models were used to make a 30 year forecast on the reservoir pressure due to future mass production rates and reinjection. Allowable reservoir pressure drawdown and practical well-head cut off pressures were assumed based on the current operational parameters of the plant. The modeling work indicates that reservoir pressure drawdown and well-head pressures will be within the acceptable operational parameters of the plant over the forecast life of 30 years.

In accordance to the Australian Geothermal Code (2008) the Reykjanes geothermal system contains a ***Proven Reserve*** with recoverable thermal energy of 100 MW_e for 30 years and an ***Indicated Resource*** with electrical generation capacity of 80 MW_e for 30 years, relative to the current operational parameters of the Reykjanes geothermal power plant and with the planned secondary flash unit successfully installed.

3.2 Svartsengi

The Svartsengi geothermal field has been studied for about 40 years. Extensive research activities and exploration campaigns have been conducted through the years and include: Geological and tectonic mapping, geochemistry analysis, resistivity explorations, gravity and elevation surveys, remote sensing using radar satellite images, tracer testing, numerical modeling and drilling of 24 wells. The capacity of the Svartsengi power plant is 75 MW_e and 150 MW_{th}. There are currently no plans to expand the capacity of the Svartsengi geothermal power plant.

The Svartsengi geothermal field is liquid dominated with temperature in the range of 235–240°C with natural steam zone found in the eastern part of the geothermal field. The produced fluid is about 2/3 seawater and 1/3 freshwater in composition (Björnsson et al., 1998. The gross mass production in 2008 was 438 kg/s on average and the total reinjection was about 193 kg/s on the average, or approximately 44% (Vatnaskil Consulting Engineers, 2009). The reinjection commenced in 2001 and has become an integral part of the reservoir management.

The geothermal reservoir is well understood and the reservoir response to production has been thoroughly monitored since the start of production in 1976 (Vatnaskil Consulting Engineers, 2009; Jónsson, 2008; Björnsson and Steingrímsson 1990). Monitoring parameters include: Mass production, water level measurements, reservoir pressure, well-head pressure, reservoir temperature, fluid chemistry, depth of scaling in production wells, gravity, elevation and GPS measurements.

Several methods and models, both simple and detailed numerical models, have been developed and used to simulate the natural and utilization state of the reservoir, since the 1980's (Kjaran et al., 1979; Björnsson, 1999; Vatnaskil Consulting Engineers, 2009). The models have been used to forecast the reservoir response given future production and reinjection scenarios. The latest models simulate the 34 years of the pressure history at Svartsengi with good confidence. The reservoir models have been used in the decision making process of HS Orka through the years.

Without going into the details of numerical simulations, the well-head pressures in the Svartsengi field are considered to be higher than the minimum preferred operational pressure of the Svartsengi power plant through 2040. It is therefore concluded with confidence that the Svartsengi reservoir is expected to be able to supply high pressure steam to the power plant for the next 30 years. However, as will be discussed below, the planned Eldvorp power plant project, scheduled for 2015, is expected to have an impact on the Svartsengi reservoir and this has to be taken into consideration in the future reservoir management of both of the fields.

The Svartsengi geothermal field has been under investigation and exploration for approximately 40 years, resulting in a comprehensive understanding of the reservoir and its response to long term mass extraction. In accordance to the Australian Geothermal Reporting Code (2008) the Svartsengi geothermal field is classified as a ***Proven Reserve*** containing recoverable thermal energy of 75 MW_e for 30 years, relative to the operational parameters of the Svartsengi geothermal power plant.

3.3 Eldvorp

The Eldvorp geothermal field is located in the western part of the Reykjanes peninsula, approximately 5 km SW from Svartsengi and about 11 km NE from the Reykjanes geothermal field (Figure 1). Eldvorp is located within the same fissure swarm as the Reykjanes and Svartsengi geothermal fields. The Eldvorp geothermal field has been studied to some extent and has been included in several surveys as a part of investigations of the Svartsengi geothermal field since the 1980's. One exploration well exists in the field that was drilled in 1983 and is 1,265 m deep (Franzson, 1987).

The reservoir temperature in Eldvorp is about 270°C, which is 30°C higher than in Svartsengi. The reservoir fluid in Eldvorp is about 2/3 seawater and 1/3 fresh water (Bjarnason, 1984). Initially, the reservoir featured natural steam zone from shallow levels to approximately 500 m depth. The steam zone has expanded to approximately 800 m depths due to the pressure drawdown in the field. Temperature and pressure has been measured in the existing well systematically since 1983 as a part of the monitoring program of the Svartsengi geothermal field (Vatnaskil Consulting Engineers, 2009; Björnsson, et al., 1998). The resistivity measurements and the pressure interference show that Eldvorp and Svartsengi are a part of the same geothermal system (Karlsdóttir and Vilhjálmsson, 2008). Eldvorp and Svartsengi are considered to be sub-fields of the same and a larger geothermal system which has two centers. Different reservoir temperatures observed within in the large geothermal system indicate Eldvorp and Svartsengi to belong to different up flow zones. HS Orka plans to develop the Eldvorp geothermal field to the point of 50 MWe power production by 2015.

Several reports are available on the Eldvorp geothermal field, which describe the geology, field characteristics, fluid chemistry and production characteristics of the existing exploration well Monitoring data, geophysical exploration results and radar remote sensing (InSAR) results show that the Eldvorp and Svartsengi geothermal fields are two separate parts of the same geothermal resource. A power plant in Eldvorp could be envisioned as an expansion to the existing power plant in Svartsengi. It is therefore important to investigate the Svartsengi reservoir pressure response to the future mass extraction in Eldvorp.

In order to investigate the impact of the planned 50 MW_e unit in Eldvorp on the Svartsengi plant, the existing Svartsengi numerical model developed by Vatnaskil Consulting Engineers was used to analyze future production scenarios for 30 years. Four scenarios, with different production and injection rates, were selected in order to investigate the sensitivity of the proposed 50 MW_e expansion in Eldvorp. The mass extraction needed to supply the proposed Eldvorp geothermal power plant with steam is based on the operational parameters of the Svartsengi power plant, because of the similarities of the fields.

Without discussing the modeling results in detail the main conclusion of the modeling effort is that large scale reinjection is essential for the Eldvorp geothermal project to be feasible. The modeling results indicate that the reservoir pressure drawdown in Eldvorp will be similar to what is observed in Svartsengi as a result of the future mass extraction in both fields. Mass extraction needed to supply the Eldvorp power plant will result in increased reservoir pressure drawdown at Svartsengi and well-head pressure decline of production wells.

The Eldvorp geothermal field is in the exploration phase and more drilling is needed in the field to further investigate the production characteristics of the geothermal reservoir. It has been concluded that it is practical to plan for a 50 MW_e unit in Eldvorp and probable that the geothermal resource can supply such a power plant with high-pressure steam with reinjection as an integral part of the resource management.

A part of the Eldvorp geothermal resource has been demonstrated to exist through direct measurements so that the recoverable thermal energy can be estimated with a reasonable level of confidence. In accordance to the Australia Geothermal Code (2008), the Eldvorp geothermal resource is classified as an ***Indicated Resource*** containing sufficient recoverable thermal energy of 50 MW_e for 30 years, assuming 50% reinjection and energy utilization parameters similar to the parameters defined by the Svartsengi geothermal power plant.

3.4 Krysuvik

The Krysuvik geothermal area is located in the Reykjanes peninsula and belongs to the Krysuvik volcanic centre and the associated fissure swarm (Figure 1). It is considered to cover approximately 80 km^2. The Krysuvik geothermal area is divided into three sub-geothermal fields named Krysuvik, Trolladyngja and Sandfell. The area has been known for a long time to be geothermally active and geothermal investigations are dated back to 1756. The area shows high intensity of geothermal activity, presented in several mud pits, many fumaroles and hot springs. The Krysuvik geothermal area was considered the fourth-largest accessible geothermal field out of approximately 30 fields in the National Assessment of Geothermal Resources of Iceland in 1985 (Pálmason, et al., 1985).

Systematic exploration at Krysuvik started in the 1940's and continued in the 1960's with the drilling of numerous shallow wells. Systematic exploration efforts continued in the 1980's, including wells drilled to depths of approximately 800 to 900 m, resulting in detailed research reports (Almenna Verkfræðistofan, 2000; Khubaeva, 2007; Mawejje, 2007). From 1997 to 2001, resistivity campaigns were conducted to outline the extent of the geothermal resource (Eysteinsson, 2001). Despite the long research history, more exploration is needed to improve the understanding of the geothermal resource. HS Orka has exclusive exploration rights in the Krysuvik geothermal area until 2016 and plans to drill 3 deep (>2,000 m) exploration wells as the next steps in the development of the field with the final aim of erecting a 100 MW_e geothermal power plant.

In the independent technical report on the resources and properties of HS Orka prepared for Magma Energy (Hjartarson and Einarsson, 2009), a volumetric assessment from 1985 was used as a base for the resource assessment of the Krysuvik geothermal area (Pálmason, et al., 1985). An updated volumetric assessment on the Krysuvik geothermal area was not performed as a part of the technical reporting. The volumetric assessment from 1985 on Krysuvik was a part of the larger national geothermal assessment made at the time. The assumptions used in the 1985 Krysuvik volumetric assessment are the following (Pálmason, et al., 1985): Geothermal field area is 60 km^2, based on the area covered by geothermal surface manifestations, alteration and resistivity results; the thickness of the geothermal system is 3 km; the temperature distribution in the overall field is estimated 70% of the boiling point curve; cut-off temperature is 130°C; geothermal recovery factor is 20%; geothermal efficiency factor is 7%; accessibility 80%; and the geothermal system is closed with no energy exchange with the surroundings.

According to the volumetric assessment from 1985 the thermal energy in place in the Krysuvik geothermal area was estimated to be 105,000 PJ, relative to 5°C. The thermal energy in place converts to recoverable thermal energy of approximately 500 MW_e for 30 years (Pálmason, et al., 1985). The 1985 estimate is considered conservative due to several reasons: new resistivity measurements indicate larger area; geothermal efficiency factors are higher today than in 1985; and the accessibility is higher today compared to 1985 because of directional drilling technology.

The geological and exploration results obtained in the Krysuvik geothermal area provide good evidence that the geothermal resource exist in a form, quality and quantity sufficient for eventual economic extraction. However, temperature data from geothermal wells and other geothermal information available are limited, compared to the indicated extent of the resource, to accurately predict the temperature distribution of the Krysuvik geothermal resource.

The geothermal resource at Krysuvik area, including Sandfell and Trölladyngja sub-geothermal fields, is classified according the Australian Geothermal Reporting Code (2008) as an ***Inferred Resource*** with approximately 105,000 PJ of thermal energy in place, relative to 5°C. The recoverable and converted energy is equivalent to approximately 500 MW_e for 30 years.

4. Conclusions

The resources and reserves of HS Orka have been classified with respect to the Australian Geothermal Reporting Code (2008). The results indicate that HS Orka has sufficient producing reserves and early stage development resources within its current operational and exploration portfolio in order to support its expansion plans of adding an additional 230 MW_e to its current operational output of 175 MW_e. The geothermal fields of HS Orka contain 175 MW_e proven reserves and additional indicated and inferred resources of 130 MW_e and 500 MW_e, respectively. In summary the resources and reserves of HS Orka are as follows (see Table 1):

Table 1. Reserves and Resources of HS Orka.

Property	**Reserves**		**Resources**		
	Proven	**Probable**	**Measured**	**Indicated**	**Inferred**
Svartsengi	75 MW_e				
Reykjanes	100 MW_e			80 MW_e	
Eldvorp				50 MW_e	
Krysuvik					500 MW_e
	Reserves = 175 MW_e		**Resources = 630 MW_e**		

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