Journal of Cleaner Production 275 (2020) 124009

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A review on geothermal wells: Well integrity issues

Payam Allahvirdizadeh

Faculty of Science and Technology, Department of Energy and Petroleum Engineering, University of Stavanger, Stavanger, Norway

ARTICLE INFO

Article history:
Received 29 April 2020
Received in revised form
21 July 2020
Accepted 29 August 2020
Available online 6 September 2020

Handling editor. Prof. Jiri Jaromir Klemeš

Keywords:
Enhanced geothermal systems
Geothermal energy
Well integrity
And well completion
Geothermal drilling

ABSTRACT

Geothermal energy is an important potential and a strategic area for developing activities regarding renewable energy and future studies. It involves a great potential and a main role in the worldwide energy sector, particularly electricity generation. Nevertheless, the role of geothermal electricity in today's world is not dominant in comparison to other renewable energy sources like solar PV and wind power.

Though Enhanced Geothermal Systems (EGS) greatly includes the potential for power generation, the EGS technology feasibility should be further studied. Numerous studies exist to investigate the energy production feasibility (heat and electricity) from such resources focusing on drilling processes. Today, the geothermal projects are mainly focused on completion operations and drilling research area, in which it is possible to reduce the costs considerably by suitable design.

To drill a geothermal well, the drilling operations are quite similar to the petroleum industry. Though, the different aspects of geothermal drilling will make it more challenging and complex than the oil and gas well drilling. The type of resource and the formation type of resource is the big differences. Normally, fissures and fractured hard volcanic rocks contain geothermal resources, however, porous media of sedimentary formations comprises oil and gas resourses. Petroleum and geothermal well drilling have different geological and physical features including rock types, reservoir pressure, temperature, well and casing design as well as the well completion program. Hence, in this paper, it is tried to present the most common issues in geothermal well drilling operations and to introduce the potential for the future research areas.

Contents

1. Introduction

Geothermal energy is a strategic area for developing the

E-mail address: payam.allahvirdizadeh@uis.no.

https://doi.org/10.1016/j.jclepro.2020.124009

activities regarding renewable energy and future research. Since billions of years ago, the earth's core produces and radiates heat. The earth center has a temperature of 5500 °C, the same as the sun's surface temperature (Fig. 1). A fundamentally limitless and renewable source of energy is created by this constant heat flow over the billion years (Blodgett, 2014).

During the centuries, geothermal energy has had various usages. The water from hot spring was used by the Maoris in New Zeeland and native Americans for medical purposes and cooking over thousands of years. Romans and Ancient Greeks possessed geothermally heated spas. People in Pompeii by living near Mount Vesuvius tapped hot water from the earth for heating their buildings. Geothermal waters were utilized by Romans to treat skin and eye diseases. The geothermal spas have been enjoyed by Japanese for centuries" (Nersesian, 2010). Though, the geothermal energy was commercially used for district heating first in Boise, Idaho, the USA in 1892 (US Department of Energy). Later at the 19th century, developing thermodynamics continuously led to the generation of power (electricity) from geothermal heat through transforming the hot steam energy in mechanical energy and then into electricity via generators and turbines. Certainly, the generation of geothermal electricity is related to the Larderello in northern Italy (Stober and Bucher, 2013) with the first geothermal discovery for industrial purposes.

1.1. Use of geothermal resource

Based on the Lindal diagram (Blodgett, 2014) (Fig. 2), the potential utilization of geothermal fluids is represented at various temperatures that are valid today as well. Nonetheless, over the temperature of 85 °C, a binary cycle plant can generate electricity now (Dickson, Fanellib).

i. Direct heat Use

The most common and oldest utilization of geothermal energy is direct use. District heating, space heating, agricultural and greenhouse applications as well as industrial applications are the most common forms of utilization worldwide (Dickson, Fanellib). In Iceland, space and district heating has been progressed vastly, where geothermal direct use had a share of 66% of primary energy usage in 2011 (Dickson, Fanellib); which has been increased to 96% of heating and cooling energy consumption in 2015 (Breembroek et al., 2013). It is interesting to know that district heating using geothermal energy is saving about 7% of Iceland's GDP. Fig. 3 shows a basic flow diagram of the geothermal district heating system of Reykjavik (Gudmundsson, 1988).

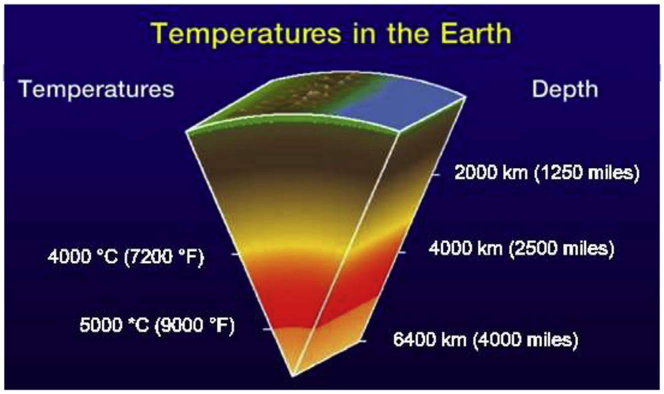

Fig. 1. The Earth's temperature (Dickson, Fanellia).

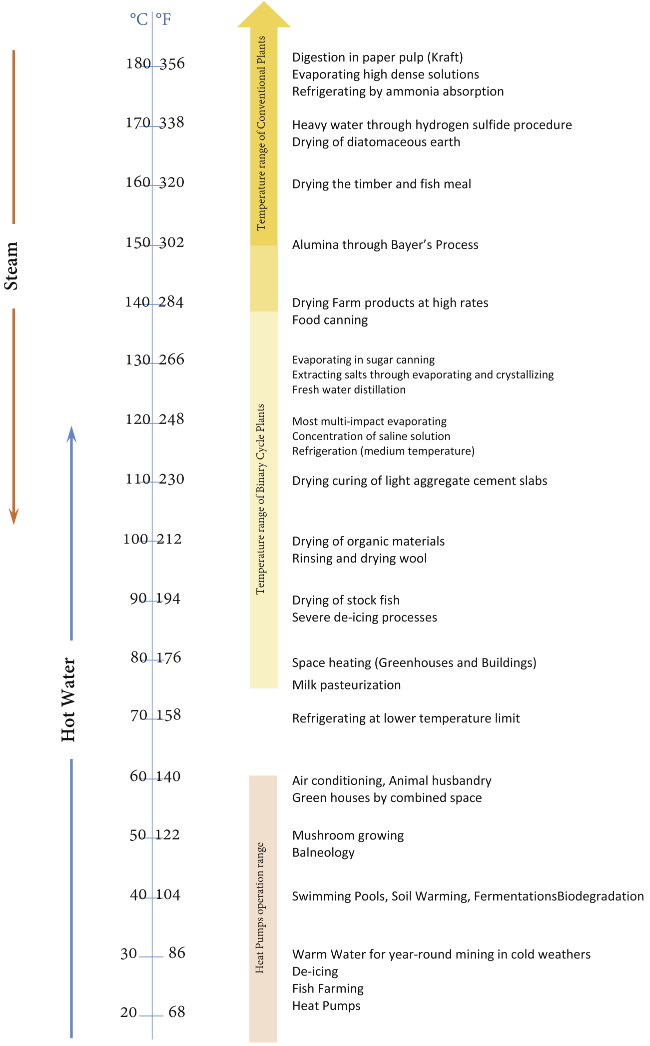

Fig. 2. Modified Lindal diagram (GNS Science Group).

Using geothermal energy for buildings air conditioning has been vastly grown since the 1980s, by the introduction of heat pumps; which allow extracting and utilizing the heat from near-surface with the sources at low temperatures, such as the ground itself, shallow aquifers and ponds (Fig. 4). Although electricity is needed for operating the heat pumps, in favorable climate circumstances and also an optimized design, there will be a positive energy balance always (Dickson, Fanellib) (Fig. 5).

Recently heat pumps became very popular all over the world, especially in the USA, Germany, and Switzerland (Dickson, Fanellib). Tables 1–3 shows the global leaders of the direct use of geothermal energy (John and Boyd, 2016).

The five countries, which are the leaders of geothermal energy direct utilization, use 65.8% of the whole world capacity (John and Boyd, 2016).

Using heat pumps has been vastly grown during the past years. The largest share of geothermal direct usage belongs to geothermal heat pumps with 55.15% of total annual energy usage and 70.9% share of installed capacity in 2015 (John and Boyd, 2016). However, as the International Energy Agency's stated in the latest report on world energy outlook (Agency and International Energy, 2018) only 3% of EU energy demand building for heating is provided by heat pumps.

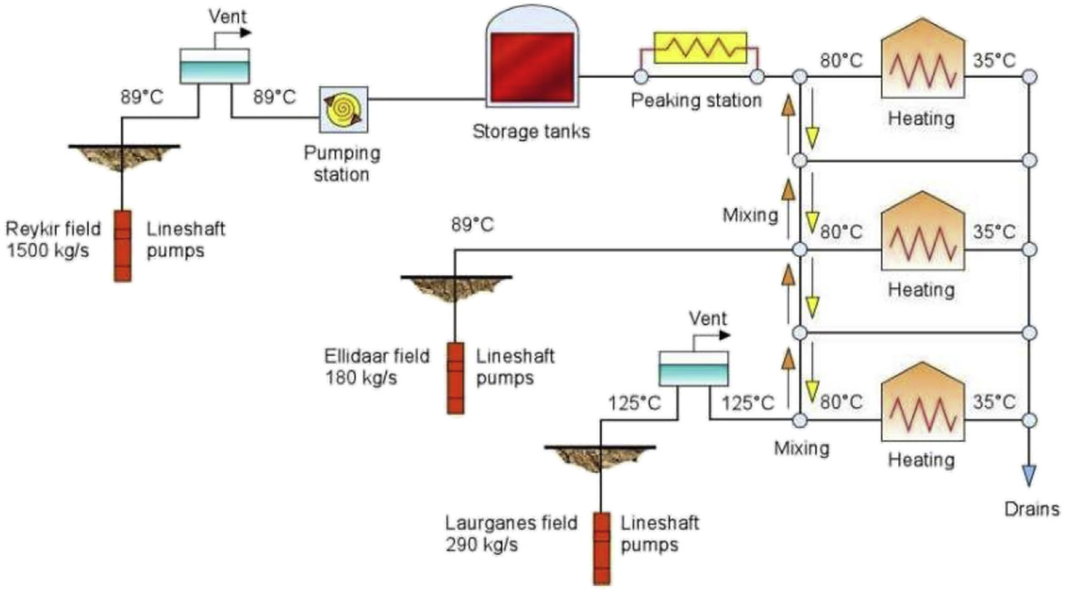

Fig. 3. The simplified flow diagram of a geothermal district heating (Gudmundsson, 1988).

ii. Electricity Generation

Geothermal primary energy can be used to generate electricity as well. Generating electricity is experiencing continuous growth worldwide. In 2011, Bertani forecasted that the installed capacity of geothermal power plants for generating electricity would be raised to 18,500 MWe by 2015 (Zarroukh and Moon, 2014). However according to an updated report released in 2015, worldwide geothermal installed capacity for electricity generation was 12,600 MWe, producing 73,549 GWh of energy in 2014 (Bertani, 2015). Fig. 6 shows the trend of geothermal electricity growth from 1950 to 2015 (2020 predicted) (Bertani, 2015).

During the past years several studies had been carried out to investigate the potential of geothermal energy production. Specially in Europe a recent studiy predicted of a rapid rise in geothermal applications by 2050 (Longa et al., 2020).

Fig. 7 shows the potential of power generation by geothermal energy which are constrained to resources in depth below 2 km (Iceland and some other countries with volcanic activities have been excluded). On the other hand, direct heat utilizztion can be reached through depth lower than 2 km (Longa et al., 2020).

Moya et al. (2018) has provided the latest development in geothermal industry. The aspects of the development in power plant technology and direct heat utilizations have been carried out in the study. Geothermal Utilization has been introduced as an alternative for current fossil feuls so the emissions can be decreased significantly through the coming years. Also direct heat utilizations could be used to increase the revenue of a geothermal project (Moya et al., 2018).

Nevertheless, despite the great benefits, various issues exist currently impeding a wider uptake of geothermal wells including the aggressive nature of geothermal fluids and high temperatures, the high costs of investment and maintenance of geothermal wells, as well as the high thermal strains on cement and tubular. Instead, the hydrothermal resources are partially available just in some geographical regions. The existing geothermal resources are mostly in the low-temperature class (less than 160 °C) (Fig. 8).

Regarding these challenges, this paper is mainly aimed at investigating well integrity issues related to the geothermal wells and establishing knowledge regarding transfer between geothermal energy and petroleum industry. Hence, it is tried to present the most common issues in geothermal well drilling operations and to introduce the potential for the future research areas.

2. Geothermal energy: subsurface

As stated earlier, geothermal energy potentially plays the main role in the energy sector of the world and the reduction of carbon dioxide footprint. Nevertheless, geothermal electricity has now a quite low share in comparison to other renewable energy sources (Fig. 9). It is not caused by the geothermal cost since on a Levelized scale it may even be cheaper than other renewables (Clauser and Ewert, 2018), however, the reason is the availability of hydrothermal reservoirs in the earth.

Instead, EGSs (mostly hot dry rocks) that are more costly compared to the usual hydrothermal resources based on USD/Mwh, exist almost accessible in all places on the earth and are able to offer clean energy for all for hundreds of years.

EGS includes a huge potential to generate power over 70 GWe by 2050. Though, further studies and developments are required for the feasibility of EGS technology. Recently, ENGINE a research group in Europe (The Enhanced Geothermal Innovative Network for Europe) including 35 R&D sub-groups, researches regarding EGS aimed at reducing drilling costs by 20–30%, exploration expenses of a geothermal project by 20%, and enhancing the efficiency of generation of electricity from the heat by 20% by 2020 to increment the popularity of EGS in Europe.

Today, completion operations and drilling research areas are more emphasized in geothermal projects where the costs may be reduced and efficiency significantly increased through good design.

2.1. Geothermal drilling

The operations in drilling a geothermal well has high similarities to the drilling operations in the petroleum industry. Nevertheless, based on numerous aspects, geothermal drilling is different making it more challenging and complicated in comparison to drilling the oil and gas wells. The kind of resource and the formation type are huge differences. The fissures and fractured hard volcanic rocks normally contain geothermal resources, however, sedimentary

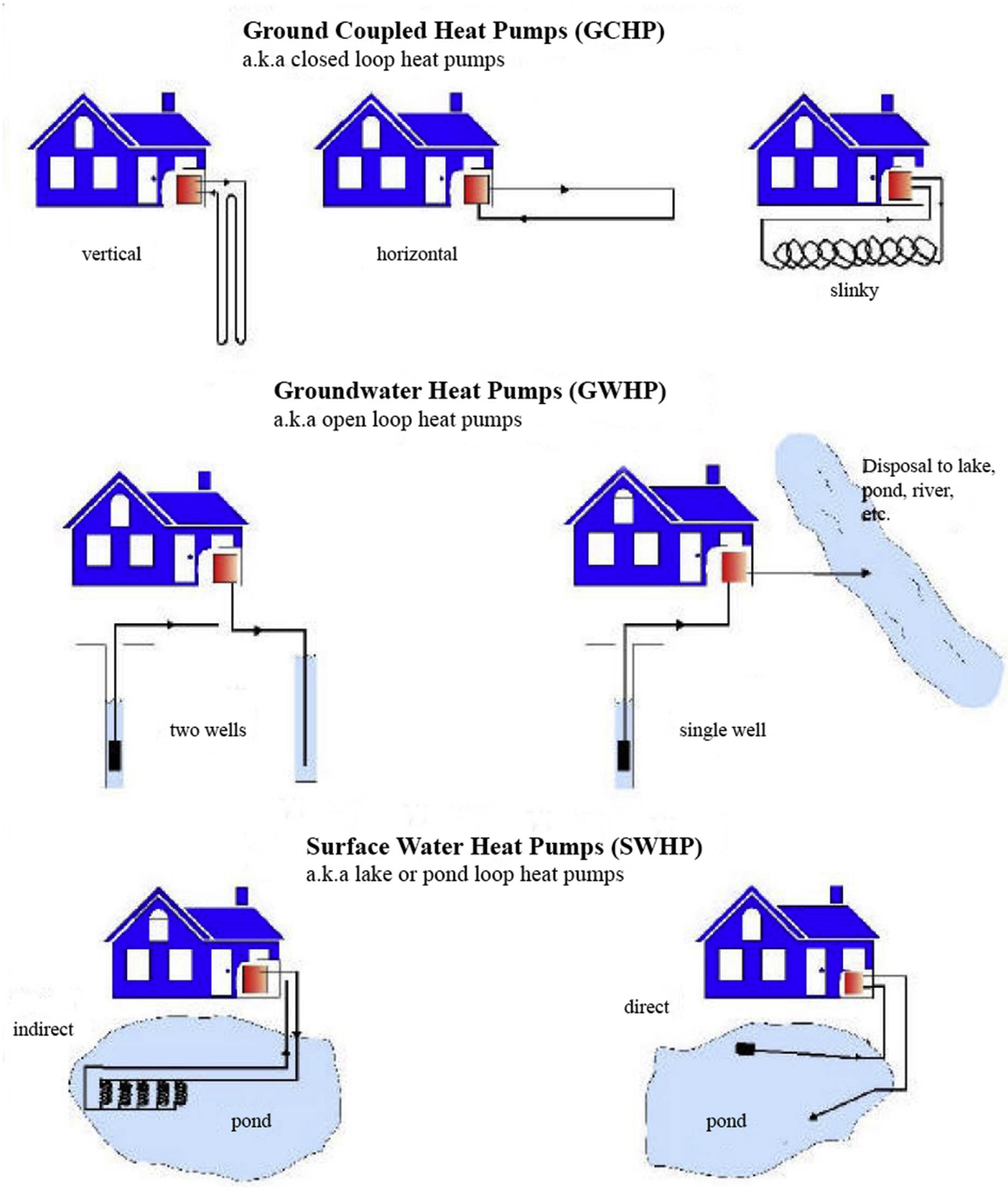

Fig. 4. A simplified ground source heat pumps (Dickson, Fanellib).

formations porous media includes oil and gas recourses. The petroleum and geothermal well drillings are different based on geological and physical features like rock types, reservoir pressure, temperature, casing, and well design, as well as the well completion program (Moya et al., 2018).

Today, completion operations and drilling research areas are more emphasized in geothermal projects where the costs may be reduced and efficiency significantly increased through good design. Over numerous decades, the cost of developing a geothermal field was estimated within 4.5 M USD-5.5 M USD per installed MW and 50% is spent approximately on wells drilling and completion (DiPippo, 2016). Here, the main issues are highlighted for a geothermal well drilling in this paper.

2.1.1. Circulation loss

Loss of circulation is the lost part of or, the whole drilling mud in severe circumstances in the drilled formation (Bugbee, 1953). The formations with high permeability including faulted, fractured, and joint formations are the zones potentially with the possible occurrence of loss of circulation. Normally, the circulation loss is

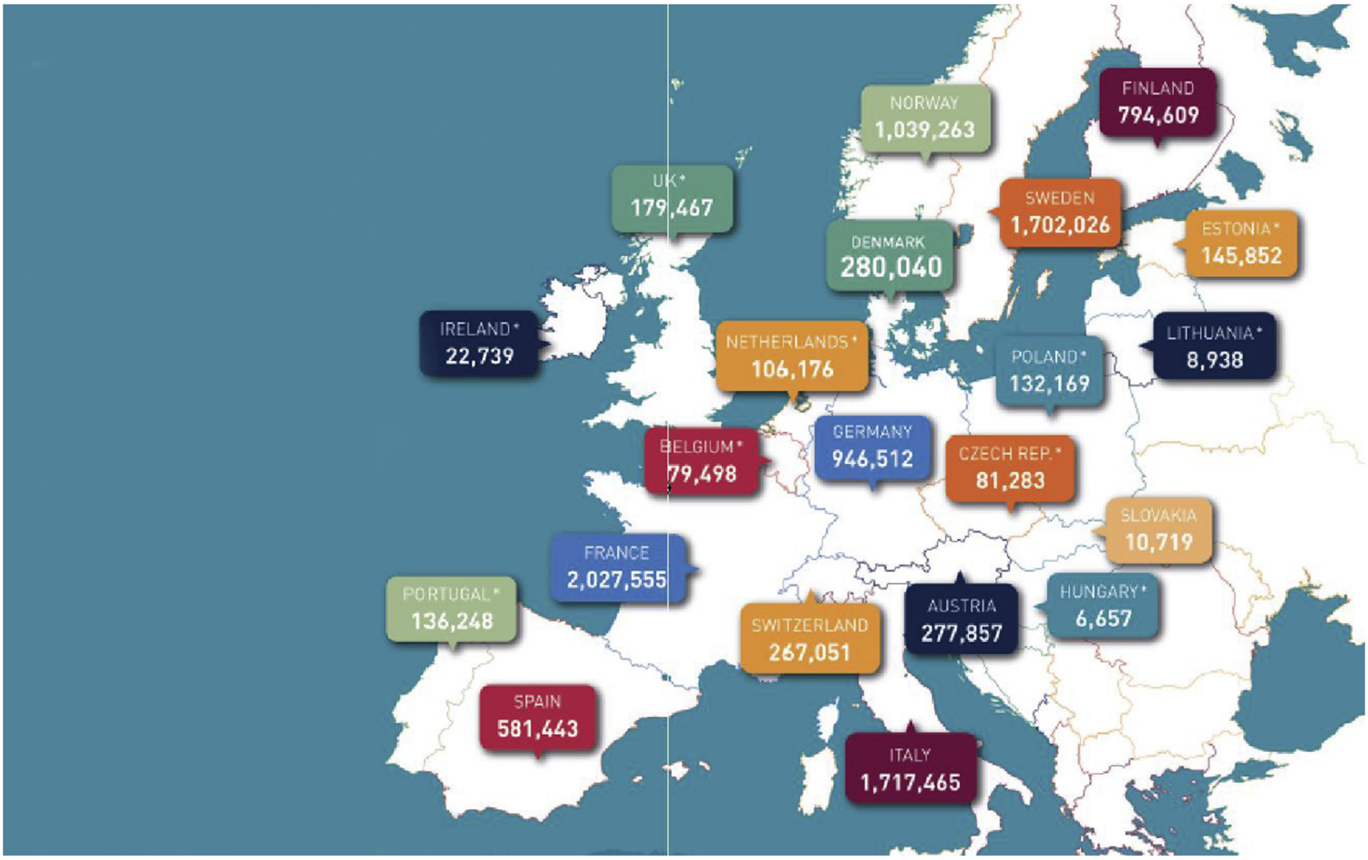

Fig. 5. Number of Heat Pumps installed in Europe Heat Pump Association (EHPA) members (Agency and International Energy, 2018).

Table 1
The leaders in direct utilization of geothermal energy in the world (such as heat pumps)-2015 (John and Boyd, 2016).

Country	MWt	TJ/year
China	17,870	174,352
USA	17,416	75,862
Sweden	5600	51,920
Turkey	2937	45,892
Germany	2849	26,717

Table 2
The leaders in direct use of geothermal energy based on population in the world (per 1000)-2015 (John and Boyd, 2016).

Country	MWt/population	TJ/year/population
Iceland	6.26	82.04
Sweden	0.57	5.30
Finland	0.28	3.29
Norway	0.25	1.61
Switzerland	0.22	–

Table 3
The leaders in direct use of geothermal energy in the world (excluding heat pumps)-2015 (John and Boyd, 2016).

MWt	TJ/year
China (6089)	China (74,041)
Turkey (2894)	Turkey (44,932)
Japan (2086)	Iceland (26,700)
Iceland (2035)	Japan (25,630)
India (986)	Hungary (9573)

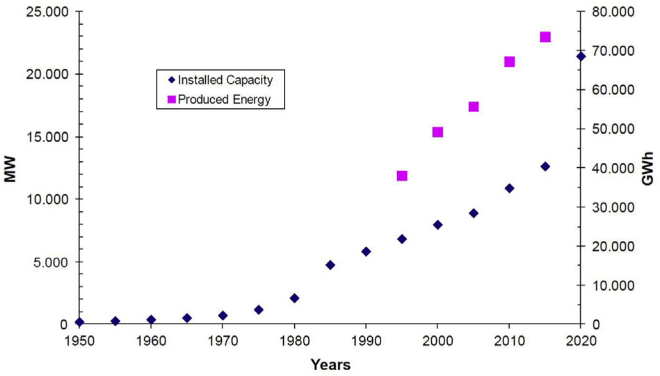

Fig. 6. Worldwide installed capacity and produced electricity by geothermal energy from 1950 to 2020 (Bertani, 2015).

expected in geothermal well drillings (Shryock, 1984).

Drilling fluid circulation lost is the main and oldest problem in a drilling operation directly affecting the drilling cost (Bugbee, 1953). It will increment the non-productive time resulting in the increased cost. In a study (Rehm et al., 2009), it was indicated that the circulation loss-related costs were around 10% of total non-productive time spent in the Gulf of Mexico within 1993–2003. Since drilling fluid and lost circulation substances are normally expensive (25–40% of overall drilling cost is related to the costs of drilling fluid (Lecolier et al., 2005)), the loss o these materials can significantly affect the costs (Lavrov, 2016). Moreover, it was reported that circulation loss costs are 10–20% of the overall drilling operation

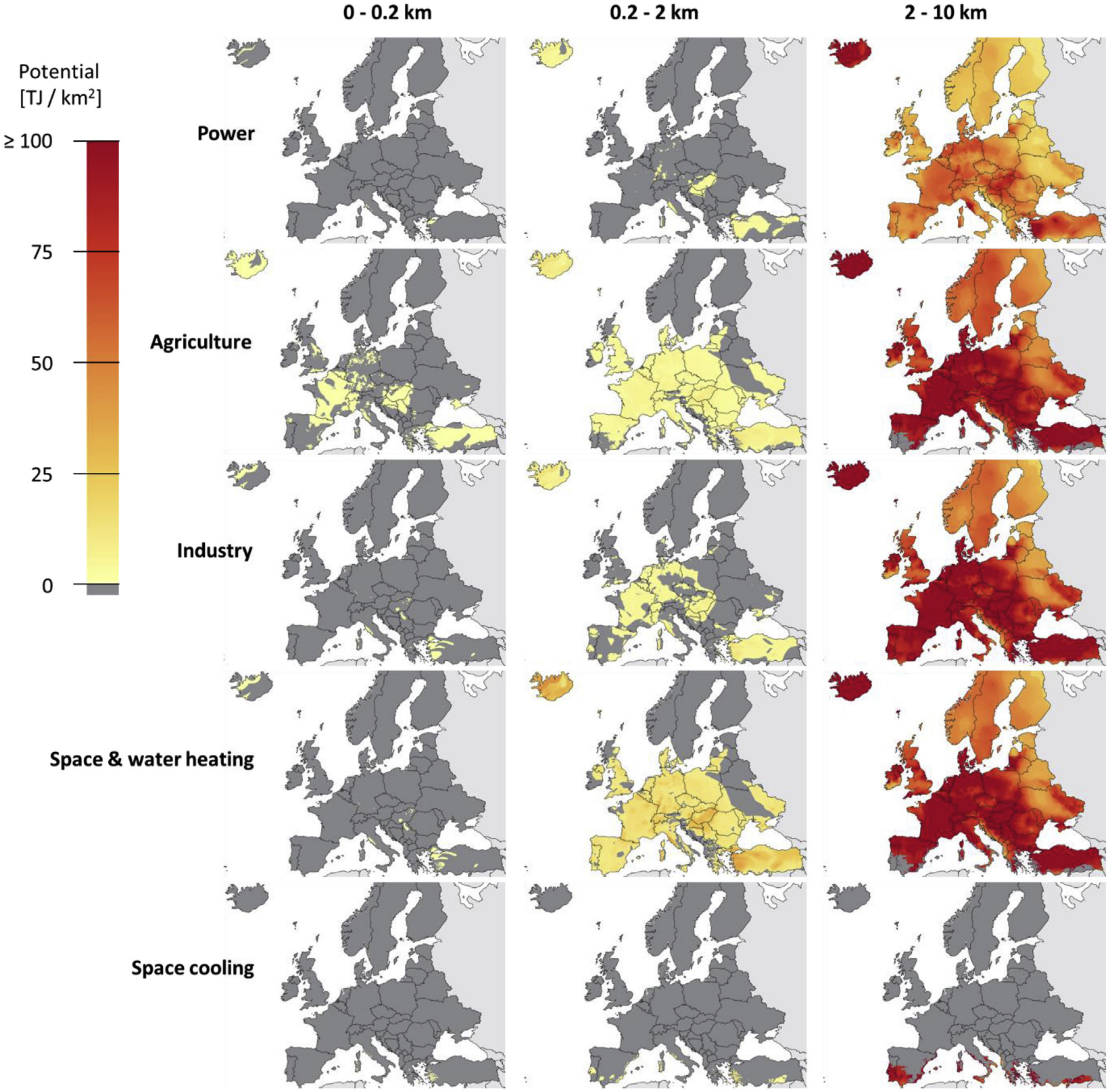

Fig. 7. Long-term economic potentials for various geothermal applications in Europe at three different depth ranges (Longa et al., 2020).

costs (Mansure et al., 2002). Based on a report (Finger and Blankenship, 2010), the circulation loss costs in the USA in geothermal drilling operations is approximately 10% of overall well costs and 20% for exploration wells. In the Hengill area in Iceland, 75% of drilled geothermal wells encountered the problems of circulation loss and wellbore collapse (Sverrir., 2014). These problems can lead to the poor cement job endangering the well integrity.

The circulation loss is a complex challenge requiring a multidisciplinary method like well design, mechanical analysis of rock, drilling fluid design such as lost circulation materials and loss prevention, and drilling hydraulics (Whitfill and Hemphil, 2003).

Fig. 10 represents a time breakdown of a sample well in Indonesia faced with a lost circulation problem. The entire time spent to fight the circulation loss problem was 194 h in that particular well, 30% of the overall operation time.

Goodman (1981) had interviewed petroleum and geothermal operators, drilling service consultants, and companies to evaluate the circulation loss issue and possible solutions to prevent it. The report indicates that implementing conventional petroleum industry methods may or may not overcome the lost circulation problem. Using lost circulation materials (LCM) is usually the first choice. Cement plugs and blind drilling can be implemented in severe low pressure-fractured formations. However, using cement plugs may not be successful either due to unknown downhole temperature to calculate the amount of retarder to be added to the slurry. In some geothermal operations, sodium silicate found to be effective to be pumped ahead of the cement slurry. Also, tie back string is recommended in geothermal drilling operations to overcome the lost circulation problem.

There are several studies investigating the proper cement to

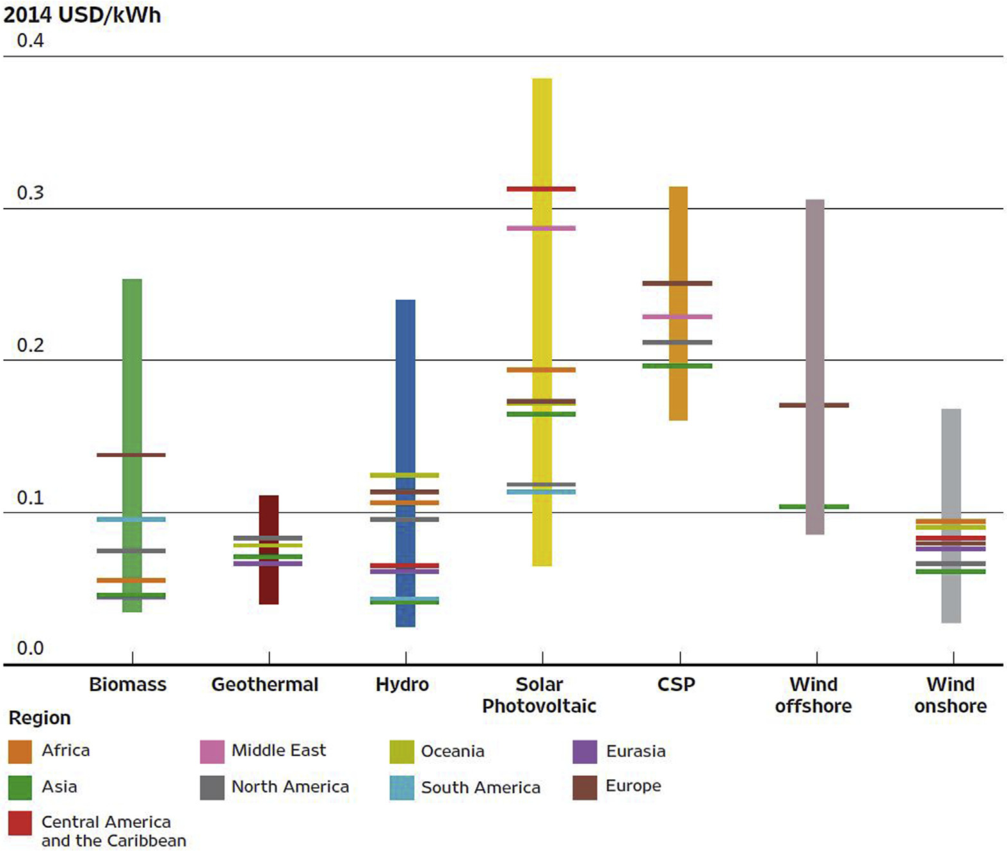

Fig. 8. Levelized cost of electricity cost range and reginal weithed average, in 2013–2014 (CSP: Concentrated Solar Power) (Taylor et al., 2015).

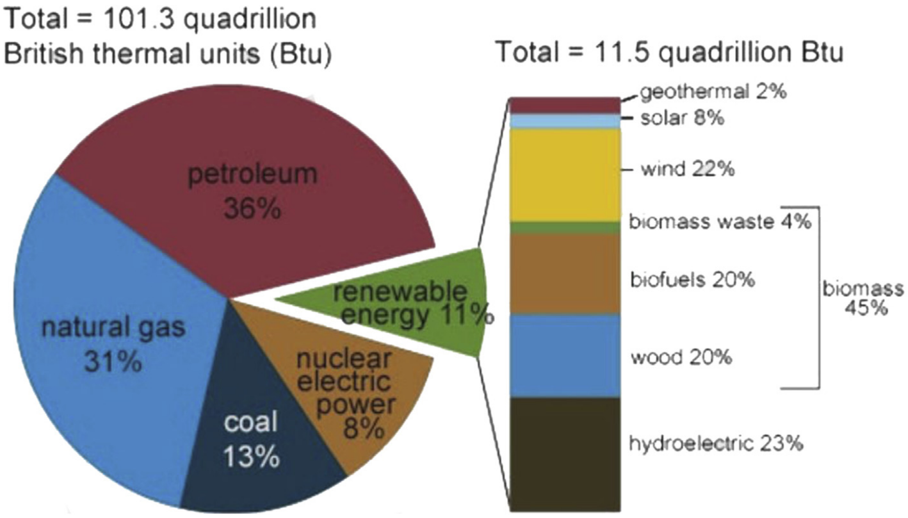

Fig. 9. The U.S. energy use by energy source, 2018 (Monthly Energy Review. s., 2018).

plug the loss in geothermal drilling conditions. A summary of the studies is given below in Table 4.

Several investigations were performed to investigate the potential of polymers to combat the lost circulation challenge. The following section is a summary of the studies investigated polymers as a potential solution that are reviewed in this paper.

Hashmat et al. (2017) studied the composition of polyacrylamide, phenol, and formaldehyde as a gel. It was successfully tested at room temperature and moderately high pressure. Mansour et al. (2017) introduced a novel lost circulation material of a thermoset shape memory polymer,[1] which activates when

---

[1] The shape memory polymer is able to change into a temporary shape and returns back to its original shape by stimulation by an external factor like temperature change or electromagnetic wave (125).

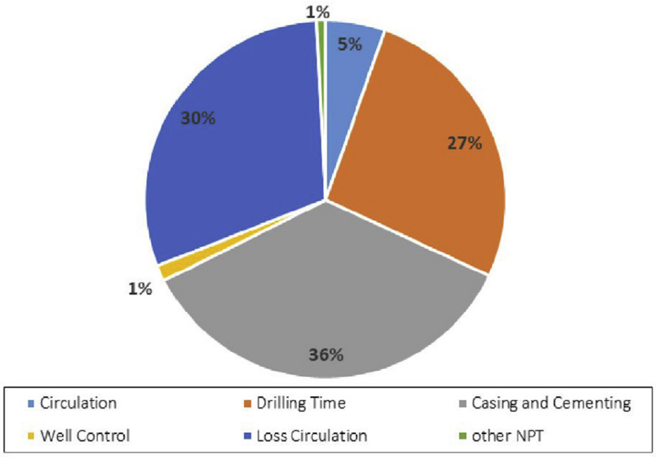

Fig. 10. The operation time, in a case study in Indonesia (Nugroho et al., 2017).

Table 4
Summary of papers which investigated proper cement plug.

Allan et al. (Allan and Kukacka, 1995)	
Reservoir type:	Geothermal
Temp. (°C):	100
Materials/Methods:	Calcium phosphate cement
Results:	Good compressive strength and low permeability of the slurry.
Mansure et al. (Mansure et al., 2002)	
Reservoir type:	Geothermal
Temp. (°C):	82
Materials/Methods:	Polyurethane grouting
Results:	Successfully sealed the loss zone by the material where conventional methods were difficult to implement.
Aadnoy et al. (Belayneh et al., 2007)	
Reservoir type:	Fractured
Temp. (°C):	–
Materials/Methods:	Proper mud design in fractured reservoirs
Results:	- Proposed a theoretical model of fractures describing mud loss physics; - Multiple additives do not necessarily have a positive effect; - Synergy between additives has to be investigated more, especially for geothermal wells.
Rickard et al. (Rickard et al., 2010)	
Reservoir type:	Geothermal
Temp. (°C):	320
Materials/Methods:	Micronized cellulose bridging material
Results:	Such materials helped to reduce the problems related to loss of circulation.
Miranda et al. (Miranda et al., 2017)	
Reservoir type:	–
Temp. (°C):	90
Materials/Methods:	Commercial bridging materials (granular, fibers, flakes) & hydrated bentonite pellets
Results:	See Table 5.
Hashamt et al. (Hashamt et al., 2016)	
Reservoir type:	–
Temp. (°C):	100–120
Materials/Methods:	A combination of polymeric systems
Results:	- An optimum concentration of polymer-crosslinker exists to obtain a stable and strong gel; - The gel strength will enhance by increasing aging time (6 h and 1 day) and temperature (100 °C and 120 °C).

exposed to loss zone temperature (Smart LCM). They conducted experiments to investigate the efficiency of the smart LCM in sealing the fractures with the activation temperature of 70 °C. Results showed that using such materials can seal the loss zone very effectively. Following this study, Mansour and Dahi (Mansour et al., 2018) introduced another smart LCM made of anionic shape memory polymer and also a numerical model to see the effect of particle and fracture size which can be a solution for lost circulation problem with the ability to seal big fractures and not plugging the drilling tools. Silva et al. (2017) also presented an algorithm modeling the loss of circulation in fractured formations, which can solve mathematical models to analyze possible solutions of differential and analytical equations for fluid flow, formation properties, fracture behavior, and drilling fluid rheology. With this info, one can determine the fracture real-time width to design drilling mud with proper weight and LCMs.

Although there are numerous studies investigating new materials performance in downhole conditions as some have been mentioned above, there still are not many studies in geothermal conditions.

In a petroleum drilling operation, if the loss of circulation could not be solved using lost circulation materials, usually cementing into the loss zone may be the solution. However, cementing the loss zone may not be the best solution in geothermal drilling operations, where usually several cement jobs are needed; which each would take up to 10–24 h (Shryock, 1984). So new methods and procedures need to be followed and documented when drilling into a loss zone with major fractures.

Mata and Veiga (2004) reported that cross-linked types of cement (CC) may be useful where conventional LCM could not overcome the lost circulation issue, which can be used up to 121 °C.

Mofunlewi and Okoto (2016) introduced a new-engineered spacer to be pumped before cement slurry where LSM does not solve the issue, to seal the zone with fractures or high permeability causing severe losses. The slurry contains hydrophobically modified polysaccharides which seal the fracture by forming a bridge at fractures. Fig. 11 shows the process of these micelles, which have hydrophilic heads and hydrophobic tails. Results showed that using this spacer could improve the cementing job quality by sealing the fractures and formation permeability to decrease the losses of circulation significantly. In the case of geothermal drillings where fractures and lost circulation is common, this might be a solution, however, the behavior in geothermal conditions have to be investigated.

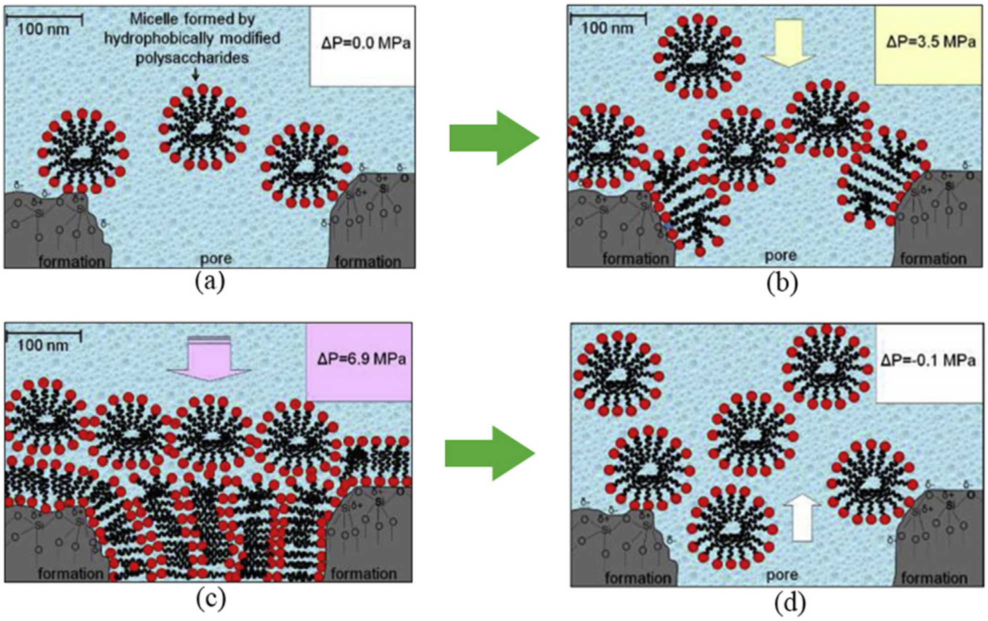

Fig. 11. Working mechanism of Sealbond Spacer: (a) The hydrophobically modified polysaccharides within the aqueous fluid from micelles. A dynamic equilibrium exists between adsorption at the formation and dissolution in the aqueous media. (b) Increasing differential pressure results in increasing number of micelles adsorb and realign along the porous formation. (c) At maximum differential pressure, the adsorbed micelles have turned into a film, completely sealing the pore. (d) When a flow forms in opposite direction easily returns the micelles into solution again (Bottiglieri et al., 2014).

In some geothermal drilling operations, the reverse circulation technique might be useful to overcome the loss of circulation cementing jobs. Moore et al. (2005) tested the reverse-circulation placement method in a deep well and a shallow geothermal well successfully for cementing a job where the loss of circulation was the issue. Lichang et al. (2006) also reported a successful application of reverse circulation drilling in geothermal drilling operations in China with lost circulation problems.

Controlled and managed pressure drilling (CPD/MPD) can be also a solution where lost circulation occurs. Sammat et al. (2012) described a successful application of CPD in a geothermal field in Germany where wells were suffering from lost circulation and stuck pipe issues. Formation damage significantly was reduced by the application of CPD. Singh et al. (2016) also reported implementing of MPD technique in Vietnam where lost circulation was a major problem in HPHT well cementing. They reported that MPD cementing in a closed-loop had been applied successfully in all wells drilled within the study.

There are several studies addressing different solutions for curing the lost circulation problem in drilling operations, but mostly suitable for normal conditions and very few studies investigated the behavior of such materials under severe geothermal conditions. More research and study in this area is needed.

2.1.2. Well cementing

This operation is aimed at creating an annular barrier in the annular space within wellbore and casing to struggle in definite environmental circumstances and holding the casing in position. It is also responsible to protect the casing from formation fluids (Ostroot and Shryock, 1964). To prevent casing expansion over production in geothermal wells, the casing needs to be completely cemented. In production phase of a geothermal well, where completion components are installed on, the casing's role becomes more critical, since it may lead to the vibration at the surface and even blowouts due to due to expansion of the fluid/steam flow (ew Advanced Method for, 1995).

The most critical issues for the geothermal include (Shryock, Smith; Salim and Amani, 2013):

- Circulation loss and thick filter cake probably reducing cement-formation bond strength;
- High temperature resulting in strength retrogression of the cement;
- Presence of corrosive components like CO_2.

Nevertheless, regarding durability, the cement stability at high temperatures leads to well integrity problems over the well life cycle (Ostroot and Shryock, 1964). The temperature is the most imperative element as a result of a robust impact on cement slurry setting time and its impacts on cement strength over the well's lifetime (Guerrero, 1998).

There exist numerous studies in the literature referring to cement behavior in different well conditions, however just a couple have discussed the geothermal high-temperature conditions and cement behavior in such severe conditions. Some of the cement compositions may show sufficient strength at the early stages of setting but will lose their strength after a while due to continuous exposure to high temperatures (Carter and Smith, 1958; Ludwig and Pence, 1956; Ostroot and Walker, 1961).

Proper cement composition for high-temperature conditions and cementing methods and equipment have been widely studied and promoted in the literature. Table 6 represents a summary of the papers reviewed in this study.

As reviewed above, numerous studies exist to address the problems related to the cementing operations and cement behavior itself; however, there are few studies on the impact of cement curing temperature, corrosive components, and thermal loads on final hardened cement. Moreover, the cement performance at high temperatures was rarely discussed (over 350 °C). The effect of rock type on cement performance and durability was not investigated much, though, few articles are available in this regard (Silva and Milestone, 2018).

Table 5
Lost Circulation Materials Performance at different severity levels.

Material	Severity Configuration			
	430 kD, 100 psi	90 kD, 100 psi	430 kD, 20 psi	90 kD, 20 psi
Pelletized Bentonite	✓	✓	✓	✓
Blast Furnace Slag Slurry	✓	✓	✓	✓
Polymeric and granular material	✗	✓	✓	✓
Proprietary Thixotropic slurry	✗	✗	✓	✓
Fibrous and granular material	✗	✗	✗	✓
Calcium Carbonate	✗	✗	✗	✗

2.1.3. *Casing*

The casing has a main role in the ultimate well cost. Therefore, selecting the suitable casing type (length, grade, and size) is very important based on the requirements and geological data (Capuano and DiPippo, 2016) (Table 9). The casing has numerous performances in a well including (Applied Drilling Engineer, 1986):

- Isolation of the well fluids from formation and formation fluids;
- Preventing of borehole collapse while drilling;
- Offering a clear pathway to the drilling fluid;
- Minimization of the damage to the subsurface environment;

Normally, in casing design, it is essential to clarify the surface and bottom hole location of the well (Applied Drilling Engineer, 1986). It is also essential to consider the number and sizes of casings/tubing, setting depth, and grades of each casing in the design. The following parameters are important in the geothermal well casing and need to be identified in the casing design (Capuano and DiPippo, 2016):

- Rock temperature;
- Resource kind (steam, liquid, or both) and temperature;
- The necessity of surface equipment or downhole;
- Preventing directional drilling if possible;
- Presence of corrosive components.

The following casing properties should be considered to meet the criteria of geothermal casing design:

- ***Grade***

Table 7 presents the American Petroleum Institute (API) grading system for the casing.

Table 8 also shows the list of non-API casing grades which are commonly used in the oil and gas industry.

In most of the geothermal environments, the presence of hydrogen sulfide (H_2S) is probable which will induce corrosion cracking issues to the casing. Only some of the casing grades are H_2S resistance, resulting in limiting the casings' designs for geothermal well drilling and completion operations (Capuano and DiPippo, 2016). Later in this paper proper casing selection for these conditions has been discussed.

- ***Tensile strength***[4]

The minimum tension force needed to damage the casing body permanently (F_{ten}) can be obtained from the following equation:

$$F_{ten} = \sigma_{yeild} * A_S \tag{1}$$

where σ_{yeild} is the minimum yield strength of the pipe in *psi*, and A_S is the cross-sectional area of pipe in in^2 (see Fig. 12). A most commonly used safety factor of 1.75 for tension forces should be considered.

So the final equation will be:

Always the greatest tension load is in the topmost casing; which can be calculated by multiplying the total length of casings hanging below by its weight per foot (buoyancy factor should not be considered in the calculations).

- ***Burst strength***[5]

Burst pressure is the minimum pressure needed to damage the pipe permanently by bursting. Fig. 13 shows a free body diagram of the casing section exposed to burst pressure, P_{br}.

If it is considered that there is no external pressure and axial loading, then the force F_1, resulting from the internal pressure of P_{br}, and acting on the projected area of LdS, can be obtained from the following equation:

$$F_1 = P_{br} L \frac{d}{2} d\theta \tag{3}$$

and the counterforce F_2, resulting from casing wall strength, σ_s, over the casing area of tL, will be obtained from the equation below:

$$F_2 = \sigma_s t L \frac{d\theta}{2} \tag{4}$$

After solving the above-mentioned equations for static condition ($F_1 - 2F_2 = 0$), P_{br} will be:

$$P_{br} = \frac{2\sigma_s t L}{d} \tag{5}$$

For the worst-case scenario with an allowable deviation of 87.5% of nominal casing wall thickness, the burst pressure in casings would be:

$$P_{br} = 0.875 \frac{2\sigma_{yield} t}{d_n} \tag{6}$$

where d_n is the nominal wall thickness of the casing.

The most commonly used safety factor in casing burst pressure calculations is 1.25.

- ***Collapse resistance***

Collapse occurs when the external pressures exceed the casing wall strength while it is empty (zero fluid pressure inside the casing). Collapse resistance of the casing is more related to geometry and casing wall thickness rather than casing grade (Applied Drilling Engineer, 1986). Usually, collapse resistance is the first design factor in casing design since it is the lowest design factor. Normally a safety factor of 1.15 is considered for collapse strength (Capuano and DiPippo, 2016).

Calculating collapse pressure is much more complicated. To see

Table 6
Reviewed papers with a focus on geothermal cementing related issues.

Gallus et al. (Gallus et al., 1979)	
Temp. (°C):	204–399
Material/method:	API class G and J + additives (silica flour with a concentration of 40–100 wt %; grinds and silica sand, 60–170 or 20–40 mesh, with a concentration of 40–106 wt %; expanding perlite with different amounts; fly ash, with and without silica)
Results:	API class G and class J cement with the addition of silica (40–80%) may be applicable to geothermal wells
Nelson et al. (Nelson et al., 1981a)	
Temp. (°C):	204
Material/method:	Different cement compositions
Results:	Using Portland cements of normal density (with the addition of silica flour) for geothermal well cementing operations at 204 °C of BHCT would be the best choice.
Nelson et al. (Nelson et al., 1981b)	
Temp. (°C):	204
Material/method:	Different cement compositions + calcium silicate hydrate
Results:	Truscottite and pectolite were identified as potential binders for geothermal conditions to increase the thermal and chemical degradation resistance.
Ostroot (Ostroot, 1964)	
Temp. (°C):	260–371
Material/method:	API Class A, E and G cement
Results:	- Using a strength stabilizing agent, such as silica flour, is necessary to achieve an acceptable compressive strength for cement compositions at all casings cement jobs; - API Class E cements are not necessary for geothermal conditions (high temperature).
Wang et al. (Wang et al., 2017)	
Temp. (°C):	150
Material/method:	Nano-silica sol (NSS)
Results:	- Nor low-dose neither high-dose NSS cannot enhance the cement's compressive strength at high temperatures; however, the addition of low dose may prevent strength retrogression at long curing times; - By adding 4–6% of NSS to a slurry of class G cement including 35% of silica flour, compressive strength will significantly improve.
Chow and Kalousek (Chow and Kalousek, 1976)	
Temp. (°C):	150–345
Material/method:	Calcium silicate cements
Results:	There is an optimum concentration for CaO, SiO_2 and Al_2O_3 mixture.
Sena Costa et al. (de Sena Leonardoet al, 2017)	
Temp. (°C):	38–300
Material/method:	Portland cement with different concentrations of silica flour (30, 35 and 40%) compared to a special Portland cement slurry (similar to type A) without silica addition
Results:	Using SiO_2 rich material is necessary for cement design of temperatures above 110 °C without which compressive strength due to retrogression decreases significantly. However, at low temperatures, silica flour mostly plays as a filler of the composition, which does not affect the mechanical strength positively.
Krakowiak et al. (Krakowiak et al. s., 2018)	
Temp. (°C):	200
Material/method:	API class G cement + silica (with a concentration higher than 35% with different solid volume fraction and particle size)
Results:	Matrix chemical composition, phase composition, porosity, pore size distribution was characterized as critical factors in cement job design in deep wells with high pressure and temperature.
Fridriksson (Fridriksson, 2017)	
Temp. (°C):	200
Material/method:	Class G cement + different additives
Results:	Adding acid-treated silicone rubber would increase the bond and compressive strength when exposed to high temperature.
Won et al. (Won et al., 2015)	
Material/method:	Physical properties (uniaxial compressive strength, profitability, thermal conductivity, bleeding potential) of G-class cement
Results:	- To obtain acceptable groutability, the water-cement ratio should be very high which will reduce the structural strength of the cement accordingly; - The thermal conductivity of G-type cement will decrease by increasing the water/cement ratio at 20 °C and 50 °C, which may reduce heat loss during production or injection operations.
Sugama (Sugama, 2006)	
Temp. (°C):	200–300
Material/method:	Sodium silicate-activated slag (SSAS) cement at H_2SO_4 and CO_2 rich environment
Results:	- At 300 °C, an unwanted porous microstructure was created by further growth of well-formed tobermorite and xonotlite crystals generated leading to the retrogression of strength and improving the water permeability; - A 20 wt% sodium silicate solution (Na2O/SiO2 mol. ratio of 3.22) was used as the alkali activator, to autoclave the SSAS cements at temperatures higher than 200 °C exhibited a minimum water permeability of less than 3.0 x 10-5 darcy and exceptional compressive strength of more than 80 MPa.
Hole (Hole, 2008)	
Material/method:	Comparing cementing techniques, material, and equipment in the petroleum industry and geothermal operations.
Results:	- API Class A or G cements with appropriate additives are commonly used in geothermal applications; - Class G cement with the proper additive of silica flour (up to 40%) would provide an acceptable strength against retrogression of cement (not appropriate in CO_2 rich environment); - A mixture of Portland Class A cement blended with blast-furnace slag in the ratio of 70:30 provides a high corrosion resistant cement.
Ravi et al. (Ravi et al., 2008)	
Material/method:	Primary cement operation in Indonesia
Results:	- Cause of cement job failure was: a) structural failure of the usual cement sheath, b) inefficient hole cleaning of drilling fluid and cement slurry placement and/or c) poor cutting transportation during the hole cleaning operation; - A new elastic cement system was designed and used combined with Industry-recognized best practices for displacement and hole cleaning to overcome the integrity issues for future wells.

(*continued on next page*)

Table 6 (*continued*)

Gallus et al. (Gallus et al., 1979)	
Rickard et al. (Rickard et al., 2012)	
Material/method:	Secondary cementation method
Results:	Top squeeze and top fill methods might be an acceptable solution in geothermal well cementing operations.
Berard et al. (Berard et al., 2009)	
Temp. (°C):	288
Material/method:	Foamed cement
Results:	Using calcium aluminate phosphate cement (CaP) can be resistant in conditions of high carbonic acid ratio. Additionally to obtain a lower density one could add nitrogen or air to the slurry which may be useful to reduce the risk of loss of circulation.
Santra et al. (Santra et al., 2009)	
Temp. (°C):	204
Material/method:	Magnesium-based Sorel cement slurries
Results:	- A new retarder is introduced to create the possibility of pumping Sorel cement based slurries at a downhole temperature of 204 °C; - No appreciable strength retrogression has been observed
Omosebi et al. (Omosebi et al., 2015)	
Temp. (°C):	<221 °C
Material/method:	Temperature effect on cement compressive strength in an acidic environment of high CO_2 gas concentration (up to 100%)
Results:	- Temperature plays a major role in dynamic cement degradation in an acidic environment; - Maximum degradation was observed to take place at temperatures between 107 °C and 177 °C.
Philippscopoulos and Berndt (Philippacopoulos and Berndt, 2002)	
Material/method:	Structural performance of the cement by calculating the cement response to pressure and temperature loads
Results:	A model-based design should be developed with a focus on the structural response of geothermal wells to different loads.
Sugama et al. (Sugama et al., 2012a)	
Material/method:	Cement composition of Class F fly ash and sodium silicate under thermal shock
Results:	- Cement sample was autoclaved at 200 °C then heated up to 500 °C by air for 24 h and then continuously immersed in 25 °C water; - Type G cement with and without Type F fly ash and quartz flour was failed and generated multiple cracks.
Sugama et al. (Sugama et al., 2012b)	
Temp. (°C):	200
Material/method:	Corrosion-resistance of modified cement mixture for carbon steels by adding foaming agent and acrylic emulsion as a corrosion inhibitor
Results:	An optimum concentration of additives is introduced to achieve a desirable slurry density lower than $1.3g/cm^3$, compressive strength higher than 500 psi, and brine caused corrosion rate below 70 mpy of CS.
Pyatina et al. (Pyatina et al., 2016)	
Temp. (°C):	270
Material/method:	Self-repairing performance of Thermal Shock Resistant cement (TSRC) and Ordinary Portland cement with SiO_2 blend (OPC)
Results:	Although OPC showed a higher compressive strength, the recoveries for TSRC was much higher (above 80% while OPC recovery was above 50%).
Pyatina and Sugama (Pyatina and Sugama, 2016)	
Temp. (°C):	90
Material/method:	Calcium Aluminate cement/Fly ash F blends in an acidic environment
Results:	- 18 days of sulfuric acid exposures at 90 °C to all samples (hydrated for 24 h at 300 °C) caused weight and diameter loss in TSRC; - Class G/silica blend gained more mass and increased diameter owing to the creation of a gypsum layer.
Vidal et al. (Vidal et al., 2018)	
Temp. (°C):	300
Material/method:	Effect of adding rice husk ash (RHA) instead of silica flour to cement compositions
Results:	- RHA as an anti-retrogression additive to cement slurry; - Using class G cement with 40% of RHA cured at 300 °C resulted in an increment in compressive strength of the composition by 11%.
Paiva et al. (Paiva et al., 2018)	
Material/method:	Cement composition with geo-polymers
Results:	A formulation with a metakaolin-potassium basis with the addition of microsilica, retarder, and mineral fiber was designed which resulted in an increase in tensile strength, higher thermal durability, and accordingly improving mechanical performance in high temperatures.
Da Silva et al. (da Silva et al., 2018)	
Temp. (°C):	300
Material/method:	Effect of polyurethane addition on thermomechanical features of Portland class A cement
Results:	Improved casing and cement sheath thermal mismatch.
Teodoriu et al. (Teodoriu et al., 2013)	
Material/method:	Cements exposed to cyclic loading conditions
Results:	A stress analysis presented using an analytical method and finite element solution to introduce a new cement specimen that is suitable for HPHT conditions.
Shaughnessy and Helweg (Shaughnessy and Helweg, 2002)	
Temp. (°C):	204
Results:	Optimized cementing method and procedure.

more details regarding collapse pressure calculation refer to (Applied Drilling Engineer, 1986).

- ***Casing weight (lbm/foot)***

Casing weight can be calculated by multiplying casing length by casing weight per foot which are available in API tables for each casing grade.

Besides the pre-mentioned criteria for casing design, the increased temperature is the main role player in geothermal drilling operations. A portion of the strength of steel pipes is lost at higher temperatures. For higher grades of casings, this loss is further even (Finger and Blankenship, 2010). For instance, by increasing the temperature from 25 °C to 371 °C, a reduction occurs from 632 MPa to 484 MPa in the yield strength of an L-80 grade casing. However, at the same temperature range, a yield strength in the K-55 casing will reduce from 388 MPa to 359 MPa (Snyder, 1979). The yield strengths of various casing grades as a function of temperature are represented in Fig. 14 (Larri, 1997).

It is important to take into account the presence of corrosive components in the geothermal project. CO_2 and H_2S are mainly present in the geothermal reservoirs. Hence, selecting the materials

Table 7
API casing grades (Applied Drilling Engineer, 1986).

API Grade	Yield stress (psi)		minimum ultimate tensile strength (psi)	minimum elongation (%)
	Min	Max		
J-55	55,000	80,000	75,000	24.0
H-40	40,000	80,000	60,000	29.5
C-75	75,000	90,000	95,000	19.5
K-55	55,000	80,000	95,000	19.5
N-80	80,000	110,000	100,000	18.5
L-80	80,000	95,000	95,000	19.5
P-110	110,000	140,000	125,000	15.0
C-90	90,000	105,000	100,000	18.5
C-95	95,000	110,000	105,000	18.0

Table 8
Common non-API casing grades (Applied Drilling Engineer, 1986).

Non-API Grade	Manufacturer	Yield stress (psi)		Min ultimate tensile strength (psi)	Min elongation (%)
		min	Max		
S-80	Lone Star Steel	75,000[a] 55,000[b]	– –	75,000	20.0
Mod. N-80	Mannesmann Tube Co.	80,000	95,000	100,000	24.0
C-90	Mannesmann Tube Co.	90,000	105,000	120,000	26.0
SS-95	Lone Star Steel	95,000[c] 75,000[d]	– –	95,000	18.0
S00-95	Mannesmann Tube Co.	95,000	110,000	110,000	20.0
S-95	Lone Star Steel	95,000[c] 92,000[d]	– –	110,000	16.0
S00-125	Mannesmann Tube Co.	125,000	150,000	135,000	18.0
S00-140	Mannesmann Tube Co.	140,000	165,000	150,000	17.0
S00-155	Mannesmann Tube Co.	155,000	180,000	165,000	20.0
V-150	U.S. Steel	150,000	180,000	160,000	14.0

[a] Circumferential.
[b] Longitudinal.
[c] The formulas taken from (Applied Drilling Engineer, 1986).
[d] The formulas taken from (Applied Drilling Engineer, 1986).

Table 9
Cost breakdown for a reference geothermal well.

Items		Time		Material		Total	
		$	%	$	%	$	%
Site & Rig movement						490,000	11.3
Section 0	0–90 m	219,048	69.2	97,648	30.8	316,696	7.3
Section 1	90–300 m	636,031	79.5	163,417	20.5	797,448	18.5
Section 2	300–800 m	633,154	60.7	410,379	39.3	1,043,533	24.2
Section 3	800–2235 m	1,202,106	72.0	468,628	28.0	1,670,734	38.7
						4,318,411	100

should be in a way to survive in such circumstances for the well's expected lifetime. CO_2 corrosion in the Imperial Valley of California had the responsibility to corrosion rate of 3 mm of the casing yearly leading to the plugging the well followed by 10–12 years that is much less than estimated (Finger and Blankenship, 2010). Most of the wells in the Imperial Valley of California were now retrofitted or completed with titanium casing to overcome the issue. Although the result was satisfactory, it enforced a very high investment expense (around 3000 USD per 1 m of casing) (Finger and Blankenship, 2010).

Snyder (1979) has discussed the casing failure modes in shallow to moderate geothermal wells with temperatures varying from 148 °C to 343 °C. Following issues were observed to be the most common problems for casings:

o Strength loss due to temperature elevation;
o Mechanical wear of casing inner side;
o Buckling due to thermal stress and pure cementing job;
o Corrosion (internal and external) and scaling.

Chiotis and Vrellis (1995) presented the failures and issues observed in deep geothermal wells over 15 years in Greece. The reservoir had a temperature of 300 °C with high salinity. Following failures were observed in the wells:

o Well head damage due to thermal expansion and poor cementing of the casing;
o Decoupled casing joints due to thermal stress;
o Buckling of the casing at some interval in well;
o Leakage in an abandoned well after 18 years due to casing corrosion.

Thermal stress during the production and cooling of the well was mostly responsible in these cases. However, these could be avoided by proper cementing, slow preheating the well before production, and good casing design. Chiotis and Vrellis proposed a

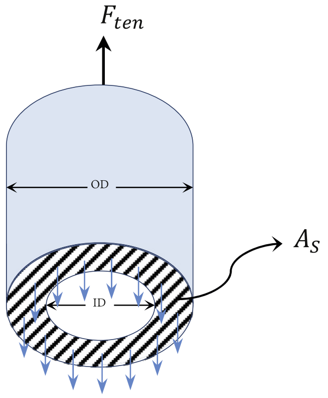

Fig. 12. Tensional force balance on casing body.

$$F_{ten} = \frac{\pi}{4}\sigma_{yeild} * [OD^2 - ID^2] \tag{2}$$

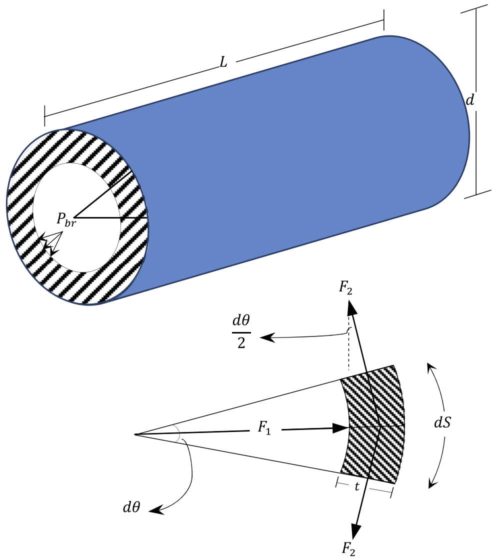

Fig. 13. Free body diagram of casing wall burst.

neutral temperature factor for casing design, which would ensure that the selected casing would not face with plastic deformation during the well life.

Southon (2005) studied the different failure modes in the casing with a specific focus on the expansion of the trapped fluid in the casing-to-casing annulus. It was indicated that using a tie-back liner might eliminate the issue; however, the tieback system itself may implement other challenges. The study stated that implementing the construction and completion techniques properly will most probably reduce the chance of such issues.

Teodorio and Falcone (Comparing completion desi, 2009) presented an experimental and theoretical model for investigation of low-cycle fatigue (LCF) resistance of an N-80 grade casing with a diameter of 18 5/8 in with buttress thread connection. The results indicate that in a geothermal environment, under severe loads, the LCF resistance of buttress connections in the casing could be very low (10 cycles). However, the temperature variation effect on other casing connection types and grades were not investigated in this study.

Torres (2014) discussed how to consider induced loads due to thermal cycling in geothermal wells. He also investigated the casing failure mechanisms by actual and numerical tests. Results showed that casing collapse by the expansion of trapped water due to poor cement job is the most common issue in tieback strings. Also in shallow sections, failures in casing connections and collapse of the casing itself due to the same issue occurred. This issue can be avoided by effectively placing the cement and selecting proper casing centralizers and grades. Liu et al. (2015) also indicated that integrated casing stress analysis with thermally induced stresses provides a perfect casing mechanical analysis.

Kaldal et al. (2015) studied the wellhead equipment displacement due to thermal stresses using finite element modeling. The model was validated by data of five different geothermal wells in Iceland. The model can be used further to study the structural analysis of casings exposed to different loads. Using the model, Kaldal et al. (2016) studied the structure of casing in deep geothermal well in Iceland. The results indicated that the thermal stress of cycling has the most effect on the production casing. However, changes in casing thickness and stiffness impose additional stress and strain on neighboring casings.

Teodoriu (2015) described casing failure models. The study listed the most issues resulting in casing failure as follows:

- Failure of cement exposed to cyclic loads;
- Failure of casing material exposed to cyclic loads;
- Local bucking in casing connections;
- Corrosion.

- ***Corrosion***

Prior to drilling the deep production wells, the geothermal fluids' nature is normally not known (Nogara and Zarrouk, 2018). The nature of the geothermal fluid is a challenge for the geothermal industry, which may usually include dissolved CO_2 and H_2S, leading to the corrosion in surface and wells facilities (Gunnlaugsson et al., 2014) (Ragnarsdottir et al., 2018). At downhole circumstances, the corrosion rate is usually worse than the well sections close to the surface (Treseder and Wieland, 1977). In geothermal drilling, the issues related to the drill-string corrosion or the nature of the casing are typically the same as the sour oil/gas drilling (Ellis et al., 1983). Pitting, wear, corrosion fatigue, and erosion are the main problems (Fig. 15). The strength of the pipes is reduced by these corrosion-related issues. In geothermal circumstances, it becomes worse owing to the high temperature and typically the existence of H_2S (Ellis et al., 1983).

Non-metallic casings were investigated for low to intermediate geothermal wells by the National Water Well Association of the US. All the suggested substituents were inert to the corrosive components within geothermal fluids, although their temperature resistance and mechanical strength are lower compared to the steel casings (Ellis et al., 1983) (ASSOCIATION and NATIONAL WATER WELL, 1979).

Another experimental study had been carried out on industrial drill pipes by Bareteri et al. (Barteri et al., 1996) to define selection criteria of steel selection in geothermal environments. Their results showed that the steel cleanliness and mechanical strength of pipes necessarily do not affect stress corrosion sensitivity in simulated geothermal conditions. All of the pipes that were studied, were subjected to stress corrosion cracking in simulated geothermal sour conditions. They showed that adding lime to the drilling fluid could be a very effective solution to reduce the environmental assisted cracking in geothermal conditions.

Thomas (Titanium in the geotherma, 2003) proposed using titanium alloys (with molybdenum, palladium, or ruthenium) in the geothermal industry can be a solution for Sulphur oxide corrosion

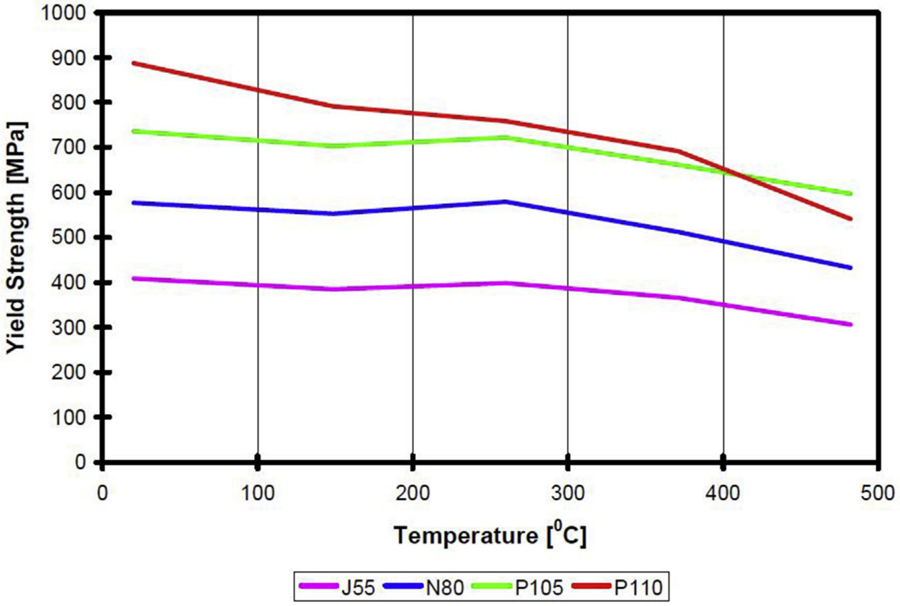

Fig. 14. The change in casing yield strength by temperature (Larri, 1997).

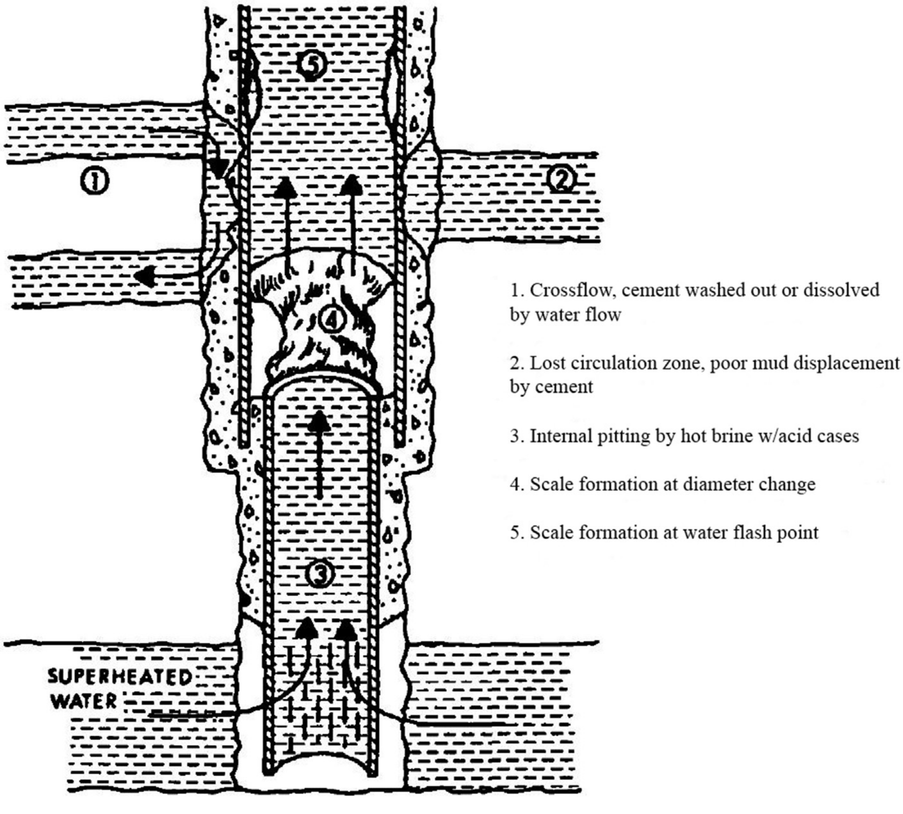

Fig. 15. Corrosion and scaling problem in geothermal wells (Snyder, 1979).

even in high temperatures (260 °C). An application of such material (casing grade 29) in Salton sea, USA, enabled the development of a highly corrosive brine from a geothermal resource. The cost for such casings may be very high and newer technologies in cost reduction of such pipes need to be applied. In this case, the technology may even allow us to inject the seawater into depleted aquifers to produce steam from hot dry rock resources.

Babler et al. (2009) studied the corrosion resistance of eight different casings (carbon steel, highly alloyed stainless steel, titanium-based alloy, and nickel-based alloy; 2 of each) with exposure to geothermal fluid. Based on the results, a recommendation was given for material selection for future geothermal sites. Accordingly, in the presence of nitrogen saturated fluid with a temperature of 150 °C, results showed that nickel-based and

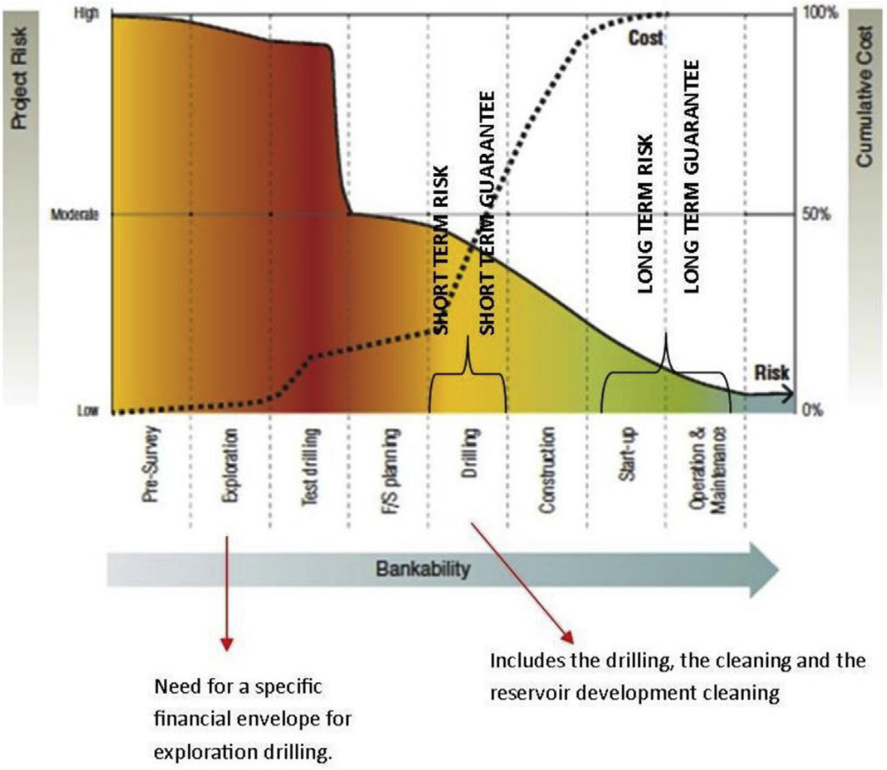

Fig. 16. Risk and Investment trend at geothermal projects.

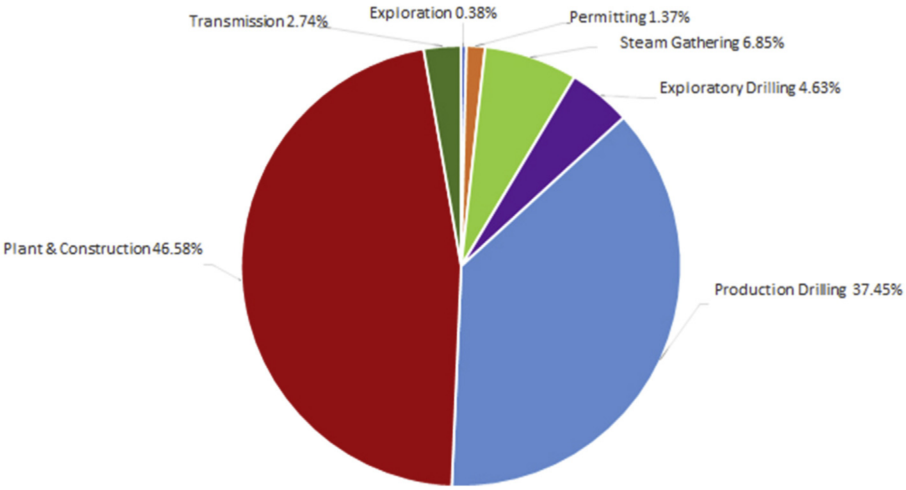

Fig. 17. Estimated Development cost for a geothermal power plant (50 MWe) (Bronicki and Meyers, 2017).

titanium-based alloys are suitable for such conditions and stainless steels are also resistant but with limitations. Where carbon steels proved to not be suitable.

Karlsdottir et al. (Karlsdottir and Thorbjornsson, 2012) investigated a corroded casing (grade K-55 and L-53) in the Krafla geothermal site located in Iceland. The study revealed the fact that the liner failed due to hydrogen embrittlement. Results showed that the maximum corrosion took place in a transition zone, where the hot steam containing H_2S, CO_2 and HCL meets a colder steam/water in a certain depth (1600 m) creates a very corrosive environment with a high concentration of HCL. The solution could be replacing these transition zones with materials resistant to corrosion as well as sealing the colder fluid coming into well.

Numerous other studies exist focusing on selecting the appropriate material for geothermal systems that mainly lead to the use of nickel-based alloys and titanium-based alloys in some cases. Nevertheless, using such substances is the high cost. The ultimate cost may be reduced by the technology developments as well as the optimal usage of such casings.

3. Time & cost analysis

Geothermal energy is a renewable source of energy found around the globe. However, due to some constraints, which mainly

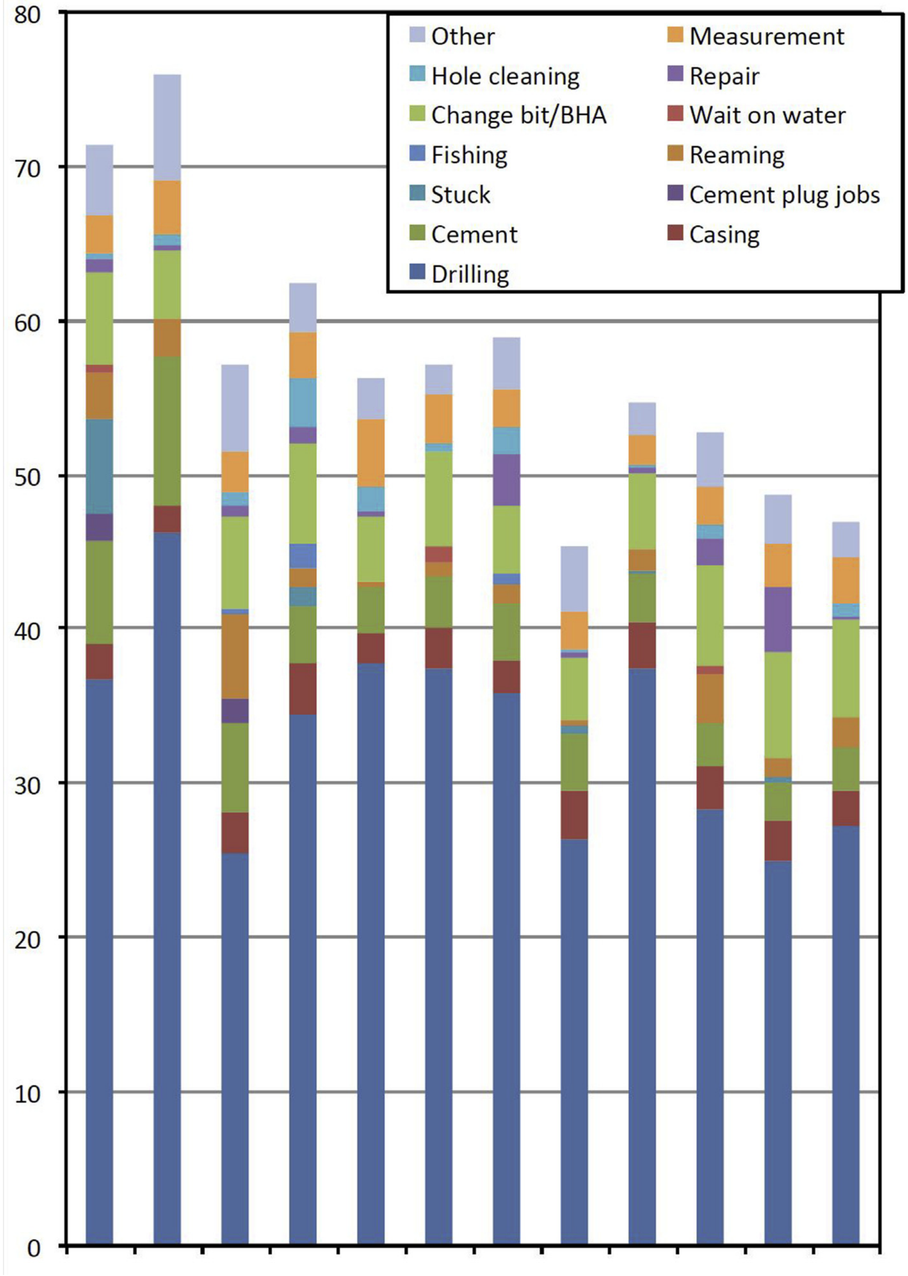

Fig. 18. Time analysis of different drilling activities, Case study in Kenya.

high upfront costs and risk, has not been much developed and widely spread compared to other renewables for electricity generation (GEO ELEC deliverable no 3.2, 2013) (Fig. 16).

Fig. 17 shows a breakdown of capital expenses for a geothermal project (Bronicki and Meyers, 2017). As shown in the figure, about 43% of the capital cost is related to exploration and drilling operations. So decreasing these costs as a major role player of deep geothermal projects can significantly improve the geothermal energy role in the energy section in the future.

Cost-effective drilling, by the possibility of cutting down the drilling and completion costs to develop new well construction solutions, is essential for economic utilization of deep geothermal resources (Reinicke and Ostermeyer, 2015).

Achieving a considerable reduction in these costs is only possible by using new and innovative methods for the construction of a well. Cutting drilling costs can be achieved for example by improving drilling methods (especially on rock destruction), new drilling equipment, and new well construction solutions (Reinicke and Ostermeyer, 2015).

Because the nature of the drilling market is competitive, thus confidential, there is not much data published on the breakdown of a geothermal drilling operation cost (106). However, a few data published for some case studies as shows a breakdown of cost for a reference well with a large diameter with a depth of 2235 m, which was studied in Nesjavellir field in the Hengill Geothermal Area, Reykjavik, Iceland (107). The estimation for this reference well was determined in terms of the number of working days for each section of the well.

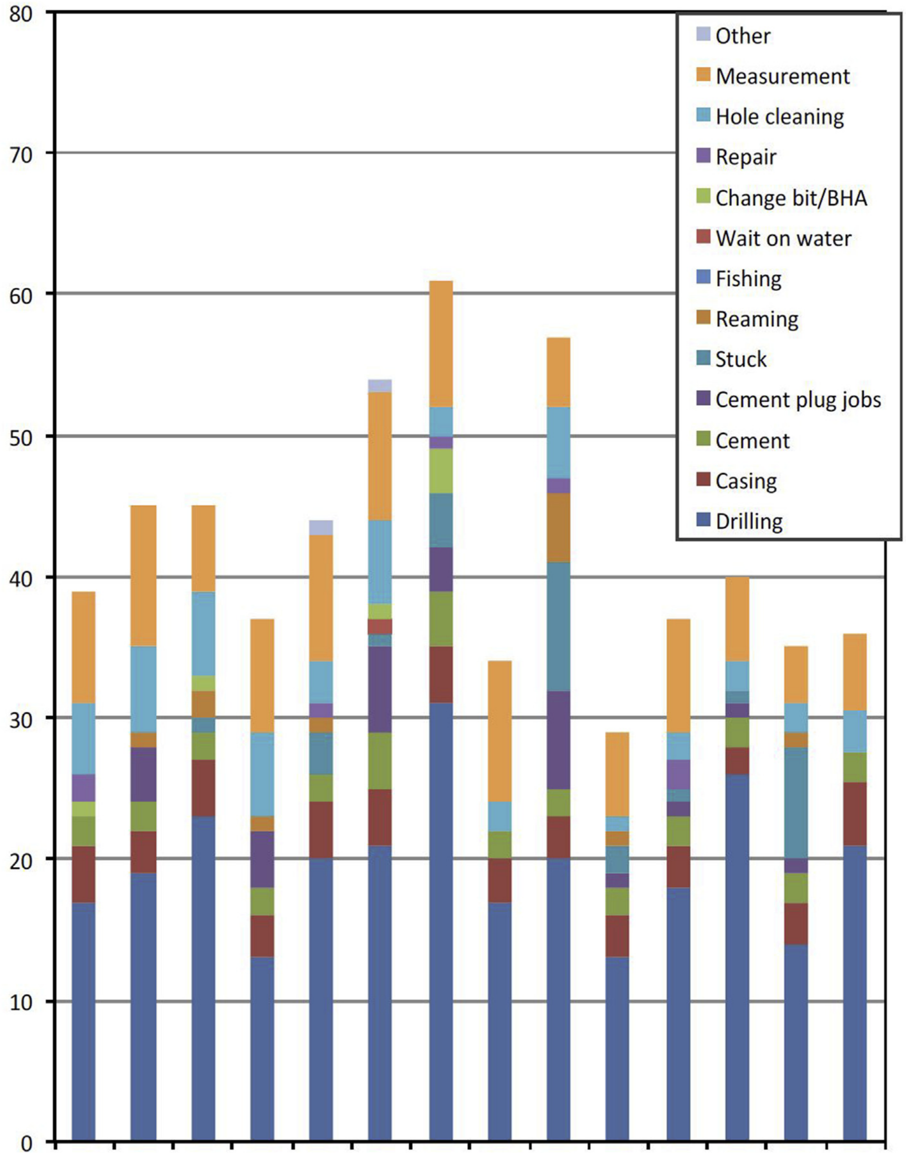

Fig. 19. Time analysis of different drilling activities, Case study in Iceland.

Fig. 18 and Fig. 19 also show the time analysis of two regular diameter wells in Iceland and Kenya (Ong'au, 2012). Table 10 also indicates the percentage of the productive time for each part of well drilling and construction operations (Reinicke and Ostermeyer, 2015). Based on the time analysis of the Kenyan and Icelandic wells, resulted that 45% of the work time is spent on actual drilling.

As stated above, the decrease of drilling time (actual drilling and tripping), as a major role player in terms of time/cost could result in total cost reduction considerably (Reinicke and Ostermeyer, 2015).

The ability to circulate while RIH or POOH operations may also be a possible solution to reduce the tripping time; however further investigations are required to find out that if it is possible and suitable for large diameter holes (Reinicke and Ostermeyer, 2015).

Another factor affecting the drilling time increase is unexpected problems that may occur during the drilling operations. Among which loss of fluid circulation is the most common issue, especially in geothermal well drilling operations (Reinicke and Ostermeyer, 2015), which can be resulted in:

a) increasing the drilling time;
b) loss of expensive drilling fluid material;
c) poor cementing;

And this ultimately can also result in well integrity issues due to the poor cementing job as well as possible equipment loos in the hole.

Table 10
Productive time percentage in a drilling operation.

Drilling Operation	Time spent, %
Drilling	26
Tripping	20
Cementing	15
Measurements	12
Other Works	8
Drilling fluid-related works	6
BOP related works	4
Top Drive	4
Repairs	2
Fishing Operations	1
Construction and dismantling	1

Plugging loss zones in conventional hydrocarbon well drilling operations is usually achieved by cementing the zone with bridging agents (Allan and Kukacka, 1995); but when loss zones include the main fractures, which is very common in geothermal well drilling, cement have to set rapidly and even may not withstand severe geothermal environment (Allan and Kukacka, 1995) and this will increase the drilling time and respectively the cost.

4. Conclusions

Although currently energy production from geothermal resources is not dominant in energy sectore, it has a huge potential to be a major role player in future energy strategy. EGS is one of these potential which can be reached in almost all over the globe. A majour challenge is drilling operations in such resources. Drilling operations of a geothermal well is quite similar to the drilling operation in petroleum industry. Though, the different aspects of geothermal drilling will make it more challenging and complex than the oil and gas well drilling. The type of resource and the formation type of resource is the big differences. Petroleum and geothermal well drilling have different geological and physical features including rock types, reservoir pressure, temperature, well and casing design as well as the well completion program. Hence, in this paper, it was tried to present the most common issues in geothermal well drilling operations and to introduce the potential for the future research areas. So the following can be concluded:

- The cost is not the main reason behind which has hold the geothermal energy behind comparing to renewable resources, rather it is the hydrothermal resources availability around the earth; • EGS is nearly presented anywhere able to offer energy to all for many of years with huge potential; • Research and development of EGS is the key for geothermal energy to make a significant contribution to energy needs, along with other renewables and new technologies for existing fossil fuel systems; • A very commen issue in geothermal well drilling operations are related to well integrity problems during the drilling and production phases. Casings, annulus cement and the liners play role in well integrity as the primary components; since a geothermal well should last much longer than a typical hydrocarbon well, the importance of well barriers' role becomes dominant in geothermal drilling;
- Amongst the challenges for drilling operations of a geothermal well, casing and cementing issues seem to mainly affect the integrity of a well in comparison to others;
- An important area of future studies could be focused on bonding between well cement and casing/annulus in high-temperature geothermal wells to enhance the knowledge and widen the aspects of the potential issues in this regard.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Acknowledgment

This work is a part of a Ph.D. program at the University of Stavanger funded by the Research Council of Norway [project number 11835, 2018]. The author would also thanks Dr. Mahmoud Khalifeh and Dr. Jan Aage Aasen for the kind support offered.

References

Agency, International Energy, 2018. World Energy Outlook 2018. OECD/IEA s.l.

CALSIUM PHOSPHATE CEMENTS FOR LOST CIRCULATION CONTROL IN GEOTHERMAL DRILLING. Allan, Marital L. and Kukacka, Lawrence E. 2, s.l. : Geometrics, Elsevier Science Ltd., 1995, Vol. vol. 24, pp. 269-282. 0375-6505(94)00052-2.

Applied Drilling Engineering. s.l.: Society of Petroleum Engineers (SPE), 1986. pp. 300-350. 1555630014.

ASSOCIATION and NATIONAL WATER WELL, December 1, 1979. Economic Impact of Using Nonmetallic Materials in Low to Intermediate Temperature Geothermal Well Construction. Department of Energy and Environment. University of North Texas Libraries, Digital Library, Ohio, United States. BROOKHAVEN NATIONAL LABORATORY.

Babler, R., et al., 2009. Evaluation OF corrosion resistance OF materials for geothermal applications. In: NACE INTERNATIONAL CORROSION CONFERENCE & EXPO. NACE International, Alanta, Georgia, USA.

Barteri, M., et al., 1996. Corrosion OF drill pipe steel IN high CO2 geothermal environments. In: CORROSION 96-The NACE International Annual Conference and Exposition. NACE, Denver, Colorado, USA.

Belayneh, Mefsin, et al., 2007. Design of well barriers to combat circulation losses. In: SPE/IADC Drilling Conference, 20-22 February. Society of Petroleum Engineers, Amsterdam, The Netherlands, 978-1-55563-158-1.

Berard, Brian, Hernandez, Rafael Alberto, Nguyen, Hao, 2009. Foamed calcium aluminate phosphate cement enables drilling and cementation of California geothermal wells. In: SPE Western Regional Meeting, 24-26 March. Society of Petroleum Engineers, San Jose, California, 978-1-55563-217-5.

Bertani, Ruggero, 2015. Geothermal Power Generation in the World 2010-2014 Update Report. World Geothermal Congress, Melbourne, Australia.

Blodgett, L., 2014. Geothermal 101: Basics of Geothermal Energy. Geothermal Energy Association (GEA), USA.

Bottiglieri, A., et al., 2014. Successful single stage cementing in a weak formation: a case history in Spain. In: SPE Energy Resources Conference, 9-11 June. Society of Petroleum Engineers, Port of Spain, Trinidad and Tobago, p. 18, 978-1-61399-335-4.

Breembroek, Gerdi, Dijkshoorn, Lydia, Ramsak, Paul, 2013. Geothermal Energy Status and Policy. Reykjavík : Coordination Office. Geothermal ERA NET.

Bronicki, Lucien Y., 2017. Geothermal power conversion technology. In: Meyers, R. (Ed.), Encyclopedia of Sustainability Science and Technology. Springer, pp. 161–268.

Bugbee, J.M., March 1953. Lost Circulation-A Major Problem in Exploration and Development. Spring meeeting of the Southwestern District, Division of Production, Shell Oil Co., Fort Worth, Texas.

Capuano Jr., L.E., 2016. Geothermal well driling. In: DiPippo, Ronald (Ed.), Geothermal Power Generation, Development and Inovation. WOODHEAD PUBLISHING, Elsevier Ltd. s.l.

Carter, L.G., Smith, D.K., 1958. Properties of cementing compositions at elevated temperatures and pressures. s.l. J. Petrol. Technol. 20–28.

Chiotis, E., Vrellis, G., 1995. Analysis of casing failures of deep geothermal wells in Greece, 5/6, Great Britain: Elsevier Science Ltd. Geothermics 24, 695–705, 0375-6505(95)0002-3.

Chow, S.Y., Kalousek, G.L., December 1976. Research on cements for geothermal and deep oil wells. s.l. : Soceity of Petroleum Engineers Soc. Petrol. Eng. J. 16 (6), 307–309, 0197-7520.

Clauser, Ch, Ewert, M., 2018. The renewables cost challenge: Levelized cost of geothermal electric energy compared to other sources of primary energy – review and case study. Renew. Sustain. Energy Rev. 82 (Part 3), 1364–0321. s.l.

Comparing completion design in hydrocarbon and geothermal wells: the need to evaluate the integrity of casing connections subject to thermal stresses. Teodorio, Catalin and Falcone. Geothermics 38, January 2009, 238–246. Gioia. Texas: Elsevier Ltd.

da Silva, Italo Cezar, et al., 2018. Dilatometric behavior and crystallographic characterization of Portland-polyurethane composites for oil well high-temperature cementing applications. J. Petrol. Sci. Eng. 169, 553–559 s.l.: Elsevier.

de Sena, Costa, Leonardo, Bruno, et al., 2017. Silica content influence on cement compressive strength fl in wells subjected to steam injection. J. Petrol. Sci. Eng. 158, 626–633. Rio Grande do Norte: Elsevier.

Dickson, M and Fanelli, M. *Introduction To Geothermal Energy*. s.l.: Geothermal Communities.

Dickson, M. H. and Fanelli, M. What Is Geothermal Energy. Pisa, Italy : Istituto di Geoscienze e Georisorse.

DiPippo, R., 2016. Geothermal Power Generation: Developments and Innovation. Woodhead Publishing, Elsevier Ltd., pp. 1–822 s.l. 978-0-08-100337–4.

Ellis II, P.F., et al., 1983. Corrosion Reference for Geothermal Downhole Materials Selection. U. S. Department of Energy, Austin, Texas. DOE/SF/11503-1 (DE83010306).

A new advanced method for top-job casing cementing. Satio, seiji. 1, tokyo : the geothermal research society of Japan. Journal of The Geothermal Research Society of Japan 17, January 1995, 33–42.

Finger, John, Blankenship, Doug, 2010. Handbook of Best Practices for Geothermal Drilling. s.L. Sandia National Laboratories. Contract Number: SAND2010-6048.

Fridriksson, Fridrik Hilmar Zimsen, 2017. An Improved Cement Slurry Formulation for Oil and Geothermal Wells. University of Stavanger, Stavanger.

Gallus, J.P., Watters, L.T., Pyle, D.E., August 1979. In: Performance of Oilwell

Cementing Compositions in Geothermal Wells, 19. Society of Petroleum Engineers, Houston, USA, pp. 233–241, 04, 0197-7520.

GEO ELEC deliverable no 3.2, 2013. Report on Risk Insurance. http://www.geoelec.eu/wp-content/uploads/2011/09/D-3.2-GEOELEC-report-on-risk-insurance.pdf.

Goodman, Malcolm A., 1981. Lost Circulation in Geothermal Wells Survey and Evaluation of Industry Experience. Sandia National Laboratories, Houston, Texas, USA.

Gudmundsson, J.S., 1988. The elements of direct use. Geometrics 17, 119–136 s.l.

Guerrero, Carlos Emilio Guerra, 1998. Cementing Of Geothermal Wells. The United Nations University, Geothermal Training Programme, Reykjavik, Iceland.

Gunnlaugsson, E., et al., 2014. Problems in geothermal operation-scaling and corrosion. In: Short Course VI on Utilization of Low and Medium Enthalpy Geothermal Resources and Financial Aspects of Utilization. UNU-GTP and LaGeo, Santa Tecla, El Salvador, p. 23.

Hashamt, M.D., et al., 2016. Crosslinked polymeric gels as loss circulation materials: an experimental study. In: SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, 25-28 April. Society of Petroleum Engineers, Dammam, Saudi Arabia, 978-1-61399-482-5.

Hashmat, M.D., et al., 2017. Flowing gels for loss circulation prevention. In: PE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, 24-27 April. Society of Petroleum Engineers, Dammam, Saudi Arabia, 978-1-61399-573-0.

Hole, H.M., 2008. Geothermal Well Cementing. s.l.. Petroleum Engineering Summer School, Dubrovnik, Croatia. June 9-13, Workshop #26.

John, W., Boyd, Tonya L., 2016. Direct utilization of geothermal energy 2015 worldwide review. Lund. s.l Geometrics 60, 66–93. Geometrics.

Kaldal, Gunnar Skulason, et al., May 2015. Structural modelling of the casing in high temperature geothermal wells. Geometrics 55, 126–137 s.l. : Elsevier Ltd.

Kaldal, G.S., et al., 2016. Structural modelling of the casing in the IDDP-1 well: load history. Geometrics 62, 1–11. Reykjavik, Iceland : Elsevier Ltd.

Karlsdottir, S.N., Thorbjornsson, I.O., 2012. Hydrogen embrittlement and corrosion in high temperature geothermal well. In: NACE INTERNATIONAL CORROSION CONFERENCE & EXPO. NACE International, Salt Lake City, Utah, USA. Reykjavik University.

Development of silica-enriched cement-based materials with improved aging resistance for application in high-temperature environments. Krakowiak, Konrad J., et al. s.l.: Elsevier, 2018, Cement Concr. Res., Vol. 105, pp. 91-110.

Larri, I., 1997. Rezistenta Coloanelor de Bulrane Tubate in Sondele Supuse Procesului. ICPT internal report, Campina, Romania.

Lavrov, Alexandre, 2016. Chapter 1-The Challenge of Lost Circulation. Lost Circulation. Elsevier Inc., Trondheim.

Lecolier, Eric, et al., 2005. Development of a nanocomposite gel for lost circulation treatment. May 25-27. In: SPE European Formation Damage Conference. Society of Petroleum Engineers, Sheveningen, The Netherlands, 978-1-55563-998-3.

Lichang, Li, et al., 2006. Research and application of reverse circulation drilling technology. In: International Oil & Gas Conference and Exhibition in China, 5-7 December. Society of Petroleum Engineersw, Beijing, China, p. 7, 978-1-55563-183-3.

Liu, Zhengchun, et al., 2015. Casing integrity: strain-based fatigue life estimation coupled with numerical thermal-flow simulation and multistring stress analysis. In: SPE Thermal Well Integrity and Design Symposium. Society of Peroleum Engineers, Banff, Alberta, Canada, 978-1-61399-430-6.

Longa, Francesco Dalla, Nogueira, Larissa P., Limberger, Jon, van Wees, Jan-Diederik, van der Zwaan, Bob, 2020. Scenarios for geothermal energy deployment in Europe. Energy 206, 118060 s.l. 0360–5442.

Properties of Portland Cement Pastes Cured at Elevated Temperatures and Pressures. Ludwig, N. C. and Pence, S. A. 2, s.l.: American Concrete Institute, 1956, Vol. vol. 52, pp. 673-687.

Mansour, A. Kh, Dahi Taleghani, A., Li, G., 2017. Smart lost circulation materials for wellbore strengthening. In: 51st US Rock Mechanics/Geomechanics Symposium, 25-28 June. American Rock Mechanics Association, San Francisco, California, USA, p. 8.

Mansour, A. Kh, Taleghani, Dahi, Abu Dhabi, A., 2018. Smart loss circulation materials for drilling highly fractured zones. In: SPE/IADC Middle East Drilling Technology Conference and Exhibition, 29-31 January. UAE : Society of Petroleum Engineers, 978-1-61399-565-5.

Mansure, A.J., et al., 2002. Polyurethane grouting of rye patch lost circulation zone. In: IADC/SPE Drilling Conference, 26-28 February. Society of Petroleum Engineers, Dallas, Texas, 978-1-55563-940-2.

Mata, F., Veiga, M., 2004. Crosslinked cements solve lost circulation problems. In: SPE Annual Technical Conference and Exhibition, 26-29 September. Society of Petroleum Engineers, Houston, Texas, 978-1-55563-151-2.

Miranda, C.R., et al., 2017. Materials for controlling severe lost circulation - laboratory evaluation. In: SPE Latin America and Caribbean Petroleum Engineering Conference, 17-19 May. Society of Petroleum Engineers, Buenos Aires, Argentina, 978-1-61399-533-4.

Mofunlewi, S.S., Okoto, F. Lagos, 2016. Curing lost circulation with an engineered spacer during cement placement. In: SPE Nigeria Annual International Conference and Exhibition, 2-4 August. Society of Petroleum Engineers, Nigeria, p. 16, 978-1-61399-487-0.

Monthly Energy Review, 2018. U. S. Energy Information Administration s.l.

Moore, Robert, et al., June 2005. High-temperature wells with lost circulation demands and reverse-circulation techniques using foamed-cement systems: two case histories. s.l: Society of Petroleum Engineers SPE Drill. Complet. 20 (2), 133–140, 1064-6671.

Moya, D., Aldas, C., Kaparaju, P., 2018. Geothermal energy: power plant technology and direct heat applications. s.l. Renew. Sustain. Energy Rev. 94, 1364–0321.

Nelson, Erik B., Eilers, Louis H., Spangle, Lloyd B., 1981a. Evaluation and Development of Cement Systems for Geothermal Wells. Society of Petroleum Engineers, San Antonio, Texas, USA, 978-1-55563-679-1.

Formation and Behavior of Calcium Silicate Hydrates in a Geothermal Environment. Nelson, E. B., Eilers, L. H. and Kalousek, G. L. 03, Tulsa, Oklahoma, USA: Elsevier, May 1981, Cement and Concrete Research, Vol. vol. 11, pp. 371-381.

Nersesian, Roy L., 2010. Energy for the 21st Century: A Comprehensive Guide to Conventional and Alterative Source, second ed. M. E. Sharpe Inc. s.l.

Nogara, James, Zarrouk, Sadiq J., 2018. Corrosion in geothermal environment: Part1: fluids and their impact. s.l.: Elsevier Ltd. Renew. Sustain. Energy Rev. 82, 1333–1346, 1364-0321.

Nugroho, W.A., Hermawan, S., Lazuardi, B.H., Mirza, R., 2017. Drilling problems mitigation in geothermal environment, case studies of stuck pipe and lost circulation. Soc. Petrol. Eng. https://doi.org/10.2118/186922-MS.

Omosebi, Omotayo, et al., August 2015. Investigating temperature effect on degradation of well cement in HPHT carbonic acid environment. s.l.: Elsevier B. V. J. Nat. Gas Sci. Eng. 26, 1344–1362.

Ong'au, Thomas Miyora, 2012. Controlled directional drilling in Kenya and Iceland (time analysis). GRC Trans. 36.

Ostroot, G. Warren, 1964. Cementing geothermal steam wells, 12, s.l.: Society of Petroleum Engineers, December J. Petrol. Technol. 15, 1425–1429, 0149-2136.

Ostroot, G. Warren, Shryock, Stanley, October 1964. Cementing Geothermal Steam Wells. Society of Petroleum Engineers, Houston, Texas, pp. 1425–1429.

Improved Compositions for Cementing Wells with Extreme Temperatures. Ostroot, G. Warren and Walker, Wayne A. 03, s.l: Society of Petroleum Engineers, 1961, Vol. vol. 13. SPE-1513-G-PA.

Paiva, Maria D.M., et al., 2018. A geopolymer cementing system for oil wells subject to steam injection. J. Petrol. Sci. Eng. 169, 748–759 s.l. : Elsevier.

Stractural analysis of geothermal well cements. Philippacopoulos, Aristodimos J. and Berndt, Marita L. 6, Newyork : Elsevier Science Ltd., October 12, 2002, Geometrics, Vol. 31, pp. 657-676.

Pyatina, Tatiana, Sugama, Toshifumi, May 2016. Acid resistance of calcium aluminate cement–fly ash F blends. Adv. Cement Res. 28 (7), 433–457 s.l. : Institution of Civil Engineers (ice).

Self-repairing Geothermal Well Cement Composites. Pyatina, T., Sugama, T. and Ronne, A. Davis, California, USA: Geothermal Resources Council, 2016, Geothermal Resources Council Transactions, Vol. vol. 40, pp. 235-244.

Ragnarsdottir, K.R., et al., 2018. Preliminary corrosion testing of explosive clad materials in geothermal environment. In: CORROSION Conference & Expo. NACE International s.l.

Ravi, Krishna, et al., 2008. Advanced cement systems used to improve geothermal well reliability in java. s.l.. In: SPE Annual Technical Conference and Exhibition, 21-24 September, Denver, Colorado, USA. Society of Petroleum Engineers.

Rehm, Bill, et al., 2009. Managed Pressure Drilling. s.l.. Gulf Publishing Company, 9780127999876.

Reinicke, Kurt M., Ostermeyer, Georg-Peter, 2015. Final Report of Geothermal Energy and High-Performance Drilling Collaborative Research Program (Gebo). CUVILLIER VERLAG, Göttingen, pp. 287–299, 978-3-7369-9080-7.

Successfully Applying Micronized Cellulose to Minimize Lost Circulation on the PUNA Geothermal Venture Wells. Rickard, Bill, et al. s.l.: Geothermal Resources Council, 2010, GRC Transactions, Vol. vol. 34.

Rickard, William M., Hernandez, Jonathan, Bailey, Alan, 2012. Top squeeze or top fill: improved secondary cementing for geothermal wells. In: 4th African Rift Geothermal Conference, 21-23 November. Nairobi, Kenya.

Salim, Prisca, Amani, Mahmood, 2013. Principal Points in cemeting geothermal wells, 1, s.l. : CSCanada Adv. Petrol. Explor. Dev. 5, 77–91, 1925-5438.

Sammat, E., et al., 2012. Successful controlled pressure drilling application in a geothermal field. In: SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, 20-21 March. Society of Petroleum Engineers, Milan, Italy, p. 11, 978-1-61399-187-9.

Santra, Ashok Kumar, Liang, Feng, Fitzgerald, Rocky, 2009. Sorel cement for HP/HT downhole applications. In: SPE International Symposium on Oilfield Chemistry, 20-22 April. Society of Petroleum Engineers, The Woodlands. Texas, USA, 978-1-55563-243-4.

Shaughnessy, John, Helweg, John, 2002. Optimizing HTHP cementing operations. In: IADC/SPE Drilling Conference, 26-28 February, Dallas, Texas. Society of Petroleum Engineers, USA, 978-1-55563-940-2.

Shryock, S.H., 1984. Geothermal well cementing technology. In: 5th Offshore South East Asia, 21-24 February. Society of Petroleum Engineers, Singapore, 978-1-55563-647-0.

Shryock, Stanley H. and Smith, Dwight K. Geothermal Cementing - the State of the Art. USA : Halliburton Services.

Silva, Joao Conde, Milestone, Neil B., 2018. The effect of the rock type on the degradation of well cements in CO2 enriched geothermal environments. Geothermics 75, 235–248 s.l. : Elsevier.

Silva, Deigo Armando Vargas, Carrillo, Zuly Calderon, Tarazona, Darwin Mateus, 2017. Numerical modeling of circulation loss in fractured formations. In: Sustainable Heavy Oil Exploitation, Innovation and Geomechanical Contributions, ISRM Specialized Conference, 13-16 March. Simposio Internacional de Geomecanica, Medellin, Antioquia, Colombia, p. 8.

Singh, H.K.D., et al., 2016. MDP closed loop cementing in high-pressure, high-temperature wells in Vietnam. In: International Petroleum Technology Conference, 14-16 November. Society of Petroleum Engineers, Bangkok, Thailand,

p. 11, 978-1-61399-451-1.

Casing Failure Modes in Geothermal Wells. Snyder, R. E. Davis, California: Geothermal Resource Council, 1979, Geothermal Resources Council Transactions, Vol. vol. 3, pp. 667-670. ISSN: 0193—5933; ISBN: 0-934412-53-7.

Southon, James N.A., 2005. In: Geothermal Well Design, Construction and Failures. World Geothermal Congress, Antalya, Turkey s.n.

Stober, I., Bucher, K., 2013. History of geothermal energy use. [book auth.] stober I. And K. Bucher. Geothermal Energy, From Theoritical Models to Exploration and Development 15—24 s.l. : Springer.

Sugama, Toshifumi, 2006. Advanced Cements for Geothermal Wells. Energy Sciences and Technology Department/Energy Resources Division, U.S. Department of Energies Office of Geothermal Technologies. s.l.. Brookhaven National Laboratory.

Sugama, T., Pyatna, T. and Gill, S. Thermal Shock-Resistant Cement. Sustainable Energy Technologies Department/Energy Conversion Group, U.S. Department of Energy, DOE Office of Energy Efficiency and Renewable Energy. s.l.: Brookhaven National Laboratory, 2012. p. 38.

Sugama, T., et al., 2012b. Corrosion=resistant Foamed Cement for Carbon Steels. U.S. Department of Energy, DOE Office of Energy Efficiency and Renewable Energy, Sustainable Energy Technologies Department/Energy Conversion Group. Brookhaven National Laboratory, p. 28 s.l.

Drilling Performance, Injectivity and Productivity of Geothermal Wells. Sveinbjornsson, Bjorn Mar and Thorhallsson, Sverrir s.l.: Elsevier Ltd., April 2014, Geometrics, Vol. vol. 50, pp. 76-84. 0375-6505.

Taylor, M., Daniel, K., Ilas, A., So, E.Y., 2015. RENEWABLE POWER GENERATION COSTS IN 2014. International Renewable Energy Agency (IRENA) s.l.

Why and when Does Casing Fail in Geothermal Wells: a Surprising Question? Teodoriu, Catalin. Melbourne, Australia: Proceeding World Geothermal Congress, 2015.

Teodoriu, Catalin, et al., February 2013. Wellbore integrity and cement failure at HPHT conditions. Int. J. Eng. Appl. Sci. 2 (2), 2305—8269 s.l. : EAAS & ARF.

Titanium in the geothermal industry. Geothermics 32, August 1, 2003, 679—687. Thomas, Roger. 4-6, s.l.: PERGAMON-Elsevier Ltd.

Torres, Angelito, 2014. Challenges of casing design in geothermal wells. In: IADC/SPE Asia Pasific Drilling Technology Conference. Society of Petroleum Engineers, Bangkok, Thailand, 978-1-61399-320-0.

Treseder, R.S., Wieland, R., 1977. Down-hole corrosion ina Salton sea geothermal well. In: SPE International Oilfield and Geothermal Chemistry Symposium, 27-28 June. Society of Petroleum Engineers, La Jolla, California, 978-1-55563-736-1.

Us Department of Energy. A History of Geothermal Energy in America. USA : Office of Energy Efficiency and Renwable Energy (www.energy.gov).

Vidal, Anderson V., Araujo, Romero G.S., Freitas, Julio C.O., September 2018. Sustainable cement slurry using rice husk ash for high temperature oil well. J. Clean. Prod. 204, 292—297 s.l. : Elsevier Ltd.

Wang, Chengwen, et al., April 2017. Can nanosilica sol prevent oil well cement from strength retrogression under high temperature? s.l.: Elsevier Ltd. Construct. Build. Mater. 144, 574—585.

Whitfill, Donald L., Hemphil, Terry, 2003. All lost-circulation materials and systems are not created equal. In: SPE Annual Technical Conference and Exhibition, 5-8 October. Society of Petroleum Engineers, Denver, Colorado, 978-1-55563-152-9.

Won, Jongmuk, et al., February 2015. Physical properties of G-class cement for geothermal well cementing in South Korea. s.l.: Elsevier Ltd. Renew. Energy 80, 123—131.

Zarroukh, Sadiq J., Moon, Hyungsul, 2014. Efficiency of geothermal power plants: a worldwide review. Geometrics 51, 142—153. Auckland, New Zealand.