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Exergetic Classification of Geothermal Resources in Japan

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ABSTRACT

Higher demand for energy consumption and importance of environmental issues has encouraged researchers and policy makers to consider renewable energies more seriously. Geothermal resources are a green energy source that can make a considerable contribution in some countries. Japan has the third ranking geothermal energy potential, and its geothermal electricity production is currently eighth in the world. Since the nature of geothermal resources dictates its method of utilization, it is important to categorize available resources. There is no consensus on classification of geothermal resources. Using exergy for resource classification benefits their comparison, according to their ability to do work. In this paper, geothermal power plants are classified using the exergy concept. Classification results can be used by decision makers as a reference for future geothermal development.

1. INTRODUCTION

Geothermal heating has been used since Roman times for bathing, cooking and as a way of heating buildings and spas using sources of hot water and hot steam that exist near the earth's surface. Water from hot springs is now used worldwide in spas, for space heating, and for agricultural and industrial uses (Dickson and Fenelli, 2004).

Geothermal energy utilization is commonly divided into two categories, i.e., electric production and direct application. The utilization method depends on parameters such as local demand for heat or electricity, distance from potential market, resource temperature, and chemistry of the geothermal fluid. These parameters are important to the feasibility of exploitation. The Lindal diagram (Lindal, 1973) emphasizes two important aspects:

- Feasibility of geothermal projects with cascade and combined uses.
- Resource temperature controls utilization purposes.

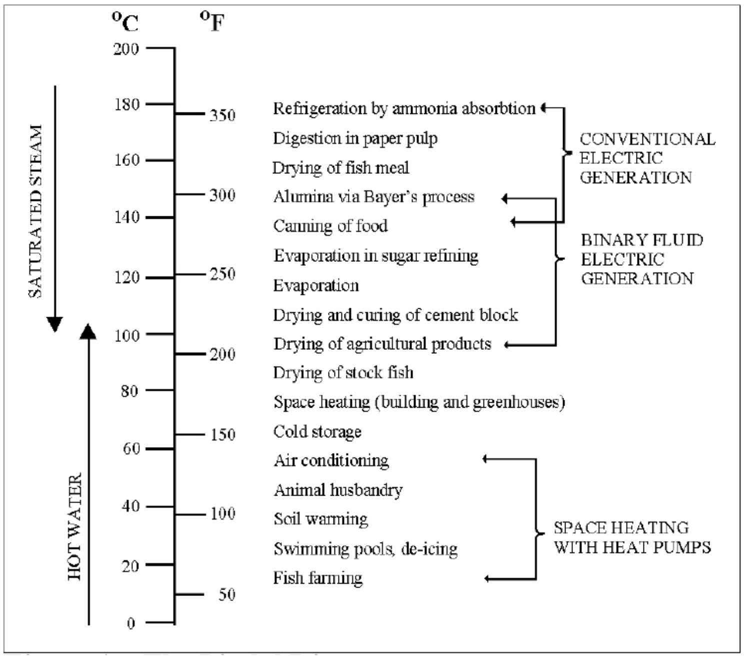

Figure 1. Lindal diagram indicating possible uses of geothermal fluids at different temperatures. Diagram emphasizes cascade and combined uses of application of geothermal sources.

Minimum temperatures required for different types of use are shown in Figure 1 (Lindal, 1973). The temperature boundaries, however, serve only as guidelines. Conventional electric power production can be realized by using fluid temperatures above 150°C, but considerably lower temperatures can be used for power generation with the application of binary systems. Ideal inlet temperatures into houses for space heating using radiators is about 80°C; however, by using floor heating radiators or applying heat pumps or auxiliary boilers, thermal waters at temperatures only a few degrees above the ambient temperature can be used beneficially (Fridleifsson, 1998).

As already explained, the nature of available resources and their specifications are important to decision makers. Once geothermal resource exploration has begun, classification of this resource with respect to temperature is a key element in future development scenarios. Given this importance, several works have been conducted from a geological standpoint on the engineering aspect of geothermal resources. Even with these works, still there is no consensus among scientists. This paper addresses classification of geothermal energy resources through introduction of the exergy concept, and the classification method of geothermal resources is applied to such resources in Japan.

2. CLASSIFICATION OF GEOTHERMAL RESOURCES

Utilization of geothermal fluid depends heavily on its thermodynamic characteristics and chemistry. These factors are determined by the geothermal system from which the fluid originates. Geothermal fluids have been classified differently by various authors (Mburu, 2010). Some authors have used temperature for a controlling factor, whereas others have used enthalpy (Dickson and Fenelli, 2004). Resources are divided into low, medium and high enthalpy. Table 1 shows classifications proposed by several authors.

Table 1. Classification of geothermal resources (°C) (Dickson and Fenelli, 2004).

	(a)	(b)	(c)	(d)	(e)
Low enthalpy resources	<90	<125	<100	≤150	≤190
Intermediate enthalpy resources	90-150	125-225	100-200	-	-
High enthalpy resources	>150	>225	>200	>150	>190
a) (Muffler and Cataldi, 1978); b) (Hochstein, 1990); c) (Benderitter and Cormy, 1990); d) (Nicholson, 1993); e) (Axelsson and Gunnlaugsson, 2000).					

Saemundsson (2009) emphasized that geothermal systems and reservoirs are classified on the basis of various aspects, such as reservoir temperature, entropy, physical state, or their nature and geological setting. The sub-classification divided low temperature systems into shallow resources, sedimentary low temperature systems, geo-pressured systems and convective low temperature systems. The high temperature fields are found without exception in volcanically active areas; their sub-classification includes rift zone regime geothermal systems, hotspot volcanism and compression regions.

Sanyal (2005) classified geothermal resources into seven categories based on temperature: Non-electrical grade (<100°C), very low temperature (100°C to <150°C), low temperature (150°C to 190°C), moderate temperature (190°C to <230°C), high temperature (230°C to <300°C), ultrahigh temperature (>300°C), and steam fields (approximately 240°C, with steam as the only mobile phase).

Williams et al. (2011) attempted a consistent terminology that encompassed both the fundamentally geological nature of geothermal resources and the practical, technological and economic aspects of resource exploitation, while remaining understandable to a broad community of non-specialists. Their work describes the scope of the effort as well as initial progress in establishing the new classification terms.

Armstead (1983) classified geothermal fields as semi-thermal (hot water up to 100°C at the surface), hyperthermal wet fields (producing hot water and steam at the surface) or hyperthermal dry fields (producing dry saturated or superheated steam).

In most classification methods, temperature is a main parameter. The main reason for this popularity is its ease of measurement. Further, most scientists, from geologist to engineers, agree on the term "temperature." However, in each classification method there are different boundaries for classifying resources, and there is no clear agreement on the temperature range of each category. In addition, temperature or enthalpy alone cannot describe the nature of fluids. Two geothermal fluids at the same temperature may have completely different abilities to do work; they can have same temperature with different phases, such as saturated water or saturated steam.

Bodvarsson and Eggers (1972) applied the exergy concept to thermal water, and concluded that improvement in efficiency for each additional flash stage decreases rapidly with increasing number of stages in geothermal flash cycles. Brook et al., (1979) also applied the concept of exergy to geothermal systems greater than 150°C.

Lee (2001) proposed a method to use temperature and enthalpy simultaneously. He used the term "exergy" or "available work," to ensure that thermodynamic properties of fluid were taken into account. Etemoglu and Can (2007) applied the method of Lee (2001) to Turkish geothermal resources.

3. GEOTHERMAL RESOURCES IN JAPAN

Japan is famous for its volcanoes, and Japanese spas (onsen) have been used for centuries. People have used them for bathing and relaxation, and onsens are currently one of the most popular tourist attractions in Japan. Onsen clearly exemplify geothermal direct use applications in Japan. There are approximately 28,000 hot springs in the country (Sugino and Akeno, 2010). The first experimental geothermal power station was built in 1925 at Beppu, Kyushu, and the first commercial power station began in 1966 at Matsukawa. With the 1973 oil crisis, development of new geothermal fields accelerated, reaching 215 MW during 1974–1978 (Sarmiento and Steingrimsson, 2007).

In 2009, 20 geothermal power plants were in operation at 17 locations nationwide. Most are in the Tohoku and Kyushu districts. Total net power output from all geothermal power plants reached 535.26 MWe in 2006. Figure 2 shows locations and details of geothermal power stations in Japan. Total installed geothermal power capacity was 0.2% of all power generation facilities in Japan in March 2009 (Sugino and Akeno, 2010).

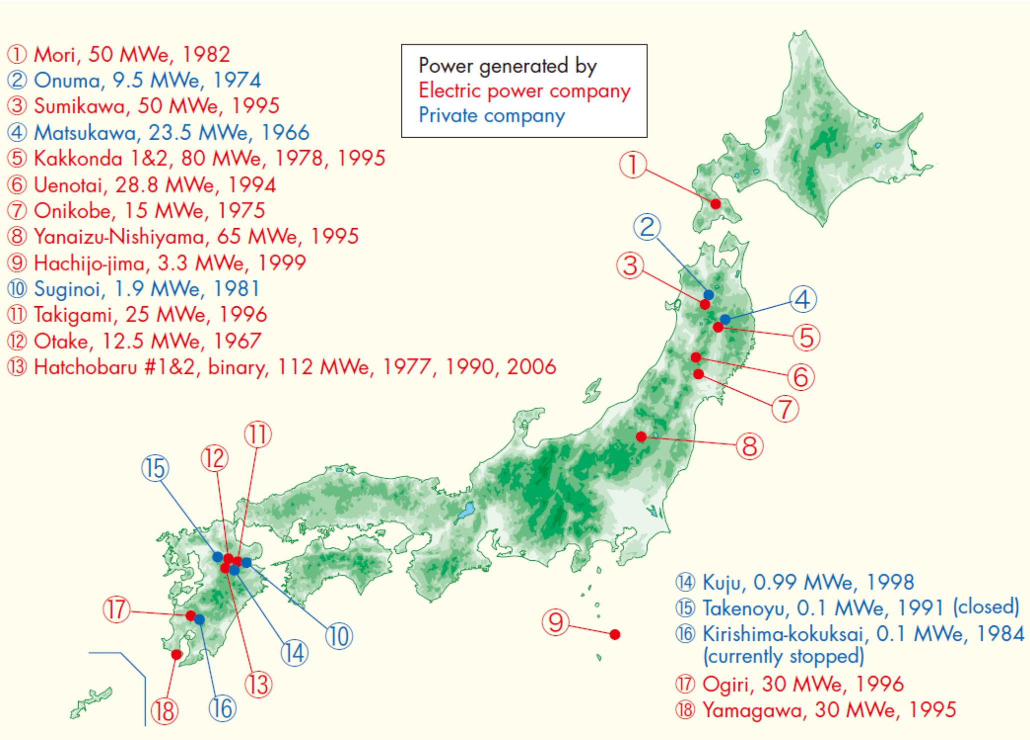

Figure 1. Geothermal power stations in Japan (GRSJ, 2011)

For prospective direct use applications of geothermal resources in Japan, it seems that direct use will change minimally. This is because demand for hot water will remain constant, because of small populations in geothermal regions. Ground source heat pumps appear to be a promising sector in this category. For power production from geothermal resources, the Japanese government has been encouraging investors with subsidies toward binary cycle plants. Nevertheless, geothermal power development and production in Japan are demanding tasks, and they need strong support from governmental sectors to be able to compete as a strong technology with other energy sectors.

Despite such technical and financial assistance, the growth of geothermal development in Japan is very slow compared with its technical and financial capabilities.

Kimabara (1988) summarized geothermal resources in Japan, and Yamano (1988) studied heat flow distribution in and around the country. Volcanic activities and earthquake history in Japan are the reasons for ample geological research and publication. The geology of Japan is very well known, and, consequently, the geothermal industry benefits from related research. However, there has been no record of exergetic classification of geothermal resources in the country; this provided motivation for this research on application of the exergy concept to classification of geothermal resources.

4. EXERGETIC CLASSIFICATION METHODOLOGY

Exergy is not a thermodynamic property; there are no “exergy tables.” Property tables such as “steam tables” only include actual properties (Dipippo, 2008). Thus, exergy evaluation of any mechanical system will yield its own unique results.

To better distinguish two geothermal resources, they must be compared quantitatively and qualitatively. Quantity can be compared by their total amounts. Quality is a more complicated issue, since it has a direct effect on the utilization method of the resource. Lee (2001) suggested examining quality of resources by their ability to do work, and this ability can be determined by the maximum specific exergy of its fluid.

Exergy is expressed as equal to the maximum work when the stream of substance is brought from its initial state to the environmental state defined by P_0 and T_0, by physical processes involving only thermal interaction with the environment (Kotas, 1995). This is expressed as follows:

$$E = m_i[(h_i - h_o) - T_0(s_i - s_0)] \quad (1)$$

where m is mass flow rate (kg/s), h is enthalpy (kJ/kg), s is entropy (kJ/kg K), and T is temperature (K). Subscripts *i* and *0* denote initial and environmental states, respectively. Assuming a mass flow rate of 1 kg/s, specific exergy can be calculated from Eq. (1).

The sink condition is no longer an important issue if SExI values are used. It is preferable to use the triple point as a sink condition, because saturated liquid enthalpy and entropy are defined as zero at the triple point. Assuming a maximum value of 1,194 kJ/kg for exergy and using Eq. (1), SExI can be formulated as

$$SExI = \frac{(h - 273.16s)}{1194} \tag{2}$$

Practically, it can be assumed that 100°C is the minimum temperature of saturated steam that can produce electricity, with 1 bar, enthalpy (*h*) of 2,676 kJ/kg and entropy (*s*) of 7.361 kJ/kgK. SExI can then be calculated by Eq. (2) as 0.557. Therefore, 0.5 is the lower limit of SExI for high quality resources. In the same manner, assuming 100°C saturated water with 1 bar, enthalpy (*h*) of 419.1 kJ/kg, and entropy (*s*) of 1.307 kJ/kgK as a boundary for direct use application, SExI may be calculated by Eq. (2) as 0.052. Hence, the upper limit of SExI for low quality resources is 0.05. Resources with SExI between 0.05 and 0.5 are evaluated as medium quality.

4.1 Classification of geothermal resources in Japan using exergy concept

Data from an annual report (TENPES, 2009) were used for classifying geothermal resources in Japan. Table 2 shows details of Japanese geothermal power plants currently under operation. A few assumptions were taken into account:

- Wellhead temperatures were not available for all power plants, so turbine inlet temperature was used in such cases.
- There were maximum and minimum wellhead (WH) pressures available for each power plant. Analysis was done according to maximum and minimum WH pressures, and results were not significantly different from those obtained using average WH pressures. Then, average WH pressures were used to obtain enthalpy and entropy of geothermal fluids.

Table 2. Geothermal power plants in Japan and their calculated SExI values.

No.	Power Plant	Capacity (kW)	*WHP (Mpa)	**x	h (kJ/kg)	s (kJ/kg)	SExI
1	Mori	50,000	1.265	0.136	1,077	2.817	0.258
2	Onuma	9,500	0.070	0.183	794	2.342	0.129
3	Sumikawa	50,000	0.455	0.323	1,309	3.446	0.307
4	Matsukawa	23,500	0.500	1.000	2,748	6.821	0.741
5	Kakkonda 2	30,000	2.050	0.119	1,139	2.920	0.286
6	Uenotai	28,800	1.090	0.820	2,420	5.765	0.708
7	Onikobe	12,500	0.995	0.164	1,093	2.869	0.259
8	Yanaizu- Nishi yama	65,000	1.300	0.796	2,385	5.629	0.709
9	Hachijojima	3,300	1.310	0.727	2,250	5.063	0.726
10	Suginoi Hotel	1,900	0.150	0.973	2,633	7.067	0.588
11	Takigami	25,000	0.275	0.177	933	2.593	0.188
12	Otake	12,500	0.290	0.196	981	2.707	0.203
13	Hatchobaru	2,000	0.430	0.133	898	2.477	0.186
13	Hatchobaru 1	55,000	1.165	0.312	1,414	3.556	0.371
13	Hatchobaru 2	55,000	0.715	0.233	1,181	3.094	0.281
14	Kujukanko Hotel	990	0.875	0.974	2,719	6.513	0.787
17	Ogiri	30,000	0.945	0.226	1,209	3.129	0.297
18	Yamagawa	30,000	2.095	0.151	1,204	3.052	0.310

*WHP: Average Wellhead Pressure; **x: Steam fraction

Analysis results are plotted in Figure 3. It can be seen that Kujukanko Hotel and Matsukawa have the highest exergy resources, and Onuma and Hatchubaru have the lowest resources. Water-dominated fields of Otake, Kakkonda 2, Ogiri, Hatchobaru 2, Yamagawa, Sumikawa and Hatchobaru 1 have SExI less than 0.5, and are located in the medium exergy zone of the figure. The specific exergy index value for Kujukanko Hotel, Matsukawa, Hachijojima, Yanaizu-Nishi yama, Uenotai and Suginoi Hotel were calculated at 0.787, 0.741, 0.726, 0.709, 0.708 and 0.588, respectively. They are plotted in the high exergy zone of the diagram.

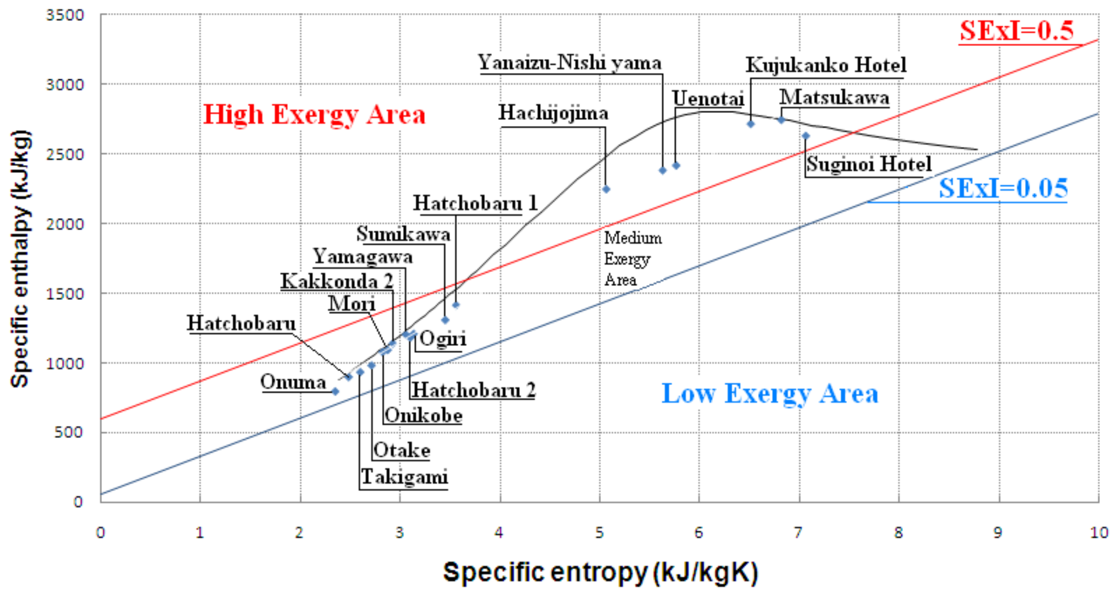

Figure 3. Distribution of Japanese geothermal resources on SExI map, according to their specific entropy and enthalpy.

5 CONCLUSIONS

Geothermal resources have been classified using geological descriptions or thermodynamic properties of geothermal fluid, such as temperature or enthalpy. Neither of these is accurate, since two geothermal fluids at the same temperature could have completely different ability to do work.

The exergy concept was developed to be used as a geothermal resources classification tool. This parameter is sensitive to sink conditions and is not reliable in different dead states, so specific exergy index was used as a parameter for classification.

Specific exergy index values are not sensitive to sink conditions, but because of easy usage and zero values for enthalpy and entropy of water at the triple point, it was assumed a desired sink condition. Low exergy resources have SExI values less than 0.05, medium exergy resources values between 0.05 and 0.5, and high exergy resources more than 0.5.

Exergetic classification of geothermal resources was applied to 18 under-operating geothermal power plants in Japan. Kujukanko Hotel, Matsukawa, Hachijojima, Yanaizu-Nishi yama, Uenotai and Suginoi Hotel geothermal fields have high exergy resources according to their SExI values in excess of 0.5. The remaining geothermal fields in Japan are classified in the medium resources zone.

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