Geothermal Resources Classification – A Review

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Keywords:

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Highlights:

A comprehensive review has been done on geothermal resources classification.

Details of key existing classification methods and their pros and cons were discussed.

The stored heat method is the most well-established.

A combination method was discussed which is easy to understand for technical and non-technical counterparts.

ABSTRACT

Renewable energy resources are gaining popularity and they have proven their reliability to achieve a sustainable future, their efficiency increases due to advancement in innovative technologies, and that leads to less uncertainty and increased contribution to the energy mix of future society.

Geothermal energy carries its own uncertainty due to its nature, it requires high capital investment owing to the very high cost of well drilling and the journey from exploration to exploitation can be very stressful for investors and decision-makers. Since the nature of geothermal resources dictates their method of utilization, it is important to categorize available resources. There is no consensus on the classification of geothermal resources. Most scientists, from geologists to engineers, agree on the term temperature. However, temperature or enthalpy alone cannot describe the nature of fluids. Other classification methods discussed in this paper are assessment confidence, Australian, Canadian, and GEA Codes, Geologic Setting,

thermodynamic properties, resources potential, stored heat, and geothermal resources utilization including direct uses. Even within the framework of each classification, there are conflicting opinions between scientists. Well-organized and easily understandable frameworks for classifying geothermal resources are essential for the assessment, exploration, development, and reporting and this paper aims to illustrate a comprehensive analysis of existing methods to come up with a recommendation of the most appropriate method for classification of the geothermal resources.

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 agricultural and industrial uses [1].

Geothermal energy is a clean and renewable source of energy characterized by a reservoir from which heat can be extracted economically and utilized for generating electric power or any other suitable industrial, agricultural, or domestic application. The geothermal system is composed of a hydrological system, the recharge zone, subsurface parts, and the outflow of the system. Geothermal reservoir indicates the hot and permeable part of a geothermal system pressurized, either by artesian or through boiling that may be directly exploited. Common rocks are volcanic rocks as well as limestone, shale, and granites.

The importance of geothermal energy originates from the availability and continuity of the source for heat exploitation, and the fact that it is clean energy that produces low harmful emissions and ensures cost stability for end-users. Furthermore, geothermal energy presents no geopolitical risk and can be used with the current industrial technology. The main challenges and limitations for geothermal energy are that most of the high-temperature resources are concentrated in specific areas usually active tectonics, and their remote optimal energy site locations have made it difficult for direct use utilization in cities and potential customers. Technological barriers lie mainly in high exploration and high initial investment costs for electricity production, long-term investment return, and the risk of failure during the exploration and drilling phase as well as low public acceptance in some countries.

Exploration of geothermal resources has advanced within the last decades employing applications from new multidisciplinary science and technologies. GIS-supported certainty factor (CF) models were proposed for the assessment of the geothermal potential of Tengchong County in the southwest of China [2]. GIS was used to assess the geothermal potential in western Anatolia, Turkey [3]. Geothermal favorability mapping by advanced geospatial overlay analysis was applied to a case study in Tuscany, Italy [4]. A quantitative method for the assessment and mapping of the shallow geothermal potential was proposed by Casasso and Sethi [5]. Artificial neural networks for the generation of geothermal maps of ground temperature at various depths by considering land configuration were proposed for Cyprus [6]. Estimations of heat mining potential using sCO2 (Supercritical CO2) were performed using the TOUGH2 computer software [7].

Falcone et al., [8] critically assessed conventional and unconventional deep geothermal well concepts, focusing on the basic Borehole Heat Exchanger (BHE) concept. A novel single-well geothermal system for hot dry rock geothermal energy exploitation was developed by Huang et al. [9].

Geothermal energy resources are characterized by geologic settings, intrinsic properties, and viability for commercial utilization [10]. Multiple classification schemes have been devised to explain and categorize geothermal energy systems. Example classifications include those developed by the United States Geological Survey [11], [12], National Renewable Energy Laboratory[13], and International Geothermal Associations [14]. These classification systems have mixed geology, engineering, and resource terminology together in a manner that is difficult to present to an investor or someone not familiar with the geothermal industry. The broadest geothermal classification and the easiest to understand is discussed at the Geo-Heat Center at the Oregon Institute of Technology [15]. This classification is based entirely on temperature ratings of low (<90^{o}C or 194^{o}F), moderate (90 – 150^{o}C or 194 – 302^{o}F) and high (>150^{o}C or >302^{o}F) and is loosely tied to the potential uses of the geothermal heat energy [16]. This classification approach is important for the public who is familiar with temperature but has limitations among professionals.

Yuafrinaldi et al., [17] provided an overview of three different established resource classifications in line with the Indonesian National Standard (SNI-1998), they also used the petroleum resource classifications system as a guideline for leveling geothermal resource classifications. The power density method for estimating potential power generation capacity was recommended for geothermal prospects at an exploration or early appraisal stage by Cumming [18]. A study by Wilmarth and Stimac [19] suggested that fault-based geothermal systems tend to be low to moderate-temperature and have low power density, volcanic arc systems tend to be moderate to high-temperature and have moderate to high power density, and rift systems tend to be high-temperature and have high power density.

Suyama [17] proposed that there are three categories of geothermal resources with huge resource bases including the hydrothermal convection system, the hot igneous system, and the regional conductive environment.

At least four other classification systems were suggested by different organizations over more than the past three decades of geothermal investigations. These schemes were devised to describe geothermal resource type using scientific and engineering terms that are more closely related to the geology of the resource when compared to a solely temperature-based description.

There are fundamental differences in prescribing a classification system that depends on whether it aims at being a reporting standard, a set of guidelines, a set of definitions, a code, or a protocol [20]. Each of the above options carries a substantially different ability to reinforce the goal of reducing the uncertainty in defining the value of a given geothermal resource and thus, the risk to investors.

It is also a challenge to develop a system that can equally satisfy the requirements of different potential end-users of the same geothermal resource including governments, field owners, operators, investors, reserves auditors, insurance companies, international energy associations, agencies, and councils.

To achieve a feasible and sustainable geothermal resources development, a sound and reliable classification could be a good starting point for the investors and developers. If one considers the different possible uses of geothermal energy, and different investment targets are equally possible, yet they carry substantially different risks and uncertainties in their identification and estimation such as the heat source, the reservoir, the fluids stored within it, and/or their pressure, the temperature of the resource, the heat stored within the reservoir, the recoverable fluid volume, the recoverable heat, the recoverable power, and the net profit/revenue from a given development project.

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, the feasibility of development, and potential impacts are important to the geothermal stakeholders [10]. Their understanding and use of globally recognizable and easily understood terms in describing and addressing these issues are important. These terms must cover the main aspects of geothermal parameters from the 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 [21].

1.1 Geothermal classification methods

Well-organized and easily understandable frameworks for classifying geothermal resources are necessary for the assessment, exploration, development, and reporting. Stakeholders at all levels of government, within the geothermal industry, and among the general public need to be able to use and understand consistent terminology when addressing geothermal resource issues such as location, quality, the feasibility of development, and potential impacts [21]. Up to date, several geothermal resource classifications are proposed by different authors and institutions. Several classification methods have been proposed and have been changing over time with geothermal research and development as a result of the expanded scope of exploitable geothermal resources.

Saemundsson [22] emphasized that geothermal systems and reservoirs are classified based on 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.

Since the 1960s and 1970s, numerous researchers have focused on the classification of geothermal resources (i.e.[23];[24];[25]). 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 [26] is foundational to recent resource assessments by the United States Geological Survey and other organizations [27],[28].

Armstead [29] classified geothermal fields as semithermal (hot water up to 100°C at the surface), hyperthermal wet field (producing hot water and steam at the surface), or hyperthermal dry fields (producing dry saturated or superheated steam).

In most classification methods, the temperature is the main parameter. The main reason for this popularity is its simplicity and ease of measurement. Further, most scientists, from geologists 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 the same temperature with different phases, such as saturated water or saturated steam [30].

Geothermal classification has no globally agreed standards, guidelines, and codes to assess, quantify and classify the resources [31]. This may lead to increased resource uncertainty, higher investment risk, less confidence in development, and misunderstanding among different stakeholders.

The following are the geothermal stakeholders who are interested in geothermal classification information to inform their decisions on different issues [32].

a. Governments

Governments need clear and consistent information on geothermal classification and resource estimates to better understand the total resource base, to make well-informed decisions on energy security, to formulate an energy strategy and policies that will guide the country on geothermal development and regulation.

b. Global Organizations

These organizations and institutions need to assess and compare global energy systems and different energy sources including renewable energy.

c. Renewable Energy Sector Participants

Enhanced overview of asset values, provide a measure of comparability with traditional energy systems, offer a basis to estimate the scale of each renewable resource, provide reliable estimates based on best practices and common standards.

d. Investment community

They need the information to guide in comparing and contrasting different investment opportunities and enhance portfolio valuation.

e. Locals

Clear and easy to understand methods of geothermal classification will lead to better communication with the local population to increase social acceptance of geothermal energy development.

f. Academic and Research Institute

Research and development of educational institutes play an important role to achieve better classification methods for geothermal resources, this has been a gradual and continuous process.

Therefore, geothermal resource classification systems should reflect the current state of knowledge regarding geothermal technology and serve as an effective means of characterizing, quantifying, assessing, and providing consistent communication within and outside the geothermal community.

The main objective of this study is to review the proposed geothermal resource classification methods and to make a comparative analysis. Furthermore, the review aims to recommend the best classification method. In this paper, a comprehensive review of the existing geothermal classification methods has been done from the widely published papers in international journals in addition to other research findings funded by renewable energy agencies on the classification and assessment of geothermal resources. A comparative analysis of the methods dependent on the parameters utilized in the classification has also been done to come up with a recommendation of the most appropriate method for the classification of the geothermal resources.

The following are the main classifications categories that will be discussed in this review:

a) Assessment Confidence
b) Geologic Setting
c) Temperature and other thermodynamic properties
d) Other classification methods

2. Assessment Confidence

Several authors have classified the geothermal resources under this category.

2.1 Classification by accessibility and discovery status

The subdivision of the geothermal resource base was done by Muffler and Cataldi [26] through a McKelvey diagram as shown in Figure 1. The degree of geologic assurance regarding resources is set along the horizontal axis whereas the economic/technological feasibility which is controlled by the depth is set along the vertical axis. According to this classification system, the geothermal resource base is all of the thermal energy in the Earth's crust beneath a specific area, measured from the local mean annual temperature.

The geothermal resource is that fraction of the resource base at depths shallow enough to be tapped by drilling in the foreseeable future that can be recovered as useful heat economically and legally at some reasonable future time. The geothermal reserve is the identified portion of the resource that can be recovered economically and legally at present using existing technology [26].

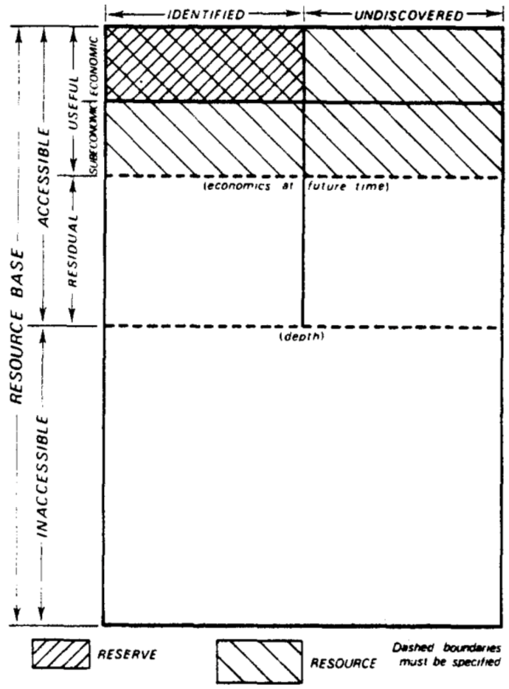

Figure 1: McKelvey diagram [26].

2.2 Geothermal classification by potential

Rybach [33] proposed a method to address the challenges posed by previous potential classifications methods which estimated geothermal potential for each country without stating which kind of potential referred to the recovery factor applied. In this method, the resource is categorized into theoretical, technical, economic, sustainable, and developable; decreasing successively in size with the potentials becoming more and more realizable and rewarding financially.

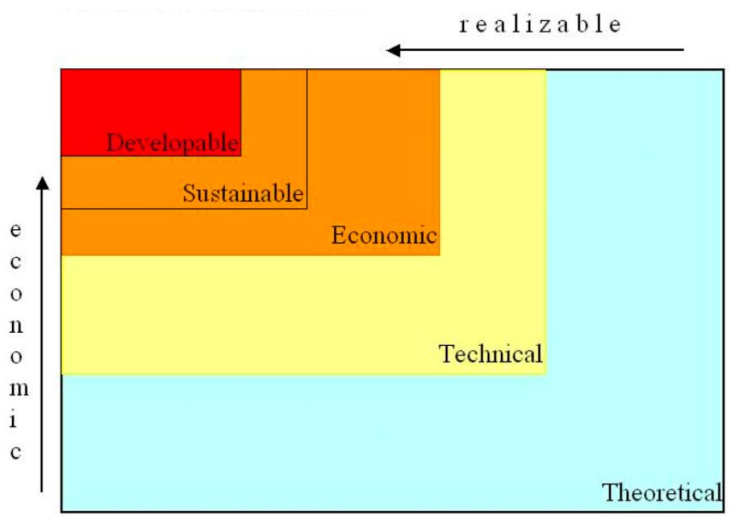

Figure 2: Classification by potential [33].

As it can be seen from Figure 2, theoretical is the physically usable energy supply often referred to as the heat in place while the technical is the percentage of theoretical potential that can be used with current technology. Economic is the time and location dependent percentage of technical potential that can be economically used whereas sustainable is the percentage of economic potential that can be used by applying sustainable production levels subject to regulations, environmental restrictions [34].

Enhanced geothermal systems in Europe were evaluated with estimation and comparison of the technical and sustainable potentials [35].

Figure 3, is an example from Goldstein et al., [36] for practical classification of geothermal resources based on the method proposed by Rybach [33]. These were done to define and describe global geothermal potentials but it can also be applied to the regional or local level.

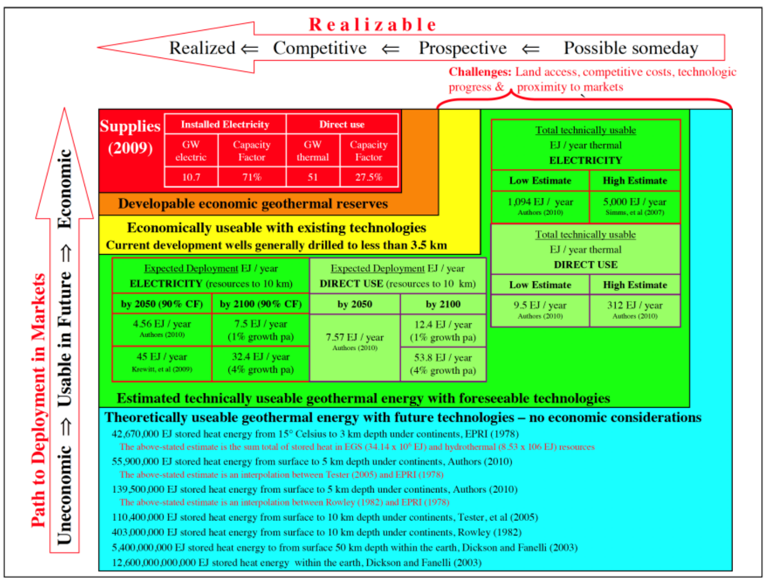

Figure 3: Global geothermal potential [36].

2.3 Geothermal assessment and estimation protocols

2.3.1 Australian and Canadian Protocol Terms

The Australian Geothermal Reporting Code Committee (AGRCC) [37] produced the world's first uniform guide on how to report geothermal data to the market in 2008 with a revision in 2010. The main aim of the Geothermal Reporting Code and Geothermal Lexicon for Resources and Reserves "Definitions and Reporting" was to provide "a methodology for estimating, assessing, quantifying and reporting geothermal resources and reserves". The key aspects of the code were later adopted by the Canadian Geothermal Code for Public Reporting, by the Canadian Geothermal Code Committee [38].

They classified a geothermal resource into three categories namely; inferred, indicated, and measured, which represent three different levels of geological knowledge and probability of occurrence as shown in figure 4. The reserves were defined as probable and proven based on the likelihood and reliability of the modifying factors and the type of resource. The modifying factors depend on economic, environmental, and political context, and assess the commercial viability of the resources.

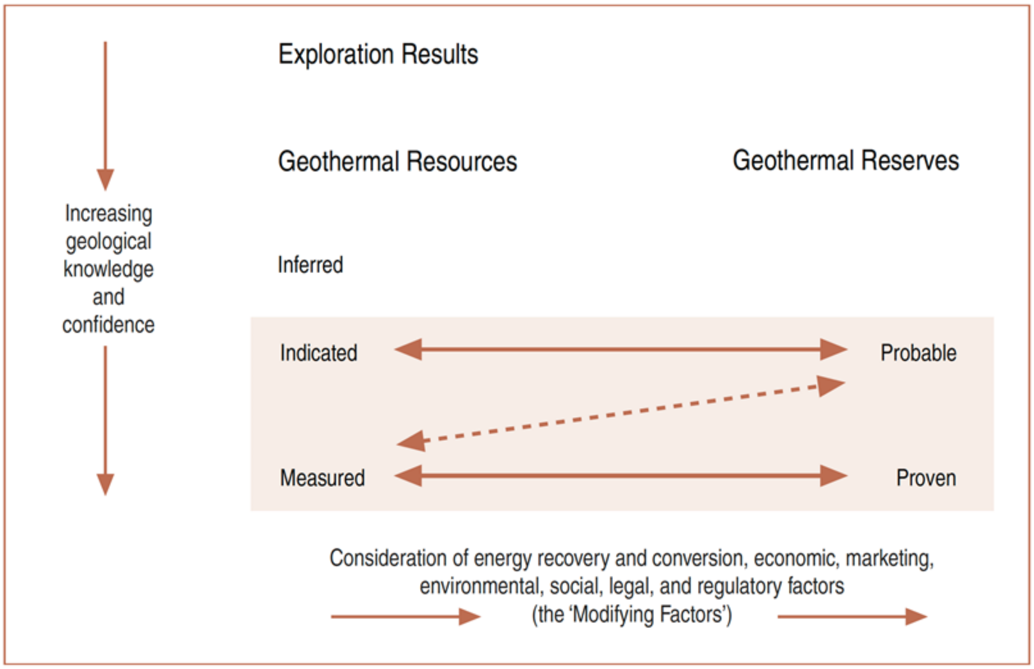

Figure 4: Classification Method (AGRCC) [39].

2.3.2 Protocol for Estimating and Mapping Global EGS Potential [37]

Estimates of EGS potential derived using the protocol will not be 'final'. They will continue to be refined as more relevant data become available. Theoretical Potential will be refined as new geological and geophysical data improve our understanding of the thermal structure of the crust. Refinements here are expected to be gradual. Technical Potential will be refined as technological advancements in drilling, power conversion and legal regimes allow greater amounts of the theoretical potential to be realized. Changes here are expected to be sudden and dramatic.

2.3.3 Resource Assessment Protocol for GEOELEC, [38].

In this project, an overview of the location of geothermal resources which can be developed in the 2020 and 2050 timeline horizons for electricity production in the pan-European region, has been investigated. This protocol has been based on the following work:

- A protocol for estimating and mapping the global EGS potential [37].

- Australian code for reporting of exploration results, geothermal resources, and geothermal reserves: the geothermal reporting code [39].
- The Canadian geothermal code for public reporting [40].
- Application of the United Nations Framework Classification for Resources (UNFC) to Geothermal Energy Resources [31].

A set of 14 case studies from Australia, Germany, Hungary, Iceland, Italy, Netherlands, New Zealand, Philippines, and the Russian Federation are presented in this report to facilitate a better understanding of the specifications and the uniform application of UNFC to geothermal resources. These application examples illustrate the classification of a range of different geothermal resource scenarios in a manner consistent with other energy resources.

3. Geologic Setting

Geothermal systems appear in diverse geological environments all over the world. The geological setting of a geothermal system has a fundamental effect on the potential temperature, fluid composition, and reservoir characteristics. Geothermal systems are commonly associated with areas of young tectonism and volcanism for example along active plate margins and inter-plate hot spots than in stable cratonic regions.

Important factors for geothermal utilization are how much heat is stored at a drillable depth and the ability to recover this heat in the surface at an economic rate for specific use (feasible development in depth of interest). Geothermal systems can be classified based on the effects of geological controls and structural plate tectonic positions on the thermal regime and heat flow, hydrogeological regime, fluid dynamics, fluid chemistry, faults and fractures, stress regime, and lithological sequence.

Several geothermal classification methods based on geological controls have been proposed by several authors.

3.1 Geological classification method proposed by Inga [41]

These classification schemes proposed classifying geothermal resources based on their heat transfer regimes and geological settings, into two broad categories of conductive systems and convective Systems.

3.1.1 Conduction Dominated Geothermal Systems

Conduction dominated geothermal systems are characterized by low to medium enthalpy resources. They occur in passive tectonic plate settings with no significant recent tectonics, volcanism occurrence, or no asthenospheric anomalies.

Conduction dominated geothermal systems occur in low permeability domains such as tight sandstone carbonates or crystalline rock and the working fluid can be present or should be supplied through EGS technology to be utilized on an economic level.

3.1.1.1 Igneous geothermal plays-basement type

Crystalline rocks such as granitic rocks host vast resources of heat energy in igneous provinces, which often underlie large areas of continents. These low porosity low permeability rocks require reservoir development by stimulation techniques to allow circulation between injector and producer wells, with the rock mass acting as the heat exchanger, referred to as Hot Dry Rock (HDR). Reasonably efficient electricity production requires water temperatures exceeding 180°C [70]. The generally accepted performance target for a well doublet is a production rate of 50 l/s and minimum rock temperature of 200°C (e.g. [71,3]).

3.1.1.2 Conduction geothermal systems in orogenic belts

Conduction dominated geothermal play systems without active igneous activity cover different types of geologic settings located within orogenic belts sand associated foreland basins. Advective heat transport may play a role in mountainous areas of the orogenic belt type, where high permeability domains and deeply rooted faults allow deep circulation of meteoric water and form hot springs.

In the adjacent mountain belt, groundwater flow and thermal gradient are strongly influenced by large hydraulic heads resulting from the pronounced topographic relief [42] & [43]. The great depth and small width of mountain belt valleys result in relatively shallow penetration of recharged water, which then discharges on valley floors or shallow valley slopes [44]. Thermal highs occur underneath high mountains and thermal lows beneath the valleys, resulting in varying local thermal gradients due to meteoric water circulation. Beneath high mountains at about 15–20°C and beneath deep valleys 30–50°C [43] & [45].

3.1.1.3 Conduction geothermal systems in intracratonic basins

In sedimentary basin settings, conduction-dominated hydrothermal plays are located in deep aquifers heated by a near normal heat flow. Effectively, sedimentary basins host prime aquifer systems from where the thermal water can be produced and utilized. The exploration target is to identify high porosity high permeability or high porosity/low permeability domains at different temperature levels and normally at great depths.

The success of EGS in tight, hot sedimentary aquifers may be strongly affected by the storage capacity expressed by the porosity of the host rock [4]. The heat content of the fluid in the porous layer setting is strongly affected by the basin geometry, an artefact of the basin type, and evolution.

3.1.2 Convection dominated geothermal systems

Convection dominated geothermal systems are associated with high enthalpy resources and occur at plate tectonic margins, or settings of active tectonism or volcanism [46] & [47].

Different tectonic settings where convection dominated geothermal systems occur include:

a. Magmatic arcs above subduction zones in convergent plate margins e.g. the Sunda arc or the Philippine-Japan arc;

b. Divergent margins located within oceanic settings e.g. the mid-Atlantic ridge, or intracontinental settings e.g. East African rift;
c. Transform plate margins with strike-slip faults e.g. the San Andreas or Alpine faults;
d. Intra-plate ocean islands formed by hotspot magmatism e.g. Hawaii.

These convective systems have two basic classes depending on the source of the thermal energy; volcanic and non-volcanic. A volcanic convective system derives its thermal energy from a magma body dominated by heat convection. The heat sources for such systems are hot intrusions or magma in volcanic complexes such as calderas, at plate hot spot areas.

Non-volcanic convective systems derive their thermal energy from meteoric water that has heated up by deep circulation in high heat flow areas of the earth hence there is no magma body associated with this system [41].

Igneous systems can induce both conduction and convection-dominated geothermal systems. The difference is that conduction-dominated systems in or close to igneous rocks are related to high radiogenic heat production from high heat-producing element-rich granites, but no active volcanism and minor or no active tectonism occurs [48] & [49].

3.1.2.1 Magmatic geothermal systems with a magma heat source

Magmatic play systems can be found in regions with active basaltic volcanism at divergent plate margins [47] and along continent-continent convergent margins with recent plutonism [50]. Magma chambers in volcanic fields, with their parental melts, recharge of basalt and crystallized melts, control fluid chemistry, fluid flow, and the overall geothermal play system. These systems can be separated into an up-flow zone and an outflow zone [9].

3.1.2.2 Magmatic geothermal systems with Plutonic heat source

Plutonism controlled geothermal systems are typically located along continent-continent convergent or transform margins with recent magmatism and with or without recent recharge of meteoric water [44]. The heat source pluton crystallized from magma and slowly cooling below the surface, ranging from hundreds of meters to some kilometers in dimension. The presence and scale of a heat source in these play types are controlled by the age of magmatism. Active and recent magmatism commonly indicates a viable underlying heat source [39], while inactive or extinct magmatism may be reflected by large scale igneous intrusions at greater depth, with remnant heat and heating by radioactive decaying granitic rock [41].

3.1.2.3 Non-Magmatic convection controlled geothermal systems

Non-magmatic convection dominated geothermal play systems are characterized by fluids circulation deep within the crust and transport heat to earth surface along permeable faults by either fault-controlled or fault leakage controlled [11]. The heat source is from zones of thinner crust corresponding to regions of upwelling asthenosphere and higher heat flow where the Moho has moved closer to the surface [51].

In purely fault-controlled play systems, convection occurs along the fault and is commonly combined with infiltration of meteoric water along the fault [11]. In fault leakage controlled play systems, the fluid leaks from the fault into a permeable concealed layer where the leak may move to the fault zone and surface.

3.1.2.4 Case Study: Application of the method proposed by Inga, 2014 [41].

Moeck, et.al, [52], applied the geothermal play method in the German case, the study was carried out on molasses basin as a modern concept to categories geothermal resources related to crustal permeability. This study presents the first geothermal play cluster of Germany and new terms for play-based geothermal exploration such as play level and play element, required for an ongoing categorization of geothermal play types. The focus is on the depth relation of the porosity – permeability/transmissivity variation and compiles data from the geothermal prospects in the Molasse Basin. New data interpretation of the deep well Gerestried, drilled in 2017 south of Munich, is integrated into this study and presented for the first time in a geothermal play context.

Table 1, summarizes the application of the geothermal play method in convection and conduction dominated geothermal resources.

Table 1: Conduction and convection dominated geothermal resources

Conduction Dominated Systems		
Basement Type	**Intracratonic Basin**	**Orogenic Belt**
Cooper basin Australia	North German basin [49]	Molasse basin, Germany [53]
Fenton hill new Mexico/USA, Rosemanowes/UK	Williston Basin of Saskatchewan, Canada Basin of the North Dakota, U.S.A	The Western Canada Sedimentary Basin associated with the Rocky Mountains
Convection Dominated Systems		
Volcanic field type	**Plutonic type**	**Extensional domain type**
Mid ocean Ridges, Reykjanes Iceland [54]	Recent magmatism, Geysers, no recharge	Metamorphic core complexes, Great Basin in U.S.
Subduction zone Taupo New Zealand [55], Java Indonesia	Recent plutonism Laderello [56] ,Italy,	Extensional terrain, Western Turkey

[99]	recharge	
Mantle plumes, Hawaii USA. [57]	Recent plutonism, southern periphery Alpine orogeny	Intra continental rift grabens, E.A rift, Upper Rhine graben in Central Europe, Sous-Foret, France

3.2 Geological classification method proposed by Richard J. [58]

These classification methods consider five parameters as key to geothermal classification namely;

a. Geologic environment and features;
b. Geological features;
c. The crustal heat source;
d. Resource category;
e. Rock type.

Table 2, explains details of this geological classification method.

Table 2: Geological classification method by [58]

Proposed Geothermal Power Classification System					
Geologic Environment		Geologic Feature	Crustal Heat Source	Resource Category	Rock Type
Plate Margin Environment	Convergent (Compressional)	Back Arc Basins	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Volcanic Arc Complex			
		Continental Volcanism			
		Intrusive Complex			
	Divergent (Extensional)	Volcanic Spreading Center	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Rift Systems			
	Transform (Strike-Slip)	Pull-Apart Basins	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Transtensional Faults			
		Volcanic / Magmatic Centers			
Intraplate Environment		Mantle Plumes (Hot Spots)	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Extensional Terrain			
		Cratonic Basins	Thermal Gradient	Stranded Geopressured	Sedimentary
		Passive Margin Basins		Hydrostatic Co-Produced	
		Basement Complex	Radiogenic	Hot Dry Rock	Igneous

a. Geologic environment

The geothermal resources are categorized into two basins on plate tectonics and geology as plate margin and intraplate-related environments. The plate margin environment is further subdivided into convergent (compressional), divergent (extensional), and transform (strike-slip) environments. Large-scale geologic features exist within each of these environments that represent the target regions for geothermal power exploration.

The intraplate environment are areas that are not presently along or very near to active plate margin environments. These are characterized by mantle plumes or hot spots, cratonic basins, passive margin basins, extensional terrain, and the basement complex.

b. Geological features

This category is the large-scale geologic feature that can be found in either the plate margin or intraplate environment. Thus a volcanic arc complex can be expected to form in a convergent plate margin whereas a pull-apart basin will be within a strike-slip environment.

c. The crustal heat source

The magmatic activity would tend to dominate along with plate margin environments where shallow depths into the Earth to where tectonic activity occurs provides conduits for magma to rise into the crust heating up a broad region or provides more local sources of heat and intraplate environment where mantle plumes and extensional terrain is found.

Another source of heat is a conductive gradient from deeper layers for example in sedimentary basins. If the rate of heat removal from some regions is constant, then a continuous flow of heat will be established into this disturbed region as a thermal gradient established between this cooler location and the hotter rock forming which is the source of heat that is extractable for power generation.

Basement rocks such as granite contain higher concentrations of radiogenic minerals when compared to other types of crystalline rocks. The heat generated within these rocks becomes a target for extraction if overlying rock strata have lower conductivity and act as a thermal blanket, trapping the heat within the granite, not allowing it to readily escape.

d. Resource Category

Resource category refers to the medium within which the heat is to be found and produced. Tapping heat within the plate margin environment and within mantle plumes and extensional features will be dominated by steam or hydromagmatic production.

Within sedimentary basins, two distinct geothermal resource categories are identified i.e stranded and co-produced. The stranded geothermal resource represents warm to a hot fluid that is in a geopressured or hydrostatic condition that was not produced when the basin was drilled originally for oil and gas. A stranded geopressured resource consists of hot brine often saturated with methane and found in large, deep aquifers that are under higher pressure due to water trapped in the burial process. These resources are often found in sedimentary strata at depths of 3 km to 6 km with water temperature could be ranging from 900°C to 2000°C.

The hot dry rock (HDR) category represents dry rocks with high heat flow that can be produced if the fluid is injected into the rock as a heat mining medium.

e. Rock Type

Geothermal resources are found mostly in three types of rocks namely igneous, metamorphic, and sedimentary. Convergent and divergent environments, along with mantle plume and extensional features, are probably dominated by igneous rocks. Transform environments have both igneous and sedimentary strata. Basins are dominated by sedimentary rocks, while igneous rocks are the target for the basement complex (Table 2).

Rajaobelison, et.al, [59] used methods described in this section to characterize the geological environment by highlighting the tectonic and structural settings at the regional scale in each area. The analysis of tectonic data was based on up-to-date geological maps and the available literature for the tectono-metamorphic domains of Madagascar. This information was then used to infer the dominant geologic control on fluid flow or the heat migration pathway, geothermal play type, and heat source. These elements were used to develop the catalogue of geothermal systems in Madagascar, similar to the manner proposed by Erdlac [58], for classifying geothermal energy sources in a geothermal power classification system and by Moeck [41] & [60] & [61] for cataloguing geothermal plays.

4. Temperature and other thermodynamic properties

4.1 Classifications of geothermal resources by temperature

Temperature is a fundamental measure of the quality of geothermal resources and consequently is the primary element of most classification systems. The temperature of the geothermal resource can be easily measured by drilling an exploration well.

Figure 5, shows the main temperature classification proposals by different researchers and it is apparent that there is no standard classification method used internationally. The temperature boundaries are set at different temperatures thought to be significant in either a thermodynamic or an economic utilization context.

Table 3 shows the classification of geothermal resources by temperature for Italy, New Zealand, Iceland, and the USA proposed with different researchers, this classification method offers 3 classes of low, intermediate, and high for Italy, New Zealand, and Iceland, and meanwhile, it offers 7 classes for the USA. The lack of consistency and conflicting boundaries for temperature values is obvious from this classification method. A geothermal fluid of 130°C is considered to be intermediate in Italy, New Zealand, and Iceland, while it is considered to be a very low temperature resource in the USA. Once again, this fact proves the demand for a unified method for the classification and confirms that temperature classification cannot be a solution alone.

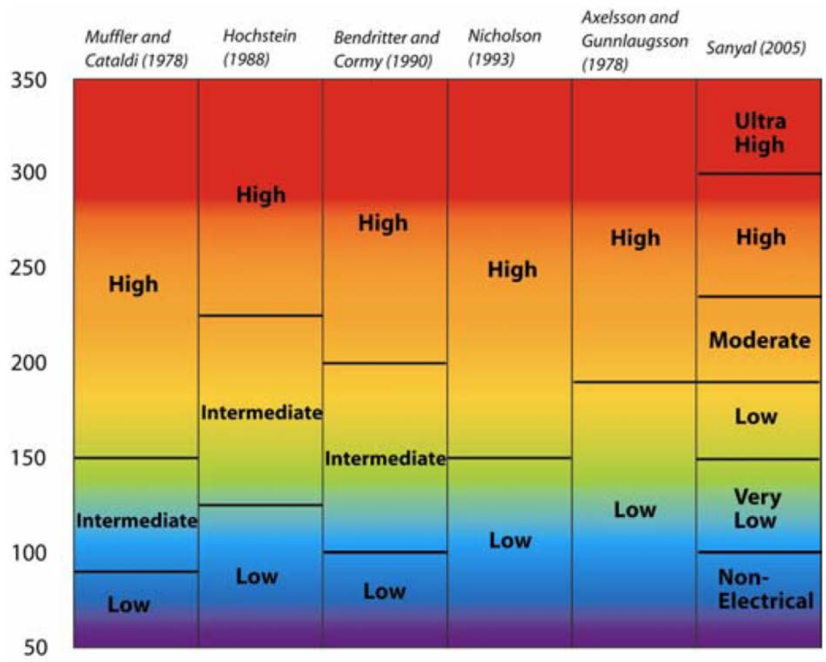

Figure 5: Classifications of geothermal resources by temperature [10].

Table 3: Classifications of geothermal resources by temperature done by various researchers

Researcher	**Country**	**Temperature boundaries**
Muffler and Cataldi [62]	Italy	3 classes: low (<90℃), intermediate (90-150℃), high (>150℃)
Hochstein [63]	New Zealand	3 classes: low (<125℃), intermediate (125-225℃), high (>225℃)
Bendritter and Cormy [64]	Iceland	3 classes: low (<100℃), intermediate (100-200℃), high (>200℃)
Sanyal [65]	USA	7 classes: non-electrical grade (<100°C), very low (100-150°C), low (150-190°C), moderate (190-230°C), high (230-300°C), ultrahigh (>300°C), steam fields

4.1.1 Classification method by Sanyal [65]

Temperature classification method proposed by Sanyal [65] on request by the US Department of Energy is further discussed in this section. In this classification method, geothermal resources are classified into seven classes 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), ultra-high temperature (>300°C), and steam fields (approximately 240°C with steam as the only mobile phase).

Table 4: A possible classification scheme for geothermal resources [65].

Class of Resource	Reservoir Temperature	Mobile Fluid Phase in Reservoir	Applicable Power Conversion Technology	Unusual Development or Operational Problems
1. Non-electrical Grade	< 100 °C	Liquid water	Direct Use	
2. Very Low Temperature	100 °C to < 150 °C		Binary	
3. Low Temperature	150 °C to < 190 °C		Binary; Two-stage Flash; Hybrid	Scaling
4. Moderate-Temperature	190 °C to < 230 °C		Single-stage Flash; Two-stage Flash; Hybrid	
5. High Temperature	230 °C to < 300 °C	Liquid water; Two-phase	Single-stage Flash; Hybrid	Scaling; corrosion; high NCG content
6. Ultra High Temperature	300 °C+		Single-stage Flash	
7. Steam Field	240 °C (33.5 bar-a pressure; 2,800 kJ/kg enthalpy)	Steam	Direct steam	Corrosion; high NCG content; silica particulate deposition

Depending on each temperature class, the phase of geothermal fluid, power generation method, and development problems will differ. Table 4, shows the temperature and additional important attributes of each class. The Classes of reservoir temperature below 230°C contain liquid water, and over 230°C contain liquid water or two-phase fluid. The geothermal resources over 100°C can be used for power generation (Figure 6). Low temperature geothermal resources are used for direct uses such as heating and bathing as well as binary power generation. Flash and hybrid power plants utilize steam from high temperature geothermal resources whereas steam fields are utilized by direct steam power plants. Scaling problems, high NCG content, and silica deposition tend to occur with high-temperature geothermal resources. Class 7 is located to the right of the saturated vapor line. The other six classes are simply classified by temperature, so it doesn't consider enthalpy and pressure.

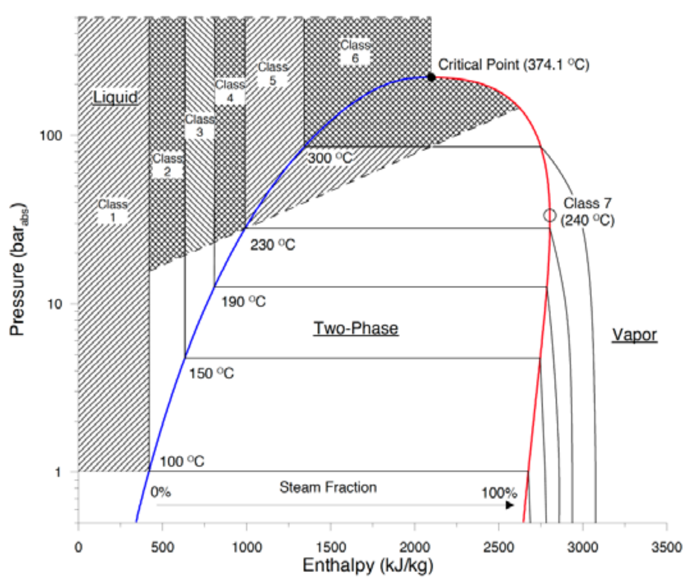

Figure 6: Classification scheme on pressure-enthalpy-temperature diagram for water [65]

4.2 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 [66].

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

m: mass flow late (kg/s)

h: enthalpy (kJ/kg)

s: entropy $(kJ/kg \cdot K)$

T: temperature (K)

The subscript i and 0 denote initial and environmental states, respectively.

The specific exergies of saturated water and steam are listed in table 5 for sink conditions of the triple point (0.01℃), 10℃, and 20℃.

Bejan [67] pointed out that the minimization of lost work in the system would provide the most efficient system. By using exergy analysis method, magnitudes and locations of exergy destructions (irreversibilities) in the whole system are identified, while the potential for energy efficiency improvements is introduced [68].

Energy, environmental and economic analysis of the four defined geothermal power plants has been performed by Chamorro et al. [71] and it was concluded that the geological structure, the depth of the reservoir, and other factors vary in a significant way from one location to another. Exergy values are sensitive to sink conditions according to Eq. (1), and they depend on location, season, and altitude. This variation proves that specific exergy cannot be a reliable parameter in classifying geothermal resources. To achieve a reliable and stable parameter, independent of the sink condition, Lee, [72] suggested normalizing exergy values by the maximum exergy of the corresponding sink condition. The normalized exergy values, known as the specific exergy index (SExI), are from 0 to 1.0 for saturated steam and water, but can theoretically exceed 1.0 for abnormally high superheated steam [30].

Table 5: Specific exergy and specific exergy index values under different sink conditions (water triple point, 10℃ and 20℃) [69] & [70].

	Temperature (°C)	Pressure (bar)	Enthalpy (kJ/kgK)	Entropy (kJ/kgK)	Triple point Exergy (kJ/kg)	Triple point SExI	10 °C Exergy (kJ/kg)	10 °C SExI	20 °C Exergy (kJ/kg)	20 °C 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	

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 1194 kJ/kg for exergy and using eq. (1), SExI can be formulated as:

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

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. Therefore, 0.5 is the lower limit of SExI for high-quality resources. In the same manner, assuming 100° 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.

Bodvarsson and Eggers [73] applied the exergy concept to thermal water and concluded that improvement in efficiency for each additional flash stage decreases rapidly with the increasing number of stages in geothermal flash cycles. Brook et al. [74] also applied the concept of exergy to geothermal systems greater than 150°C.

4.2.1 Case study: Worldwide application

Figure 7, explains Lee's SExI plot with applications on some important worldwide geothermal fields [72]. As seen from the figure most geothermal areas are located in high and medium exergy areas.

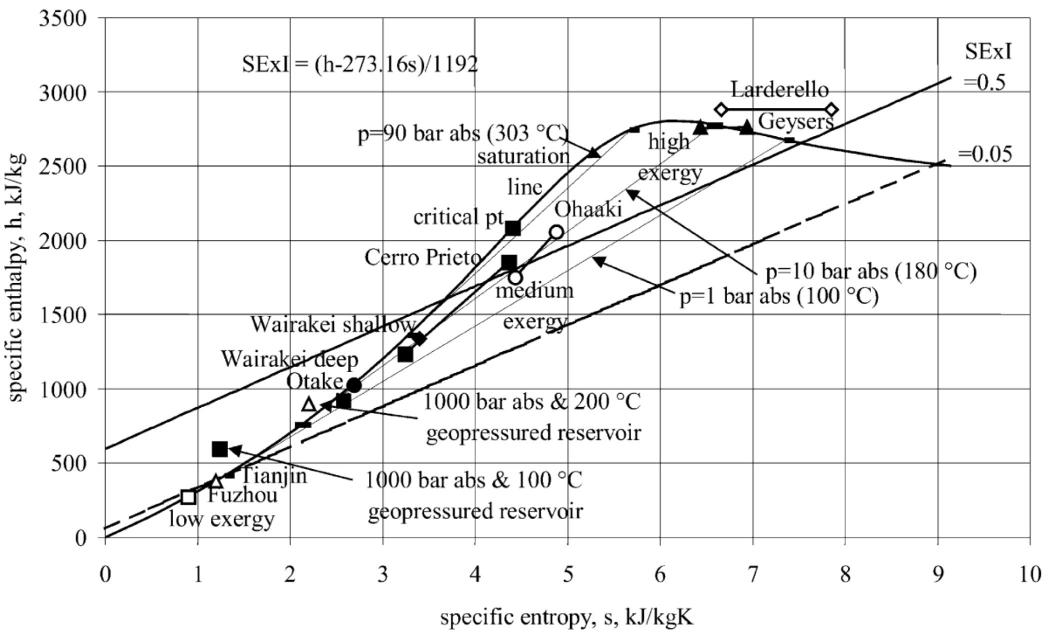

Figure 7: Lee's SExI plot with some important worldwide geothermal fields [75] modified from Lee [72] & [76].

4.2.2 Case study: Application in Turkey

A significant development was achieved in Turkey in geothermal electricity production and direct uses (district heating, greenhouse heating, and thermal tourism) for the last decade. These are mainly attributed to new Geothermal laws on regulations and the feed-in tariff. About 450 geothermal fields have been discovered in Turkey, geothermal electricity installed capacity reached up 1282 MWe as of the end of 2018 [77]. A liquid carbon dioxide and dry ice production factory is integrated into 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) [78] [79]. Figure 8 is an exergic classification map for turkey and most geothermal areas are located in high and medium exergy area.

Hepbasli and Ozgener [80] presented an overview of geothermal energy utilization, historical development, and opportunities in Turkey. Finally, a thermodynamic optimization was performed for the Denizli-Kızıldere power plant using real data, and the most suitable working fluid for the binary cycle were also investigated by Dağdaş et al., [81].

The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policymakers, involved in green energy and technologies in tandem with other objectives and constraints. Exergy clearly identifies efficiency improvements and reductions in thermodynamic losses attributable to green technologies. Thus, exergy has an important role to play in increasing the utilization of green energy and technologies [82] & [83] & [84].

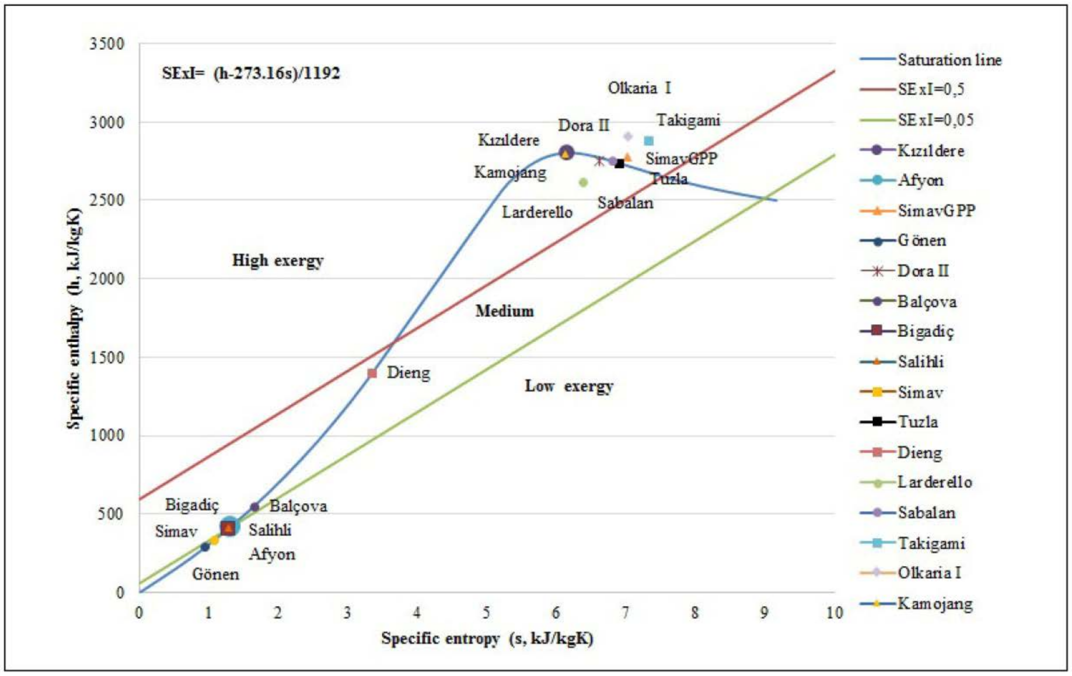

Figure 8: Examples of geothermal fields plotted on classification map of geothermal resources [85] & [86].

4.2.3 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 [87]. Figure 9 shows most geothermal areas in Poland are located in medium exergy area.

4.2.4 Case study: Application in the Slovak Republic

Geothermal waters are 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 [92] and [93]. The resources fall under the medium exergy area as shown in figure 10.

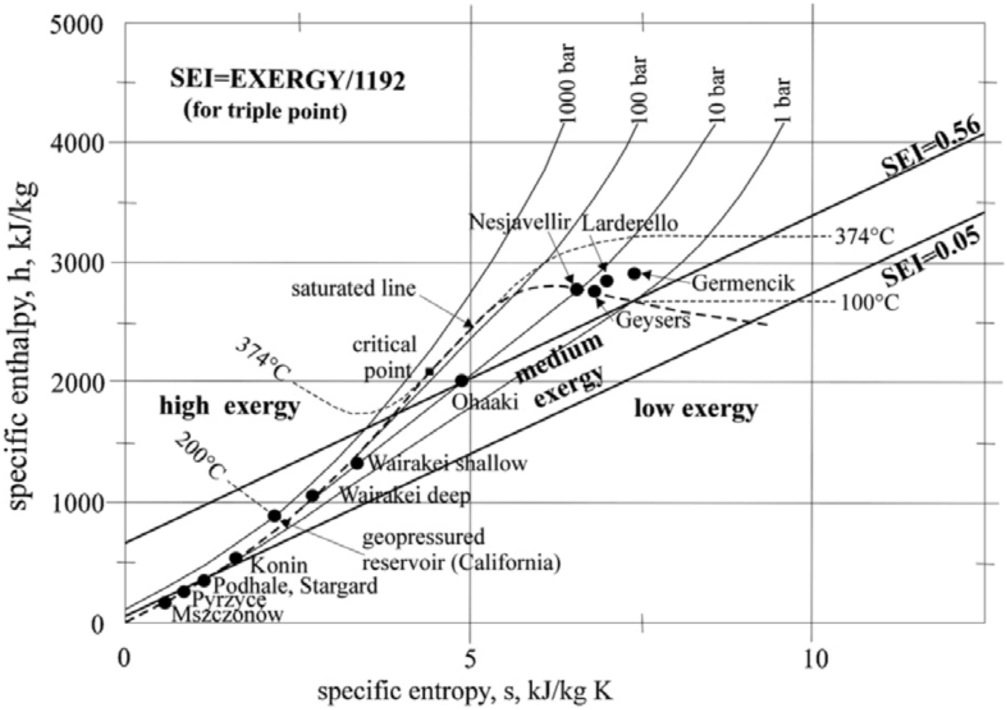

Figure 9: Classification of geothermal resources by SEI in Poland and selected global fields plotted on Mollier diagram, [88],[89], [90], [91].

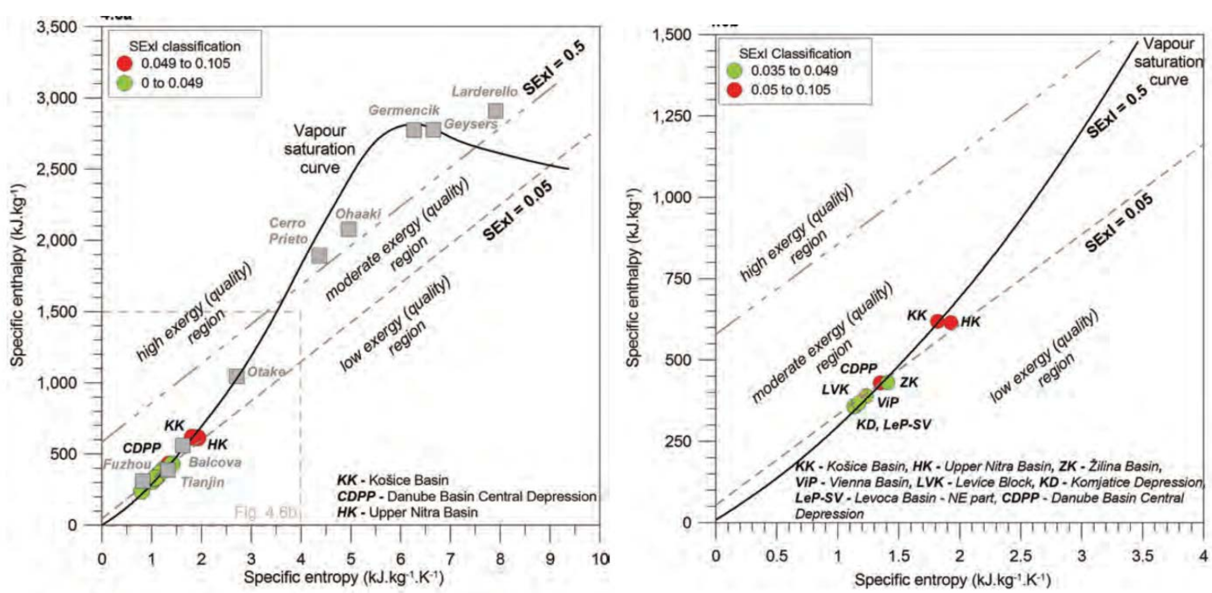

Figure 10: Prospective geothermal localities map of Slovakia on a Mollier's diagram with the perspective of global geothermal fields [92].

4.2.5 Case study: Application in Japan

Despite the large geothermal potential of the country, estimated at around 20 GWe, the present total capacity of the 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 the 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) [94] & [95] &[96].

Japan has a large area with a viable geothermal resource. The geothermal resource potential is the third in the world [97]. From figure 11, it can be seen that most of the geothermal resources are located in high and medium exergy area. From this, it is understood that the 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 [30] and [70].

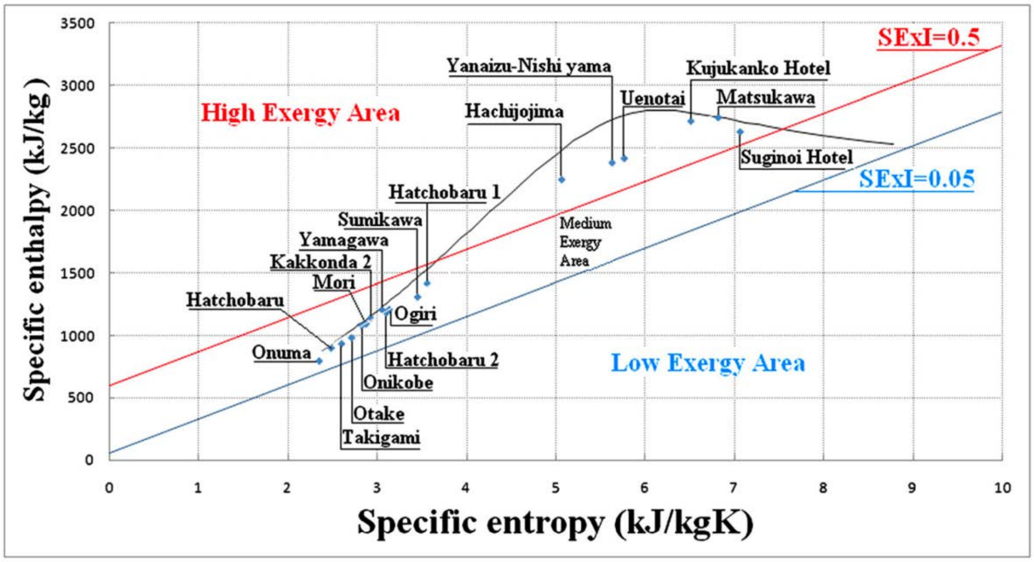

Figure 11: Distribution of Japanese geothermal resources on SExI map, according to their specific entropy and enthalpy [69] &[98].

Geothermal resources in Nigeria were classified using thermodynamic-based resource classification [99] and the classification of geothermal resources in Indonesia by applying exergy concept was done by [100].

5. Other classification methods

5.1 Combinational Terminology for Geothermal Systems

Combinational terminology of geological and temperature-based classifications was proposed by [101]. This method takes into consideration three parameters i.e geological setting, temperature, and physical state of the geothermal reservoir. According to geological settings, in combinational terminology, the class of geothermal resource's name would be decided first based on the geological environment, then the physical state of the reservoir which is liquid-dominated, two-phase, or vapor-dominated, and finally, the class of the geothermal reservoir which is related to its temperature. These encompass both the fundamentally geological nature of geothermal resources and almost the practical technological and economic aspects of resource exploitation while remaining understandable to the broad community of non-experts and experts [101].

5.1.1 Case study: Berlín Geothermal Field, El Salvador

The Berlín geothermal field is one of the geothermal fields in El Salvador. It is located 110 km east of San Salvador, the capital city, in the District of Usulutan, near Berlín City. This geothermal field is located on the northern flank of the Berlín-Tecapa volcanic complex, inside a system of faults in the southern part of the east-west oriented Central American graben. Table 6 shows the classification of the Berlín Geothermal resource based on the combination methodology and it can be classified as a volcanic liquid-dominated high temperature geothermal system [101].

Table 6: Application of Combinational Method on Berlin Geothermal Resource.

Classification	**Class**
Geology	Volcanic geothermal system
The physical state of water	Liquid-dominated geothermal system
Sanyal [65]	High temperature geothermal system
USGS [102]	High temperature geothermal system
Enthalpy [103]	High enthalpy geothermal system
Combinational terminology	Volcanic liquid dominated high temperature geothermal system

5.2 By Stored Heat

The heat in place approach was developed by Nathenson [104], White and Williams [105], Muffler and Cataldi [106] & [107], and quickly became a well-established method for the assessment of geothermal resources. The data is collected or calculated based on proven correlations and then the thermal energy available in a volume of porous and permeable rock, given the thickness, areal extent, porosity, average temperature, rock density and specific heat of the rock in the reservoir, and physical properties of fluids are estimated. This method is the most commonly used method for the assessment of green fields. Its accuracy depends on available data and more data can lead to more reliable simulation. Stored heat calculations were modified to account for the difference between hydrothermal and enhanced geothermal systems behavior by incorporating natural heat input into the reservoir [108].

A case study was done by Agemar et al. [60] to assess geothermal resources in Germany, to emphasize the renewability of geothermal energy, they proposed the reporting of geothermal capacities (per km^2) instead of recoverable heat energy which depends very much on project lifetime and other factors.

5.3 By Electric Power Generation Potential

The results from the stored heat estimation can be used to assess the electric power generation potential of the identified geothermal occurrence. For electric power generation projects, the potential is a function of the thermal energy stored in the reservoir, the thermal energy that can be recovered at the wellhead, and the efficiency with which the latter can be converted into electric power. The potential can be estimated from the stored heat through the application of a recovery factor, an energy conversion factor, a power plant capacity factor, and power plant life.

Pezzuolo et al. [109] proposed a computer tool, called “ORC Plant Designer”, able to perform the fluid screening and the design point analysis of different ORC plant configurations with different heat sources. Kang [110] investigated the performance of an ORC with a two-stage radial turbine.

Real-time energy convex optimization, via electrical storage, in buildings was performed by Georgiou et al. [111]. A multidisciplinary approach for sustainable exploitation of medium to low enthalpy sources was proposed by Franco and Vaccaro [112]. In the study by Astolfi et al. [113] a techno-economic optimization of different ORC configurations operating with a number of working fluids was performed, considering equipment cost correlations and a model to estimate the turbine design and efficiency.

As a case study in the Republic of Croatia, the possibility of geothermal electricity was investigated and ORC cycle was suggested to be suitable to utilize their geothermal potential [114] & [115]. The traditional classification of working fluids, with merely three categories (wet, dry, isentropic), is not sufficient to reliably predict or exclude the formation of liquid droplets in the low-pressure stage of the turbine of an ORC power plant, therefore a novel classification of pure working fluid selection was proposed by Gyorke et al. [116]. The study by Usman et.al [117] compares the part-load operation of air-cooled and cooling tower based low-medium temperature geothermal Organic Rankine Cycle (ORC) systems installed at different geographical locations.

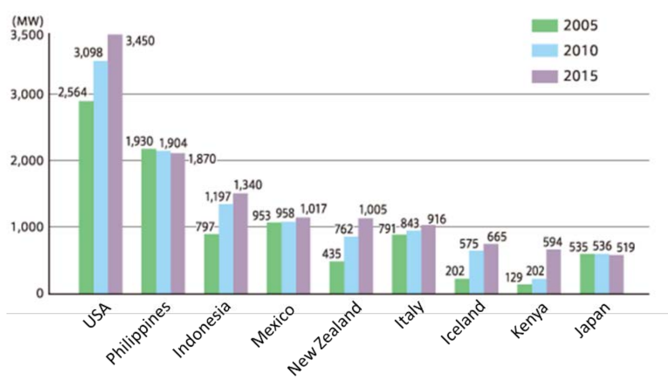

Figure 12: Geothermal power generation capacity from 2005 to 2015 [118].

An investigation was done to determine the temperature classes application on geothermal resources. These were achieved by investigating production wells used for geothermal power generation or direct uses which were drilled in recent years by different countries. Figure 12, shows trends in geothermal power generation capacity by major countries in 2005, 2010, and 2015.

The countries with the biggest generation capacity increase in this period i.e United States, New Zealand, and Kenya were further investigated in detail and the results are shown in tables 7, 8, and 9 respectively. In addition, the case of Japan was also further investigated within the same period.

Table 7: Wells drilled for different uses in the USA from 2010 to 2014 [119] [120].

Purpose	Wellhead Temperature	Number of Wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration[1)]	(all)	114	4	5	15	72.13
Production	>150° C	14	0	1	0	20.66
	150-100° C	67	0	0	0	124.34
	<100° C	0	5	2	0	0.21
Injection	(all)	36	1	4		41.03
Total		231	10	12	15	258.37

From table 7, drilled wells for geothermal uses between 2010 and 2014 in the USA are divided as over 150°C, 100°C to 150°C, and below 100°C based on temperature. Production wells ranging from 100°C to 150°C were the most numerous, and 67 wells were drilled for power generation.

Table 8: Wells drilled for different uses in New Zealand from 2010 to 2014 [121].

		No. of wells drilled				
Purpose	**Wellhead temp**	**Electric po**	**Direct use**	**Combined**	**Other (specify)**	**Total depth (km)**
Exploration	(all)	9				7.75
Production	>150°C	21		5		49.57
	150-100°C		9			0.79
	<100°		18		5	7.06
Injection	(all)	21	11	1		45.92
Total		51	38	6	5	111.09

It can be seen from table 8 that production wells of over 150°C are used for power generation and combined utilization. There is no well for power generation in the production well below 150°C and twenty-six production wells were drilled in a temperature classification of over 150°C.

In Kenya, a large number of production wells were drilled between 2010 and 2014. Most of the production wells are for power generation. Wells with temperature classification of over 150℃ is the largest category, and more than 200 production wells were drilled as shown in table 9.

Table 9: Wells drilled for different uses in Kenya from 2010 to 2014 [122].

Purpose	Wellhead Temperature	Number of Wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration[1)]	(all)	27	0	0	0	43
Production	>150° C	206	1	4	0	432.6
	150-100° C	35	0	0	0	73.5
	<100° C	10	0	0	0	21
Injection	(all)	35	0	0	0	73.5
Total		313	1	4	0	643.6

Table 10 shows wells drilled for geothermal use between 2005 and 2008 in Japan. There was no construction of a large power station during this period, but 13 production wells were over 150°C.

Table 10: Geothermal wells drilled for power generation in Japan from April 1, 2005, to December 31, 2008 [123].

Purpose	Wellhead Temperature	Number of Wells Drilled		Total Depth (km)
		Electric Power	Other	
Exploration	(all)	20	0	27.0
Production	>150° C	13	0	20.9
	150-100° C	0	0	0
	<100° C	0	0	0
Injection	(all)	14	0	15.6
Total		47	0	63.5

5.4 By Direct Utilization

Geothermal energy utilization is commonly divided into two categories, i.e., electric production and direct application. Direct use is typically associated with lower-temperature geothermal resources, though some applications may require higher temperatures. In this method, the famous Lindal diagram [124] and its cascade utilization method is being used in order to maximize the optimum utilization of the resources. It is a similar scheme to the temperature classification method, but with more focus on applications such as bathing and swimming, space heating, agriculture and aquaculture, Industrial applications [125], and Ground Source Heat Pumps (GSHP) [126].

In order to assess the technical and economic potential of shallow geothermal energy in individual and district heating systems, a framework was proposed with a case study of Slovenia

[127]. An open heat exchanger was proposed to increase the sustainability of geothermal utilization in Icelandic hot spas [128].

To maximize the multiplication of effectiveness and capacity ratio to maximize heat transfer, a new model was suggested for the determination of the heat capacity ratio that provides the maximum heat transfer and the best type of heat exchanger [129].

Geothermal heat exchanger energy prediction based on times series and monitoring sensors optimization was performed by Barugue et al., [130]. A proposed method by Georgiou [131] can be applied for simultaneous minimization of a building's import and export (surplus) grid energy of geothermal district heating system.

6. New Geothermal Terms and Definitions, by the Geothermal Energy Association (GEA) [132].

GEA issued a guideline requesting geothermal project developers to define the resource type under one of the following categories: conventional hydrothermal (un-produced resource), conventional hydrothermal (produced resource), conventional hydrothermal expansion, geothermal energy, and hydrocarbon co-production, geopressured systems, and enhanced geothermal systems.

GEA requests developers to indicate at what stage of development each separate geothermal project falls under. Stages of development have been divided into four different phases labeled Phase I, II, III, and IV. Each project must meet certain criteria to be considered and reported by the GEA as being in a respective phase of development. The separate phases are specified below:

Phase I: Resource procurement and identification

Phase II: Resource Exploration and Confirmation

Phase III: Permitting and initial development

Phase IV: Resource Production and Power Plant Construction

Conclusions

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.

By stored heat- Classifying geothermal resources based on the heat in place only leads to large figures that may be misunderstood by non-specialists, who may wrongly interpret them as recoverable energy. On the other hand, when the process to be implemented to recover given resources is still unknown or highly uncertain, the heat in place may represent the only reference estimate.

By electric power generation potential- Classification by electric power generation potential requires reliable values for the recovery factor in the conversion of heat in place into power potential. The use of term potential, applied to power generation that could be obtained from a given geothermal occurrence, may generate confusion in the classification system.

By accessibility and discovery status- Impressive figures are usually stated for unconventional, undiscovered, and currently unrecoverable geothermal resources worldwide. There is also the risk of confusing resources with reserves, which increases the risk to the investor and decreases confidence in geothermal development. There is therefore a need to apply a common framework from in-situ potential to confirmed economic production.

Potential- Reliable values for the recovery factor are needed to convert theoretical potentials into technical potentials which are hard to get. There is hardly any solid data about recovery factors, not even for hydrothermal systems, let alone for petrothermal/EGS [133] & [134]. Therefore, the quality of geothermal fluid may be different even in the same class. Hard to differentiate the potential referred to e.g theoretical, technical, economic, sustainable, or developable.

Temperature- Temperature classification is a simple and easy to understand classification method, but it does not represent the enthalpy and pressure of the geothermal fluid, so it isn't enough to accurately evaluate the value of geothermal resources. Temperature cut-off gives information on heat content regardless of other physical properties (e.g. permeability, porosity, geochemistry, thermal capacity, and conductivity). Pressure, quality, and enthalpy are important parameters for geothermal power generation. Classification by temperature can represent the approximate usefulness of geothermal resources, but it isn't enough to properly evaluate the value of geothermal resources, and other classifications need to be used to make an accurate assessment.

Exergy- This 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 the availability of wellhead pressure and temperature data.

Geological setting- Effectively volcanic and fault-controlled extensional domain plays may coexist in the same geologic system e.g the East African Rift System.

Currently, there is no universally and globally recognized standard level of confidence for classifying and reporting geothermal resources. Inconsistent estimates which do not translate into sustainable production may damage the perception of geothermal energy as an investment option. The current classification systems have drawbacks and limitations on their own leaving the door open for ambiguity and subjectivity.

A combinational method should be therefore be developed based on economic and social viability, project status and feasibility, thermodynamic properties, and geological knowledge to address these challenges. Table 11 summarizes the key classification methods discussed in this paper and their advantages and disadvantages.

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Table 11: Key classification methods discussed in this paper and their pros and cons.

Classification Method	**Pros**	**Cons**
Temperature	The range of temperature for geothermal fluid is used to classify the resources based on their potential to do work.	
	Simple and easy to understand. Can represent the approximate usefulness of geothermal resources	Different boundaries for classifying resources. There is no certain agreed temperature range for each category. It could be misleading to conclude the nature of the fluids based on only temperature or enthalpy.
Geological	The initial data will be used to create geological models, and these models will provide a criteria to classify geothermal system based on likelihood of discovery. Can be developed parallel to conceptual model development and they can complement each other. Based on heat transfer regimes and geological settings, the geothermal resources could be classified under two categories of conductive and convective Systems.	
	Gives an idea of prospects for development scenarios. It is possible to perform from the planning phase of the development and can be upgraded as the project progresses.	Requires comprehensive geological knowledge. Outcomes are not clear enough for development scenarios.
Stored Heat	Mainly based on the reservoir's temperature and enthalpy. The reservoir size and temperature distribution have a very significant role in the calculation of the resource potential. The stored thermal energy in a rock with estimated permeability and porosity are being estimated. Input parameters are the dimensions of the assumed reservoir, temperature, rock properties (such as density, specific heat) and fluid properties.	
	Simple and widely used. Well-recognized geothermal resources assessment method. The data is collected or calculated based on proven correlations.	Uncertainty in required input parameters increases the inaccuracy of the stored heat estimation. Doesn't clearly address the sustainability of the resource. Results might be misleading.
Accessibility and discovery	Geothermal resources are categorized as resource and reserve. Geothermal resource, include all the thermal energy beneath a specific area judged from the measured temperature. Geothermal reserve, include those resources that are feasible to recover using current technology.	
	Can give a general idea of the resources.	Not enough to convince investors unless there is very obvious evidence.
Potential	The resource is categorized into theoretical, technical, economic, sustainable, and developable. Feasibility of the geothermal potential is in reverse proportion to its size.	
	Simple with sensible numbers in technical and economics. Utilization proposals in forms of potential could be prepared.	Needs plenty of data with uncertain utilization scenarios due to the wide range of parameters.
Exergy	Using exergy for resource classification has the advantage of comparing according to the ability to do work.	
	Very accurate and sensible results. Too technical. Points out exergy losses and destructions.	It is very difficult to obtain the required information for exergy classification at the early stages of a project.
Combinational Terminology	Takes into consideration three parameters i.e geological setting, temperature, and physical state of the geothermal reservoir.	
	Easy to understand for technical and non-technical counterparts.	Requires more input data and that increases the risk of uncertainty.
Utilization	The geothermal resources utilization method can be decided based on conclusion from the stored heat estimation.	
	It can deliver numbers and sensible results for developers at the early stages of development. A development scenario can be proposed based on the estimated potential.	Not an independent method, it relies on other methods such as stored heat. Results are not very accurate and their reliability might improve with additional data obtained from advancement of the development.