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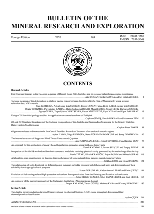

The electric power production targeted Unconventional Geothermal Systems (UGS), some conceptual designs and their thermodynamics classification

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ABSTRACT

The geothermal energy is a renewable and relatively clean energy resource. The amount of geothermal energy stored just in the upper crust of the earth is large enough to meet the world's energy needs for thousands of years. Unfortunately, only a small portion of this potential can be utilized today by the conventional methods. The rest corresponds to the hot, fluid-poor areas which cannot be utilized by the current technology. The first concrete steps towards the utilization of such high potential areas emerged in the late 1960s and early 1970s. These studies have gradually continued in the following years, and many new terms and conceptual designs have been proposed so far. Unfortunately, no comprehensive definition has been established on this subject yet. This may bring about some difficulties such as the failure to express the intended concept in the right manner, the inability to determine the legal boundaries for the regulations required by the countries to make use of these areas which pose high risks in the commercial point of view. In this paper, some of the major terms and conceptual designs used for the projects targeting the power generation from fluid-poor hot areas are discussed. Furthermore, all of these terms have been gathered under the title of "Unconventional Geothermal Systems-UGS" and these designs are classified according to the types of thermodynamic system for the first time in this study. In addition, some new suggestions that can be used to define the definitional boundaries of these terms are put forward.

1. Introduction

The conventional geothermal exploration activities significantly increased following the legislation of the "Geothermal Resources and Natural Mineral Waters Law of Turkey (No: 5686) in 2007. The installed geothermal power capacity significantly increased from nearly 20 MWe to ~1.514,7 MWe as of September 2020. This value is foreseen to exceed 2.000 MWe in the next few years with the projects which are in planning phase, licensed phase and construction phase. According to these numbers, Turkey ranks first in Europe and 4th in the world in terms of power generation from the geothermal energy.

A conventional geothermal system consists of 5 fundamental components; the heat source, the reservoir rock, the cap rock, the recharge area and the working fluid. Particularly, the reservoir rock, the recharge area, the cap rock and the working fluid must be at desired levels for a viable conventional geothermal system. Otherwise, it will not be possible to commercially use the heat energy stored inside the earth. In fact, the conventional geothermal systems constitute less than 1% of the overall geothermal areas with high temperatures at accessible depths (0-10 km). Majority of these fields correspond to currently unexploitable fluid-poor hot areas.

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The first concrete steps towards the utilization of fluid-poor areas began in the late 1960s and early 1970s in "The Valles Caldera" region of New Mexico, the United States. In 1972, this region was selected as a test area (https://openei.org/wiki/Fenton_Hill_HDR_Geothermal_Area). Then, the Arab-Israeli War in 1973 caused some problems in oil and gas supply in the world. This led the countries to conduct research on the fluid-poor hot areas. Thus, the Fenton Hill HDR Project accelerated. Following this, some developed countries such as Germany, Japan, France etc. took part inside similar projects due to promising primary results. Moreover, the experience gained from the project and tremendous energy potential have paved the way for the emergence of some new pilot projects in some other countries.

Extensive research carried out particularly since 2008 have unearthed the presence of 295 °C bottom hole temperatures between 0-5.000 m in Turkey. As in the world, some of these hot areas present the characteristics of conventional geothermal systems in Turkey while many others not. This shows that there are many fluid-poor hot areas in Turkey. Based on this, necessary awareness is needed to evaluate these areas in Turkey. Therefore, one of the main aims of this study is to raise awareness on this subject in Turkey.

In this context, in the first part of this study, the terms related to the fluid-poor hot areas are discussed and grouped under the title of "Unconventional Geothermal Systems-UGS". In the second part, evolution of the UGS term through time is briefly summarized. In addition, some fundamental criteria are proposed here to understand whether a geothermal system is UGS. In the third part, power production targeted significant conceptual UGS designs are classified based on thermodynamic system types. In the final part, various suggestions on UGS are put forward for Turkey.

2. Some UGS Sub-concepts

Plenty of terms have been proposed to define the studies conducted on the utilization of hot, fluid-poor areas so far. These terms and many associated concepts may vary by the system temperature, flow rate, the enhancement methods, the geological characteristics and the depth etc. Optimization processes in engineering designs are generally project-based and vary according to engineering provision (Canoğlu and Kurtuluş, 2016; 2017; Canoğlu, 2019). Today, majority of the UGS projects are only applied commercially in the areas with low temperature. The number of UGS projects producing long-term commercial energy is almost negligible. However, the dizzying potential of such projects globally attracts the attention of many countries and energy companies (Figure 1). However, no satisfying summary has been found on the fundamental principles of such systems. As a result, this study has emerged based on this motivation. Unless otherwise stated, all contents referred to as "Unconventional Geothermal Systems-UGS" during this study are valid only for power production.

In this study, the concept to be addressed as UGS was first put forward by a series of patented scientific studies. These studies constitute the base of Fenton Hill Project, known as "Hot Dry Rock (HDR)". However, the term HDR has not been able to completely represent many other project sites emerged with similar motivations. Therefore, many new terms have arisen on this subject. As a result, the first concept has undergone many changes through time. It has been used under various titles such as "Enhanced Geothermal Systems (EGS), Engineered Geothermal Systems (EGS), Hot Wet Rock (HWR), Deep Geothermal Energy (DGE), Petrothermal Systems (PS), Hot Fractured Rock (HFR), Hot Sedimentary Aquifers (HSA) and Unconventional Geothermal Systems (UGS) etc. In this study, all these terms are collectively gathered under "Unconventional Geothermal Systems (UGS)". Some important ones are summarized below.

The first high-temperature UGS concept was coined as Hot Dry Rock (HDR). In fact, this term was first suggested in the late 1960s and early 1970s by the employees of the Los Alamos National Laboratory in the Fenton Hill site, the New Mexico, the United States (Brown et al., 2012). The HDR is often used for high temperature crystalline and brittle rocks with no natural geothermal fluid production (Brown et al., 2012). Based on this, the first and only project that complies with the HDR term is the Fenton Hill project (Brown et al., 2012).

The second term that can be classified under the concept of UGS is the "Enhanced Geothermal Systems-EGS". This term was first coined by Grassiani et al. (1999). Tester et al. (2006) described this concept as

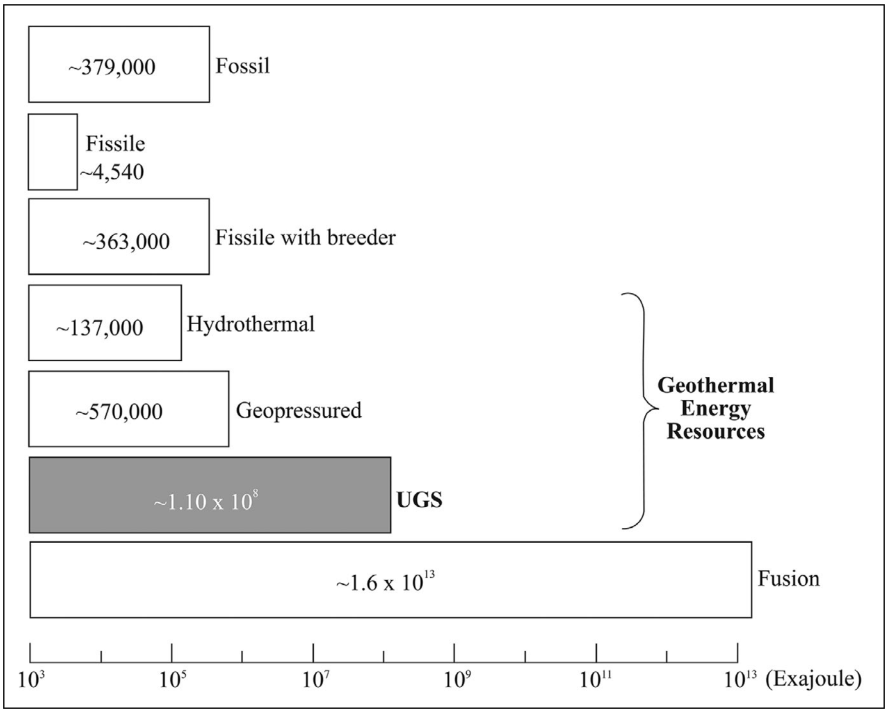

Figure 1- Some of the energy types and their potentials suggested on the global scale (After Armstead and Tester, 1987).

“the reservoirs where engineering methods have been applied for the commercial recovery of heat from low porosity/permeability geothermal resources” (Hıdıroğlu and Parlaktuna, 2019). However, Breede et al. (2013) have referred to the term as “all the geothermal systems enhanced by engineering methods”. In addition, some conventional geothermal system applications (e.g. acidizing and fracturing) may also refer to as “enhancement”. So, this leads to some confusions. In this study, the definition suggested by Breede et al. (2013) is adopted based on etymology. In addition, the term “Engineered Geothermal Systems-EGS is also used as an alternative to “Enhanced Geothermal Systems-EGS”. It is mostly used in the same sense as “Enhanced Geothermal Systems”.

Another term considered in this study is the “Hot Wet Rock-HWR”. HWR was mainly used by Japanese researchers (e.g. Takahashi and Hashida, 1993). It is often used for brittle and hot rocks that do not produce commercial natural geothermal fluids despite conventional well completion work.

The next one that may be addressed under the UGS is the “Deep Geothermal Energy-DGE”. DGE is mostly used by Western European researchers. Some researchers have subdivided the deep geothermal systems into two as “hydrothermal” and “petrothermal” systems (e.g. Breede et al., 2015; Hıdıroğlu and Parlaktuna, 2019). This term is still under hot debate (Breede et al., 2015). The majority uses this term as the geothermal systems for > 20 ºC and > 400 m, whereas some others use the “Medium Depth Geothermal Systems” term for 400-1.000 m depth range (Breede et al., 2015). They suggested “Deep Geothermal Systems” for the geothermal systems for > 1.000 m deep hot geological rocks (Breede et al., 2015). Indeed, this inherently covers both conventional and unconventional geothermal systems. It also causes further conceptual confusion.

Another common term is Petrothermal Systems. This was first coined by Roberts and Kruger (1982) (Breede et al., 2015). PS is typically used for the fields which do not have commercial permeability and > 150 °C (Breede et al., 2015). Today, on the other hand, power can also be generated at temperatures below 150 °C. Therefore, this term also cannot exactly cover the concept intended herein.

Another important term is the “Hot Fractured Rock-HFR”. This was first proposed by Genter et al.

(2003) for hot and typically crystalline rocks with natural pre-existing fractures or artificial fractures (Breede et al., 2015). Based on etymology, HFR has a broader meaning, representing both conventional and unconventional hot rocks fractured via the artificial methods. In this context, this term may also be used for "the conventional geothermal reservoirs where the power generation is commercially possible, and the wells can be enhanced by fracturing method". Briefly, this also cannot fully cover the desired concept either.

Recently, the term "Hot Sedimentary Aquifers-HSA" has intensively appeared in the scientific studies (e.g. Breede et al., 2015). The first researcher who suggested this is unknown. The depth range, temperature, porosity, permeability, density of the reservoir rock, cap rock etc. of the system have led to serious discussions and brought the concept confusion to another level. Hence, the term HSA, like many others, is quite controversial. Yet, based on the etymology, the term HSA should be used for "all the sedimentary geothermal systems with commercial power production potential". Because, the fluid-poor hot rocks do not necessarily have to be sedimentary in origin. There are many such practical examples in the literature. Accordingly, the term HSA remains also insufficient to fully explain the concept aforementioned.

The "Unconventional Geothermal Systems-UGS" term is extensively used in recent literature (e.g., He et al., 2018). The UGS term can be defined as "*any hot rock without commercial natural geothermal fluid production after conventional well completion works*". Accordingly, the term UGS is regarded as more inclusive for the concept. Based on this, the UGS term is preferred in this study.

Apart from these, there are many other less known terms in the literature. Some are "Deep Heat Mining", "Stimulated Geothermal Systems", "Deep Geothermal Probes". These were described by Breede et al. (2015) to some extent. The interested reader can refer to Breede et al. (2015) for further detail.

3. The History and Definition of Electric Power Targeted UGS Concepts

The first definition related to the UGS concept emerged at the beginning of the 1970s in Fenton Hill rocks as "Hot Dry Rock-HDR" (Brown et al., 2012). In some subsequent projects such as Hijiori/Japan, Soultz-sous-Foréts/France, it is understood that the target reservoirs are not completely dry. Instead, they are filled with natural noncommercial geothermal fluids (Kuriyagawa, 1987; Takahashi and Hashida, 1993; Genter et al., 2010; Serpen, 2019). These showed that the term "HDR" is not enough to fully describe the desired concept. The concept formerly called as "Hot Dry Rock-HDR" has been later recalled as "Hot Wet Rock-HWR" (Takahashi and Hashida, 1993) particularly since 1993. Studies in the Soultz-Sous-Foréts Project led to the emergence of another term called as "Enhanced Geothermal Systems-EGS". This has been commonly used especially following the study of Grassiani et al. (1999). Afterwards, many well completion operations, frequently used in fluid poor hot areas, have been successfully applied in many subsequent conventional geothermal projects. Therefore, this showed that not only the fluid-poor hot rocks but also many conventional geothermal studies may be evaluated under the "Enhanced Geothermal Systems-EGS" (Breede et al., 2013). In recent studies, the concept has come to be known as "Unconventional Geothermal Systems". Because, the concept is quite different from conventional geothermal systems. Based on this, a more inclusive term, the "Unconventional Geothermal Systems-UGS", has emerged recently. This seems more inclusive than others. Thus, UGS is used in the course of this work.

Unfortunately, some target zone(s) cannot produce commercial natural geothermal fluid even all conventional well completion techniques are applied such as simple acidizing, simple nitrogen injection etc. Many geothermal projects failed due to insufficient commercial geothermal fluid production although the rock temperature is quite sufficient. If a project aims to commercialize such a geothermal system by applying unconventional engineering techniques such as sophisticated hydraulic fracturing, sophisticated acidizing, sophisticated thermal fracturing etc., this system can undoubtedly be considered as UGS.

Various types of working fluids may be used in an UGS work. If conventional geothermal fluid is used as working fluid in fluid-poor hot rocks, it must be supplied outside of the geothermal reservoir(s) that have commercial electricity generation potential. Otherwise, this should be regarded as typical conventional reinjection operation. The use of unconventional working fluids or non-power producing conventional thermal waters originated from a low temperature reservoir as the main heat recovery agent such as CO_2, NH_3 etc., shows that this system is not a conventional geothermal system. Therefore, such a system can undoubtedly be regarded as UGS.

The hydraulic fracturing technique is widely used to enhance well productivity in both some recent geothermal and oil/gas projects. However, the artificial fractures required to increase productivity reclose due to earth stresses. To solve this problem, some special materials (i.e. proppant) are injected into the fractures. This technique is not normally preferred in a conventional geothermal system. Therefore, applying such a technique may be regarded as an unconventional geothermal operation. This shows that such a project is undoubtedly an UGS project.

Project costs are vital for a viable geothermal study. Therefore, cost management is carefully considered during the implementation of geothermal projects. However, despite the cost increase, some costly engineering practices (i.e. sophisticated hydraulic fracturing, acidizing, thermal fracturing etc.) are required to increase the productivity of hot and fluid-poor rocks. Although not used in a typical conventional geothermal project, unusually high grade well equipment is needed to avoid such problems in an unconventional geothermal project. Therefore, the widespread use of the unusual well equipment helps us to determine whether a project is UGS or not.

Commercial fluid production is crucial in a conventional geothermal project. Based on this, if any rock unit is hot and fluid-poor, some unconventional engineering designs are required to overcome these obstacles. Hence, an unusual conceptual design needs to be used to exploit the stored earth heat energy. Therefore, application of such a design shows that the project is UGS. These designs are further discussed below.

4. Substantial UGS Designs Targeting Electric Power Production

Despite the experience and know-how gained from a number of UGS projects since the early 1970s, this technology has not yet reached the desired level in the long term. On the other hand, global warming, fossil fuel depletion, energy supply security concerns, dizzying UGS potential, etc. have led to the emergence of many new conceptual designs. Apart from the most widely known design (i.e. classical UGS design), some other less known UGS conceptual designs are discussed in this paper. They are also classified here for the first time according to thermodynamic system types (Figures 2, 3, 4, 5, 6, 7, 8, 9 and 10).

Existing UGS designs can be grouped under three main headings according to thermodynamic system types. They are (1) Open-loop UGS designs, (2) Closed-loop UGS designs and (3) Hybrid UGS designs. The "Open-loop UGS designs" are the designs where there is direct contact between the working fluid and the main target zone. Hence, there is both heat and mass transfer between the working fluid and the main target zone in such systems. In the Closed-loop UGS designs, on the other hand, there is no direct mass transfer between the working fluid and the main target zone. In these, only heat transfer is expected. In the scope of this study, the Hybrid UGS designs are defined as the designs where some characteristics of both "Closed and Open-loop UGS" systems exist at the same time. They are summarized in table 1.

4.1. The Open-loop UGS Designs

There are numerous UGS designs classified under this topic in the literature. Open-loop UGS designs are quite common in practice due to huge experience and know-how gained from previous projects since 1970s. On the other hand, the major disadvantages of them are induced seismicity, scaling, healing (i.e. reclosing) of the induced fractures, loss in working fluid, limited working fluid option, displacement in the earth surface, risk of flow-channeling (i.e. short-circuit flow) in working fluid etc. (Table 1).

Many "Open-loop UGS design" sub-classes exist in the literature. Only some significant designs are briefly summarized here. They are (1) Classical UGS design, (2) Multi-stage UGS design, (3) Hot Ductile Formations UGS design, and (4) Eavor-Loop UGS design (Table 1, figure 2, 3, 4 and 5).

4.1.1. The Classical UGS Design

Among the Open-loop UGS designs, the most significant one is the "Classical UGS design"

Table 1- Some conceptual UGS designs suggested based on the thermodynamic system, their advantages, disadvantages and risks.

Explanations	**Open loop UGS designs**				**Closed loop UGS designs**		**Hybrid UGS designs**	
	Classical	**Multi-stage**	**Hot ductile formations**	**Eavor-loop**	**Simple "U" or "L" shaped**	**Finned "U" or "L" shaped**	**Multiple Micro-hole Array**	**The Earth Energy Extraction System**
Advantages, risks, obstacles and disadvantages								
Number of projects implemented	3	3	N/A	1	0	0	0	0
Flexibility in working fluid	1	1	1	3	3	3	1	1
CO_2 storage potential	2	1	1	0	0	0	1	1
Mineral extraction potential	N/A	N/A	3	0	0	0	N/A	N/A
Purification of unusable waters	N/A	N/A	3	0	0	0	N/A	N/A
Thermal stresses	0	0	N/A	1	0	0	1	1
Induced seismicity	3	2	0	0	0	0	1-2	1-2
Scaling	2	2	2	1	0	0	1-2	1-2
Back-closure risk of induced fractures	3	2	3	0	0	0	3	3
Losses in working fluid	3	1-2	N/A	0	0	0	1-2	1-2
Vertical displacement	2	1	N/A	0	0	0	1	1
Flow-channeling risk (i.e. short-circuit) in working fluid	3	1	N/A	0	0	0	0-1	0-1
Contamination of shallow aquifers	2	1	1	0	0	0	1	1
Predicted costs	2	1	N/A	2	3	2	3	3
Effective heat exchange area	2	3	3	1	1	2	3	3
Predicted internal energy consumption	3	2-3	3	0	0	0	2	2
Current feasible technical and technological infrastructure	2	3	N/A	3	3	1-2	2-3	2-3

* 0: Never or negligible, 1: Very few, 2: Moderate, 3: High and N/A: Not applicable.

** The evaluations may vary with many parameters such as the tectonic regime, temperature, depth, state of the geological structures through the main target zone, lithological features, technical and technological advancements.

(Figure 2). This has many variations based on well number and configuration such as single-well, double-well (i.e. doublet), triple-well (i.e. triplet) etc. As the detailed description is beyond the scope of this study, it will not be discussed further here.

The concept of the Classical UGS design was first suggested as HDR (Brown et al., 2012). It has been widely used as "Enhanced Geothermal Systems-EGS" particularly since early 2000s. In the late 1960s and early 1970s, this design was first proposed by the employees of the Los Alamos National Laboratory in the United States (Brown et al., 2012). The model can be described as "an artificial geothermal reservoir formed by fracking of usually fluid-poor crystalline hot rocks". On the other hand, non-crystalline rocks are also targeted in some similar practical applications.

Water-based conventional fluids are frequently preferred as the working fluid in these designs. Recently, extensive theoretical work has been done to use some alternative fluids such as "CO_2" and "N_2O". These studies have significantly increased in recent years. But no significant practical application is found in the literature. Classical UGS designs have not reached the technologically desired level yet. Due to simplicity, easy supply of working fluid, practical experience and know-how gained since the early 1970s, it is still applied in many projects. Although it has been implemented in dozens of projects, there are many obstacles to overcome in them (Table 1).

There are many practical projects on that type of Open-loop UGS. Some significant projects are as follows; (e.g. Fenton Hill, Newberry, Raft River, Coso), Germany (e.g. Bad Urach, Bruschal,

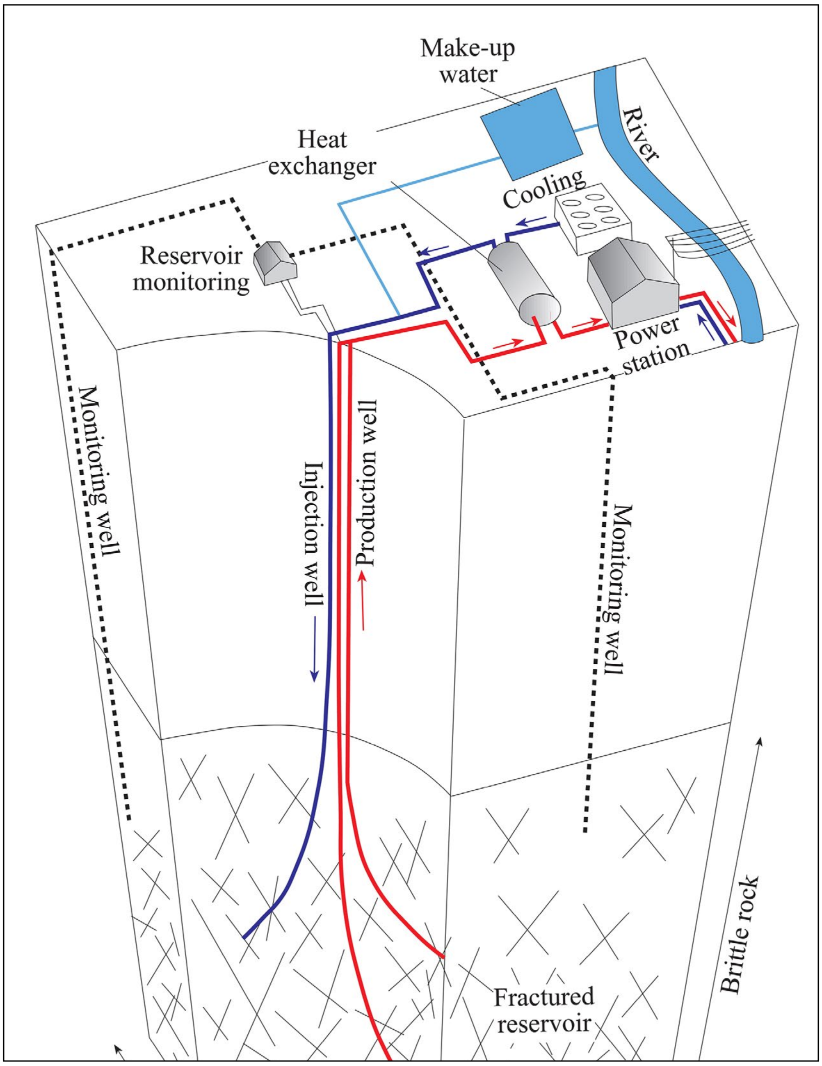

Figure 2- Schematic representation of the Classical UGS design (Re-drawn from Geothermal Explorers Ltd., 2003).

GENESYS project), France (Soultz-sous-Foréts), Japan (Hijiori and Ogachi).

Some problems terminated or paused these projects. They were briefly discussed in Çiçek, (2019). There have been done many research studies to overcome these problems. The strongest advantage of the system is the enormous amount of know-how and experience gained as a result of numerous applications. Classical UGS designs have many advantages and disadvantages compared to others (Table 1).

4.1.2. The Multi-stage UGS Design

The Multi-stage UGS design is another type of the "Open-loop UGS" design (Figure 3). The first study dealing with the multi-stage UGS conceptual design is unknown. In these, heat exploitation is provided via stage by stage hydraulic fracturing along the main target zone (Figure 10). The main purpose of the Multi-stage hydraulic fracturing is to increase the heat exchange area as in the Classical UGS.

In such studies, the Multi-stage hydraulic fracturing operation is carried out sequentially and systematically along different stages (levels) in the well (Figure 10). In addition, stage size, geometry and distance between stages require careful planning. Otherwise, unwanted consequences may develop (Li and Zhang, 2017). For example, if the distance between each fracture is chosen short, undesired fracture geometries may occur (Li and Zhang, 2017). This type of geometric fractures

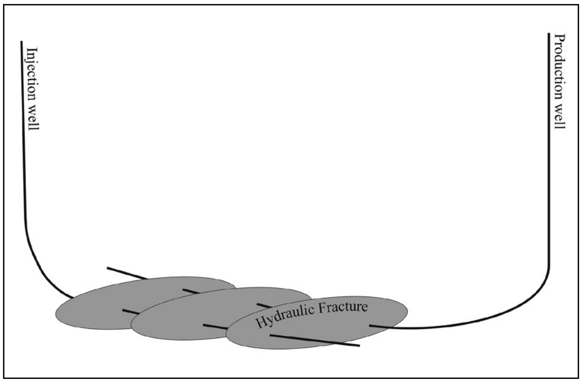

Figure 3- Schematic representation of the Multi-stage UGS design (Re-drawn from Shiozawa, 2015).

may cause interaction among themselves, which may also cause other problems (e.g. Li and Zhang, 2017). In planning phase, earth stress orientations along the main target zone, cooling-induced stresses, stress anisotropies, pore water pressure distribution, stress magnitudes, discontinuity geometries, fracture propped width or equivalent net pressure, planned fracture height, formation (rock) stiffness etc. need to be taken into account (https://dnicolasespinoza.github.io/; Li and Zhang, 2017).

There are some important differences between Multi-stage UGS designs and Classical UGS designs. These differences are mostly due to hydraulic fracture dimensions, geometry and size (Table 2).

Water-based conventional fluids will most likely be used as working fluid in future projects. It is officially reported that the hydraulic fracturing phase of the FORGE project has been successfully completed (https://openei.org/wiki/EGS_Collab_Project_Overview).

Problems encountered with conventional UGS are also quite possible in Multi-stage UGS designs (Table 1). However, the Multi-stage UGS designs have more practical hydraulic fracturing technique, solid know-how and huge experience gained from unconventional oil projects. Therefore, this is expected to be implemented in many other near-future UGS projects.

4.1.3. The Hot Ductile Formations

Another important Open-loop UGS design is known as the “Hot Ductile Formations UGS” (Figure 4). It was first introduced by a private company called “GeoSierra” (http://www.geosierra.com/geothermal.html).

In this, some vertical fracture sets with different azimuths are formed within the hot and ductile geological formation (Figure 4). The fracture sets (i.e. cells) cover an area of approximately 0,324 km^2 (80 acre). A production well in the center of each cell is surrounded by three injection wells (http://www.geosierra.com/geothermal.html) (Figure 4). According to current technology-based research studies, such a design is unlikely to be commercial on its own (http://www.geosierra.com/geothermal.html). For this reason, it is thought that projects based on this will be more commercial if more than one benefit is obtained (http://www.geosierra.com/geothermal.html). In this context, it is planned to achieve four main outputs in such a project: (1) the power production, (2) extraction of secondary elements such as Li, Si, Mn, B etc. from the mineral waters, (3) purification of mineral waters and earning extra income, and (4) CO_2 storage.

In the initial stage, CO_2 is planned as working fluid. However, conventional water-based fluids may also be used as needed (http://www.geosierra.com/geothermal.html).

It is considered that the implementation of such a project may have so many advantages as stated in

Table 2- Main differences between Multi-stage and Classical UGS designs.

	Multi-stage UGS design	**Classical UGS design**
1	The fractures are usually normal to the well axis and are penny-shaped	It varies from project to project.
2	Fracture orientations are relatively more regular.	Fracture systems are relatively irregular.
3	Fracture frequencies are quite systematic and more homogeneously distributed throughout the well.	Fractures are generally concentrated in certain zone(s).
4	It consists of dozens of stages.	Usually it does not exceed a few stages.
5	Fracture sizes are relatively smaller.	Fracture dimensions are relatively larger.

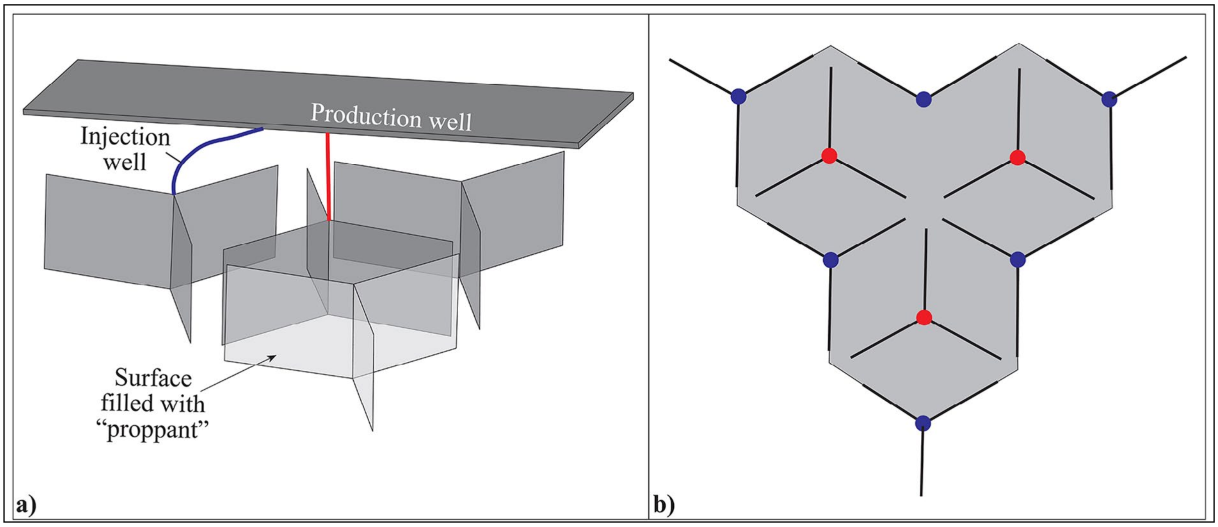

Figure 4- Schematic representation of the Hot Ductile Formations UGS design. a) 3D side view and b) top view (http://www.geosierra.com/geothermal.html).

table 1. On the other hand, main significant disadvantage of this design is the lack of any practical experience and know-how.

It has been announced that a pilot project is planned in the "Salton Sea" geothermal field in the state of California, USA in the near future (http://www.geosierra.com/geothermal.html). The significant side effects of this design are not known yet.

4.1.4. The Eavor-Loop UGS Design

Another Open-loop UGS design is the "Eavor-Loop UGS". It was first proposed and implemented as a pilot project in the Rocky Mountains near Alberta, Canada under the leadership of Eavor Technologies LLC. The other partners are Precision Drilling, Shell New Energies, Shear Fluids, Certus Oil and Gas, Rangeland Engineering Canada, the University of Alberta, Codeco-Vanoco Engineering, the University of Toronto, Rangeland Engineering Canada, Enlighten Geoscience Ltd., Petrel Robertson Consulting, Chinook Petroleum, and GL (Figure 5) (https://eavor.com/press/).

Considering the information disclosed publicly, there is no hydraulic fracturing operation along the main target zone (https://eavor.com/press/). In this, two opposing geothermal wells on the surface are linked from toe to toe by horizontal drilling technology inside the main target zone (https://eavor.com/press/). Later, additional pad(es) are drilled approximately parallel to main axis of the well (https://eavor.com/press/). Hence, it is aimed to form a commercially efficient surface area for geothermal exploitation (https://eavor.com/press/). According to the presented information, the Eavor-Loop design has been introduced as a Closed-loop design. However, in this, both mass and heat transfer are expected between the working fluid and the wellbore wall (https://eavor.com/press/). Although this may be regarded as a physically Closed-loop system, it seems more convenient to regard it as an "Open-loop UGS design" based on thermodynamic system types.

This project consists of three main phases: (1) the surface studies and drilling, (2) practical efficiency test of the physically Closed-loop system and (3) the thermodynamic production tests (https://eavor.com/press/). In the first phase of this project, the two opposing wells were tied toe to toe in the main target zone (https://eavor.com/press/). In the second phase, the target wells were successfully sealed, and a physically Closed-loop system was achieved inside 15 m thick sandstones in 2019 (Figure 5a) (https://eavor.com/press/; Robert Winsloe, official e-mail communication, 2019). In addition, third phase was successfully achieved in 2020 as well (https://eavor.com/press/). The pilot project still continues as of September 2020 (https://eavor.com/press/). Moreover, Enex Power Germany GmbH and Eavor Technologies Inc. have agreed on a letter of intent to form a

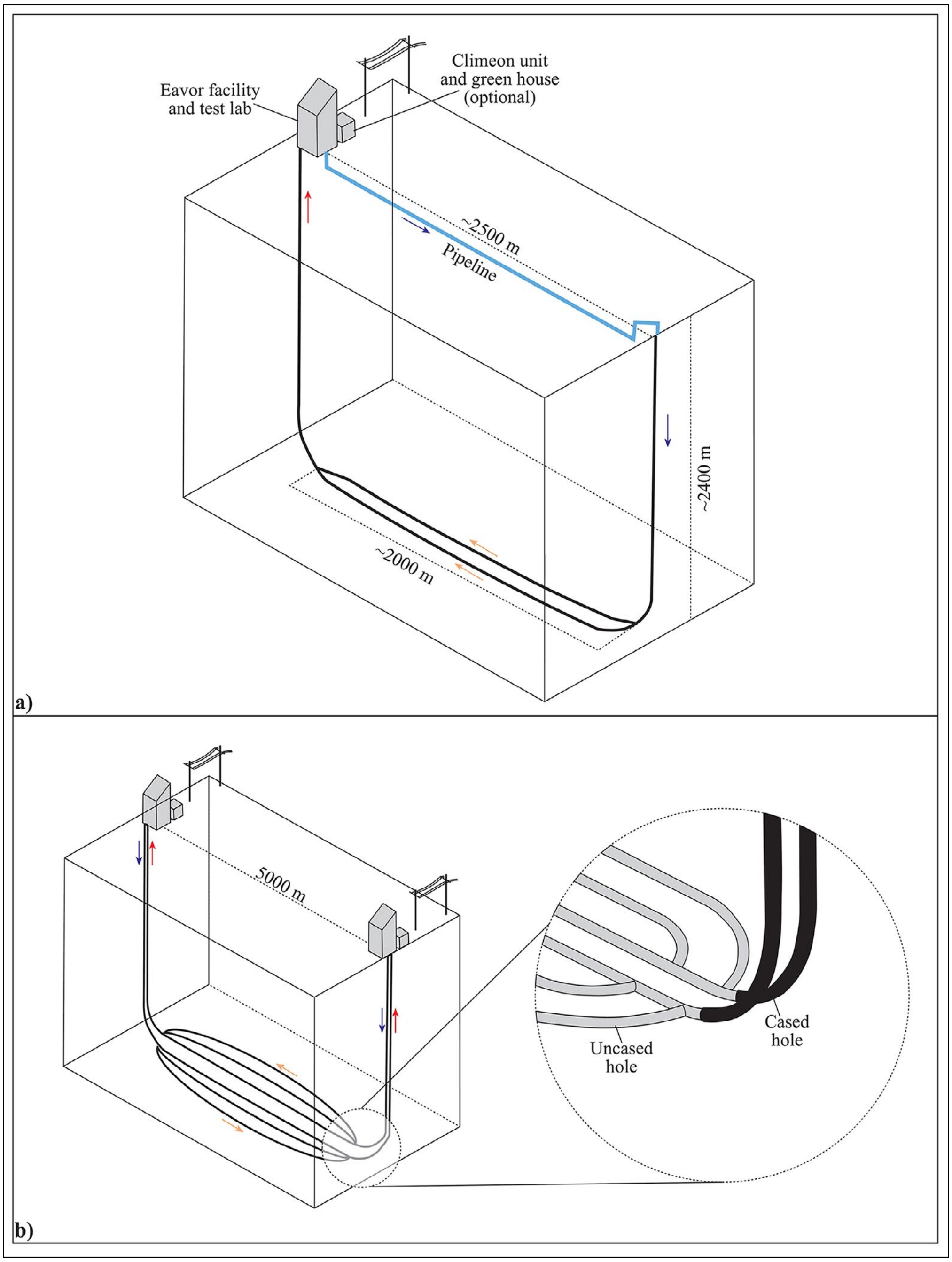

Figure 5- Schematic representation of the Eavor-loop UGS design. a) Eavor-Loop design implemented on a pilot scale, b) more comprehensive Eavor-Loop design (https://eavor.com/press/).

geothermal project development company to construct Eavor-Loop heat and power projects within Enex's existing geothermal license area in Bavaria, Germany (https://eavor.com/press-release/eavor-announces-commercial-eavor-Loop-project-be-built-geretsried-germany). Accordingly, a commercial power project is planned via "full-scale Eavor-Loop UGS design". Some of the extracted heat has the potential to be used in residential heating as secondary revenue (https://eavor.com/press-release/eavor-announces-commercial-eavor-Loop-project-be-built-geretsried-germany).

There are some questions about the conceptual design of the project. As a result of the inquiries made, two slightly different designs have been observed in the official web page of the Eavor Technologies LLC. (Figure 5).

According to official information presented in written form by Eavor Technologies LLC officials, the water-based fluids with special additives is being used as the working fluid in order to increase the heat exchange and reduce the friction (Robert Winsloe, official E-mail communication, 2019).

This seems to eliminate many problems experienced in the "Classical UGS design" (Table 1). Furthermore, it is expected to have thermosiphon effect within the system as the density of heated working fluid decreases with respect to increase in the temperature along its path. The effect is expected to have positive consequences on the net power output of the system during operation. Nevertheless, it is inevitable that there will be some mass transfer between working fluid and the main target zone. Therefore, this may bring about some scaling and associated problems in the long term (Table 1).

4.2. The Closed-loop UGS Designs

There are various types of Closed-loop UGS designs in the literature. These studies were mostly inspired by geothermal heat pump designs. They generally emerged as a result of the perception that the problems experienced in Open-loop Classical UGS designs may not be solved in the near future. Consequently, the demand for them has increased recently.

Closed-loop UGS designs have some significant advantages over Open-loop UGS designs such as flexibility in working fluid options, reduced seismicity, scaling, vertical displacement, flow-channeling (i.e. short-circuit fluid circulation) etc. (Table 1). These designs are not widely practically implemented in power projects, especially due to expected inefficient heat exchange area. However, it has become important recently. Because, many novel alternative working fluids have emerged lately. In this study, only two crucial types are briefly discussed below: (1) Simple U and L-shaped UGS designs and (2) Finned L-shaped UGS designs (Table 1, figures 6 and 7).

4.2.1. The Simple U and L-shaped UGS Designs

The Simple U and L-shaped UGS designs are the most well-known varieties of the Closed-loop UGS designs (Figure 6). It is unknown when and by whom it was first suggested. Some used these in their theoretical studies (e.g. Riahi et al., (2017).

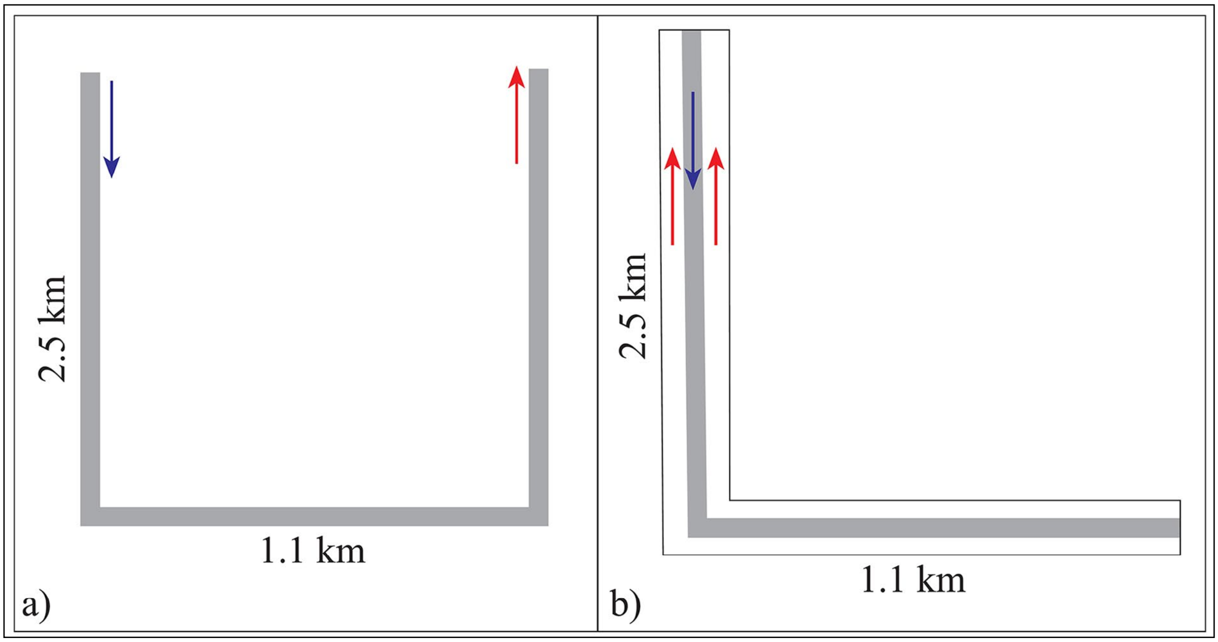

Figure 6- Schematic representation of the Simple "U" and "L"-shaped UGS designs, a) Simple "U"-shaped design and b) Simple "L"-shaped design (Re-drawn from Rihai et al., 2017).

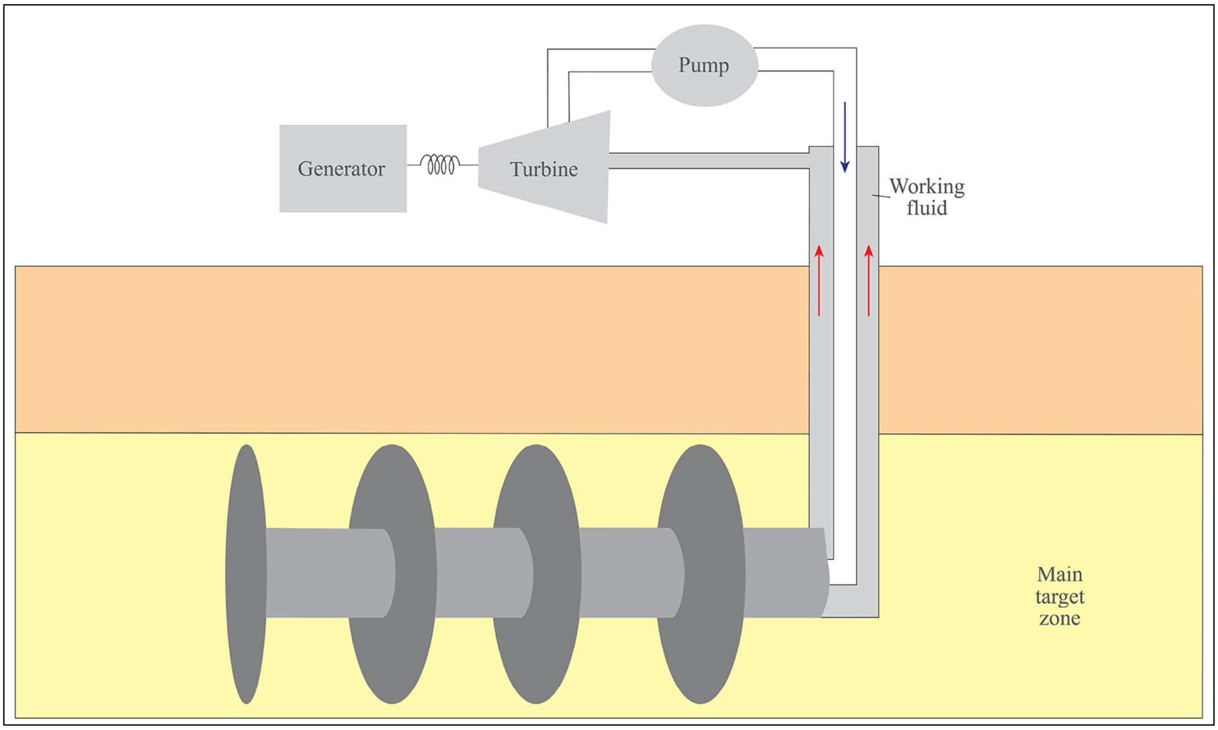

Figure 7- Schematic representation of the Finned "L"-shaped UGS design (Re-drawn from Taleghani, 2013).

Although these are simple designs, they are generally not preferred as the heat exchange surface area needed to generate power is insufficient. There are two well-known variations of them known as "U" and "L" shaped types (Figure 6). In "U" shaped designs, usually two opposing boreholes are tied toe to toe at depth via horizontal drilling technology (Figure 6a). On the other hand, a single "L"-shaped well with inner tubing is formed in the "L" shaped types (Figure 6b). The wells are first drilled vertically until the target depth, then diverted nearly or completely to horizontal along the main target zone. The drilling operations are then stopped. Later, the wellbore is cased with cemented casing. After all, the heat is exploited by using a suitable working fluid. In the U-shaped designs, the working fluid is usually directly circulated inside the casing, whereas, in the L-shaped designs, the working fluid is circulated through a secondary pipe (i.e. tubing) set inside the casing. The working fluid is retaken through the annulus in between (Figure 6b). In addition, some parts of the casing and the tubing are insulated to prevent heat loss. In some Simple U and L-shaped sub-types, it is recommended to drill a series of additional ultra-slim holes parallel to the main axis of the well, similar to the Eavor-Loop design mentioned above. Later on, the walls of these extra legs are sealed with a cemented casing. Thus, the effective heat transfer area needed for power production is achieved.

These designs require extremely high temperatures and commercially accessible geological units for commercial power generation. Many other parameters are considered in well planning and system design of "U" and "L" shaped UGS such as distance between well locations, temperature profile, target depth etc.

These have many advantages and disadvantages like any others (Table 1). The main disadvantage of them is the significant increase in project costs due to the large number of drilling expanses. Therefore, they are not widely preferred in contemporary UGS practices. However, modeling studies and new developments in working fluid technology have led to the increase in popularity of such designs in recent years (Riahi et al., 2017). Unfortunately, they have some disadvantages such as the flexibility in working fluid options, possible reduced contamination risk of the freshwater reservoirs and existing technological infrastructure as well as others (Table 1).

Although there is no well-known practical power generation project on this, some heating-targeted applications are common particularly in Germany.

4.2.2. The Finned L-Shaped Design

Another important type of the Closed-loop UGS design is the “Finned L-Shaped” design. This significantly differs from the simple “U” and “L”-shaped counterparts in a way that some fins are formed normal to the well axis along the main heat recovery zone (Figure 7). Although this is quite common in ground source heat pump applications, it was first proposed by Taleghani (2013) for power generation. The major disadvantage of such designs is the technological barriers to underground fin applications. However, it is thought that the existing technological barriers will be overcome with the future R and D studies. Therefore, such designs may become important in the near future.

In this, as with simple “U” and “L” shaped designs, geological units should be suitable for commercial projects. The most promising aspect of this is the injection of materials with suitable thermal properties to accelerate the exploitation of heat energy. Thus, it is thought that the required effective heat exchange surface area can be obtained.

Such designs are highly flexible in terms of working fluid. No project open to the public is yet known regarding this type of novel designs for high temperature systems. On the other hand, despite the technological barriers, it is expected that the number of researches will increase in the following years thanks to many potential advantages it has. The most important two advantages of these systems are (1) possibility to have an effective heat transfer area with shorter and less conventional wells, and (2) access to numerous effective alternative working fluid options (Table 1). Such a design is thought to be promising because it reduces the costs and some technical challenges in comparison to simple “U” and “L”-shaped counterparts. On the other hand, the most important disadvantage is the current technological barriers in the construction of effective underground fins (Table 1).

4.3. The Hybrid UGS Designs

There are many conceptual UGS designs under this topic in the literature. These studies mostly aim to take some of the strengths of Open and Closed-loop designs and combine them under a single design. Only two main types are considered within the scope of this study. They are (1) The Multiple Microhole Array and (2) Earth Energy Extraction System (Table 1, figure 8 and 9).

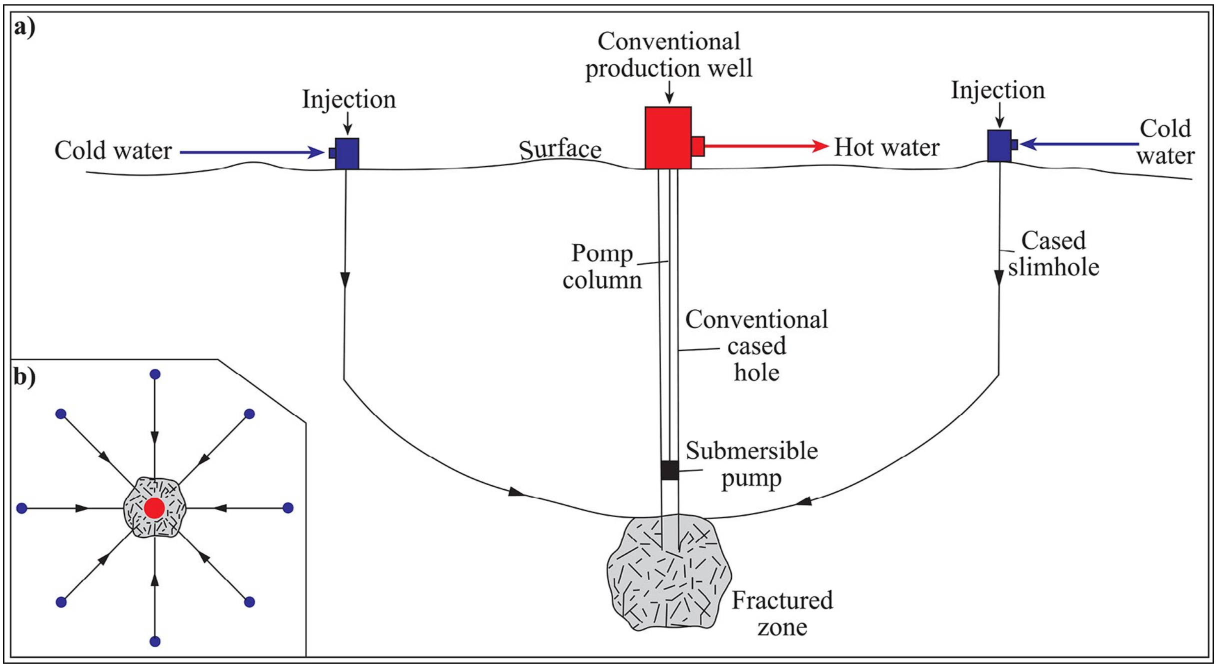

Figure 8- Schematic representation of the Earth Energy Extraction System UGS design (Re-drawn from Sanyal et al., 2005), a) side view and b) top view.

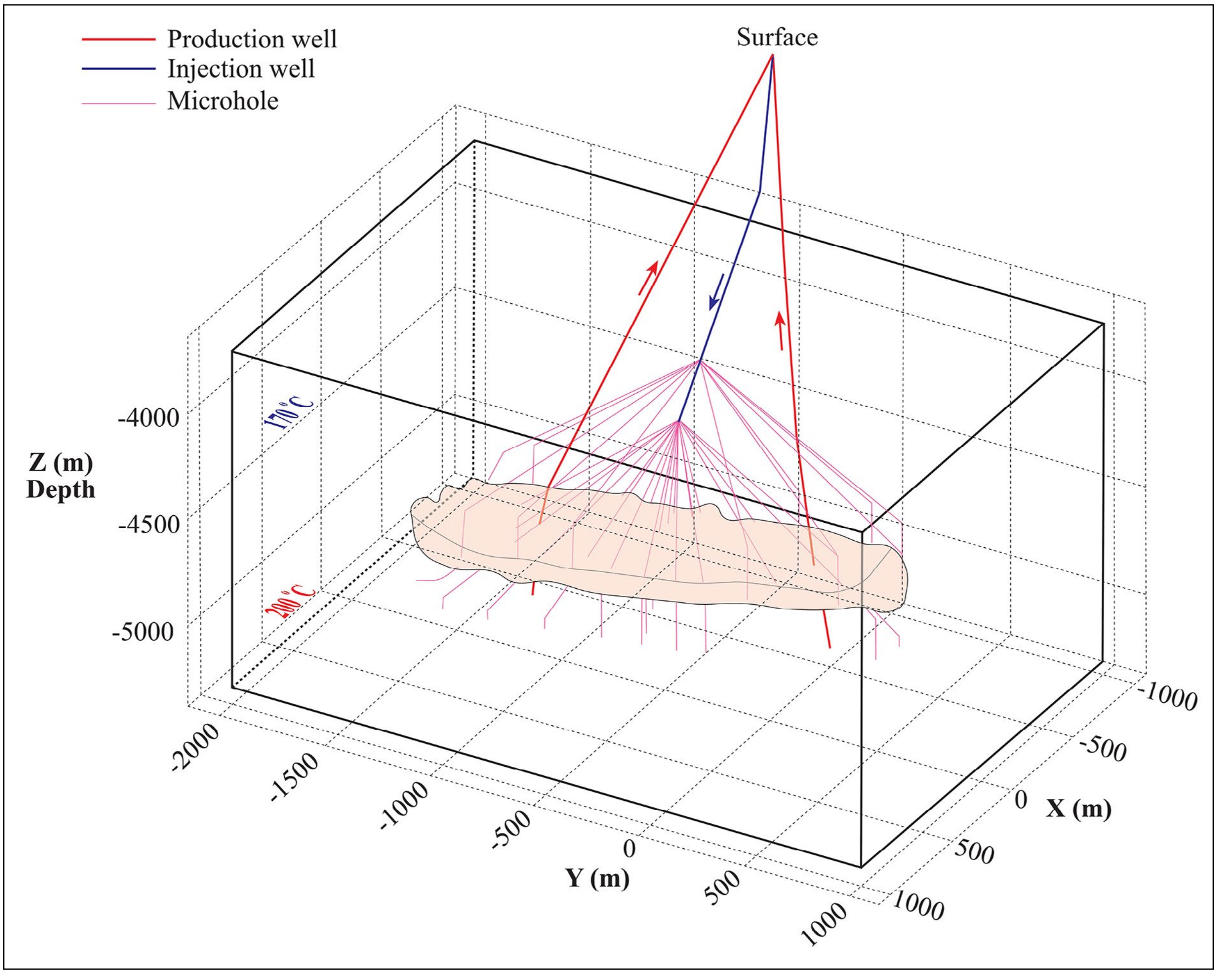

Figure 9- Schematic representation of the Multiple Micro-hole Array UGS design (adopted from Finsterle et al., 2013).

4.3.1. The Multiple Microhole Array

This is one of the most important type of the Hybrid UGS design (Figure 8). Although the first proposed design is unknown, it became popular with some patented studies after 1996 (e.g. U.S. Patent No: 5,515,679 and 6,247,313B1, Zhang et al., 2012; Finsterle et al., 2013).

The Multiple Microhole Array UGS design is possible inside any suitable geological medium. In this, large number of ultra-slim holes (mostly <10 cm) are drilled through the main target zone (Figure 8). The main purpose here is to increase the effective heat exchange area and to prevent some obstacles. These obstacles are localized reservoir associated with flow-channeling (i.e. short-circuit) in working fluids and reduced energy extraction as in many Open-loop UGS designs (Table 1).

In this type, water-based conventional fluid is proposed as the working fluid (Finsterle et al., 2013). However, some alternative fluids like CO_2 also seem possible. It has still not reached the technologically desired practical level yet. In addition, no commercial-scale practical study has been found on the Multiple Microhole Array UGS design so far. In addition, as of 2020, no practical project has been found based on this.

It aims to reduce or eliminate the problems experienced both Open and Closed-loop designs (Table 1). However, although reduced, all problems such as scaling and hydraulic fracturing are also expected (Table 1). In addition, the other significant disadvantage of this is the risk of shallow drinking reservoir contamination, especially in shallow applications (Table 1). These studies are still ongoing on this subject.

4.3.2. The Earth Energy Extraction System (Triple-E)

Another important Hybrid UGS design is the "Earth Energy Extraction System" proposed by Sanyal et al. (2005) (Figure 9). However, this UGS was inspired by another patented study (i.e. U.S. Patent no: 6,247,313B1, 19 June 2001). The Earth Energy Extraction System is similar to the Multiple Microhole Array design in many ways (Table 1). In this, suitable fluid-poor, hot and brittle rocks are utilized with relatively localized fracturing operations (Figure 9). In top view, a conventional production well is surrounded by many ultra-slim injection wells (<10 cm diameter) (Figure 9b). The main purpose of this is generally quite similar to other hybrid systems (Table 1).

In the Earth Energy Extraction System, it is anticipated that water-based fluids will be used as the working fluid. However, some other alternative working fluids seem also possible. The main advantages of it are reduced induced seismicity risk, reduced losses in working fluid, reduced vertical displacement risk, reduced risk of flow-channeling (i.e. short-circuit) in working fluid, increased effective heat exchange area etc. (Table 1). This system has not reached the technologically desired level so far. In addition, as of 2020, no commercial practical study has been found on the Earth Energy Extraction System UGS design.

It aims to reduce or eliminate the problems experienced both Open and Closed-loop UGS designs (Table 1). However, although reduced, all problems related to scaling and fracturing are expected to some extent as well (Table 1). In addition, the other significant disadvantage of this is the risk of shallow drinking reservoir contamination, especially in shallow applications (Table 1). Nowadays, studies are still ongoing to overcome these problems.

5. Conclusions and Suggestions

So far, numerous terms are collected under the "Unconventional Geothermal Systems-UGS". These terms can cause conceptual confusion. Hence, the original meaning of this concept should be expressed

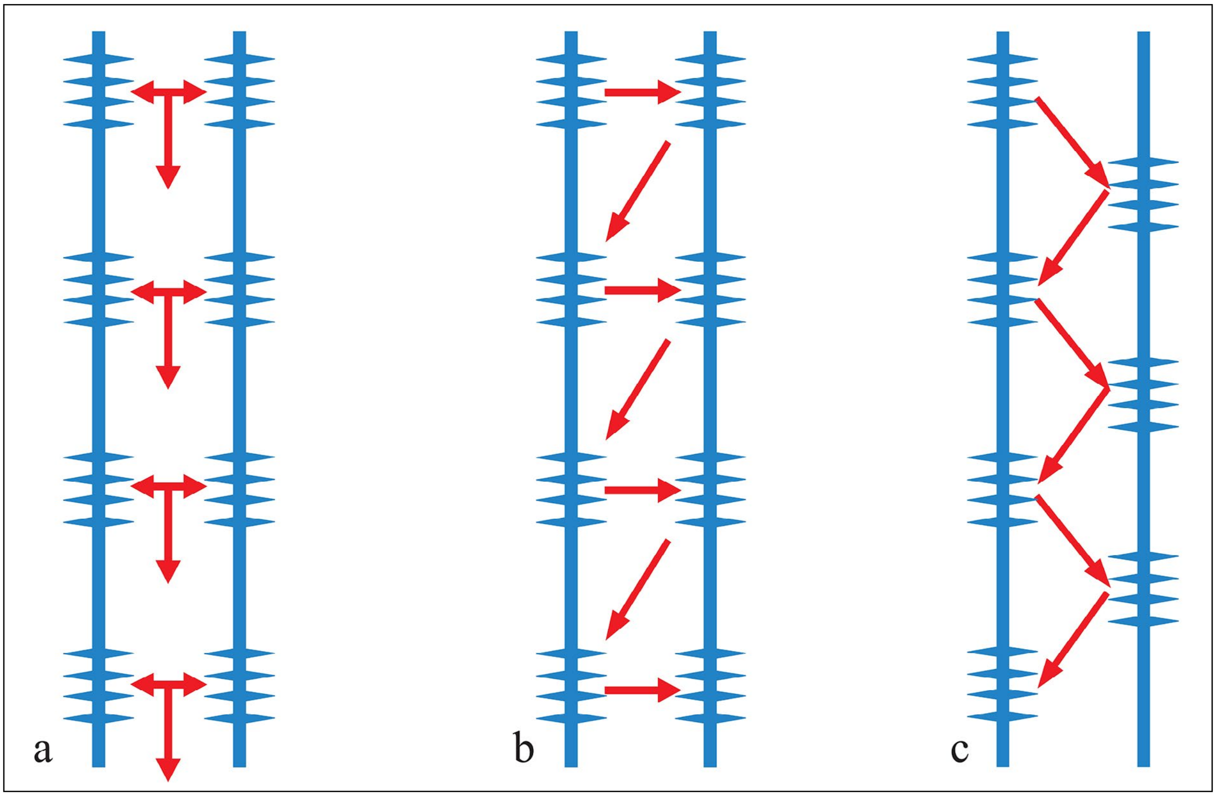

Figure 10- Main types of Multi-stage hydraulic fracturing; a) simultaneous hydraulic fracturing, b) sequential hydraulic fracturing (zipper-frac) and c) modified zipper-frac (Re-drawn from Nagel et al., 2013).

in full. In addition, these uncertainties may cause some problems in determining the limits of the legal regulations regarding some state-supported funds. In this context; some restrictive criteria are needed to determine whether a study is UGS or not. So, the most important criteria are briefly summarized as: (1) lack of commercial conventional geothermal fluid production even despite all conventional well completion techniques are applied such as simple chemical treatment, water-loss, compressor test, pumping tests etc., (2) application of sophisticated unconventional well enhancement techniques such as advanced hydraulic fracturing, acidizing, nitrogen treatment etc., (3) in case, conventional geothermal fluid(s) (i.e. typical conventional geothermal production fluid) is/are used as working fluid through the main target zone, the fluid(s) should be supplied out of conventional power producing geothermal reservoir(s), (4) use of unconventional fluids as the main working fluid such as CO_2, NH_3 etc., (5) the proppant and associated additive injection into the target zone in order to keep the fractures open, (6) extensive use of unusually high grade well equipment such as high pressure casing, wellhead elements etc. required for extreme operations, (7) use of unusual conceptual designs to exploit earth heat. If a geothermal study includes any of these criteria, it can easily be regarded as a UGS.

Based on thermodynamic system types, it is possible to group conceptual UGS designs under three topics: (1) Open-loop UGS designs, (2) Closed-loop UGS designs and (3) Hybrid UGS designs. These consist of many sub-types. Each design discussed here has its own advantages and disadvantages.

For Turkey, the following suggestions can be made with respect to UGS

1- The national geothermal energy potential should be comprehensively calculated, and an inventory should be prepared for some crucial depths such as 1, 3, 5 km in the light of the available data on UGS,

2- A comprehensive national action plan needs to be prepared with broad participation of stakeholders regarding UGS,

3- Young bright researchers need to be trained and supported for future UGS projects,

4- As in developed countries, government support and incentive should be provided to companies and/or institutions that implement or plan to implement UGS projects,

5- Awareness/knowledge of the society, investors and public need to be increased by organizing domestic workshops, conferences etc. on UGS,

6- The exploration/research stage of these projects generally requires much longer time periods compared to the conventional geothermal systems. Therefore, the specified exploration-operating license periods in the geothermal law need to be extended,

7- A team of the expert researchers needs to be established with high practical and theoretical experience in the areas of expertise that are vital for UGS projects such as structural geology, hydrogeology, water chemistry, inclined or horizontal drilling technologies, microseismic monitoring, hydraulic fracturing, reservoir geomechanics, fluid mechanics and heat transfer etc.,

8- The hydraulic fracturing technique, fluid mechanics and heat transfer studies have been extensively utilized in the conventional geothermal reservoirs, the UGS reservoirs, the petroleum reservoirs and the coal bed methane extraction studies etc. In addition, they are also crucial for not only Earth Sciences but also other areas of expertise such as Civil Engineering, Mechanical Engineering, Space and Aviation studies etc. Based on this, some high-tech national research laboratories need to be established similar to Los Alamos National Laboratory in The United States,

9- After the necessary infrastructure is prepared, it is appropriate to carry out a joint research project consisting of relevant public institutions/organizations, universities and private sector stakeholders in a pilot field.

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References

ABD Patent ve Marka Ofisi, Patent No: 5,515,679, May 14, 1996.

ABD Patent ve Marka Ofisi, Patent No: 6,247,313B1, June 19, 2001.

Armstead, H. C. H., Tester, J. W. 1987. Heat Mining. E. and F. N. Spon, London and New York, 478 p.

Breede, K., Dzebisashvili, K., Liu, X., Falcone, G. 2013. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geothermal Energy, 1, 4.

Breede, K., Dzebisashvili, K., Falcone, G. 2015. Overcoming challenges in the classification of deep geothermal potential. Geothermal Energy Sciences, 3, 19-39.

Brown, D.W., Duchane, D.V., Heiken, G. Hriscu, V.T. 2012. Mining the Earth's Heat: Hot Dry Rock Geothermal Energy. Springer-Verlag, 657 p.

Çiçek, A. 2019. Enerji hedefli geleneksel olmayan jeotermal sistemlerin (UGS) uygulandığı sahalarda yaşanan önemli teknik sorunlar. MTA Doğal Kaynaklar ve Ekonomi Bülteni, 28, 73-77.

Canoğlu, M.C., Kurtuluş, B. 2016. Body type optimization of water structures and engineering parameters determination of natural structural materials: an example from Kışlademirli Dam (Kütahya). Karaelmas Science and Engineering Journal, 6, 2, 250-264.

Canoğlu, M. C., Kurtulus, B. 2017. Permeability of Savcıbey dam (Bilecik) axis location and design of grout curtain. Bulletin of the Mineral Research and Exploration, 154, 157-168.

Canoğlu, M. C. 2019. Selection of Suitable Dam Axis Location Considering Permeability and Grout Curtain Optimization Environmental and Engineering Geoscience, 25, 1, 15-25.

Eavor Technologies Inc. https://eavor.com/press/.September 12, 2020.

Espinoza, G. https://dnicolasespinoza.github.io/, September 12, 2020.

Finsterle, S., Zhang, Y., Pan, L., Dobson, P. Oglesby, K. 2013. Microhole arrays for improved heat mining from enhanced geothermal systems. Geothermics, 47, 104-115.

Genter, A., Guillou-Frottier, L., Feybesse, J.-L., Nicol, N., Dezayes, C., Schwartz, S. 2003. Typology of potential hot fractured rock resources in Europe, Geothermics, 32, 701-710.

Genter, A., Evans, K., Cuenot, N., Fritsch, D., Sanjuan, B. 2010. Contribution of Exploration of Deep Crystalline Fractured Reservoir of Soultz to the Knowledge of Enhanced Geothermal Systems (EGS). Comptes Rendus Geoscience, 342, 502-516.

GeoSierra LLC. http://www.geosierra.com/geothermal.html. September 12, 2020.

Geothermal Explorers Ltd., 2003. Schematic representation of the Classical UGS design

Grassiani, M., Krieger, Z., Legmann, H. 1999. Advanced power plants for use with HDR/enhanced geothermal technology. Bulletin D'Hydrogéologie, 17, 165-172.

He, Z., Zhang, Y., Feng, J., Ding, Q., Li, P. 2018. An EGS Site Evaluation Method for Geothermal Resources Based on Geology, Engineering and Economic Considerations. PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018, SGP-TR-213.

Hıdıroğlu, İ. A., Parlaktuna, M. 2019. Dünyada Kızgın Kuru Kaya (HDR) Projeleri ve Türkiye'nin Muhtemel HDR Alanları. Jeotermal Elektrik Santral Yatırımcıları Derneği, 6-7 Şubat GT2019 Türkiye Jeotermal Kongresi Bildiriler Kitabı, Ankara, 91-103.

https://eavor.com/press-release/eavor-announcescommercial-eavor-loop-project-be-builtgeretsried-germany. September 12, 2020.

Kuriyagawa, M. 1987. Hot dry rock geothermal energy in Japan. Geothermics, 6, 4, 401-403.

Li, S., Zhang, D. 2017. A fully coupled model for hydraulic fracture growth during multi-well fracturing treatments: enhancing fracture complexity. SPE-182674-MS.

Nagel, N., Zhang, F., Sanchez-Nagel, M., Lee, B. 2013. Quantitative Evaluation of Completion Techniques on Influencing Shale Fracture 'Complexity'. In ISRM International Conference for Effective and Sustainable Hydraulic Fracturing. International Society for Rock Mechanics. May 22-23, 2013. Brisbane, Australia.

OpenEI, https://openei.org/wiki/Fenton_Hill_HDR_Geothermal_Area, September 12, 2020.

OpenEI, https://openei.org/wiki/EGS_Collab_Project_Overview, September 12, 2020

Riahi, A., Moncarz, P., Kolbe, W., Damjanac, B. 2017. Innovative Closed-Loop Geothermal Well

Designs Using Water and Super Critical Carbon Dioxide as Working Fluids. Geothermal Resources Council Bulletin, 7-10, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 13-15, 2017, SGP-TR-212.

Roberts, V., Kruger, P. 1982. Utility Industry Estimates of Geothermal Electricity-Geothermal power production to continue rapid growth through the year 2000. Geothermal Resources Council Bulletin, 7-10.

Sanyal, S.K., Granados, E.E., Butler, S.J., Horne, R.N. 2005. An alternative and modular approach to enhanced geothermal systems. Transactions Geothermal Resources Council, 29, 139-144.

Serpen, Ü. 2019. Sıcak Kuru Kayalar'ın (EGS) Potansiyeli, Geçmişi, Geleceği ve Gerçekler, 14. Ulusal Tesisat Mühendisliği Kongresi Bildiriler Kitabı, 17-20 Nisan 2019, İzmir, 238-249.

Shiozawa, S. 2015. Designing Enhanced Geothermal and Hydraulic Fracturing Systems Based on Multiple Stages and Proppant. MSc Thesis, University of Texas at Austin, 86 p. (unpublished).

Taleghani, A. D. 2013. An Improved Closed-Loop Heat Extraction Method From Geothermal Resources. Journal of Energy Resources Technology, 135/042904-1.

Takahashi, H., Hashida, T. 1993. New Project for Hot Wet Rock Geothermal Reservoir Design Concept. Proceedings, 18th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, USA, 26-28 Ocak 1993, SGP-TR-145, 6 s.

Tester, J. W., Anderson, B. J., Batchelor, A. S., Blackwell, D. D., DiPippo, R., Drake, E. M., Garnish, J., Livesay, B., Moore, M. C., Nichols, K., Petty, S., Toksöz, M. N., Veatch Jr., R.W. 2006. The future of geothermal energy-impact of enhanced geothermal systems on the United States in the 21st Century. MIT (Massachusetts Institute of Technology) Cambridge MA., 372 s.

Winsloe, R. 2019. official e-mail communication.

Zhang, Y., Pan, L., Dobson, P., Oglesby, K., Finsterle, S. 2012. Microhole for Improved Heat Extraction From EGS Reservoirs: Numerical Evaluation. Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30- February 1, 2012, SGP-TR-194.