CLASSIFICATION OF GEOTHERMAL RESOURCES

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ABSTRACT

Resource classification is a key element in the characterization, assessment and development of energy resources, including geothermal energy. Geothermal resource issues such as location, quality, feasibility of development, and potential impacts are important to the geothermal stakeholders. Their understanding and use of globally recognizable and easily understood terms in describing and addressing these issues is important. These terms must cover the main aspects of geothermal parameters from fundamental geological nature of geothermal resources to the practical technological and economic aspects of resource exploitation while remaining understandable to the broad community of non-specialists. This paper will investigate worldwide status of geothermal resources classification.

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).

In 1892, the first geothermal district heating system began operation in Boise, Idaho (USA). In 1928, Iceland, another pioneer in the utilization of geothermal energy, also began exploiting its geothermal fluids, mainly hot water for domestic heating purposes (Dickson and Fenelli, 2004).
Using geothermal energy to produce electricity is a relatively new industry. The Larderello field in Tuscany, Italy, produced the world's first geothermal electricity in 1904. In the experiment, five light bulbs were lit by electricity produced through steam emerging from vents. The success of this experiment clearly indicated the industrial value of geothermal energy and marked the beginning of a form of exploitation that was to develop significantly from then on. Electricity generation at Larderello was a commercial success. Major production at Larderello began in the 1930s; in 1970, the power capacity reached 350 MWe. In 1911, the world's first geothermal power plant was built in Italy's Valle del Diavolo (Devil's Valley), named for the boiling water that rises there.

After the Second World War, many countries were attracted to geothermal energy, considering its economic competitiveness with other forms of energy. It does not need to be imported, and, in some cases, it is the only energy source available locally. More recently, extensive direct heat utilization projects have been undertaken in many European countries, and electric power developed extensively in Italy and Iceland. Geothermal heat pumps have been widely used in Austria, Switzerland, Germany and Sweden (Antice and Sanner, 2007).

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.

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.

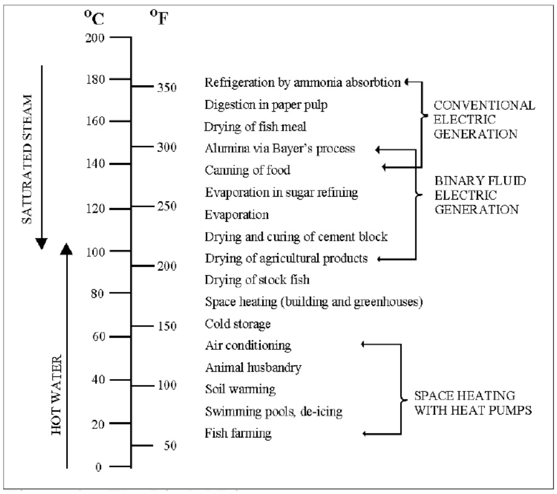


Figure 1: Lindal diagram indicating possible uses of geothermal fluids at different temperatures. Diagram emphasizes cascade and combined uses of application of geothermal sources.

This paper addresses classification of geothermal energy resources through introduction of the exergy concept, and the exergetic classification method of geothermal resources in the world.

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 G 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.

Since the 1960s and 1970s, numerous researchers have focused on classification of geothermal resources (i.e., (White, 1965); (White, et. Al., 1971); (Kruger and Otte, 1973)). Some of those definitions are still in use by developers. For example, the basic framework for geothermal resource characterization and assessment of Muffler and Cataldi [1978] is foundational to recent resource assessments by the United States Geological Survey (USGS) and other organizations (Williams, et al., 2008).

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. CLASSIFICATION OF GEOTHERMAL RESOURCES BY EXERGY

Temperature and enthalpy alone cannot represent fluid properties (For fluids with different phases such as saturated water or saturated steam).

Using exergy for resource classification has the advantage of comparing according to the ability to do work. 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 TJ, 1995).

$$E = m_i[(h_i - h_0) - T_0(S_i - S_0)] \quad (1)$$

m: mass flow late (kg/s)
h: enthalpy (kJ/kg)
S: entropy (kJ/kg.K)
T: temperature (K)
Subscript i and 0 denote initial and environmental states, respectively.

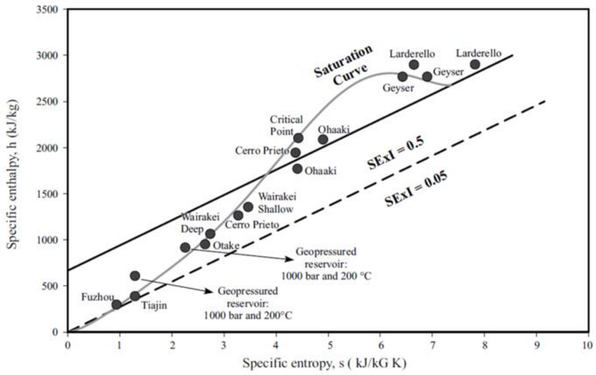


Figure 2: Lee's SExI plot with some important worldwide geothermal fields (Hipólita Ramajo et al, 2010; modified from Lee, 1996, 2001).

The specific exergies of saturated water and steam are listed in table 2 for sink conditions of the triple point (0.01℃), 10℃, and 20℃.
To achieve a reliable and stable parameter, Lee suggested normalizing exergy values by the maximum exergy of the corresponding sink condition (Jalilinasrabady and Itoi, 2013). Assuming a maximum value of 1194 kJ/kg for exergy and using eq. (1), SExI can be formulated as:

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

Practically, it can be assumed that 100℃ is the minimum temperature of saturated steam that can produce electricity, with 1 bar, enthalpy (h) of 2676 kJ/kg and entropy of 7.361 kJ/kgK. SExI can be calculated by Eq. (2) as 0.557.

3.1 Case study: World wide application

Figure 2, explains Lee's SExI plot with applications on some important worldwide geothermal fields. As seen from the figure most of the geothermal areas are in high and medium exergy areas.

3.2 Case study: Application in Turkey

A significant development was achieved in Turkey in geothermal electricity production and direct uses (district, greenhouse heating and thermal tourism) for the last five years. These are mainly attributed to new Geothermal Laws on regulations and the feed-in tariff. About 225 geothermal fields have been discovered in Turkey. A liquid carbon dioxide and dry ice production factory is integrated to the Kizildere geothermal power plant. The existing plants are in the following areas: Çanakkale-Tuzla 7 MWe, Aydin-Hidirbeyli 68 MWe, Aydin-Salavath 35 MWe, Aydin-Germencik 98 MWe, Aydin-Gümüsköy 7 MWe, Denizli-Kizildere 107 MWe, Aydin-Pamukören 48 MWe, Manisa-Alasheir 24 MWe, Denizli-Gerali 3 MWe) (Mertoglu, et al., 2015). Figure 3, is an exergetic classification for Turkey and most of the geothermal areas are in high and medium exergy area.

3.3 Case study: Application in Poland

The geothermal potential of the country is well known, with important development for direct heat supply. As yet, there is no operational geothermal power-plant in Poland, but a small binary pilot plant at Lodz is under evaluation (Kępińska, 2015). Figure 4, shows most geothermal areas are in medium exergy areas.

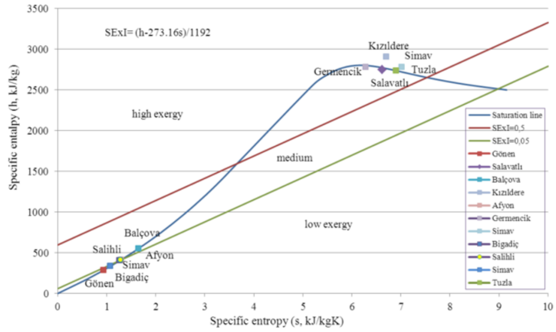


Figure 3: Examples of geothermal fields plotted on classification map of geothermal resources (Ebru, 2015).

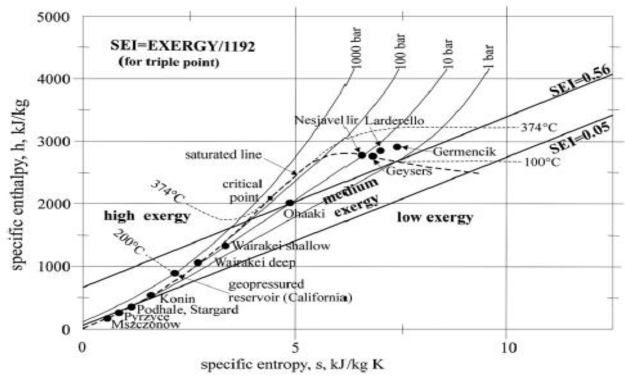


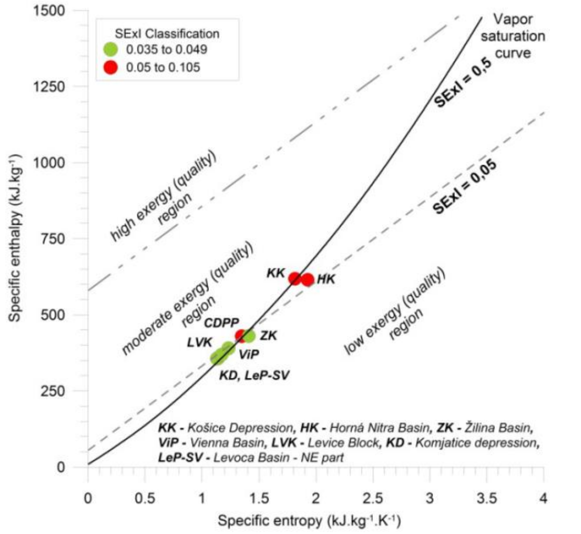
Figure 4: Classification of geothermal resources by SEI in Poland and selected global fields plotted on Mollier diagram, (Antoni, 2012).

3.4 Case study: Application in Slovak Republic

Geothermal energy is widely used for recreational purposes, mostly in very popular aqua parks in many places of Slovakia, with several others direct utilization. A small pilot plant is under evaluation at Kosice, for a combined heat and electricity project (Fendek and Fendekova, 2015). The resources fall under medium exergy area as shown in figure 5.

3.5 Case study: Application in Japan

Despite the large geothermal potential of the country, estimated at around 20 GWe, the present total capacity of geothermal power plant is still around 500 MWe, almost unchanged for more than a decade. After the nuclear accident in March 2011, the government restarted an incentive scheme for geothermal development and mitigation of constraints in national parks, encouraging new geothermal exploration activities by private sectors as well as quick installation of small binary systems. About 40 projects are either in exploration or development stage. The following fields are active: Akita (88 MWe), Fukushima (65 MWe), Hachijojima (3 MWe), Hokkaido (25 MWe), Iwate (103



MWe), Kagoshima (60 MWe), Kumamoto (2 MWe), Miyagi (15 MWe), Oita (155 MWe), and Tokamachi (2 MWe) (Yasukawa and Sasada, 2015).

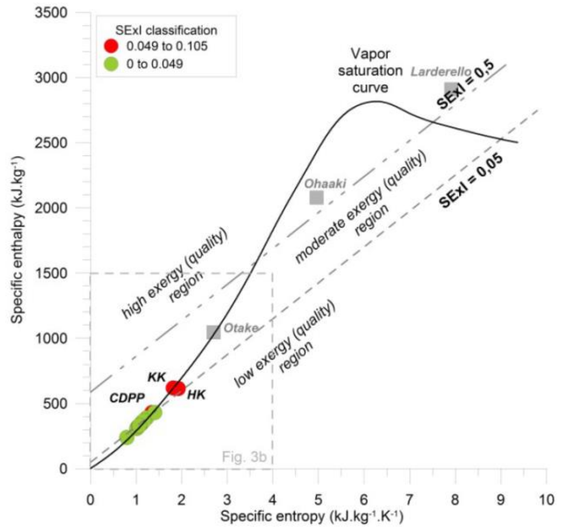


Figure 5: Geothermal resources classification in Slovakia (Fricovsky et al. 2016)

Japan has third geothermal resource potential in the world. From figure 6, it can be can be seen that most of the geothermal areas are in high and medium exergy area. From this, it is understood that use of low exergy area is not advanced. Plans are in place for the development of hot springs (Onsen) binary units hence the development of resources under low exergy area.

4. DISCUSSION

On a global scale, geothermal energy is tied to the geologic environment and the large-scale features specific to that environment. In defining geothermal prospects, resources and reserves, clear terms and definitions are required to provide reliable and comparable reserve estimation analogous to the classifications schemes developed for petroleum resources.

Various classifications face various challenges in accessing, quantifying and classification of geothermal resources.

Exergyetic classification method is considered more accurate as compared to the temperature and enthalpy methods because of the advantage of comparison according to the ability to do work. However, the main disadvantage is the difficulty in acceptance by the non-specialists (less accustomed to thermodynamics terminology, and also dependent on availability of wellhead pressure and temperature data.

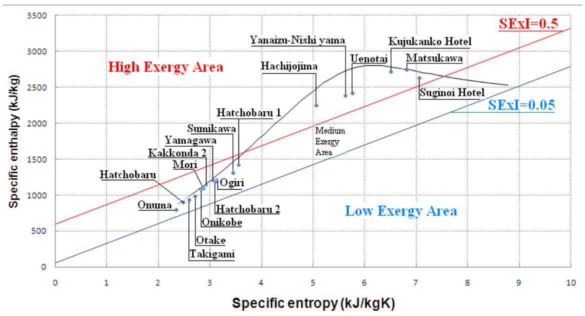


Figure 6. Distribution of Japanese geothermal resources on SExI map, according to their specific entropy and enthalpy.

5. CONCLUSION

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 delivers straightforward values to decision makers but unfortunately it is not applicable to the fields at their early stage developments due to lack of information. It is the weakest point of this classification method.

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Table 2. Specific exergy and specific exergy index values under different sink conditions (water triple point, 10°C, and 20°C).

					Triple Point		10°C		20°C	
	Temperature (°C)	Pressure (bar)	Enthalpy (kJ/kgK)	Entropy (kJ/kgK)	Exergy (kJ/kg)	SExI	Exergy (kJ/kg)	SExI	Exergy (kJ/kg)	SExI
Triple point	0.01	0.006	0.00	0	0.00	0.00	0.76	0.00	3.00	0.00
	99.60	1.00	417.40	1.302	61.62	0.05	49.37	0.04	38.59	0.04
	179.90	10.00	762.80	2.139	178.60	0.15	158.00	0.14	138.80	0.13
	212.40	20.00	908.60	2.447	240.20	0.20	216.50	0.19	194.30	0.18
Critical point	374.15	221.20	2027.00	4.319	850.20	0.71	805.20	0.71	764.30	0.71
Saturated water	263.90	50.00	1154.00	2.919	356.40	0.30	327.90	0.29	301.00	0.28
	311.00	100.00	1407.00	3.359	489.60	0.41	456.80	0.40	425.50	0.39
	336.60	140.00	1570.00	3.621	580.60	0.49	545.20	0.48	511.20	0.47
	365.70	200.00	1825.00	4.011	728.90	0.61	689.50	0.61	651.70	0.60
	365.70	200.00	2415.00	4.935	1069.00	0.90	1018.00	0.90	971.10	0.90
	336.60	140.00	2638.00	5.372	1173.00	0.98	1117.00	0.98	1066.00	0.99
	311.00	100.00	2725.00	5.614	1193.00	1.00	1136.00	1.00	1082.00	1.00
	303.30	90.00	2742.00	5.678	1194.00	1.00	1135.00	1.00	1081.00	1.00
Saturated steam	263.90	50.00	2794.00	5.973	1165.00	0.98	1103.00	0.97	1046.00	0.97
	212.40	20.00	2799.00	6.34	1069.00	0.90	1004.00	0.88	943.00	0.87
	179.90	10.00	2778.00	6.586	981.10	0.82	913.50	0.80	849.90	0.79
	151.80	5.00	2749.00	6.822	887.50	0.74	817.60	0.72	751.60	0.69
	99.60	1.00	2675.00	7.359	667.30	0.56	592.00	0.52	520.60	0.48
	0.01	0.006	2501.00	9.154	0.00	0.00	-90.79	-0.08	-180.10	-0.17
	Max				1194.00		1136.00		1082.00	