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Project Silverstone: Reduction of CO_2 emissions by 95% at the Hellisheidi geothermal power plant, SW-Iceland

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ABSTRACT

The Silverstone Project will move the demonstrated Carbfix CO_2 mineral storage solution to full-scale at the ON Power Hellisheidi Geothermal Power Plant in SW-Iceland, enabling the world's first zero-emission geothermal combined heat and power production and advancing the technology for further reduction of CO_2 emissions from concentrated emission streams. The Carbfix technology involves dissolving otherwise emitted CO_2 in water in a dedicated capture plant and injecting into the basaltic bedrock for permanent mineral storage of the injected CO_2, where it mineralizes in less than two years through geochemical reactions. The Silverstone project will build on over a decade of experience gained by both Carbfix and ON Power at the Hellisheidi site. The timeline of the project spans from 2021 until 2030, with commissioning of the Silverstone capture plant planned early 2025. Full scale operations at Hellisheidi will deliver 10% of the emission reductions that Iceland's Climate Action Plan calls for by 2030 within the energy and industrial sectors, and furthermore provide a great potential for limiting geothermal gas emissions worldwide.

1. INTRODUCTION

The world is facing its biggest environmental crisis due to the rapid warming of the Earth's surface: 2011-2020 was the warmest decade recorded, with global average temperature reaching 1.1°C above pre-industrial levels in 2019. The leading cause of this rapid change in climate over the past half century is the increase in the amount of atmospheric greenhouse gases (GHG), mainly emitted by human activities with the major contributor being carbon dioxide (CO_2). The consequences of this rapid warming are already apparent with signs including diminished ice sheets and glacial retreats, sea level rise, ocean, and an increased number of extreme weather events. The continued emission of greenhouse gases will cause further warming of the atmosphere and oceans. This, in turn, will cause long-lasting changes in all components of the climate system with increased likelihood of severe, inescapable, and irreversible impacts for people and ecosystems.

In December 2015, the world's leaders signed the Paris Agreement with the aim to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5°C [1]. As part of this agreement the Icelandic government has released a Climate Action Plan [2] for Iceland pledging to reduce emissions by 40% by 2030, as part of a joint effort with the EU and Norway. The International Energy Agency (IEA) has stated that with increasing global energy demand, renewable energy needs to prevail over fossil fuels and energy usage be more efficient to be able to reach the Net-Zero goal by 2050, for example via the use of geothermal resources for district heating instead of fossil fuels, reducing CO_2 emissions significantly as well as air pollution [3].

Geothermal power is a renewable and clean energy source, the utilization of geothermal energy is nevertheless generally associated with emissions of geothermal gases, mainly CO_2 and hydrogen sulphide (H_2S). Geothermal power production reached 95,100 GWh/yr in 2020, a 23% growth since 2015 [4], with CO_2 emissions estimated to be on average 134 g/kWh [5]. Such emission rates for geothermal power plants are only just over 10% of those for coal fired power plants. The average value in Iceland is even lower, or about 27 g/kWh.

The Iceland's 2020 Climate Action Plan aims to lower the emissions derived from geothermal utilization even further and reduce CO_2 emissions from geothermal production by 47% by 2030 [2]. The Silverstone project will contribute significantly to this climate goal by capturing about 95% of the total CO_2 emissions from the Hellisheidi Geothermal Plant, Iceland's largest geothermal plant, which is located in SW-Iceland. Full scale operations at Hellisheidi will deliver 10% of the emission reductions that Iceland's Climate Action Plan calls for by 2030 within the energy and industrial sectors. The project is funded by the European Union's Innovation Fund and is a collaboration between ON Power, the owner and operator of the Hellisheidi Power Plant, and Carbfix which has developed a technology to capture CO_2 from the plant's emission stream and inject it into the basaltic bedrock at the site for permanent mineral storage of the injected CO_2. Here we report on the aim of the Silverstone project.

2. CO_2 EMISSION REDUCTIONS AT HELLISHEIDI POWER PLANT

The Hellisheidi geothermal plant is one of the largest geothermal plants in the world, with installed capacity of 303 MWe and 200 MWth. The plant currently produces annually about 37,000 tonnes of CO_2 and about 9,000 tonnes of H_2S out of the geothermal reservoir. The plant is owned and operated by ON Power, a subsidiary of Orkuveita Reykjavíkur (OR), which is owned principally by The City of Reykjavik. ON Power has firm focus on making the operations environmentally responsible, with the goal of reaching carbon neutrality by 2030. Capture and injection of CO_2 from the Hellisheidi Plant has taken place since 2014, and currently about 12,000 tonnes/yr of CO_2, along with about 6,000 tonnes/yr of H_2S are dissolved in water and injected back into the basaltic subsurface where they react with the subsurface rocks and mineralize for save and long-term storage [6].

The research and development of this method has been carried out by Carbfix. Carbfix was founded as a research collaboration between OR, the University of Iceland, CNRS in Toulouse and Columbia University in 2007. In 2020, Carbfix was founded as a subsidiary of OR. Carbfix has demonstrated the rapid mineralization of CO_2 through injection of dissolved CO_2 into basaltic rocks in Hellisheidi SW-Iceland since 2012.

2.1 The Carbfix Technology

The Carbfix technology accelerates natural processes that are known to regulate the long-term CO_2 concentrations in the atmosphere: Carbon mineralization proceeds through the reaction of water-dissolved CO_2 with rocks, notably mafic or ultramafic rocks, which contain high concentrations of divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}). By dissolving CO_2 in water, the risk of CO_2 leaking back to the atmosphere is negligible due to the higher density of the injected fluids, achieving immediate solubility trapping [7], and no cap rock is required above the storage formations.

The first pilot injection of CO_2 into the basaltic subsurface was carried out in Hellisheidi in 2012. There the CO_2 was dissolved in water during injection into permeable basalts at 500-800 m depth at about 35°C. Over 95% of the injected CO_2 was mineralized within 2 years at ambient temperatures, quantified using reactive and non-reactive tracers, and isotopes [8, 9]. With the injected CO_2 being rapidly transformed into minerals, it is permanently fixed and there is a negligible risk of it ever returning to the atmosphere. Furthermore, once mineralization has been confirmed, no further monitoring of the storage site is required. This fundamental difference, eliminating the risk of leakage, has significant advantages that have led to high public acceptance of the CO_2 injection in Hellisheidi [10].

The Carbfix technology relies on two utility streams for operation: Water and electricity. The water demand is minimized with increased partial pressure of the CO_2. The main advantage of the technology is that the process does not require any addition of chemicals, such as organic solvents, as required for example in CO_2 capture based on e.g. amine processes. The water supply required for dissolving the CO_2 is in some cases available in the form of effluent condensate water from the steam turbines, essentially a by-product of electricity generation. The water acts as a solvent and a carrier for the captured CO_2, leaving the CO_2 behind in the reservoir as solid carbonate minerals, and can then be extracted and recirculated. An added value of this process is that it allows for co-capture of other emission gases, such as sulfur which can be co-injected and mineralized.

Following the success of the initial Carbfix pilot injections in Hellisheidi, the project was scaled up starting in 2014 by capturing and injecting CO_2 and H_2S from the Hellisheidi plant, with a stepwise increase in quantity of the geothermal gases injected [6, 11]. The geothermal gases are captured directly from the power plant exhaust stream via dissolution into condensate from the plant's turbines in a scrubbing tower (Fig. 1). The resulting gas charged water is injected to about ~800 m depth into the basaltic reservoir at temperatures of ~250°C. Since the injected gas-charged fluid is acidic, it is strongly undersaturated with respect to the primary and secondary minerals of the basaltic reservoir, and hence no mineralisation occurs in the vicinity of the injection point [12]. This has been confirmed during current operations, as to date there is no sign of decreasing system injectivity since the initiation of the injection in 2014.

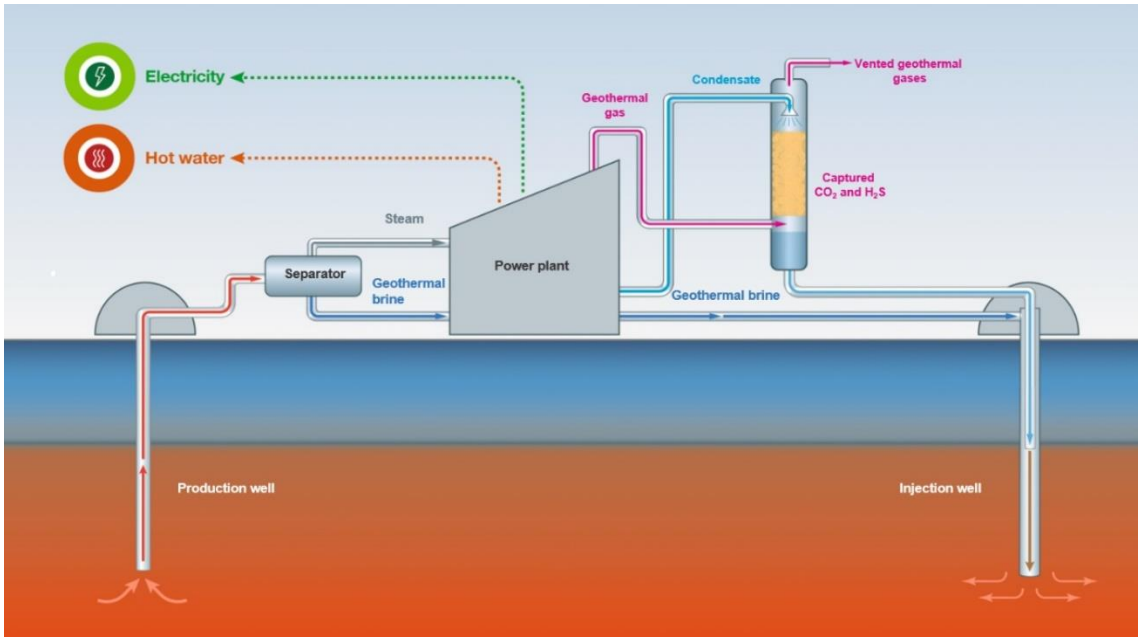

Figure 11: A schematic diagram of CO_2 and H_2S capture from the Hellisheidi Power Plant. Non-condensable geothermal gases are fed to the capture plant where the CO_2 and H_2S are dissolved in condensate water under pressure while other less soluble geothermal gases, such as hydrogen and nitrogen, are vented. The CO_2 and H_2S charged fluid is then injected into the storage reservoir to >800 meters depth and nearby monitoring wells will be used to monitor, verify, and validate the mineralization process using geochemical tracers.

The dissolution of the subsurface rocks through interaction with the gas-charged fluid gradually increases its pH to a range suitable for carbon mineralisation of the injected gases some distance from the injection. The process is monitored through geochemical sampling of a nearby monitoring well [13], as well as through extensive reservoir modelling [14]. As previously mentioned, about 12,000 tonnes of CO_2, or about one-third of the plant's CO_2 emissions are captured and injected annually, along with about 5,000 tonnes of H_2S, equivalent to about 75% of the plant's H_2S emissions [6]. To date about 90,000 tonnes of CO_2, and about 40,000 tonnes of H_2S have been injected for mineral storage at the Hellisheidi site. Furthermore, capture and injection of CO_2 and H_2S from a second geothermal plant owned and operated by ON Power, the Nesjavellir Geothermal Power Plant, is to be commissioned early 2023 [15]. Carbfix, along with ON Power, is working on the implementation of full-scale capture and injection from the Hellisheidi geothermal plant to be commissioned in 2025 as a part of the EU Innovation Fund funded Silverstone project.

3. THE SILVERSTONE PROJECT

The Silverstone Project will move the demonstrated Carbfix CO_2 mineral storage solution to full-scale at the ON Power Hellisheidi Geothermal Power Plant, enabling the world's first zero-emission geothermal combined heat and power production and advancing the technology for further reduction of CO_2 emissions from concentrated emission streams. This will be done through the design and construction of a new capture plant at the Hellisheidi Power Plant based on previous designs which will bring the capture efficiency to about 95% of the total CO_2 produced out of the reservoir at the plant, and about 99% of the H_2S.

The project will build on over a decade of experience gained by both Carbfix and ON Power at the Hellisheidi site, ensuring proper reservoir management and verification of the mineralisation process through best practice monitoring and modelling procedures. The monitoring strategy of Project Silverstone monitors the transport of the captured CO_2 towards the injection well, the conditions at the injection well, the chemical and physical reservoir response to the injection, and verifies the mineralisation process of the injected CO_2.

The Carbfix operations at Hellisheidi have reached a large audience and the technology has enjoyed high public acceptance. Likely reasons for its wide acceptance are that the Carbfix method is based on processes that already occur in nature, the rapid mineralisation, the elimination of the risk of CO_2 leakage, and the technology being born from the renewable geothermal energy sector. The results from polls indicate that an informed public will readily accept the upscaled climate action proposed within the Silverstone Project. To maintain this high acceptance rate and ensure open communication, active stakeholder engagement will be carried out throughout the lifetime of the project.

The timeline of the Silverstone project spans from 2021 until 2030 (Fig. 2). The project is divided into three phases: 1) Preparation phase (2021-2023), 2) Construction and commission phase (2023 to 2025), and 3) Operation phase (2025 to end of 2030). Each of the phases have defined milestones and deliverables, and continuous monitoring and management of project schedule, resource, cost, quality, and risks takes place throughout the project's lifetime

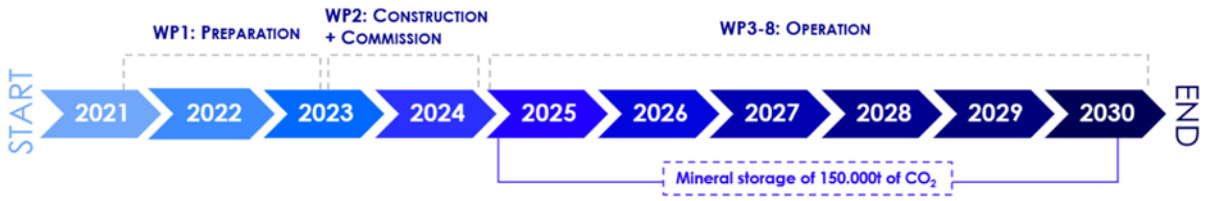

Figure 2: The Project Silverstone timeline

3.1 Preparation phase

The preparation phase of the Silverstone project started in 2021 and will continue until mid-2023. During this phase, necessary preparation for the construction and commission of the new capture plant and the increased injection of CO_2 and H_2S will take place. This includes the designing of the capture plant and relevant infrastructure (the front-end engineering and full design), tendering and procurement process as well as preparation of the construction phase of the capture plant at the Silverstone site. At the end of the preparation phase the project will be ready for the start of construction of the infrastructure on site following the final preparation of the construction.

Furthermore, new tracer tests have been carried out, and reservoir models have been used to evaluate the effect of the increased gas injection. These results will be used to design the injection strategy, including selection of which injection wells will be used for the injection of the gas-charged condensate, and design of the monitoring plan for the scaled-up injection. Other important tasks during the preparation phase are the application of permits, both on municipal and national levels, Environmental Impact Assessment (EIA) of the proposed CO_2 and H_2S injection, and active and constructive stakeholder engagement to secure the legal and social license of operation for the project.

The Silverstone project is a first-of-a-kind in many ways, both for the project partners through the development of the new capture plant and the increased injection of CO_2 and H_2S, as well as stakeholders such as the permitting bodies. This has required additional stakeholder engagement and communication between all parties.

One of the challenges of the project is the Icelandic legislation, which is somewhat lagging. The legislative framework was amended in early 2021 to allow for injection and storage of CO_2 in Iceland. This was done by transposing the CCS directive [16] into Icelandic law. This amendment resulted in changes to the EIA Act making injection of CO_2 and CO_2 storage sites subject to EIA. The legislation requires a new regulation on CO_2 injection and storage which should act as a guidance when applying for Injection and Storage Permit. This has posed some challenges in the development of the project, especially since the timeline is quite tight.

3.2 Construction and Commissioning phase:

The construction and commissioning phase starts mid-2023. During this phase, earthwork constructions will be finalized, followed by construction of the capture plant (Figure 3) and underground pipework. Process equipment will furthermore be installed and connected to the capture plant. Finally, the commissioning of the capture plant will start by testing all system components and training of personnel.

The construction work taking place within the Construction and Commissioning phase is based on the design work from the previous phase, with the objective of having all relevant infrastructure in place and all parts of the process tested and verified before timely launch of operations. At the end of the phase, in late 2024, Project Silverstone will be ready for the operational phase.



Figure 3: The proposed design of the Silverstone capture plant for full-scale capture of CO_2 and H_2S from the Hellisheidi Geothermal Power Plant.

3.3 Operational phase:

The Operational phase of the Silverstone project extends from the beginning of 2025 to mid-2030. At the beginning of the Operational phase of the Silverstone project, in the first quarter of 2025, the new capture plant and relevant infrastructure will start operations. All permits will have been secured and the monitoring strategy for the increased CO_2 and H_2S injection finalized.

By the end of the project in 2030, Project Silverstone will have captured and injected up to 150.000 tonnes of CO_2 for mineral storage and contributed to the Iceland climate goals through emission reduction from the geothermal sector.

4. THE GOAL OF THE SILVERSTONE PROJECT – TOWARDS ZERO EMISSION GEOTHERMAL PRODUCTION

The Hellisheidi site has been the flagship of CO_2 storage via mineralization since 2012, with the world's first injection of CO_2 into the basaltic subsurface. Since 2014, ON Power and Carbfix have pioneered in capturing and injecting geothermally derived CO_2, along with H_2S, from the Hellisheidi Geothermal Power Plant's emission stream.

The Silverstone Project will enable the next step of this collaboration with the development of a new capture plant making the Hellisheidi Geothermal Power Plant the world's first zero-emission geothermal combined heat and power production facility. Furthermore, the project will advance the demonstrated technology for further reduction of CO_2 emissions from concentrated emission streams worldwide.

The current world total emissions from geothermal activity are estimated to be ~10 $MtCO_2$/yr, and ~0.2 MtH_2S/yr, with the largest contributions from Italy, Turkey, United States, Mexico, and New Zealand [5]. As already apparent in Iceland's Climate Action Plans [2], the increased demand on emission reductions worldwide will involve CO_2 capture and storage from geothermal power production, especially from geothermal plants with high emission rates.

There is a great potential for limiting geothermal gas emissions worldwide: Estimates for storage potential of CO_2 and H_2S associated with geothermal power production reveal that almost all countries that utilize geothermal energy for power production have the potential of emission reductions via re-injection of these gases for permanent mineral storage [5]. In many instances the capture technology demonstrated through the Silverstone project can be applied in a safe and cost-effective way. The geothermal industry can benefit considerably from decades experience in terms of reservoir management and operation of gas-, steam- and water systems. Furthermore, the infrastructure in place at geothermal power plants can contribute significantly to the instalment of CO_2 capture and injection systems. This will ensure capture and injection of geothermal CO_2, and even H_2S for safe and permanent mineral storage in a cost-effective way.

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