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Carbfix – Rock Solid Climate Action

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ABSTRACT

Carbfix is the cost-effective and environmentally benign proprietary industrial technology to capture carbon dioxide (CO_2) and other sour gases from emission sources and permanently store it as solid minerals in the subsurface. The process can furthermore be applied in relation to direct capture of CO_2 from air. The technology was developed and proven at Hellisheidi geothermal power plant in Iceland where over 95% of CO_2 captured and injected was transformed into minerals in the subsurface in less than two years through natural processes. This contrasts the previous common view that mineral storage in carbon capture and storage (CCS) projects takes hundreds to thousands of years.

The Carbfix process has now been operated at an industrial scale at the Hellisheidi geothermal power plant since 2014. The process can be applied widely on a global scale in the power and industrial sectors and preparations are already underway to apply the process at several new sites in e.g. Iceland, Italy, Turkey and Germany, partly in relation to geothermal operations.

The Carbfix technology provides the geothermal sector with a proven, economic and environmentally benign solution to further decrease its carbon footprint which in turn increases the competitiveness of the sector. Carbfix provides interested parties with consulting and access to its rock-solid, proprietary climate solution.

1. INTRODUCTION

The climate crisis is a global challenge that does not respect national borders. It has already affected all countries and continents, is disrupting national economies and affecting people's livelihood. The poorest and most vulnerable nations are being affected the most, despite them having contributed the least to the problem (United Nations, 2018). Weather patterns are changing, sea levels are rising, oceans acidifying, and weather events are becoming more extreme as global greenhouse gas emissions continue to rise.

The immense benefits of limiting temperature increase to 1,5°C to 2°C have been demonstrated beyond doubt (e.g. IPCC, 2018). For us to reach this challenging but necessary goal, unprecedented changes in society are needed involving drastic climate actions by nations, cities, industries, businesses and individuals. Without such efforts, the world's average surface temperature rise is likely to surpass 3°C this century. Affordable, scalable solutions for reducing emissions are now available to enable countries to leapfrog to cleaner, more resilient economies. These include but are not limited to transitioning to renewable energy sources such as solar, wind and geothermal, carbon removal technologies and carbon capture, utilization and storage (CCUS).

In this paper we describe how over a period of seven years, Carbfix was transformed from an idea on paper to a fully operational, cost-effective and environmentally benign industrial process to capture carbon dioxide (CO_2) and hydrogen sulfide (H_2S) from emission sources and permanently store it as solid minerals in the subsurface. This rapid and successful innovation development was founded on an industry-academia collaboration led by Reykjavik Energy, with active involvement of interdisciplinary scientists, engineers and tradespeople. Next generation climate solution experts were simultaneously actively trained through undergraduate and graduate level research posts.

The idea behind Carbfix involves imitating and accelerating a natural process through which dissolved CO_2 and reactive rock formations interact to form thermodynamically stable carbonate minerals, thereby providing a permanent and environmentally benign carbon storage host. Silicate rocks rich in divalent metal cations such as basalts and ultramafic rocks are examples of favorable storage formations (Gíslason et al., 2010 and references therein).

This carbon mineralization process is very active in nature and provides the largest carbon reservoir on Earth (Gíslason and Oelkers, 2014). It has e.g. been estimated that just in the Hellisheidi geothermal field, the home of Carbfix, about 1650 megatons of CO_2 are being stored naturally (Wiese et al., 2008). This amounts to ca. 350-fold annual CO_2 emissions from Iceland in 2018 (The Environment Agency of Iceland, 2020).

Carbon storage in sedimentary basins typically proceeds via the injection of pure CO_2 into porous sedimentary rocks (Figure 1A) For common geothermal gradients, CO_2 is a supercritical fluid below 800 m in sedimentary basins. As supercritical CO_2 is less dense than the formation waters near this depth, it is buoyant and tends to rise to the surface. Ideally this CO_2 is trapped below an impermeable caprock via structural or stratigraphic trapping as shown on Figure 1A. In contrast, the Carbfix process involves dissolving CO_2 into water prior to or during its injection into the subsurface (Figure 1B). No caprock is required because the dissolved CO_2 is not buoyant and will not tend to migrate back to the surface (Gíslason and Oelkers, 2014; Sigfússon et al., 2015).

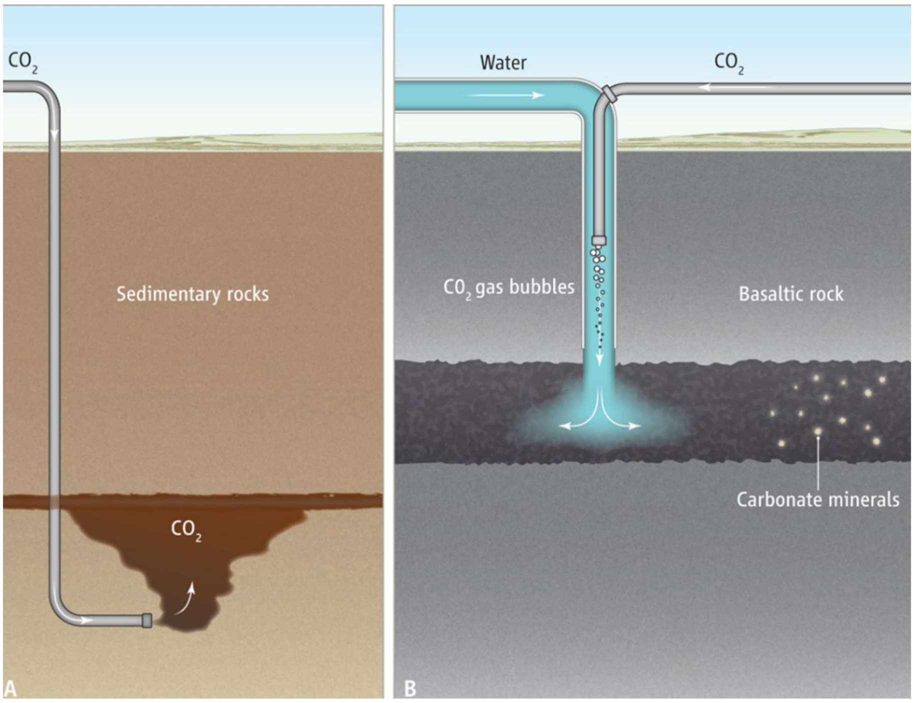

Figure 1: Schematic illustration of A) storage of supercritical CO_2 in sedimentary rocks in which buoyancy forces cause CO_2 to rise towards the surface unless storage formation is located beneath impermeable caprocks, and B) immediate solubility storage of CO_2 through the Carbfix injection process, which involves dissolving CO_2 into water prior to or during injection. No caprock is required in Carbfix because the dissolved CO_2 is not buoyant and will not tend to migrate back to the surface. Figure from Gíslason and Oelkers, (2014).

2. THE CARBFIX JOURNEY

The overall goal of Carbfix was manifested at the first Carbfix organization meeting held in October 2006 to create a demonstration project designed to show the world that CO_2 can be economically removed from the atmosphere and stored in basalt Since 2006, the Carbfix consortium has developed, designed and constructed methods, technology and equipment for capturing otherwise emitted CO_2, injecting the captured CO_2 into the subsurface and monitoring its fate. The work can be split into three stages; Preparation stage, Pilot phase operations and industrial scale operations.

2.1 Preparation stage

The preparation stage of Carbfix involved the design of methods and equipment, laboratory studies on primary and secondary minerals expected to participate in the carbon fixing reactions in the subsurface, background field hydrology and geochemical studies, numerical modelling and studies of natural analogues (e.g. Khalilabad et al., 2008; Alfredsson et al., 2013; Aradóttir et al. 2012; Gislason et al., 2010). To address all of these aspects the Carbfix consortium decided to involve a large number of PhD and MSc students. The involvement of these students held a number of advantages, the most important one being that through their training within the Carbfix project, it was possible to generate the human capital that would be able to apply the technology developed by Carbfix in the future. A list of the PhD and MSc students and projects completed as a part of Carbfix can be found in Gislason et al. (2018).

The preparation stage further involved a comprehensive licensing process, in which over ten permits were acquired for the intended field operations, some of which needed to be renewed on an annual basis throughout the pilot phase (Gíslason et al., 2018).

2.2 Pilot phase operations

A prerequisite for being able to carry out a pilot field scale injection at Hellisheidi was to capture CO_2 from the geothermal power plant‘s emissions. Emissions from the power plant are over 99,5% steam, while the remaining 0,5% by mass are geothermal gases, CO_2, H_2S and hydrogen (H_2). Original plans for gas capture at Hellisheidi involved a two-stage separation resulting in pure CO_2 and H_2S streams whereas the remaining H_2 was to be vented off. These plans were however abandoned and a single stage co-capture of CO_2 and H_2S was carried out in a pilot gas separation plant that that was constructed and began operations in 2012.

A calibration of the Carbfix pilot injection system was carried out in March 2011 with commercially bought pure CO_2. For the first few weeks of continuous gas injections at the site in January 2012, pure commercial CO_2 was injected to ca. 500 m depth into a basaltic storage formation of temperatures ranging from 20-30°C for the intended period of five weeks. In June 2012, injection of a

CO_2-H_2S gas mixture from the pilot gas capture plant commenced in the same reservoir. Unstable supply of gas from the capture plant caused some problems with injection but these were resolved through airlifting of the injection well. Plans had called for running the pilot phase continuously for some months until about 1000 tons of CO_2 had been injected. Unfortunately, the gas pipe that transported the gas from the gas capture plant to the injection site, located 3 km away, got damaged beyond repair due to nearby road construction, resulting in the death of the pilot injection before that goal was reached.

Solubility trapping occurs immediately during the CO_2 injection process (Sigfússon et al., 2015), and due to the reactivity of the basaltic rocks the bulk of the carbon is trapped rapidly in minerals. Despite the premature shutdown of the injection phase, a successful monitoring campaign followed which was based on the use of a cocktail of tracers that was co-injected with the gases. Through this comprehensive and innovative monitoring program, the team was able to prove that the Carbfix method turns over 95% of the aptured and injected CO_2 into stone in the subsurface in less than two years (Matter et al., 2016). This is a completely different time scale than previously reported for conventional CCS where mineralization takes place within the timeframe of hundreds to thousands of years if it happens at all (Figure 2a; Benson et al., 2005). CO_2 is predominantly sequestered into stable calcium carbonates as is explained in detail by Matter et al. (2016) and Snæbjörnsdóttir et al. (2017 and 2018). Detailed information on injection parameters and storage formation for pilot scale Carbfix operations at Hellisheidi can be found in Aradóttir et al. (2015), Matter et al. (2016), Snæbjörnsdóttir et al. (2017 and 2018) and references therein.

Through these exciting results, the perceived time scale of CCS in reactive rock formations such as basalt was changed, demonstrating that mineralization believed to take hundreds to thousands of years could proceed within just two years' time. This rapid carbonation of injected CO_2 provides a permanent and safe carbon storage option; once fixed into a carbonate mineral, the risk of leakage is non-existent and little if any further monitoring of the site will be necessary.

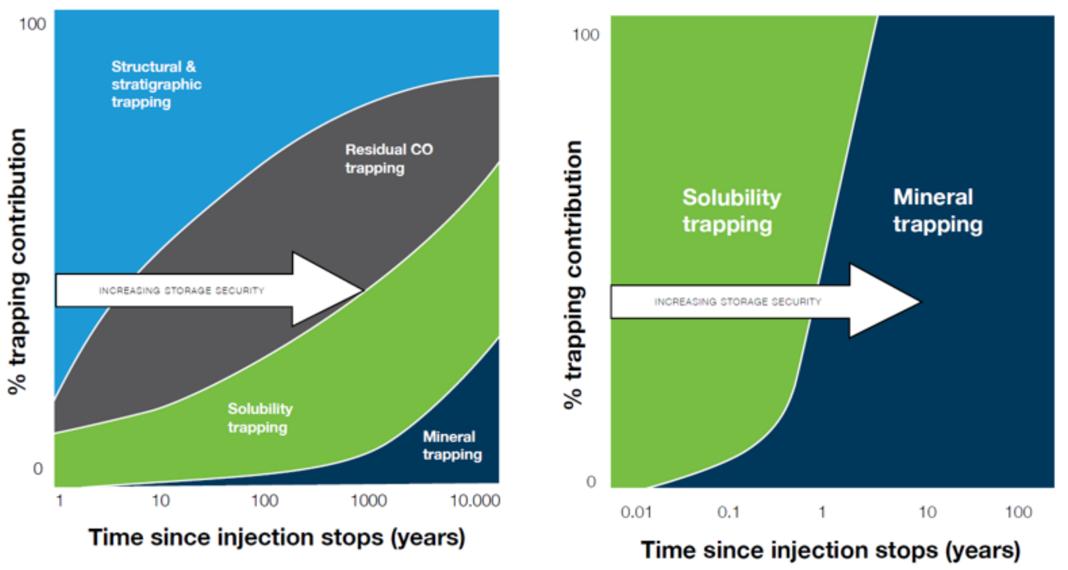

Figure 2: Schematic illustration of the contribution of various trapping mechanisms to the geologic storage as a function of time, a) injection of buoyant supercritical CO_2 into sedimentary rocks, modified from Benson et al. (2005), b) injection of CO_2 dissolved in water into basaltic rocks via the Carbfix method, modified from Snæbjörnsdóttir et al. (2017).

2.3 Industrial scale operations

Following successful Carbfix pilot operations and early indications of rapid mineral storage, it was decided to scale up CCS operations at ON Power's Hellisheidi power plant to industrial scale and simultaneously capture CO_2 and H_2S through a simple single-stage water scrubbing process. A full-scale capture plant for two of six high pressure turbines was constructed next to the turbine hall which began pilot industrial scale operations in 2014. The capture plant has been running continuously, more or less without incident ever since, with its capture capacity being doubled in 2016. Plans call for bringing the power plant's emissions down to near-zero in the coming years.

The aerial footprint of the CO_2 and H_2S capture and injection infrastructure at the Hellisheidi Power plant is small as shown in Figure 3. The only visible added infrastructure is the gas separation station shown with the red circle. Figure 4 shows a schematic illustration of how the CO_2 and H_2S capture was added to the pre-existing geothermal power process at the Hellisheidi Power Plant. Geothermal gases travel through the power plant process with the steam phase coming from production wells. The gases account for 0,5% of the steam phase by mass. After flowing through the turbines, the gas mixture is separated from the steam through condensers. Thereafter, the gas mixture, consisting predominantly of CO_2, H_2S and H_2, is transported to the gas capture plant where pressure is elevated before the gas flows into the bottom of its scrubbing tower. A shower of condensate is sprayed down the top of the scrubber. When these two phases meet while flowing in opposite directions, a large portion of CO_2 and H_2S is dissolved into the water phase. Water containing dissolved CO_2 and H_2S is then diverted towards the Húsmúli injection field (Ratouis et al., 2020a; Ratouis et al., 2020b and references therein), while the uncaptured H_2 together with remnants of CO_2 and H_2S and other geothermal gases are vented off through cooling towers.

For over six years, the Carbfix process has been operated at an industrial scale at the Hellisheidi power plant in Iceland and during this time capture of CO_2 and H_2S has steadily increased as shown in Figure 5. In 2020, about 12 thousand tons of CO_2 and 5 thousand tons of H_2S were captured and injected to >1000 m depth, or 33% and 75% of total emissions from the power plant, respectively. We observe the same rapid mineralization of both gases into carbonates and sulfides in industrial scale operations as we did in the pilot phase. And just as importantly, the permeability of gas injection wells has remained stable throughout the injection (Gunnarsson et al., 2018; Sigfússon et al., 2018). Detailed information on injection parameters and storage formation for industrial scale Carbfix operations at Hellisheidi can be found in Gunnarsson et al. (2018), Sigfússon et al. (2018), Clark et al. (2020), and references therein.

Figure 3: The aerial footprint of carbon and sulfur capture and injection infrastructure at Hellisheidi Power plant is small, with the only visible added infrastructure being the gas separation station shown within the red circle.

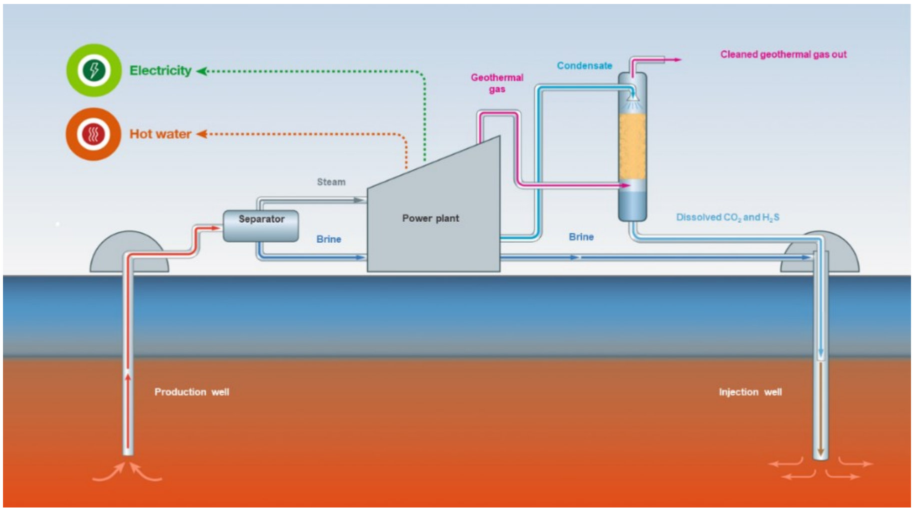

Figure 4: A schematic illustration of how the capture of CO_2 and H_2S was added to the pre-existing geothermal power process at Hellisheidi Power Plant.

3. COST OF CARBFIX OPERATIONS

Although it has been repeatedly shown that the cost of coping with climate change would be greater than the cost of preventing it, the cost of CCS operations has been a bottleneck for widespread application of this available technology for fighting climate change. A major advantage of the Carbfix CCS approach is its cost and safety relative to conventional technologies. The capture does not involve the separation of a pure and dry CO_2 phase; the process captures all water-soluble gases in a single step by its dissolution into water, which is then directly injected into the subsurface: The injection pressure of the Hellisheidi injection system is 9 bar-a. As a result, only water and electricity are needed for capture. The overall "on site cost" of this gas mixture capture, transport and storage at the Carbfix Hellisheidi site is US $24.8/ton (Figure 6). This number is comparable or lower than price of carbon quota in the EU Emission Trading System in 2020. Detailed information on "on-site cost" for operating Carbfix at Hellisheidi can be found in Gunnarsson et al. (2018).

By applying the Carbfix process to capture and mineralize H_2S, instead of conventional sulfur removal methods that involve either turning H_2S to elemental sulfur or sulfuric acid, significant economic benefits have been achieved. CapEx and OpEx of the Carbfix approach only amount to about 30% and 3% of conventional sulfur removal methods. Thus, Net Present Value of savings over a 20-year operation time account to 77-144 million EUR depending on the real discount rate used.

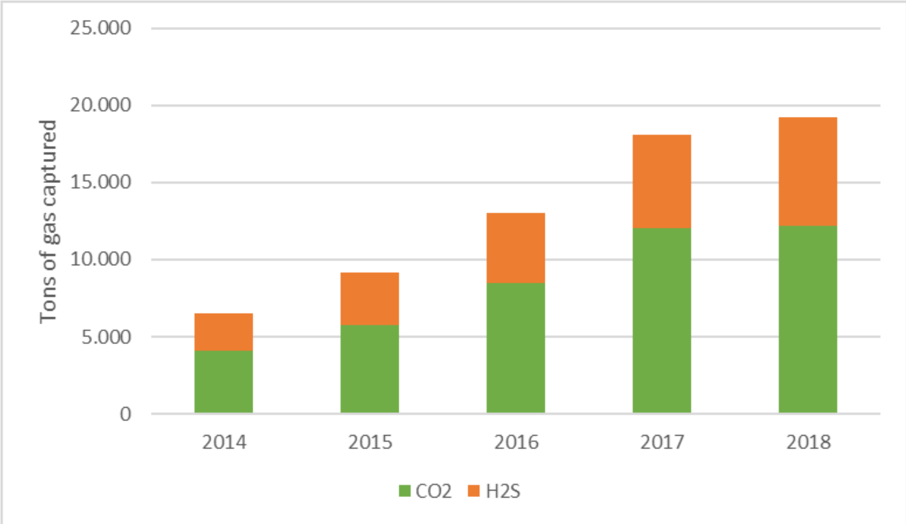

Figure 5: Amounts of CO_2 and H_2S captured on an annual basis since industrial scale Carbfix operations began at Hellisheidi in 2014.

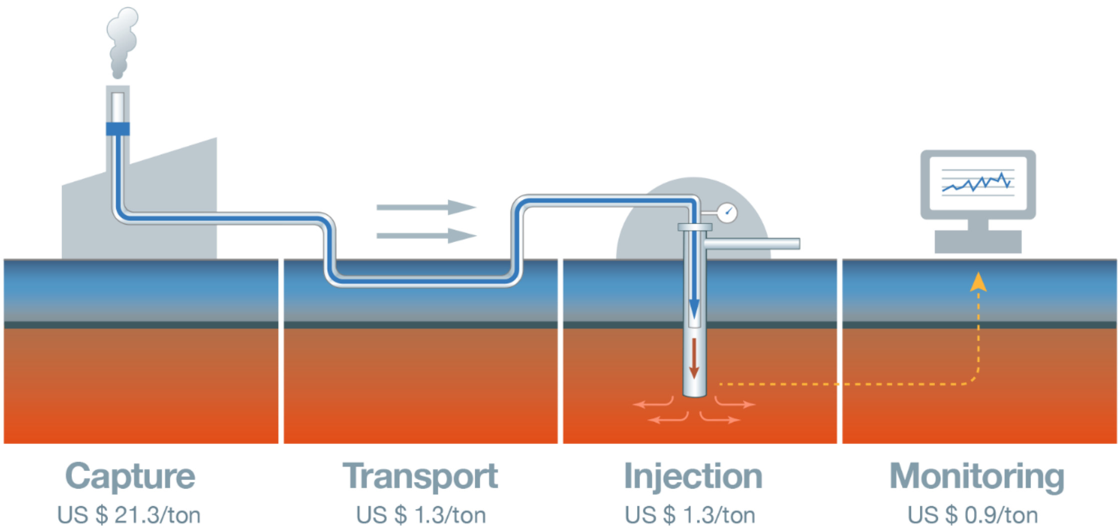

Figure 6: Schematic illustration of the running cost of CCS at the Carbfix Hellisheidi site. Costs are given in US$ per ton of gas mixture (CO_2 + H_2S) injected and assuming "on- site" existing infrastructure. Figure from Gunnarsson et al. (2018).

4. SOCIETAL READINESS AND ACCEPTANCE

Throughout its 13-year history, Carbfix has not met resistance from the public in relation to CCS activities. This is noteworthy, as the project's operations are located at Hellisheidi Geothermal Power Plant, which is close to the capital city of Reykjavik, and during development the power plant was contested and its operations scrutinized. It could even be argued that Carbfix has played an important part in increasing the Hellisheidi Plant's acceptance. An active and multilateral framework of stakeholder engagement and transparency in relation to industrial scale operations within Carbfix has played a vital role in achieving and maintaining this high level of public acceptance. Scientific transparency, open and continuous dissemination of information about the method globally, as well as active training of next generation scientists and engineers are among the actions that Carbfix and related activities have undertaken. For further information on stakeholder engagement and related issues we refer to Aradóttir and Hjálmarsson (2018).

5. GLOBAL IMPLICATIONS AND FURTHER CARBFIX DEVELOPMENT

The three factors needed for Carbfix to be a viable solution to reducing emissions at a specific location, are 1) favorable rock formations, 2) a source of water, and 3) a source of CO_2 captured from point sources or ambient air. Basalts and other favorable rock formations for the Carbfix process are among the most common rock types on Earth, covering a significant part of continental surfaces and most of the ocean floor. Altogether, the global storage capacity in such rocks is much larger than emissions from burning all fossil fuel available on Earth (Snæbjörnsdóttir, 2016; Snæbjörnsdóttir et al., 2020. We thus have plenty of viable storage formations. Furthermore, we have plenty of water – in fact over 70% of the surface on Earth is covered with water. Finally, we have more than enough CO_2.

Further development of the Carbfix process is currently being carried out on several fronts. Firstly, continued demonstration and scale-up of conjugate application of Carbfix in relation to direct capture of CO_2 from air (DAC) in collaboration with the Swiss company Climeworks (see e.g. Gutknecht et al, 2018 and Snæbjörnsdóttir et al., 2020). Secondly, Carbfix is being exported to new locations with different geological conditions than Iceland (basalts), i.e. in Italy (gneiss), Germany (sedimentary) and Turkey (Volcano-clastic/limestone) (Sigfússon et al, this volume) as well as to older basaltic formations than found in Hellisheidi. Thirdly, recently launched collaboration with heavy industry in Iceland aims at exploring the technical and financial feasibility of applying Carbfix to reduce emissions from non-ferrous metals production. Finally, the CarbFix team continues to further develop the process so that it can be applied in submarine basalts and other similar formations.

6. CONCLUSIONS

How we act now, and in the next few years, will profoundly affect life on Earth in the next few thousand years. Affordable, scalable climate solutions are now available to enable countries to leapfrog to cleaner, more resilient economies. Widespread, political actions and support are, however, vital to facilitate rapid uptake and roll-out of these solutions. The Carbfix process described in this paper is a proven, economic and environmentally benign solution to permanently reduce atmospheric CO_2 levels as well as reducing emissions from the power and industrial sectors. Application of Carbfix at Reykjavík Energy's geothermal power stations plays a leading role in the groups larger ambitious climate strategy which involves a commitment to bringing the group's carbon footprint to zero by 2030 (Hafthorsdottir et al., this volume). We challenge the global geothermal community to join us on the journey towards solving the climate crisis by applying Carbfix or similar methods for reducing emissions as well as putting broader climate strategies into place. There are no excuses not to take drastic and immediate actions towards that goal.

7. ACKNOWLEDGEMENTS

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