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CARBFIX AND SULFIX IN GEOTHERMAL PRODUCTION, AND THE BLUE LAGOON IN ICELAND: GRINDAVÍK URBAN SETTLEMENT, AND VOLCANIC ACTIVITY

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Abstract. This article analyses ways to maintain reservoir sustainability in the area surrounding the Blue Lagoon in Iceland, near the urban settlement of Grindavík on the Reykjanes Peninsula in Iceland. The Svartsengi geothermal power plant operations have pioneered the simultaneous production of electricity and hot water from a geothermal reservoir. The Blue Lagoon is a warm geothermal pool using brine from the power plant. This paper reports on the processes and procedures at the Blue Lagoon and the Svartsengi power station, aimed at increasing sustainability of the geothermal resource by injecting the geothermal brine back to ground, to ensure the geothermal resource sustainability in the area. This paper also discusses and explains in details the reduction of greenhouse gas emissions from geothermal plant operations in Iceland. When the steam from a geothermal reservoir emerges from the ground, it comes up with enough energy to drive turbine generators for electricity production. However, this involves releasing several greenhouse gases into the atmosphere, including hydrogen sulphide (H_2S) and carbon dioxide (CO_2). This research spotlights a geothermal power plant in Hellisheiði, Iceland, and the use of the CarbFix procedure of capturing and storing carbon dioxide, reducing CO_2 emissions from the harnessing of geothermal resources for electricity. CarbFix is a carbon capture and storage (CCS) or carbon mineralization procedure aimed at binding CO_2 to rock. This procedure has been used at Hellisheiði power plant for the past decade in Iceland. Scientists have also developed the SulFix procedure, to capture sulphate H2S in ground. These procedures, SulFix and CarbFix, reduce outlet of greenhouse gases by storing them in basalt rock – also referred to as mineral carbonation or carbon capture and storage. This involves dissolving the greenhouse gases in water, and re-injecting them back into the ground through boreholes, in Hellisheiði. This current research also shows the geology in these areas and reports on calculations that have found re-injection of greenhouse gasses to ground to be economically feasible. The paper covers several scenarios that have already been tested to determine the financial feasibility of capture and storage. These have involved calculating the estimated internal rate of return (IRR), the return on investment (ROI) and the present value (NPV). Economic calculations have been made, showing the CarbFix project to be a feasible option contributing to decreased greenhouse gas emissions.

Key words: Greenhouse gas emissions, hydrogen sulphide, SulFix, carbon dioxide, geothermal energy, CO_2 fixation, CarbFix, carbon capture and storage, trade, urban planning, volcanic activity.

JEL Classifications: M21, R51, R52

1. Introduction

The Eurasian and North American plate boundaries run through Iceland, with their movement referred to as the continental drift. Recent volcanic activity on the Mid-Atlantic Ridge started in the area on March 19th, 2021, with volcanic eruption and lava flow.

This type of volcanic activity stresses the significant importance of taking threat into account in the infrastructure of the town Grindavík, where urban settlement initiative is supported by the neighbourhood of rich fishing resources. Also, it reflects on the concerns of having urban settlement in the form of town Grindavík in area, and the Blue Lagoon. Keeping in mind that although knowledge of the geothermal water utilization, this threat of volcanic activity has been considered insignificant. There has not been volcanic activity in this area for about 800 years. Not since around the days of

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Figure 1A. Volcanic Eruption on the Reykjanes Peninsula starting March 19, 2021

Source: Ágúst Kristjánsson (2021)

the great historian Snorri Sturluson, the author of "Snorra Edda" (Prose Edda) published around 1220, considered the most comprehensive source for modern information of Norse mythology. Geothermal resources from underground reservoirs in the area have beenare harnessed for decades to produce warm water for heating houses and swimming pools, and to generate electricity (Kristjánsdóttir, 2015). The focus is also on Iceland's famous Blue Lagoon near the urban settlement of Grindavík, and the geothermal power plant in Svartsengi.

Harnessing geothermal energy in this way also involves the releasing of biogases into the air the CarbFix procedure is employed at Hellisheiði power plant to reduce the environmental impact, also in the geothermal plant in Svartsengi scientists are developing a procedure to clean the gas, separate CO_2, and tap on gas containers (potentially for export) for general use of CO_2. CarbFix is a carbon capture and storage (CCS) or carbon mineralization procedure aimed at reducing CO_2 emissions from the harnessing of geothermal resources for electricity production by binding CO_2 to rock (Gíslason and Oelkers 2014; Ragnheiðardóttir et al. 2011). This procedure has been used at Hellisheiði power plant for the past decade in Iceland for the past decade, as well as the SulFix procedure (Gíslason et al. 2009; Gíslason and Oelkers 2014; Ragnheiðardóttir et al. 2011).

2. The Blue Lagoon and geothermal energy

The Blue Lagoon in Iceland was created from this brine, as is shown in Figures 2 and 3 (Gíslason et al. 2009; Gíslason and Oelkers 2014; Ragnheiðardóttir et al. 2011). Figure 4 shows where the Blue Lagoon is currently situated on the map of Iceland.

The Blue Lagoon was created out of brine of the Svartsengi Geothermal power plant, for the use of bathing. Brine is seawater, heated up in the reservoir. The salt in the reservoir in Svartsengi equals about 2/3 of the salt in the sea. Indicating that the liquid within the reservoir contains about 2/3 sea, and 1/3 fresh water.

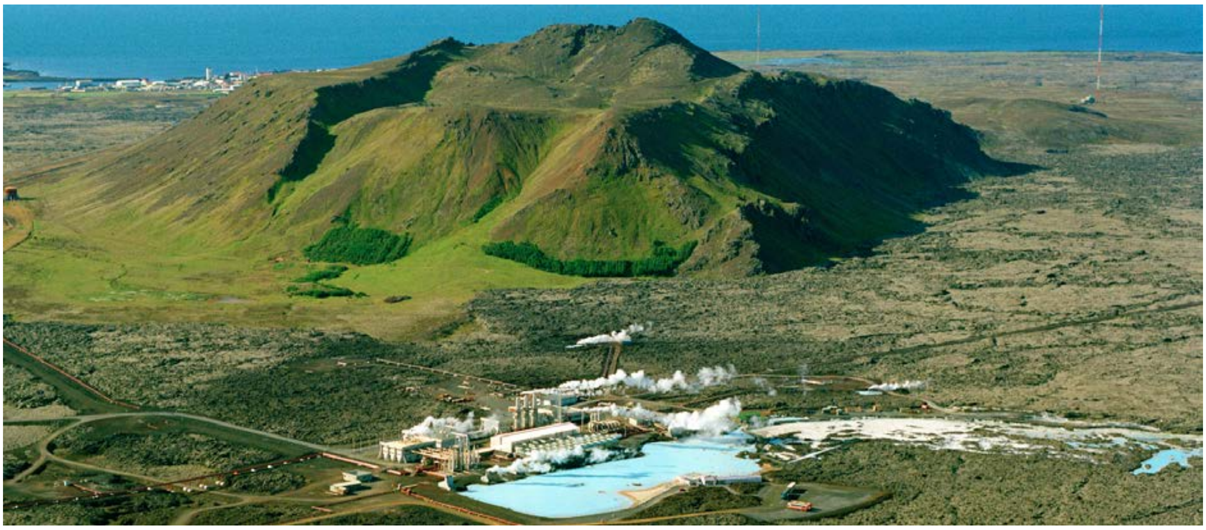

Figure 1B. Blue Lagoon, mountain Þorbjörn and town Grindavík This the Blue Lagoon setting was operated until 1999, next to the smoking geothermal plant in Svartsengi. The photo is interesting, showing mountain Þorbjörn and the fishing town Grindavík behind the mountain, next to sea. Currently, the Blue Lagoon is much further away from the geothermal plant

Source: Lund, 1993

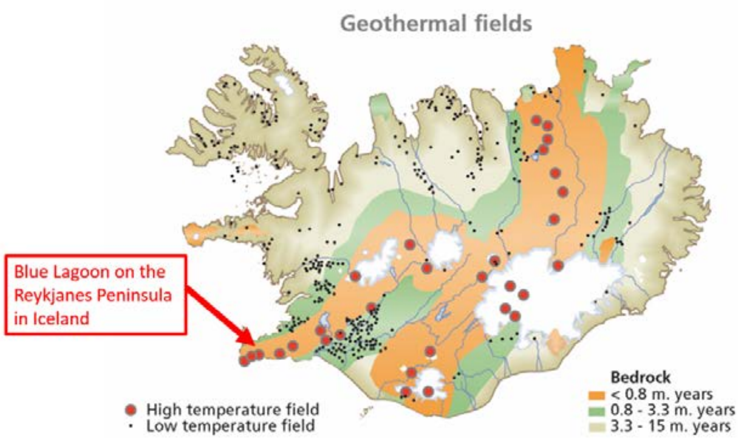

Figure 2. Man standing outside the Blue Lagoon Iceland. Author's photo (2014)

Figure 3. People bathing in the Blue Lagoon Iceland. Author's photo (2014)

Figure 4. Geothermal Fields in Iceland

Sources: National Energy Authority (2020) and authors' drawings

As the figure shows, the power station is located next to the dormant volcano Þorbjörn; on the other side of mountain Þorbjörn is the urban settlement of the fishing town Grindavík, currently with a population of 3500 people (Statistics Iceland, 2020). Grindavík urban settlement by the Vikings was impacted by the fact how close Grindavík is to the Mid-Atlantic ridge, visible on land on the Reykjanes Peninsula in Iceland. The geothermal project at Svartsengi can be characterized by three stages: the first stage is the prefeasibility stage, which is followed by the construction stage, and finally the operational stage. The harnessing of geothermal energy begins with the identification of an appropriate geothermal reservoir – a natural underground area that can provide warm water or wet steam depending on the reservoir temperature (Gíslason et al. 2009; Gíslason and Oelkers 2014; Ragnheiðardóttir et al. 2011). Other factors must be taken into consideration as well, such as the reservoir depth, fluid yield, and drilling conditions.

3. Geology CO_2 and H_2S storage

In the Hellisheidi mountain area in Iceland, the geothermal plant re-injects carbon dioxide CO_2 and hydrogen sulphide H_2S (Ragnheiðardóttir et al., 2011).

When the steam from a geothermal reservoir emerges from the ground, it comes up with enough energy to drive turbine generators for electricity production. However, this involves releasing several greenhouse

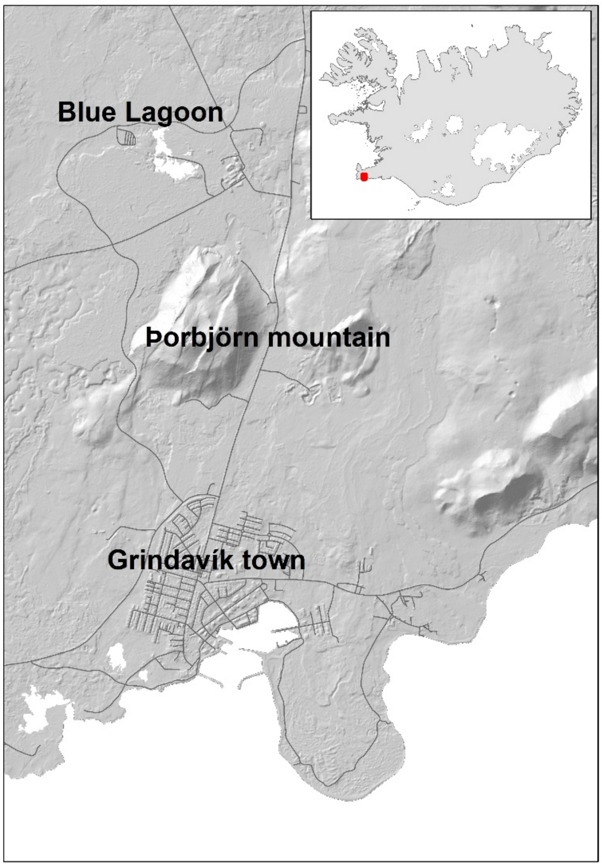

Figure 5. Showing map, a of Grindavík town, Þorbjörn mountain and Blue Lagoon

Source: National Land Survey of Iceland (2020a). Showing the street pattern of town Grindavík (Kristjánsdóttir S., 2015b, 2017, 2019b)

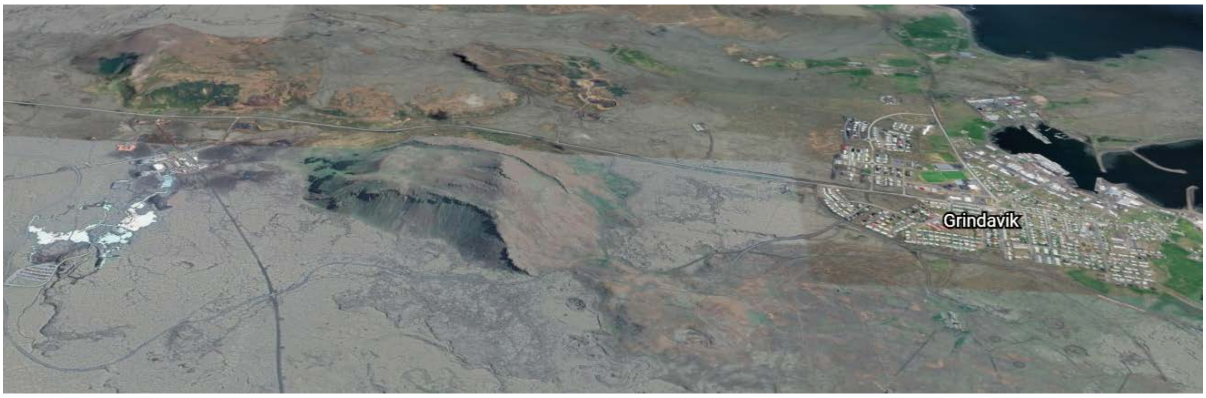

Figure 6. Another view of Grindavík, Þorbjörn and Blue Lagoon (Google Earth 2020).
The figure exhibits the 3-division figure reflecting on the nature in the lava area on the Reykjanes peninsula

Figure 7. Shows current zoom-in on the Blue Lagoon area, before visible in Figure 6 (Google Earth, 2020). Through use of Google-Earth shows clearly the area where the Svartsengi Geothermal Power Plant is, and the Blue Lagoon.
The power plant constructions, roads and outlet water "outside Blue Lagoon" are also visible

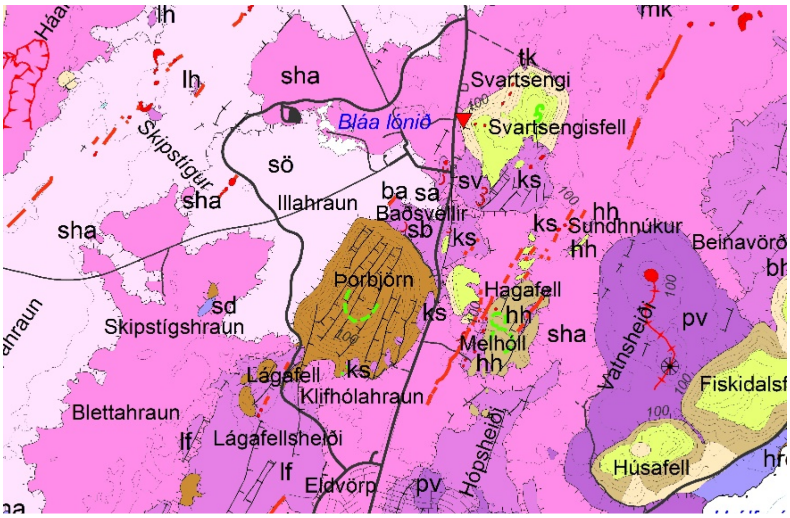

Figure 8. Showing the Blue Lagoon (Bláa Lónið) and mountain Þorbjörn, and the street pattern of town Grindavík. Geological Map of Southwest Iceland, 1:100 000 (2nd Ed.). Reykjavík: Iceland GeoSurvey

Source: Sæmundsson K., Sigurgeirsson M.Á., Hjartarson Á., Kaldal I., Kristinsson S.G. and Víkingsson S., 2016

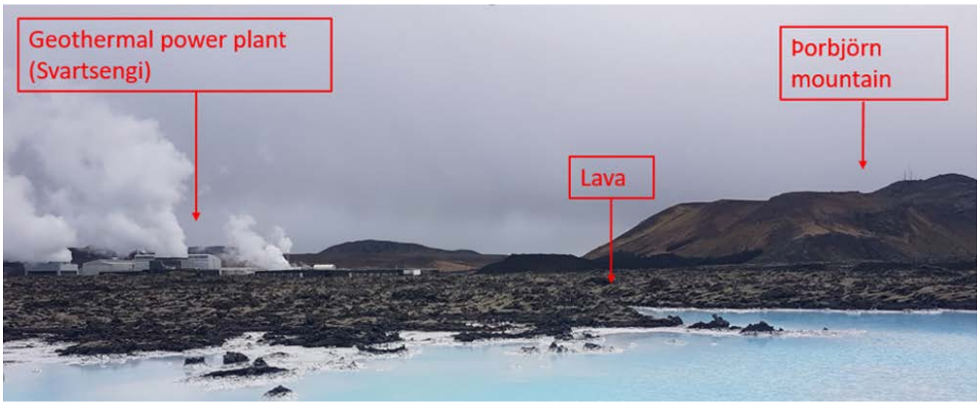

Figure 9. Blue Lagoon area

Source: Author's photo (2020)

gases into the atmosphere (Ragnheiðardóttir et al. 2011) including hydrogen sulphide (H_2S) and carbon dioxide (CO_2). With increasing environmental and climate change awareness, countries around the world are seeking ways to reduce H_2S and CO_2 emissions to slow global warming, (following e.g. the (1997) Kyoto Protocol to the United Nations Framework Convention on Climate Change). Correspondingly, scientists in Iceland have developed procedures in which greenhouse gases from geothermal power plants are returned into the geothermal reservoir, where they are bound in the basalt bedrock (Gíslason et al. 2009; Gíslason and Oelkers 2014; Ragnheiðardóttir et al. 2011). This is done to reduce emissions and sustain the pressure in the reservoir, making the geothermal resource more sustainable. This paper focuses specifically on two such procedures, the CarbFix and SulFix procedures (Ragnheiðardóttir et al., 2011; CarbFix, 2020), currently employed at the Hellisheiði Geothermal Power Plant.

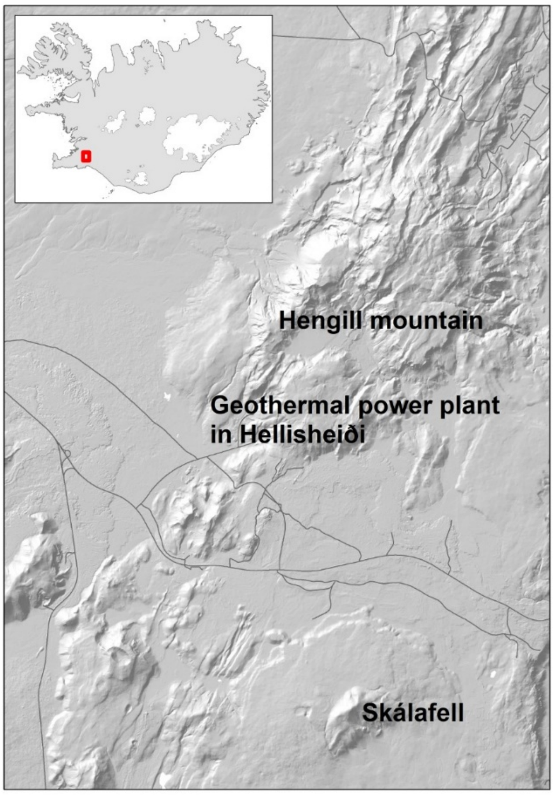

Figure 10. Showing map of the geothermal power plant in Hellisheiði, referred to as

Source: National Land Survey of Iceland (2020b)

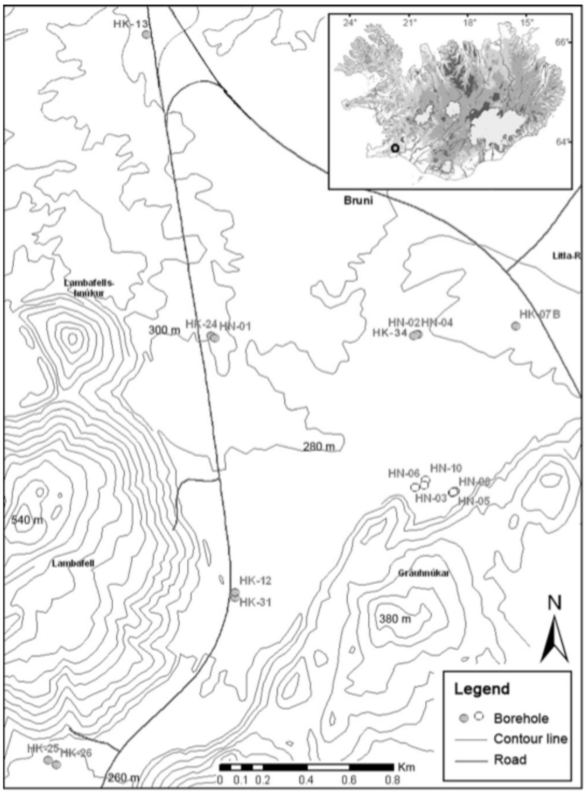

Figure 11. Shows the geology near Hellisheiði geothermal plant on Hellisheidi in Iceland

Source: (Ragnheiðardóttir, Sigurðardóttir, Kristjánsdóttir, Harvey, 2011)

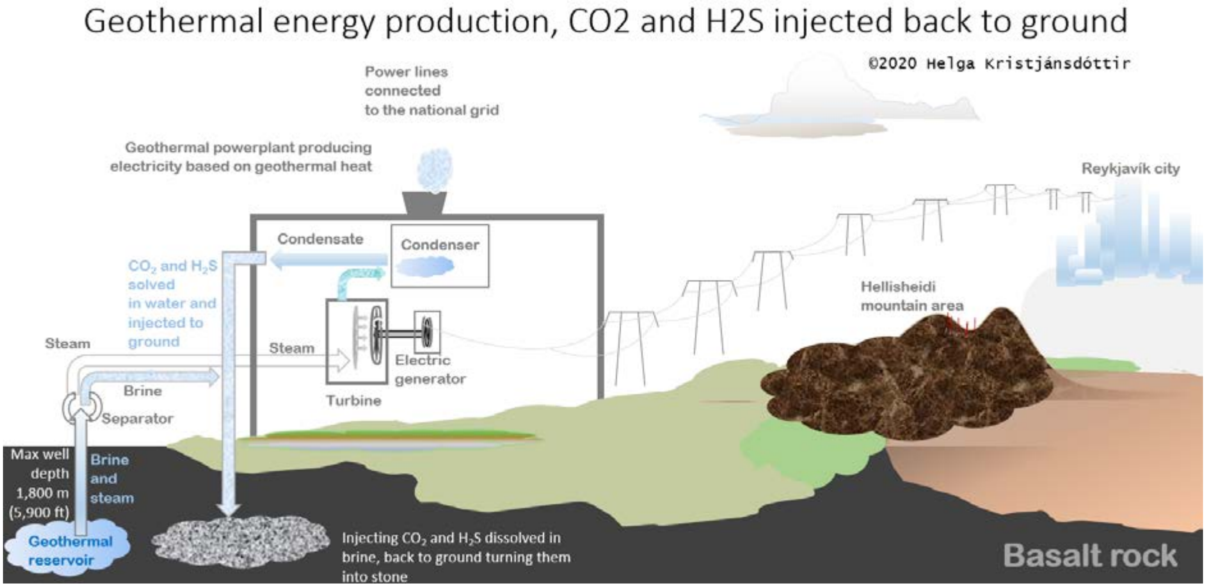

Figure 12. Geothermal energy production and injection to ground. Figure 12 exhibits how geothermal energy is produced at Hellisheiði, through the harnessing of steam from the ground, making this a clean and sustainable way of producing electricity. As the steam makes its way through the powerhouse, goes through the condenser and becomes a condensate, the steam cools down and is transformed into outlet water, referred to as "brine". There are two outlet streams, brine or condensate

Source: Author's drownings (2020)

4. The injection process

The CarbFix procedure involves taking greenhouse gases from the geothermal steam and dissolving them in water under high pressure, then injecting them into porous basalt rock at a depth of 500 to 800 metres (Koukouzas et al. 2019). The basalt acts like a sponge and captures CO_2 for permanent storage in the ground. At Hellisheiðarvirkjun, a geothermal plant of Reykjavik Energy, this procedure currently binds about 33 tons of CO_2 every day to rock each day (Ragnheiðardóttir et al. 2011).

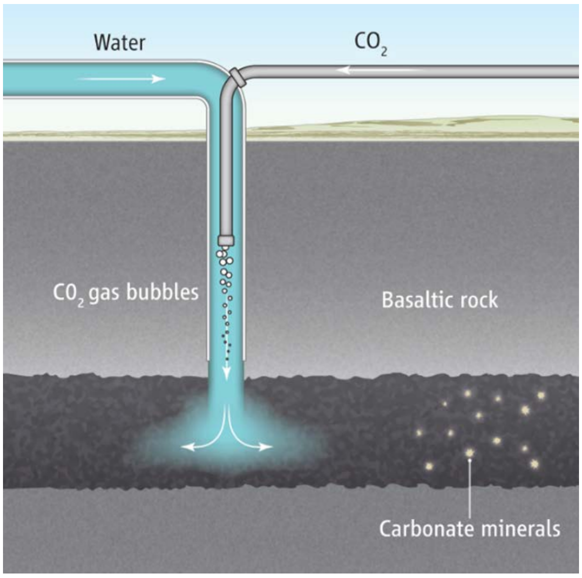

Figure 13. Shows CO_2 injection into basaltic rock, in Hellisheiði geothermal plant

Source: (Gíslason and Oelkers, 2014)

Equation [1] $(Fe^{2+}, Ca^{2+}, Mg^{2+}) + CO_2 + H_2O =$
$= (Fe, Ca, Mg)CO_3 + 2H^+$

Equation [1] shows the relationship between chemical factors and the chemical reaction when CO_2 is injected into the bedrock after being dissolved in water. It is attached in the bedrock iron via a process called mineralization (Rosenbauer et al. 2012; Gíslason and Oelkers 2014; Alfredsson et al. 2013; Gaus 2010; Gíslason et al. 2014; Gíslason et al. 2010). When H2S and CO_2 are dissolved in water and rushed down the injection wells, they bind with basalt rock over time, and form minerals. For every tonne of carbon dioxide bound in the bedrock, an estimated 8.8 tonnes of basalt glass is required (Arnórsson 2003; Oelkers and Cole 2008; Gíslason et al. 2009).

5. Cost structure issues and analysis

The SulFix and CarbFix procedures have been analysed with the objective of estimating the potential cost of carbon capture and sequestration (CCS) projects (Giovanni and Richards 2010; Ragnheiðardóttir et al. 2011). SulFix in relation to CarbFix is similar in that it involves injecting a greenhouse gas to ground, as sulphate dissolved in water. When estimating geothermal project cost structure issues, interest has been estimated by the use of the CAPEX ***capital expenditure***, and the OPEX ***operating expense*** (Kristjánsdóttir and Margeirsson 2015).

Figure 14. Author, Helga Kristjánsdóttir, at the Volcanic mountain March 27, 2021

Cost analysis for these kinds of procedures must take several factors into consideration. These include the ***capital costs*** (the fixed costs of setting up operations) (Kristjánsdóttir 2014a, 2015a) and the ***variable costs*** (the costs that change with increased production). The ***internal rate of return***, or interest rate, is the discount rate resulting in the ***net present value*** (NPV) of a particular project being equal to zero. The ***net present value*** (NPV) is modelled to estimate cash flow in the future, taking the time value of money (TVM) into account. To compare the economic benefits of different investment projects, analysts have used the ***internal rate of return*** (IRR) to determine which projects are beneficial financially. For financial calculations, investors are also interested in the ***return on investment*** (ROI), since it shows the financial return on a particular investment, determined by the interest rates applied.

Findings show that the initial cost is mostly in the form of capital costs, after which the variable cost becomes more significant, making the investment feasible after 30 years of operation, with costs of the CarbFix project have been evaluated by Ragnheiðardóttir et al. (2011) by calculating the present value, IRR and EURIBOR (the Euro Interbank Offer Rate). These factors are important regarding both domestic and foreign investment (Kristjánsdóttir 2010, 2012, 2013, 2014, 2020; Kristjánsdóttir and Óskarsdóttir 2020; Kristjánsdóttir and Margeirsson 2020), also a factor like culture (Kristjánsdóttir et al. 2017, 2020; Kristjánsdóttir and Karlsdóttir, 2020). Researchers have found that, when injecting CO_2 back into the earth, approximately 80% or more of the CO_2 binds to the earth basalt rock within a year (Gíslason and Oelkers 2014).

Scientists have developed several other capture and storage procedures, with the German power market as an example (Spiecker et al. 2014; Kelektsoglou 2018; Koukouzas et al. 2009; McGrail et al. 2006; Oelkers et al. 2008; Schaef et al. 2010). These procedures help countries attract more investment (Kristjánsdóttir 2019a, 2020) and become more competitive (Kristjánsdóttir 2017).

6. Summary and conclusions

The Blue Lagoon in Iceland is created using brine from the Svartsengi geothermal power plant for bathing, near the urban settlement of Grindavík on the Reykjanes Peninsula in Iceland. Scientists have developed procedures to re-inject some of the brine from Svartsengi geothermal power plant back into the reservoir, to maintain the reservoir pressure and thus its sustainability. In addition, the focus is also on Hellisheiði geothermal power plant. Scientists have developed unique ways of dealing with the greenhouse gases coming out of the ground during the harnessing of geothermal water. These procedures, SulFix and CarbFix, fix H_2S and CO_2 in the rock, to reduce outlet of greenhouse gases by storing them in basalt rock – also referred to as mineral carbonation or carbon capture and storage. This involves dissolving the greenhouse gases in water, and re-injecting them back into the ground through boreholes, in Hellisheiði.

Moreover, in the neighbourhood of the Svartsengi power plant, in the neighbourhood of the Blue Lagoon, there is injection of brine to return to reservoir ad maintain pressure in reservoir.

The paper also covers several scenarios that have already been tested to determine the financial feasibility of capture and storage. These have involved calculating the estimated internal rate of return (IRR), the return on investment (ROI) and the present value (NPV). Calculations have shown the CarbFix project to be a feasible option contributing to decreased greenhouse gas emissions.

The objective of this article was to provide an overall picture of the operations and potential around geothermal areas. First, the article described how brine and steam are retrieved from boreholes to drive turbines for clean energy production. Second, it explained how the brine, and greenhouse gases dissolved in water are re-injected into the reservoir and then bound and stored in the basalt rock. Finally, it showed how these procedures represent an enduring and economically feasible solution.

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