Current Status and Future Outlook of Geothermal Reinjection: A Review of the Ongoing Debate

Nuvarande status samt framtida utsikter för geotermisk re-injektion: En översikt av den pågående debatten

Gabriella Skog
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Abstract

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Geothermal energy is a renewable energy source which has not yet had the same breakthrough as other renewables, e.g. solar PV and wind. There may still be some technical issues to be solved before geothermal can reach its full potential.

One of these technical challenges concerns reinjection, i.e. the return of geothermal fluids back into the ground after surface energy extraction. In traditional geothermal energy utilization, hot geothermal fluid is brought up from underground reservoirs to the surface. Depending on the design of the power plant, the fluid can either be kept one-phased or get separated into two phases, i.e. hot steam and water. Hot steam, or vapor of another working fluid, is used to drive electricity generating turbines.

Whether the condensate is returned back into the ground after energy extraction, i.e. reinjected, is nowadays usually a matter of how rather than if. However, the magnitude and strategy varies in countries as well as for specific power plant operators.

From a sustainable management perspective, the majority of operators as well as scientist agree that reinjection is the best way practice in order to take care of a resource and leave the smallest possible environmental footprint. However, it is a quite complicated and not always problem free operation. There are numerous examples where reinjection has led to complications such as scaling, induced seismicity and cooling of the reservoir.

The purpose of this study was to describe the current status of geothermal reinjection from a neutral third-party perspective, e.g. by describing current obstacles and negative as well as positive outcomes. The aim is to conclude whether current technology is enough to successfully reinject, or if there are still some gaps of knowledge to fill. The method consists partly of a literature study of previously written technical reports but also of interviews with experts in the area. In addition, the study summarizes the legal framework regarding reinjection in some geothermal active countries, e.g. if it is required by law or not.

Although currently technology is enough to do a fairly good job at reinjecting geothermal fluids, the result of the study also shows that there are still some technical barriers to overcome in order to fully optimize it. However, it remains the best currently known way to keep geothermal energy sustainable. Better technologies will be needed in order for geothermal to reach its fully green potential.

Key words: geothermal energy, reinjection, sustainability, challenges

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Sammanfattning

Nuvarande status samt framtida utsikter för geotermisk re-injektion: En översikt av den pågående debatten
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Geotermisk energi är en förnybar energikälla som ännu inte har fått samma genombrott som t.ex. sol- och vindkraft. Det är möjligt att det fortfarande finns några tekniska hinder som måste lösas innan geotermisk energi kan nå sin fulla potential.

En av dessa tekniska utmaningar gäller re-injektion, i.e. återförandet av geotermiskt vatten tillbaka i marken efter energiutvinning. Vid traditionell geotermisk energiutvinning tas varm geotermisk vätska och/eller gas upp från underjordiska reservoarer till markytan. Beroende på kraftverksdesign hålls vätskan antingen i en fas eller separeras till två faser, ånga och vatten. Ängan, eller gasen från en annan arbetsvätska, används till att driva elektricitetsgenererande turbiner. Huruvida denna vätska sedan förs tillbaka till marken efter energiutväxlingen är vanligtvis en fråga om hur, inte om. De re-injiceringsmetoder som används och förhållningssätt varierar dock i länder och även för specifika kraftverksoperatörer.

Från ett hållbarhetsperspektiv är de flesta operatörer och forskare överens om att re-injektion är det bästa sättet att ta hand om en geotermisk resurs och lämna den minsta möjliga miljöpåverkan. Re-injektion är dock en ganska komplicerad och inte alltid problemfri operation. Det finns många exempel där det har lett till komplikationer som mineralutfällningar, inducerade jordskalv och avsvalning av den geotermiska reservoaren.

Syftet med denna studie var att beskriva den nuvarande globala statusen för geotermisk re-injektion från ett neutralt tredjepartsperspektiv, bl.a. genom att beskriva nuvarande hinder samt negativa såväl som positiva konsekvenser. Målet var att avgöra om nuvarande teknik är tillräcklig för att kunna re-injicera problemfritt, eller om det fortfarande finns kunskapsluckor att fylla. Metoden bestod dels av en litteraturstudie av tidigare tekniska rapporter samt av kvalitativa intervjuer med experter inom området. Dessutom sammanställdes den rättsliga ramen för re-injektion, i.e. om det krävs av lag eller inte, i geotermiskt aktiva länder.

Även om nuvarande teknologier verkar vara tillräckliga för att kunna re-injicera på ett godtyckligt sätt, visar studien på att det finns vissa tekniska hinder som behöver överkommas. Re-injektion kvarstår dock som det nuvarande mest miljövänliga sättet att utvinna geotermisk energi på. I framtiden kommer dock bättre teknologier att behövas för att geotermisk energi ska kunna nå sin fullt gröna potential.

Nyckelord: geotermisk energi, re-injektion, hållbarhet, utmaningar

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1. Introduction

Future notes on the 21st century will probably include descriptions of e.g. a rising global economy, Third World consumerism and Millennials. However, perhaps the most notable topic of our current time is global climate change. As stated by UN Secretary-General António Guterres at a summit on climate action in 2018, “none of the world’s challenges loom as large as climate change”, later also referring to climate change as an “existential threat to humanity”.

Never before has leadership action or technology innovation been as focused on trying to solve the climate crisis. Industry, agriculture and the financial sector is undergoing an important transition toward new and green solutions. On an individual level, the discussion on how to transport, eat and live as energy efficient as possible has never been as vivid.

The largest transition may arguably the one that currently takes place in the energy sector, i.e. going from fossil fuels to renewable and less polluting energy forms. As reported in REN21’s 2018 global status report, “The number of cities powered by at least 70% renewable electricity more than doubled between 2015 and 2017”. Although declining, more than three quarters of the global electricity production is still powered by fossil fuels, as can be seen in figure 1 (REN21, 2019).

![Figure 1. Global energy distribution after final consumption in 2016 and the estimated share of modern renewable energy sources.](source: REN21, 2019)

The problem with fossil fuels is not only that they are harmful to our environment, they are also finite. In other words, although they will most likely continue to supply us with energy for several more decades to come - we will eventually run out of oil, coal and gas. Therefore, one of the largest challenges on human innovation is the development of enough alternative power to provide our fast developing world.

One of those alternative power sources is the one which utilizes the enormous...
amount of heat stored within the Earth; *geothermal energy*. This immense energy resource can be utilized by bringing up hot geothermal fluids from the subsurface, both for direct use or for electricity production. Although it currently supplies less than 1% of global electricity production, it is not a new energy resource (REN21, 2019). Quite the opposite, geothermal energy has been utilized since the time of our early ancestors, e.g. for cooking, cleaning and bathing (Duffield and Sass, 2003).

Despite its long tradition of utilization, geothermal energy has not yet had the same breakthrough as e.g. solar photovoltaic (solar PV), hydro and wind. The reason for this can for example be tied to the high upfront risk associated to geothermal projects, together with lack of funding and geothermal incentives. New investment in solar and wind power accounted for a total of 268 billion USD in 2017, compared to 1.7 billion USD for geothermal (REN21, 2019). In order to reach its full potential, it is possible that the geothermal industry has some barriers to overcome, both in technology as well as knowledge. Rewarding incentives and refined legal frameworks would probably also speed up the development.

One specific topic which needs to be further researched concerns the sustainable parameters of geothermal power plants. Although geothermal energy per se can be defined as a renewable energy source, in fact, some geothermal power plants leave quite a substantial environmental footprint. Greenhouse gas emissions, induced seismicity and water pollution are all examples of reported consequences. The measures taken to reduce these impacts varies a lot.

Perhaps the most common part of sustainable geothermal resource management regards the return of geothermal fluids back into the reservoir after energy extraction, commonly referred to as reinjection. Although the number of fields which use reinjection continues to increase with each year, it remains quite a complicated and far from problem free operation for many power plants (Axelsson, 2012). There are numerous examples where reinjection has led to complications such as scaling, induced seismicity and cooling of the reservoir, all of which will be discussed further later on in the report.

2. Purpose

The purpose of this study was to describe the current status of geothermal reinjection from a neutral third-party perspective, e.g. by mapping out current obstacles and by reporting negative as wells as positive outcomes. These outcomes will be supported by case studies in 5 geothermal active countries, together with qualitative interviews with chosen experts. The main questions of interest are:

- What are the main technical obstacles in geothermal reinjection today, and how can they be overcome?
- Is reinjection always necessary?
- Is current technology enough to successfully reinject, or are there still some gaps of knowledge to fill?

Geothermal energy is often claimed to be one of the greenest energy sources available today. However, since the industry is still behind schedule in terms of production magnitude, this type of internally investigative study is important in order to drive the development forward. In terms of the industry, studies like this could also be a push in the right direction, for example by suggesting the most sustainable method.
3. Background

3.1 Geothermal energy

This chapter will give a brief introduction to the geological factors behind geothermal energy, its history of utilization and its current status of development.

3.1.1 Introduction

Geothermal energy can shortly be described as the heat stored within the Earth. The heat sources can be divided into:

1. Primordial heat, i.e. the heat that was generated during the creation of the Earth and, to some extent, is accumulated within the core.

2. Radiogenic heat, i.e. the heat which is constantly produced in the core or crust due to radioactive decay of certain elements. (Dye, 2012)

The heat spreads out into the crust mainly by convection of magma and geothermal fluids, but also through radiation and conduction. As a natural consequence, the crust is heated up simultaneously as it spreads the heat into the atmosphere and eventually into space. The total heat flow from the core to the surface of the earth has been estimated to be around 47 ± 2 TW, which equals to an average heat flow of around 82 mW/m² (Davies and Davies, 2010; Fowler, 2005). Although present everywhere, the heat flow is not evenly distributed on the planet. For example, the heat flow is greater at active tectonic boundaries, on hot spots or in areas with a thinner crust. For examples, countries sited in the tectonic area of ‘The Ring of Fire’ all have a high potential for utilizing geothermal energy.

In volcanic active areas, such as Iceland, the heat is mainly transported through convection of magma and geothermal fluids, and the heat flow averages to 175 mW/m² (Hjartarson, 2015). As a comparison, in old and inactive tectonic bedrock where the crustal heat is mainly transported through conduction, such as in Sweden, the heat flow is usually a lot lower, ca 45 mW/m² (Näslund et al., 2004).

Since the late 80’s, it has been widely accepted that the Earth’s core is slowly cooling down due to the lack of equilibrium between the radiogenic heat and the constant heat loss to the atmosphere (Stacey and Loper, 1988). In other words, the heat which is produced is not enough to compensate for the heat which is lost. Although cooling, the rate is less than 100°C per billion years (Labrosse et al., 1997).

The heat which is accumulated in the earth is an immense source of energy. In 1987, Electric Power Research Institute (EPRI) estimated the energy stored down to a 3 km depth in the crust to a total of 43 x 10⁶ EJ. In comparison, the world’s total primary energy supply (TPES) was around 580 EJ in 2016 (IEA, 2019).

3.1.2 Classification of geothermal systems

Geothermal resources can be categorized based on several factors. Temperature, reservoir properties, bedrock geology and fluid chemistry to mention a few. Some of the most common classification systems can be seen in table 1.
Table 1. Different classification systems A, B and C, of geothermal resources based on temperature, enthalpy and brine properties.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low temperature</td>
<td>T &lt;150 °C</td>
<td>Low enthalpy systems</td>
<td>Hot water, liquid dominated hydrothermal resources</td>
</tr>
<tr>
<td>Medium temperature</td>
<td>150°C&lt;T&lt;200°C</td>
<td>High enthalpy systems</td>
<td>Two-phase, liquid dominated</td>
</tr>
<tr>
<td>High temperature</td>
<td>T &gt;200°C</td>
<td>Two-phase, gas dominated</td>
<td></td>
</tr>
</tbody>
</table>

Source: (Axelsson and Gunnlaugsson, 2000; Bödvarsson, 1964; Kaya et al., 2011).

Classification system A is solely based on the resource temperature. Classification system B is based on enthalpy (i.e. internal energy) and is used to classify geothermal systems based on their energy potential. For example, low enthalpy systems have a lower energy density than high enthalpy systems. Therefore, low versus high enthalpy resources are suitable for different utilization purposes.

When discussing reinjection strategies, it is interesting to know the gas to water ratio (GWR) of the brine. Especially with regards to the content of non-condensable gas (NCG), e.g. CO2, NH2, N2, H2S etc., a natural component of all geothermal fluids. Therefore, the classification system C is suggested by Kaya et al., (2011) in Reinjection in geothermal fields - A worldwide review update. It should be noted that Kayla et al. (2010) also divides the liquid dominated two-phase category into low (220 < T < 250), medium (250 < T < 300) and high enthalpy (300 < T < 330) resources.

3.1.3 Utilization of geothermal energy

As mentioned in the introduction, geothermal energy has been acknowledged and utilized by humans through direct use for a very long time. Direct use means to use the geothermal heat for direct purposes, such as balneology, i.e. hot spring bathing and spa activities, or in and district heating systems. However, owing technology improvements of the early 20th century, geothermal energy can also be used to generate electricity. The first geothermal power plant began operation in 1904 in Larderello, Italy (DiPippo, 2012). The development after that has continued steadily, but slowly.

The basic principle behind the majority of current geothermal power generation is to bring up hot geothermal fluid or steam from subsurface geothermal reservoirs. Although there are many different geothermal power plant designs, this report will mostly discuss the three most common systems: binary, dry steam and flash, all of which can be seen illustrated in figure 2 (EIA, 2018). It should be added that several other types and subgroups exist, such as single, double and triple flash plants, hot dry dock (HDR) and enhanced geothermal systems (EGS).
The first geothermal power plant in Larderello, previously mentioned, was a dry steam power plant, which brings up hot geothermal steam from the subsurface. The steam is directly used from the wells to spin electricity generating turbines (Duffield and Sass, 2003). After the energy transferring process, the steam is usually condensed and reinjected back into the ground.

The process is largely the same in flash plants. The difference is that brine can be either water or vapor dominated. As the brine depressurizes inside the power plant some of the it will “flash”, i.e. boil, which also is the process that spins the turbines (Duffield and Sass, 2003). The water which was not used is usually reinjected back into the ground together with the condensate. Flash and dry steam power plants are designed for high enthalpy geothermal systems with resources normally above 200°C.

Binary power plants are adapted for geothermal hot water reservoirs utilize of usually less than 200°C, i.e. low enthalpy. Through pumping, the brine is brought up to the surface and put in contact with a working fluid of a lower boiling point. The rapid vaporization of the working fluid is the process which is used to spin the electricity generating turbines (Duffield and Sass, 2003). In other words, binary power plants have two working fluids in comparison to dry steam and flash plants which only utilizes steam.

3.1.4 Current global status

Since the estimation done by EPRI in 1987, several estimations on the actual extractable potential of geothermal energy in the crust have been made, ranging from 70GWₑ to 280 GWₑ (Stefansson, 2005; Bertani, 2009; Christiansborg and Richter, 2018). Regardless of the correct estimated potential, geothermal energy is evidently a huge as well as nearly untapped resource. In 2018, the total geothermal energy capacity reached 14.6 GW (Richter, 2019). The distribution of this installed capacity can be seen in figure 3. The top 10 countries includes USA, Indonesia, Philippines, Turkey, New Zealand, Mexico, Italy, Iceland, Kenya and Japan.
Although having been utilized for more than a hundred years, the development of geothermal electricity production is going slow. A total of 2.9 GW was added to the global capacity during the period of 2012 – 2017 (IEA, 2019). For comparison, solar PV and hydro added 205 and 210 GW respectively during the same period.

3.1.5 Sustainable utilization

The term sustainable development can be derived back to the so-called Brundtland report (World Commission on Environment and Development, 1987), where it is defined as the following:

“Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs”

When applying the Brundtland definition on geothermal energy, one obvious criterion is to use a geothermal resource without depleting it. For example, not to lower its natural water pressure or temperature. The opposite to sustainable development could be referred to as excessive utilization, meaning to extract more energy from a resource than it is naturally recharged with (Axelsson et al., 2004). However, it has been suggested that excessive production not necessarily has to be unsustainable from a long-term perspective as long as the resource is given time to recover, also known as periodical utilization (Christiansborg and Richter, 2018).
To date, there is no global standard in how to manage a geothermal resource in a sustainable way. Perhaps the closest is the Geothermal Sustainability Assessment Protocol (GSAP), currently under development, which rates geothermal power plants based on their sustainability (Richter, 2018). In addition, the legal framework for geothermal energy is still underdeveloped, even in countries with an active geothermal industry.

Geothermal energy is often being referred to as one of the best alternatives to fossil fuels. However, many geothermal power plants are associated with some negative environmental consequences. Pollution, such as lowered air and/or water quality, and terrain changes, such as small earthquakes or even land subsidence, are all examples of environmental impacts from geothermal power stations.

Greenhouse gas emissions can also be significant. For example, the CO₂ emissions from some geothermal fields in Turkey amounts up to 1800 g/kWh (Aksoy et al., 2015) which is almost twice as much as the emission from traditional coal burning plants at around 950 g/kWh (Layman, 2017). High CO₂ emissions from geothermal power plants have been reported in several other countries too, e.g. in areas with carbonate rich rocks in New Zealand and Italy (Fridriksson et al., 2016). However, it should be noted that these are rare cases and the highest reported examples of emissions from geothermal power plants. The average CO₂ emission from geothermal power plants is around 300-400 g/kWh.

3.2 Reinjection of geothermal water

This section will give a brief introduction to the reinjection of geothermal water and current methods that are used.

3.2.1 Definition, history and purpose

Reinjection can be defined as pumping back parts or all of the geothermal fluids which were brought up from the geothermal reservoir during energy utilization. In some special cases, such as in high enthalpy steam-dominated fields with a low natural recharge, waste water from e.g. nearby communities can be used as an additional reinjection fluid (Kaya et al., 2011). In cases of where the geothermal system has a high natural recharge, reinjection sometimes occur into bedrock which is not connected to the reservoir.

The first cases of geothermal reinjection probably occurred sometime during the 1960’s (Stefansson, 1997). It was then used as an effective and simple way to dispose the utilized water. In addition, similar methods of reinjecting brine have been used in the oil industry since at least the 1930’s (Clark et al., 2005).

In a report from 1982, Roland N. Horn wrote that “Reservoir maintenance by reinjection is a controversial subject, and, in actual field cases to date, water has been reinjected solely for disposal purposes” (Horn, 1982). In 2012, Guðni Axelsson wrote; “By now reinjection is considered an important part of comprehensive geothermal resource management as well as an essential part of sustainable and environmentally friendly geothermal utilization” (Axelsson, 2012). Although hard to conclude only based on the two previous citations, the view on reinjection can be considered to have changed from mostly being a way to effectively dispose fluids to now also serve as an important function to maintain resource health and to minimize the global footprint. In addition, reinjection is nowadays required by law in some countries (Dumas et al, 2013).
3.2.2 Current methods

The most notable difference in reinjection methods regards whether the reinjection occurs *infield* or *outfield* in relation to the geothermal resource. As it is described by Kaya et al. (2011), a reinjection well that is drilled into a geothermal system would be regarded as infield reinjection. In comparison, a reinjection well that is drilled into another depth or even into another aquifer would be regarded as outfield reinjection.

The strategy and purpose of reinjection depends highly on the properties of the geothermal field. In one field, reservoir pressure support could be the main reason to reinject whereas in another, water discharge and environmental protection is more relevant. For example, for vapor dominated two-phase geothermal system it has proven to be successful to reinject the condensate infield in order to prevent water shortage in the reservoir (Kaya et al., 2011). In comparison, in liquid dominated two-phase systems it is more common for reinjection wells to be placed outfield. The reason for this is that pressure support is not the main objective, and that infield reinjection often leads to the cooling of the production field (Kaya et al., 2011). This will be brought up and discussed further in chapter 5.1.1.

In hot water systems, the main purpose of reinjection is usually to sustain pressure and water levels in the reservoir. Therefore, infield reinjection is encouraged (Kaya et al., 2011). The ultimate reinjection strategy as expressed by Kaya et al. (2011) is when the reinjection wells are close enough to provide support to the geothermal reservoir, but far enough so they do not induce cooling of the production wells. However, as written by Axelsson, this balance can take several years to understand (Axelsson, 2016). At that point, natural changes of the dynamic geothermal system may have led to a forced change of the reinjection strategy.

With regards to new trends, the addition of binary cycles to high enthalpy fields has increased during the last decade. The binary cycles are used to bring down the temperature of the condensate, making reinjection easier while still utilizing the high temperature of the condensate. There is also an increased interest in the reinjection of the greenhouse gases which are a natural part of geothermal fluids. Today, these gases are mostly released directly into the atmosphere. This too will be brought up and discussed further in chapter 5.2.3.

4. Method

This chapter summarizes the method which was used in this study.

4.1 Collection of data

The search of data for this report has been mainly through databases such as Elsevier’s GEOBASE (via Engineering Village) and GRC’s Geothermal Library. The main keywords which have been used is *reinjection* and *geothermal energy*.

Two reports which have been of especially large help are *Reinjection in Geothermal fields: A review of worldwide experience* by Kaya et al., (2011) and *Reinjection in geothermal fields - A worldwide review update* by Rivera et al., (2016). Both reports contain databases of reinjection experience in geothermal developments all over the world, the latter containing experience from a total of 126 geothermal power stations.
4.2 Interviews

In addition to the literature study, personal interviews have been used to support the current status of geothermal reinjection. The reason for this was first of all to get in touch with first source opinions, and secondly due to the fact that some experiences are not always gathered and published in technical reports. However, the expressed experiences were all supported by publications.

The selection of interviewees was done based on a type selection (Larsson and Ekström, 2010). A type selection means that interview subjects are chosen based on characteristics that are relevant to the study. For this specific study, it was assumed that individuals with several years of experience in the geothermal industry, either through academic research or as a private developer, will have some type of opinion with regards to reinjection to share. Based on this premise, experts of each country were asked to participate for an interview.

According to Larsson and Ekström, a qualitative interview study is suited for studies in which a deeper understanding of a subject is desired (Larsson and Ekström, 2010). Since the reason for the interviews was to gather a deeper understanding of the public view on reinjection, a qualitative rather than a quantitative interview method was chosen. In addition, a good qualitative interview study usually contains 15 ± 10 subjects (Kvale and Brinkmann, 2014). A a total of 8 subjects were interviewed in this study, which matches this idea. Some subjects were asked specifically whether they wanted to participate, while others were found through an open inquiry for geothermal reinjection expertise on an online forum. All subjects were contacted for private interviews. The chosen experts can be found in table 2.

Table 2. List of interview subjects.

<table>
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<th>Name</th>
<th>Country</th>
<th>Profession</th>
<th>Company/Association</th>
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<tbody>
<tr>
<td>Guðni Axelsson</td>
<td>Iceland</td>
<td>Director Geothermal Training</td>
<td>ISOR (Iceland GeoSurvey)</td>
</tr>
<tr>
<td>María Guðmundsdóttir</td>
<td>Iceland</td>
<td>Specialist in Geothermal Utilization</td>
<td>Orkustofnun (Icelandic National Energy Authority)</td>
</tr>
<tr>
<td>Hrefna Kristmansdóttir</td>
<td>Iceland</td>
<td>Professor emeritus in Geology</td>
<td>Freelance consultant</td>
</tr>
<tr>
<td>Bjarni Palsson</td>
<td>Iceland</td>
<td>Manager Geothermal Department</td>
<td>Landsvirkjun</td>
</tr>
<tr>
<td>Hugh O’Keefee</td>
<td>Japan</td>
<td>Geologist</td>
<td>Baseload Power Japan</td>
</tr>
<tr>
<td>Paul Siratovich</td>
<td>New Zealand</td>
<td>Geothermal Scientist &amp; Director of operations</td>
<td>Upflow Ltd</td>
</tr>
<tr>
<td>Matt Uddenberg</td>
<td>USA</td>
<td>Geothermal consultant and researcher</td>
<td>Stravan Consulting LLC and Hotrock Energy Research Organization</td>
</tr>
<tr>
<td>Arwin Palad</td>
<td>Philippines</td>
<td>Operations Engineer</td>
<td>Shell Philippines Exploration</td>
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The interviews were made either through personal meetings or through email contact. To get the most valuable information out of the interviews, a semi-structured interview method was chosen. Based on the semi-structured interview description by Kvale and Brinkmann, all interviewees were asked the same main questions. However, room was left for follow-up questions and open reasoning (Kvale and Brinkmann, 2014).

4.3 Compilation of data

After a general scanning of published data of technical reports as well as the two status reports mentioned in chapter 4.1., obstacles and benefits related to reinjection were summarized in the results.

In addition to that, a case study was compiled for Iceland, Japan, USA, New Zealand and the Philippines. The selection of countries was based on the fact that they all have an active and experienced geothermal industry. In addition, they all have varying geological settings and geothermal resources, which were thought to bring dimensions and width to the discussion.

The case studies present the experience of geothermal reinjection in each country supported by both technical reports as well as the interviews. In addition to the case studies, the legal framework regarding reinjection can be found summarized for each country in chapter 5.3.

5. Result

This chapter presents the results of this study. It includes the current obstacles and benefits related to reinjection. The results also include a summary of the legal framework in geothermal active countries and an elaborative case study for each country.

5.1 Current benefits of reinjection

This chapter includes a summarization of documented benefits and positive outcomes related to reinjection which have been identified and selected in this study. The summarized benefits of geothermal reinjection are pressure support, higher production rates and reduced pollution. These are presented below with no particular order.

5.1.1 Pressure support

As discussed in chapter 3.1.2, geothermal reservoirs are hot permeable rock containing fluids and/or gases. Since the fluids hold a pressure on all surrounding rock, a pressure decline in the reservoir is to be expected when they are brought up from the subsurface (Bodvarsson and Stefansson, 1989). In hot water resources, the pressure decline is usually noticed in a lowering of the reservoir's water level. The most common way for geothermal operators to work their way around this is to support the reservoir by reinjecting all or parts of the produced fluid.

To use reinjection as a mean to maintain the pressure in the reservoir not only means to maintain the original water level of a reservoir, it is also an effective way to discourage the possible inflow of cold groundwater (Axelsson, 2012). In fact, thermal
breakthroughs, i.e. induced cooling of a production well and/or geothermal reservoir, mentioned later in chapter 5.2.1, are not only caused by reinjection wells but can also happen due to colder groundwater water finding its way into a reservoir. The risk for this increase rapidly if the reservoir pressure has decreased due to excessive production. However, there are several reinjection strategies to avoid this problem. One effective way to provide additional pressure support to a system is by placing reinjection wells below the reservoir, the Ngatamariki binary geothermal power plant in New Zealand being one successful example (Legmann, 2015).

The risk of land subsidence, i.e. the lowering of the ground surface, is another reason to why pressure support of geothermal reservoirs is important (Bodvarsson and Stefansson, 1989). There are several cases where ground movement have been reported due to lowered reservoir pressure. In New Zealand, a subsidence of 11.6 m was observed in the Wairakei field in 1989 (Allis, 1980). However, this specific event was special in the meaning that it occurred outside of the production field and is also the largest subsidence event related to a geothermal power station to date (Stefansson, 1997). In other fields in New Zealand, e.g. Broadlands and Kaweru, a total subsidence of 30 versus 25 cm was observed during a course of 8 and 12 years respectively (Allis, 1981). For both fields, added pressure support in the form of increased reinjection was an effective solution.

Another consequence that may happen due to pressure declines in reservoirs is harm on surface geothermal activity, such as hot spring and geysers (Bodvarsson and Stefansson, 1989). Since the feed zones of such are often connected to deeper geothermal systems, changes in those can affect systems higher up in the crust too. In other words, pressure decrease in a deep geothermal reservoir could have a direct impact on shallower systems as well.

5.1.2 Higher production rates

Large pressure declines of a geothermal reservoir will have a direct impact on the energy output of the production wells, i.e. on the net power produced by the power plant. Out of economic reasons, it is therefore of interest for geothermal operators to maintain a sustainable pressure in the reservoir. In addition, some operators choose to increase the original reservoir pressure in order to increase production rates. This method has been adapted from the oil industry (Cheremisinoff and Rosenfeld, 2009).

For some geothermal fields, production would not be possible without reinjection, e.g. in some low permeability geothermal fields where the natural recharge is very limited (Axelsson, 2012). In other fields, reinjection is a way to increase production rates and thereby the net power output of the power plant.

5.1.3 Reduced pollution (air and water)

As mentioned in chapter 3.2.1, reinjection of geothermal fluids was originally introduced as an effective way of disposing geothermal fluids in the ground rather than discharging them on the surface. Nowadays, reinjection is sometimes inevitable due to laws e.g. on water protection. In fact, some geothermal waters contain minerals and chemicals which are hazardous to ecosystems (Rivera et al., 2016). In addition, hot water discharge directly into surface water bodies, such as creeks and river, may lead to unwanted temperature increases. One example is the Krafla power station on Iceland, where algae and bacteria growth can be found in the river where the hot water is discharged from the power plant (Ármannsson and Ólafsson, 2002).
An actively discussed subject regarding geothermal energy is the emission of greenhouse gases from geothermal power plants, especially with regards to CO₂. In many power plants, mostly flash and dry steam plants, non-condensable gases (NCG’s) are released directly into the atmosphere after being separated from the steam. In other words, the amount of CO₂ which is released from those geothermal plants depend directly on the ratio of the NCG’s of their associated geothermal reservoir. For example, reservoirs sited in carbonate rich rocks usually have a very high CO₂ content.

Due to the NCG separation, the condensate which is reinjected from dry steam and flash plants is normally completely depleted from such gases. Over time, a natural consequence could be that these reservoirs will have a decline in gas-to-water ratio. However, this is an area of research which has not been studied sufficiently. In addition, public data on the subject is generally hard to find, probably due to the fact that operators are not obliged to share such information (Fridriksson et al., 2016).

During the past decade, there has been an increased interest in the handling of NCG’s from geothermal power plants, e.g. to use them in another way then by simply emitting them into the atmosphere - reinjection being one of them. The reinjection of NCG’s, e.g. CO₂, could both be done in a supercritical form, or by dissolving the NCG’s in the brine (Saldaña et al., 2016). This would more or less eliminate the emissions from geothermal power plants. However, to dissolve CO₂ in brine, or to keep a geothermal brine one-phased, requires a lot of pressure, i.e. power (Fridriksson et al., 2016). In other words, an added cost in terms of equipment and a parasitic load to the power plant. However, it has been attempted and proven possible e.g. in the Puna power station in Hawaii and Hellisheiði on Iceland (Fridriksson et al., 2016).

Some claim that the future of geothermal energy will be to fully reinject all NCG’s, e.g. by closed and completely pressurized systems (Stacey et al., 2016).

5.2 Current obstacles to successful reinjection

As Axelsson wrote in the report Role and Management of Geothermal Reinjection (2012) “some operational dangers and problems are associated with reinjection”. This chapter includes a summary of documented struggles and negative outcomes related to reinjection which have been identified and collected in this study.

The listed obstacles are scaling, cooling of production wells, induced seismicity, parasitic loads and finding the right reinjection strategy. These are presented below with no particular order.

5.2.1 Scaling

Geothermal water naturally contains a lot of dissolved solids, generally expressed as concentrations of total dissolved solids (TDS). The amount can range below 100 mg/L up to 300,000 mg/L for some high salinity fields, such as Salton Sea in the US (Pári, n.d.). When bringing up hot geothermal water from the subsurface, pressure and temperature conditions change, something which highly effect the saturation level of the dissolved minerals. The risk of mineral precipitation, e.g. scaling, is therefore always present during geothermal electricity production. The result can be damage to and clogging of wells and in surface equipment (Kaypakoğlu and Aksoy, 2012).
The most common type of scaling is calcite (CaCO₃) and silica (SiO₂), both with varying solubility properties. For example, the solubility of calcite increases with lower temperature, i.e. cold water can contain more dissolved calcite than hot water. The risk of calcite scaling related to reinjection is therefore low. However, silica scaling is one of the most common problems related to reinjection (Rivera et al., 2016). The reason for this has to do with the fact that the silica saturation index (SSI) is dependent on pH and temperature, and in general, silica is more soluble in water of high temperatures (Gunnlaugsson et al., 2014). It is therefore common for silica scaling to occur in reinjection wells, where the brine sometimes is significantly colder than the production temperature.

A common way to mitigate silica scaling is to design each power plant around the SSI, e.g. to never let the brine become colder than below the point of silica saturation. For example, an Icelandic rule of thumb to is to never let the water cool more than 100°C below its production temperature (Gunnlaugsson et al., 2014). Another common way to avoid silica scales is through acidification, i.e. to lower the pH of the geothermal water by adding acids (Guerra and Jacobo, 2012).

### 5.2.1 Cooling of production wells

Temperature drops of production wells or in a geothermal reservoir is another common phenomena in geothermal operations. However, it should be added that geothermal reservoirs are highly dynamic systems and that it is normal for temperatures to fluctuate by several degrees even on a daily basis.

However, induced cooling, i.e. thermal or cold-front breakthroughs, due to geothermal utilization is an issue which geothermal power plant operators try to avoid. A typical cause is when a reinjection well is too closely connected to a production well, either by distance or through flow paths (Rivera et al., 2016). This may lead to short-circuiting of the system, meaning that the cold reinjection fluids will make its way to the production area (Axelsson, 2012). This will lower the temperature of the production fluid and could also reduce the net power production.

When the cooling of a production well is discovered, the most common action is to change the reinjection strategy, e.g. by changing the location of the reinjection well. For example, the reinjection could be placed outfield instead of infield with regards to horizontal and vertical distance from the production area (Rivera et al., 2016).

The prevention of thermal breakthroughs is usually done by developing good models of the geothermal system, e.g. of its flow paths and natural recharge zones. For this, tracer testing, i.e. to inject traceable elements into the geothermal system, is by far the most common as well as powerful method (Axelsson, 2012). However, to map out underground flow paths is a quite complicated as well as expensive research.

Although there are several examples of where tracers have played an important part in successful reinjection modelling, there is evidently still some research left to be done (Rivera et al., 2016). For example, some tracer elements are not stable in higher temperatures which complicates their use in high enthalpy fields (Sajkowski et al., 2017). According to Axelsson, it is also the handling and modelling of tracer data that needs to develop further rather than only the actual tracers (Axelsson, 2012).
5.2.2 Induced seismicity

Induced seismicity can be defined as earthquakes caused by human action. In the oil and gas industry, induced seismicity is relatively common and normally related to large pressure declines in the reservoirs (Khan, 2010). However, in the geothermal industry, induced seismicity is rather related to high-rate reinjection of geothermal fluids. The can occur as bedrock near the reinjection wells cool, which in turn causes them to shrink and rub against nearby faults and/or fractures.

The Geysers (USA), Hellisheiði (Iceland) and Larderello (Italy) are all examples of locations where micro-earthquakes can be derived directly from the practice of geothermal reinjection (Bolognesi, 2011; Gunnarsson, 2011; Khan, 2010). However, no large earthquakes so far have been related to a geothermal power plant.

The forecasting of seismic events caused by geothermal operations is a complicated and fairly new topic of research. According to Gaucher et al., “only an integration of all current research and development efforts into measuring, monitoring, modelling, and matching will allow for the successful forecasting of induced seismicity in geothermal fields” (Gaucher et al., 2015). However, such large projects would be time consuming as well as costly, and further research is needed in several areas.

5.2.3 Parasitic loads

Most geothermal production wells are non-artesian, meaning that they do not flow freely but require pumps in order to bring geothermal fluids to the surface for energy extraction (Kaya and Mertoglu, 2005). In many hot water geothermal power plants, pumps are also used to pressurize the water so that it does not boil, i.e. “flash” and become two-phased, mostly in order to prevent scaling and corrosion. Another use of pumps is during the reinjection of geothermal water, where pumping power along with the force of gravity is used in order to put brine back into the subsurface (Verkís, 2014). The required pumping power may vary depending on reinjection strategy as well as the properties of the brine, e.g. non condensable gas (NCG) content and temperature.

One inevitable aspect of using geothermal pumps is that they have a negative impact on the net power production (DiPippo, 2012). Since the required power for the pumps decreases the amount of salable power, it is generally referred to as “parasitic load”. This also includes loads from e.g. cooling towers. At its highest, some plants have been recorded to lose up to 30-40% of its gross generated power to parasitic loads of which normally 5-10% is consumed by production and reinjection pumps (DiPippo, 2012).

In the past, some geothermal projects have been abandoned due to high parasitic loads from geothermal pumps. However, due to higher energy efficiencies as well as better resource modeling, most geothermal plants are able to compensate for their parasitic loads today. A study done by Verkís Consulting Engineers concluded that small and low temperature geothermal systems are more economically fragile with regards to their net production and high parasitic loads than large units in high temperatures (Verkís, 2014).
5.2.4 Finding the right strategy

There are several aspects of finding the ultimate strategy to reinjection. Although the position of the reinjection wells is the most crucial point, temperature, rate and magnitude are all factors which too will have an impact the success rate. Reinjection modelling, e.g. finding the ultimate position of the reinjection wells, is far from an easy task (Axelsson, 2012).

A weak reinjection strategy does not necessarily have to mean that scaling, cooling of production wells and/or induced seismic activity will occur. A weak reinjection strategy should rather be defined as when the purpose of reinjection is not fulfilled. For example, if the main purpose of reinjection is pressure support, but pressure levels decline despite reinjection, then the reinjection strategy could be defined as weak, or non-effective. If the purpose of reinjection is more about waste water disposal, but pollutive geothermal water is found to reach ground water bodies outside the production area, then the reinjection strategy could also be defined as weak.

As reported by Rivera et al. (2016), is common for power plants to change the reinjection strategy after production start. In some cases, the change of strategy is solely due to the dynamic change of the geothermal system, i.e. something inevitable. In others, it has been due to weak original reinjection strategies that have led to unforeseeable complications: Scaling, well cooling and seismic activity to mention a few.

5.3 Legal framework regarding reinjection

This chapter summarizes the legal framework for reinjection in chosen geothermal active countries, e.g. whether reinjection is required by law or not. For example, in the EU it is “within the competence of the national governments to decide whether reinjection of the geothermal fluid is required” (Dumas et al., 2013).

Although reinjection per se may not be required by law in many countries, it is usually required indirectly due to laws regulating surface water discharge (Saemundsson et al., 2011).

Table 3. The legal framework regarding reinjection of Iceland, Japan, USA, New Zealand and Philippines.

<table>
<thead>
<tr>
<th>Country</th>
<th>Legal framework regarding reinjection</th>
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<tbody>
<tr>
<td>Iceland</td>
<td>Reinjection is not specifically required. However, the licenses for power production contain restriction regarding the maximum water level drop in reservoirs (Ketilsson et al., 2015). In addition, there are regulations on the surface discharge of geothermal water.</td>
</tr>
<tr>
<td>Japan</td>
<td>Japan has largely adapted the geothermal regulation of their Hot Spring Law, which does not require reinjection for power plants below 2 MW (Masahiko, 2016). For larger power plants, the regulatory framework remains unclear.</td>
</tr>
<tr>
<td>USA</td>
<td>Reinjection is generally required by law, although it is up to each state to decide its local framework (Sato and Crocker, 1977).</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Geothermal operations are governed by the Resource Management Act since 1991, under which operating conditions for fields are set by the local governments, i.e. regional councils (Luketina, 2000). For</td>
</tr>
</tbody>
</table>
new fields, reinjection is more or less required by law. However, there are some fields where old framework is still in place that allow discharge of spent geothermal fluids into nearby rivers.

Philippines

Reinjection is not specifically required by law. However, there is a law pertaining to clean water act in which it prohibits the discharge material to find its way into bodies of water. Therefore, reinjection is practiced as a brine disposal method in nearly all geothermal fields (Palad, pers. comm).

5.4 Case studies/public opinions

This chapter presents the result from case studies on the situation regarding reinjection in five active geothermal countries: Iceland, Japan, USA, New Zealand and Japan. The case studies are supported by relevant published reports as well as personal experience from chosen experts in each country.

5.4.1 Iceland

As mentioned in chapter 4.3, Iceland has no legal framework which specifically requires reinjection. However, The National Energy Authority i.e. Orkustofnun (OS) issues geothermal licenses with detailed resource management requirements that must be met by each geothermal power plant operator (Ketilsson et al., 2015). In addition, each operator must annually present several monitoring data, e.g. water level changes, to Orkustofnun in order to keep their license. If the water level in the reservoir should go down beyond Orkustofnun’s limitation, “the license holder needs to re-evaluate the reservoir model, change the extraction levels within the area or increase reinjection into the same geological formation to maintain long-term water balance (Ketilsson et al., 2015)”. In addition, there are regulations on the discharge of geothermal water considering its potentially environmentally hazardous content.

According to Maria Guðmundsdóttir (Guðmundsdóttir, pers. comm), specialist in geothermal utilization at Orkustofnun, most power plants where reinjection is required for in Iceland are large and connected to high enthalpy systems. The main purpose of reinjection is resource and environment preservation. She confirms that for Iceland’s low enthalpy resources, the water is usually clean enough to be discharged on the surface. In addition, they normally have a high natural recharge, making reinjection less vital (Axelsson, 2012).

Although reinjection may technically be obliged, most power stations do not reinject all of the brought up water. For example, the district heating power plant in the Laugaland low enthalpy field discharges all of their used water in a district heating system. Around 20 – 25% of this water is later reinjected as “an important part of the management of the geothermal system” (Axelsson et al., 2001). The rest of the water is discharged on the surface. The reinjection, which started in 1997, was Iceland’s first case and led to an increased production as well as stable water-levels.

Another case of reinjection is in the Hofsstadir low enthalpy field, where reinjection started in 2006 at around 30 - 40% and is now up to 70 – 80% (Khalilabad and Axelsson, 2008). Thanks to reinjection, a trend in water-level decline, which went from a 50 m down to 150 m in only 7 years, was abruptly reversed and recovered, as can be seen in figure 2 (Axelsson, 2011).
Another example is Seltjarnarnes geothermal field, utilized through district heating by the suburb of Reykjavík, Seltjarnarnes. After being pumped up at around 50 l/s, the geothermal fluid of 95–120 °C is mixed with cold surface water in order to cool it down to 80 °C before using it in the heating system (Kristmannsdóttir et al., 2015). Any excess water is reinjected, although no large amounts. As reported, “the regional drawdown in the field has not increased for the last 20 years even though the production rate has increased slightly” (Kristmannsdóttir et al., 2015). In addition, there have been suggestions on whether to use the produced water in a binary cycle to produce electricity as a more energy efficient way to cool it down rather than the current method of cold-water mixing.

An example of a combined geothermal electricity and heating system is the small developing power plant Flúðaorka of 600 kW capacity connected to well KV-02 in the Reykjabol geothermal system. The current utilization plan is to extract water at around 40 l/s and carefully monitor the water table in the reservoir to see whether reinjection will necessary. Until then, the excess water will either be discharged into the nearby creek or connected to the heating system of the small nearby municipality of Hrunamannahreppur. It should be added that the water itself is clean enough with regards to that its discharge does not pose a threat to the environment. However, an earlier study on the site stated that “when water was pumped out of KV-02, the water level dropped in an area nearby” (R3207A Reykjabol, 2015).

In an interview on the subject with Guðni Axelsson, Director of Geothermal Training at ÍSOR, he explains that for small power plants, such as Flúðaorka, the water recharge may very well be enough to produce 30-40 l/s without drying out the resource completely (Axelsson, pers. comm). However, some type of initial water level drawdown should probably be expected, making the monitoring of the resource essential. Axelsson adds that for small power plants on Iceland, reinjection wells will probably not be drilled if they are not fully necessary. However, granted that drilling costs as well as monitoring techniques become cheaper and more sophisticated in the future, Axelsson believes that reinjection will be the norm also for small power stations.

Hrefna Kristmannsdóttir, Professor emeritus in Geothermal sciences and expert in

Figure 4. Water level changes of the Hofsstadir geothermal field during the years of 2000 – 2010 (x-axis). As reinjection started in 2006, a positive water-level change can be observed. Source:(Axelsson, 2011)
e.g. environmental impacts of geothermal development, expresses in a personal interview that reinjection should always be considered (Kristmansdóttir, pers. comm). Regarding the future, Kristmansdóttir shares Axelsson’s belief that probably all power plants will have reinjection wells as a natural part of their design. However, she would rather not see it required by law as there are some clear examples where it is simply not necessary – e.g. in Deildartunguhver geothermal field, the highest self-flowing hot spring system in Europe (Kristmannsdóttir et al., 2005).

Landsvirkjun, The National Power Company of Iceland, reinjects water at all three of their geothermal power stations – Krafla (60 MW), Theistareykir (90 MW) and Bjarnafjöll (3 MW). Although Krafla and Bjarnarfjöll both have old permits in which reinjection is not required by Orkustofnun, it is still practiced it in order to maintain pressure levels in the reservoir as well as to follow regulations.

Both Krafla and Bjarnarfjöll have been productive for a long time with a long and stable utilization record. However, reinjection has been far from problem free. At Krafla power station, the reinjection has been up to 90% in the past. Today however, due to issues especially related to silica scaling and cold-water breakthroughs, the reinjection is only at around 60%. The rest of the water is discharged into the nearby stream Hlíðardalslækur. In an interview with Bjarni Palsson, Manager of the Geothermal Department at Landsvirkjun, he states that the Landsvirkjun’s long-time goal is to reinject at 100% (Palsson, pers. comm). However, it is simply not possible today, silica scaling being the largest problem by far.

5.4.2 Japan

Japan has a long tradition of utilizing geothermal energy for recreational uses. The geothermal power potential is huge, estimated to be up to 33GW, but is currently only 0.2% of the total electricity mix (Yasukawa and Sasada, 2015).

The reason for the slow development could be for example that around 80% of the resources are estimated to be in restricted areas, such as protected national parks, but also due to community resistance. According to Yutaka Seki, executive managing director of the Japan Spa Association, some onsen (i.e. Japanese spa) operators in Japan believe that the natural recharge and also water quality of onsen hot springs could be impacted by geothermal power plants (McClure, 2019). One example which Seki mentions is the dried up Ebino Kogen hot springs in Kyushu, whose operator claim were depleted due to the nearby geothermal power plant. However, Seki adds, the reason for the depletion has not been studied.

As further reported by Masahiko Kaneko in the report Geothermal Energy Laws in the World, Japan is currently using the “Hot Spring Law, that was enacted to regulate small wells for thermal baths, [also] to regulate large-scale wells for geothermal power plants in Japan”. This is probably the reason that in Japan, reinjection is not required for power plants below the size of 2 MW. For example, a small 50kW binary plant was connected to the onsen at the Matsunoyama hot spring in 2010 (Yanagisawa et al., 2019). Geothermal water of 70°C < T < 120°C was used to produce electricity prior to discharging it for onsen use. However, the technical report does not mention any reinjection methods (Yanagisawa et al., 2019).

According to Hugh O’Keefe (O’Keefe, pers. comm), a geologist working for Baseload Power Japan who is involved in the development of low temperature resources in Japan, reinjection is not the norm for spa owners simply because the drilling for hot spring resources are usually very shallow and does not require reinjection. Although not obliged by law, O’Keefe says that out of sustainability and
resource protection reasons, reinjection will most likely be a part of the small-scale project which he is involved in.

There are several high temperature geothermal fields in Japan that apply reinjection as a part of their power plant design; Takigami, Mori, Otake and Onikobe are all interesting examples. Both Mori and Onikobe fields have reported temperature declines in their reservoirs connected to reinjection wells (Rivera et al., 2016). In Onikobe, the problem was solved by drilling the production wells deeper and further from the reinjection wells. However, the reinjection at the Mori field is still reported to result in both reservoir cooling and scaling of wells. In the Otake field, both positive pressure support and temperature declines have been experienced (Rivera et al., 2016).

Kaneko, previously mentioned, concludes that Japan has a need to enact “its own “Geothermal Energy Law,” of which objective is to control and to promote geothermal energy development, with reference of other country’s geothermal laws” (Masahiko, 2016).

For further discussions it should be added that in 2012, permission was given to develop small scale geothermal power plants in some previously restricted natural park areas (Yasukawa and Sasada, 2015).

5.4.3 USA

In the United States, reinjection is generally required by law, although it is up to each state to decide its local framework. In California, where the vast majority of US geothermal recourses are located, reinjection is required in order to get full property right of the resource (Sato and Crocker, 1977). In addition, it is a highly necessary part of production given the fact that California’s dry climate limits the natural recharge of the local geothermal fields.

The Geysers in California is the largest geothermal field in the world and perhaps also the most obvious example of a successful reinjection strategy. The power station started operating in 1960 but the production slowed down rapidly in 1987 due to major condensate decline in the reservoir (Khan, 2010). At that point, the reinjection rate was only at 25%. The solution, Khan writes, was to use the waste water of nearby cities as reinjection effluent, summing up to around 85% of production. The result was a “sustained steam production, a decrease in NCG’s, improved electric generation efficiency, and lower air emissions” (Khan, 2010)

A similar example is the Coso Geothermal Power Plant, also situated in California, where a pipeline was built in order to inject additional water from the surrounding area. However, Coso has also experienced induced seismicity, scaling and lowered power generation due to reinjection (Kaya et al., 2011; Rivera et al., 2016).

The Blue Mountain geothermal field is another example where reinjection is a crucial part of the power production. During 2009-2011, a temperature decline was observed connected to reinjection wells, and a decision to change injection strategy was taken. Based on a refined method of tracer testing, the 3D model of the reservoir was updated and a new take on the reinjection method managed to reduce the previous temperature declines by 70% (Swyer et al., 2016).

In an interview with Matt Uddenberg, one of the researchers who was a part of the Blue Mountain project, he expresses a confidence in that current reinjection technology is enough to do a fairly good job at creating functional reinjection systems, Blue Mountain being an example (Uddenberg, pers. comm). However, he admits that there are still a few missing pieces left to the puzzle of being
able to fully optimize it, cost being one factor. Another example which he mentions is a more effective way to map the flow pathways through faults and fractures between different wells, e.g. by tracers in targeted areas. For example, a cheaper and more sophisticated way is needed to decrease and increase the permeability of problematic vs. important flow paths, e.g. by reversible sealing agents.

Based on his research in North America, Uddenberg’s experience is that most geothermal power plants need reinjection as a part of their utilization plan. The rare exceptions would be in places where the natural recharge of the resource is very large, e.g. in some steam dominated reservoirs, or in areas with high self-flowing hot springs. In the cases of water dominated systems, Uddenberg confirms that reservoir pressure declines would occur rapidly directly after production start if no injection strategy is employed. In general, Uddenberg means that the question is how to reinject, not if.

5.4.4 New Zealand

In New Zealand, geothermal operations are governed by the Resource Management Act since 1991, under which operating conditions for fields are set by the local governments, i.e. regional councils (Luketina, 2000). Most fields have similar guidelines, but there are some power plants where the old framework is still in place. For example, the Kawerau and Wairakei field still have old resource consents that allow discharge of spent geothermal fluids into nearby rivers. However, for new fields it is more or less required by law to have some degree of injection, or at least it is heavily encouraged by the council (Luketina, 2000).

According to New Zealander geothermal geologist Paul Siratovich, surface discharge of geothermal water on New Zealand is beginning to be discontinued in favor of full reinjection (Siratovich, pers. comm). Siratovich adds that for most fields, reinjection is a critical part of reservoir management and is used as an effort to maintain high reservoir pressures and to “discourage the encroachment of colder groundwater”. One successful example is the increased reinjection at Wairakei power station which stopped a continued pressure decline in the Tauhara power station, both stations connected to the Wairakei-Tauhara geothermal field (Rivera et al., 2016).

Further, the negative consequences related to reinjection have been quite substantial also in New Zealand. Scaling and temperature declines appear to be by far the most common problems (Rivera et al., 2016). This is normally treated with acidification of the brine, but there are reported cases with wells clogging even with acid-dosed brine (Addison et al., 2015). Additionally, cold water breakthroughs from reinjection wells appears to be a significant problem in cases where wells intersect fractures that production wells also produce from.

Regarding improvements, Siratovich agrees that there is still work to be done, for example regarding the use of tracers (Siratovich, pers. comm). Previous research in New Zealand has e.g. focused on the thermal stability of some organic tracers under geothermal conditions (Sajkowski et al., 2017). Siratovich adds that the cost as well as implementation complexity of brine acidification is also an issue. In addition, he thinks that especially reservoir flow interaction from reinjection wells is a knowledge “under scrutiny”, and admits that a lot of work still needs to be done in fluid/rock interaction studies to give true clarity to how the brines react once put back into the reservoir. To summarize, Siratovich agrees that the geothermal industry “is doing
quite well at the moment”, but that there are still some barriers especially in reinjection technology that need to be overcome in order to make it perfect.

5.4.5 Philippines

The Philippines does not specifically require reinjection by law. However, there is a law pertaining to clean water act in which it prohibits the discharge material to find its way into bodies of water. Therefore, reinjection is practiced as a brine disposal method in nearly all geothermal fields (Palad, pers. comm).

Regarding Philippine experience of reinjection, two good examples are the Palipinon and Tongonan fields which both have been under exploitation since 1983 by the same company (Bayon and Ogena, 2005). The problems which have been encountered are especially related to high pressure draw downs in the reservoir, which in turn lead to “rapid return of injected brine into the production sector, affecting the output of production wells”. However, after several attempts and careful monitoring both fields now have relatively stable reservoir pressures as well as power generations. According to Bayon and Ogena, “injection-related problems have been encountered and overcome in both fields to date”. The same scenario of trial and error took place in the Mahanagdong geothermal field, where rapid induced cooling of the reservoir occurred before finding the right stable reinjection method (Salonga et al., 2004).

Thermal as well as mineral breakthroughs is a reoccurring consequence in reported Pilipino power plants (Kaya et al., 2011). However, successful pressure support is often mentioned as a positive outcome.

According to Arwin Palad, who has many years of experience as an operation engineer for geothermal projects in the Philippines, current reinjection technology is not enough in to reinject successfully, the biggest problem being scaling in the reinjection wells (Palad, pers. comm).

6. Discussion

One of the main claims to this report was to investigate the current debate on geothermal reinjection. However, during the course of the study is has become quite clear that most geothermal operators agree that reinjection, at least to some extent, is important. It is also evident that for many geothermal fields, full reinjection (i.e. 100% of the produced fluid) is simply not possible with today’s technology and/or knowledge. In addition, from a production point of view, full reinjection is in most cases not necessary. That being stated, the interesting question to discuss is whether full reinjection, NCG’s included, will be the norm in the future due to sustainable reasons, e.g. to reaching a geothermal industry goal of zero emissions.

It is clear from this study that not even top-player geothermal countries have a legal framework which specifically requires reinjection. Instead, regulations are generally focused on prohibiting surface discharge, or on geothermal reservoir health data. It could be argued that legislation which would make reinjection obligatory may speed up the development process and consequently the overcoming of technical obstacles. However, a required reinjection would probably also eliminate the development of small-scale power plants, where the drilling coast and parasitic loads of an added reinjection well would be ruinous. As brought up in chapter 5.4.1, for some fields on Iceland it may not make sense to reinject the brine simply because of the unique characteristics of the resource, such as a high natural recharge and fluids
of low chemical content. A possible scenario could be a law which adapts on different geothermal fields. These aforementioned Icelandic resources could then be a part of the rare cases where reinjection is not needed, nor should be required.

To comment on current reinjection strategies, it is clear that many geothermal operators use a form of trial-and-error method when it comes to finding the right method. In most cases, this is eventually successful but can be related to high costs. It would be interesting to study the magnitude of current reinjection failures (e.g. reservoir cooling, scaling, subsidence, induced seismicity, lack of pressure support etc.), i.e. lost money, which could be avoided by using the right current technology and knowledge. For example, it is possible that the depletion of onsen hot springs in Japan could have been avoided if the geothermal power plants had used better reinjection and modelling strategies. An addition to this is that the geothermal industry is still vastly fragmented, meaning that only a few large operators work internationally. It is possible that current knowledge has a need to be shared in a more widespread way.

However, the trial-and-error method in finding the right reinjection strategy should not be mistaken for the change in reinjection strategy which is often a necessary action in response to reservoir changes. Since the characteristics of a geothermal resource may change, both as a function of natural reasons and to the rate of production, so will the reinjection strategy, e.g. location and magnitude of reinjection wells, have to follow.

There are some recurring topics when it comes to technology and knowledge that may need further development in order to optimize current reinjection strategies. For example, the scaling and induced cooling of geothermal production wells appear to be by far the most common problems. As mentioned by both Uddenberg (chapter 5.4.3) and Siratovich (chapter 5.4.4), a better understanding as well as engineering of flow paths is needed. An example of such an improvement could be better and especially cheaper tracers, as well as tracer modelling methods, as mentioned by Axelsson (chapter 5.4.1). In addition, a better understanding of scaling and preventive methods would probably be a huge relief for geothermal operators worldwide. A theory could be that there is a need for methods that are tailored and designed for geothermal systems solely, in contrast to those which have been adopted from the oil and gas industry. For example, the separation and release of NCG’s is something which the geothermal industry could benefit greatly in developing another more sustainable method for.

Coming back to the original topic, i.e. whether full reinjection will be practiced as a norm in the future, it is evident that many factors need to be in place for that development to happen. Improvements in technology is definitely one. Development of legal framework may be another. For small binary power plants, more efficient and power saving ways to reinject is needed. However, in the future it is possible that they will be replaced completely by closed loop enhanced geothermal systems (EGS).

The sustainability of geothermal energy clearly comes with some reservations. It is possible that underdeveloped framework, both with regards to emissions and reinjection, has led to a gap in which geothermal operators have been allowed to utilize resources in an unsustainable way. Hopefully, this will not give geothermal energy a bad reputation. Although geothermal power plants which separate and release NCG’s into the atmosphere are far from the best examples of geothermal utilization, they are still a better alternative to fossil fuels.

Coming back to the Brundtland report and its definition of sustainable
development, if humanity has the ability to make the geothermal industry more environmentally friendly, zero emissions included, so should the goal be of today’s research as well as of future projects.

7. Conclusions

Based on this study, following conclusions can be made;

- Although not being problem free for geothermal operators, reinjection continues to be one of the best ways to maintain a sustainable geothermal production. Both from the perspective of maintaining a healthy resource, and with regards to reducing the global footprint. However, in some rare cases reinjection may not be needed from a resource perspective.

- Far from every power plant reinject a 100% of their geothermal effluent. Whether this would be the case if current reinjection methods were cheaper, better or safer is hard to tell. Although some geothermal operators claim that they would reinject fully if it were possible, it cannot be assumed for all. It’s possible that a more defined legal framework is needed.

- From an environmental perspective, the best scenario would be if power operators would reinject all of their produced fluid as well as their NCG’s. However, due to a variety of reasons, this is not possible today. For example, due to the high pumping power required, or the design of most two-phased power plants, or lack of suitable technology.

- Although current methods are enough to do a fairly good job, better technologies are needed in order for reinjection to be fully optimized. In addition, better technologies as well as research on the reinjection of NCG’s is needed in order for geothermal power plants to become more sustainable.

- It is possible that even with current technology, many geothermal power plants could lower their emissions if they would apply a better reinjection method or make better use of their NCG’s rather than just emitting them into the atmosphere.

- Since geothermal systems are dynamic resources, so should the reinjection strategies be as well. A sudden need for e.g. an added reinjection well or a changed reinjection location can appear even after several years of stable production. Although having been emphasized by many before, it is clear that careful monitoring of every resource is one of the most important part of geothermal energy utilization.

- The currently available best practice utilization of geothermal energy would be to have a one-phase closed system, where both brine and NCG’s are reinjected. However, such a system is likely to be threatened by high parasitic loads. Future solutions could possibly be closed loop EGS-systems.
• Although not free from emissions, geothermal power plants, dry steam and flash plants included, are a lot more environmentally friendly than traditional fossil fuel plants.

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**Appendix**

**Appendix.** Acronyms, abbreviations and important terms.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Aquifer</td>
<td>A body of permeable rock which is able to hold water.</td>
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<tr>
<td>Brine</td>
<td>The geothermal fluid and/or gas which is brought up from the geothermal reservoir.</td>
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<tr>
<td>Closed loop geothermal systems</td>
<td>A closed geothermal system where the brine is never in contact with the atmosphere.</td>
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<tr>
<td>Direct use</td>
<td>Using geothermal heat for direct uses, e.g. the heating of houses, spas and pools.</td>
</tr>
<tr>
<td>EGS</td>
<td>Enhanced Geothermal Systems. A developing technology to utilize geothermal reservoir that lacks current needed factors for geothermal utilization, such as hot fluid or permeability.</td>
</tr>
<tr>
<td>Geothermal operators</td>
<td>Owners/Operators of geothermal power plants.</td>
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<tr>
<td>g/kWh</td>
<td>Grams per kilo watt hour.</td>
</tr>
<tr>
<td>HDR</td>
<td>Hot Dry Rock. A geothermal energy system under development, which utilizes hot reservoirs which lacks fluid. Cold water is pumped into the reservoir which then vaporizes on the hot rock. The steam is then produced in a power plant.</td>
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<tr>
<td>MW</td>
<td>Mega watt.</td>
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<tr>
<td>NCG</td>
<td>Non-Condensable-Gases, e.g. CO₂, NH₃, N₂, H₂S etc. A natural part of geothermal fluids.</td>
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<tr>
<td>Thermal/Cold-front breakthrough</td>
<td>Induced cooling of a production well and/or geothermal reservoir.</td>
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<tr>
<td>Production well</td>
<td>The well which is used to bring geothermal fluids from the subsurface up to surface energy utilization, i.e. to the power plant.</td>
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<tr>
<td>Production temperature</td>
<td>The temperature at which the brine is pumped up from the subsurface, and on which the power plant extracts energy from.</td>
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<tr>
<td>Reinjection well</td>
<td>The well which is used to bring geothermal fluids (or other surface water) down back into the geothermal reservoir, post surface energy utilization.</td>
</tr>
<tr>
<td>Reinjection temperature</td>
<td>The temperature which the brine is pumped back into the reservoir, lower than production temperature.</td>
</tr>
<tr>
<td>Scaling</td>
<td>The precipitation of minerals which can cause a coating. This normally occurs in wells and equipment of geothermal power stations. It can also lead to clogging of reservoir flow paths.</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
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