Institution: University College London

Unit of Assessment: 7 - Earth Sciences

Title of case study: The cost efficient capture and storage of carbon dioxide and sulphur with CarbFix for economic, environmental and societal impact.

Period when the underpinning research was undertaken: 2014 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Eric Oelkers	Professor of Aqueous Geochemistry	October 2013 - 2020

Period when the claimed impact occurred: 2014 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Professor Oelkers' team at UCL and international partners developed a novel, cost effective and environmentally safe carbon capture and storage method to capture and store carbon dioxide (CO_2) and hydrogen sulphide (H_2S) through the mineralisation of basaltic rocks - CarbFix. The method was first implemented at the Hellisheiði Power Plant in Iceland, resulting in approximately 33% of the CO_2 and 75% of the H_2S emissions from the plant being captured, which represents a financial saving of GBP23,500,000 for the company. The method was then adopted by countries around the world, with four more industrial scale carbon capture sites. Oelkers' research is reducing the burden of greenhouse gases on the environment, inspiring a new generation of scientists and informing updates to the UN's global environmental policy.

2. Underpinning research (indicative maximum 500 words)

Professor Oelkers (at UCL since 2013), together with collaborators at UCL, the University of Iceland, Centre National de la Recherche Scientifique (CNRS in France), the Earth Institute at Columbia University (USA) and Reykjavik Energy (Iceland), developed carbon capture and storage technology (CarbFix) using an efficient method based on the accelerated mineralization of injected acid gases in reactive subsurface rocks. The work of Oelkers and collaborators, conducted since 1999, on the interaction of water-dissolved carbon dioxide and basalts in the laboratory and in the field formed the scientific basis of the CarbFix technology. Measurement of the rate of basalt-fluid interaction in the laboratory and the development of models allowed the fate of carbon dioxide injected into the subsurface in response to mineral reactions to be predicted. Results showed carbon mineralization is the safest way of storing CO_2 in the subsurface (**R1**).

Following global concern about the effect of increasing carbon dioxide emissions on the global climate, efforts were made to explore the use of the technology by 1) selecting a pilot site, 2) focusing laboratory work on site-specific samples, and 3) performing detailed modelling on this selected pilot site. UCL researchers were involved in most of the scientific aspects of these efforts. Oelkers has co-directed this project since 2006 and contributed to designing the injection system, the water sampling system and the monitoring plan. 175t of pure CO_2 were injected into subsurface porous basalts from January to March 2012, and 73t of a gas mixture from the Hellisheiði power plant in Iceland consisting of 75mol% CO_2 and 25mol% H_2S were injected into subsurface porous basalts from June to August 2012 (**R2, R3**). In each case, the gases were dissolved into water during their injection (**R4**). Development of novel stable isotope applications at the UCL LOGIC mass spectroscopic facilities, in collaboration with Dr Philip Pogge von Strandmann (UCL), allowed the fate of the injected carbon to be verified (**R5**). A combination of chemical and tracer analyses, geochemical calculations, and physical evidence demonstrated that the injected gases

were fixed in minerals, notably calcite and pyrite, within 2 years of injection at 20-50°C (**R1, R3**). This stands out from other technologies, which require more than 100 years.

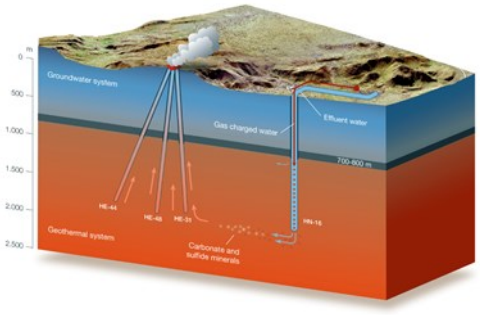

Fig. 1. Schematic illustration of the CarbFix2 injection site. Gas-charged water is injected to a depth of 750m, then enters the main feed zones at 1,900 and 2,200m depth in injection well HN-16. The fluid flows down a hydraulic pressure gradient to monitoring wells HE-31, HE-48, and HE-44, located 984, 1,356, and 1,482m away from the injection well at the reservoir depth.

Based on the success of the CarbFix2 injection, the process was extended to the economically viable capture and storage of all the acid gases emitted from the Hellisheiði power plant. By the end of 2017, 23,200t of CO_2 and 11,800t of H_2S had been injected to a depth of 750m into fractured, hydrothermally altered basalts (**R6**).

The fate of the injected gas mixture was monitored by the regular sampling of the three monitoring wells (Fig. 1). A combination of geochemical and chemical mass balance equations demonstrated that over 50% of the injected CO_2 and 75% of the injected H_2S were mineralized through water-gas-rock interaction during the three months required for its transport from the injection site/well to the monitoring wells (**R6**). The team calculated fluid saturation states showing that the fluids are at saturation or supersaturation with respect to calcite and pyrite in the reservoir (**R4**). Once mineralized, the risk of gas leakage to the surface is eliminated, thus enhancing storage security.

UCL researchers were directly involved in measuring fluid samples, performing the mass balance calculations and publicising the results for the body of research described in this Section.

3. References to the research (indicative maximum of six references)

R1. Gislason SR, **Oelkers EH.** (2014) Carbon Storage in Basalt. Science 344, 373-374. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science* 352, 1312-1314. DOI: 10.1126/science.1250828
R2. Snæbjörnsdóttir SÓ, **Oelkers EH**, Mesfin K, Aradottir ES, Dideriksen K, Gunnarsson I, Gunnlaugsson E, Matter JM, Stute M, Gislason SR. (2017) The chemistry and saturation states of subsurface fluids during the in situ mineralization of CO_2 and H_2S at the CarbFix site in SW-Iceland. Int. *J. of Greenh. Gas Cont*. 58. 87–102. DOI: 10.1016/j.ijggc.2017.01.007
R3. Sigfusson B, Gislason SR, Matter JM, Stute M, Gunnlaugsson E, Gunnarsson I, Aradottir ES, Sigurdardottir H, Mesfin K, Alfredsson HA, Wolff-Boenisch D, Arnarsson MT, **Oelkers EH.** (2015) Solving the carbon-dioxide buoyancy challenge: the design and field testing of a dissolved CO_2 injection system. *Int. J. Greenh. Gas Control* 37, 213–219. DOI: 10.1016/j.ijggc.2015.02.022
R4. Pogge von Strandmann PAE, Burton KW, Snaebjornsdottir SO, Sigfusson B, Aradottir, ES, Gunnarsson I, Alfredsson HA, Mesfin KG, **Oelkers EH**, Gislason SR. (2019) Rapid CO_2 mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes. *Nature Comm.* 10, 1983-1992. DOI: 10.1038/s41467-019-10003-8
R5. Clark DE, **Oelkers EH**, Gunnarsson I, Sigfússon B, Gíslason SR. (2020) CarbFix2: CO_2 and H_2S mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. *Geochimica et Cosmochimica Acta* 27915, 45-66. DOI: 10.1016/j.gca.2020.03.039
R6. Clark, D.E., **Oelkers, EH**, Gunnarsson, I., Sigfússon, B., Gíslason, S.R (2020) CarbFix2: CO2 and H2S mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. Geochimica et Cosmochimica Acta 27915, 45-66. DOI: 10.1016/j.gca.2020.03.039

4. Details of the impact (indicative maximum 750 words)

Professor Oelkers and his research group at UCL – based in the Department of Earth Sciences – conducted research in the field of carbon capture and storage (CCS) and the technology to capture and store CO_2 and H_2S through the mineralisation of basaltic rocks (CarbFix). This innovative technology has influenced policymakers and generated a plethora of impacts worldwide through commercial implementation in Iceland, Turkey, Italy and Germany, with strong environmental impact via direct capture of CO_2 from the atmosphere. Subsequent worldwide media coverage has improved public understanding of CCS and CarbFix as a solution against climate change.

Offset carbon emission for power plants in Iceland

Although Iceland is known for its clean environment, its per capita carbon emissions are high due to the large amount of mineral processing that occurs in the country. As the first industrial scale carbon mineralisation project in the world, CarbFix technology has proved its success in offsetting carbon emission for power plants since its launch in 2013. At the Hellisheiði Power Plant, the third-largest geothermal power station in the world, CarbFix has captured approximately **95,000t CO_2 and H_2S** between 2016 and 2020. At current capturing capacity, **33% of the CO_2 and 75% of the H_2S emissions** (or 12,000t of CO_2 and 7,000t of H_2S) from the plant are being re-injected annually (**S1**).

The implementation of CarbFix technology at the Nesjavellir Geothermal Power Station, the second-largest geothermal power station in Iceland, doubled the amount of CO_2 and H_2S being reinjected at the site. The power station is expected to reach carbon neutrality by 2030, 10 years earlier than planned (**S1**).

A multi-million cost-saving gas storage solution

The cost per tonne of gas captured and stored is approximately USD30 with CarbFix; this corresponds to a saving of USD22 to USD60 per tonne compared to the costs of industry-standard CO_2 storage methods, and a saving of USD270 to USD570/t for sulphur storage (**S1**). Such financial saving makes CarbFix the most economical carbon and sulphur storage solution in the world today. As stated by the CEO of Reykjavik Energy, "the company has **saved ISK3,250,000,000 (approximately GBP23,500,000) with the implementation of CarbFix** at the Hellisheiði Power Plant between 2016 to 2020" (**S2**).

The initial success of implementing CarbFix technology at the power stations has led to Reykjavik Energy (Iceland) launching CarbFix as a subsidiary to exploit its financial and environmental benefits. The company was officially launched in 2019 and employs five specialists (FTE: 5). The CEO of CarbFix commented on the importance of Oelkers' research to the company's success: "Eric [Oelkers] and UCL Earth Science Department have played an essential role in the development, validation and academic acceptance of CarbFix. […] CarbFix would not be possible without this input" (**S3**). In addition, four new industrial sites across Turkey, Italy, Germany and Iceland have adopted CarbFix technology with four jobs generated (FTE: 4) across these sites (**S4**).

Amphos21, a consulting firm that provides services for CO_2 storage verification after injection by CarbFix also benefited from directly research collaboration with Oelkers. Between 2013 and 2020, Amphos21 generated additional funding to recruit specialists (FTE: 3) and increased its annual revenue in EUR85,000 (for the period 2010-2020) (**S5**).

Underpinning the development of climate change policies

CarbFix technology is an effective method against global warming caused by fossil fuel emissions from power plants. The Executive Secretary of the United Nations Framework Convention on Climate Change (UNFCCC) was "impressed by the CarbFix injection method, which greatly increased the safety of geological carbon storage compared to conventional supercritical or mineral storage of CO_2" (**S6**).

Project CarbFix2, a collaboration between Reykjavik Energy and international partners, aims to produce the first ever negative-emission carbon storage solution via direct capture of CO_2 from the atmosphere using both freshwater and seawater (**S7**). The former President of Iceland commented that the "launch of the Climeworks Direct Air Capture plant at the CarbFix site is 'revolutionary' for the climate fight" (**S7**). In April 2019, CarbFix2 project received the National Energy Globe Award Iceland, one of the most prestigious environmental awards, the goal of which is "to present successful sustainable projects to a broad audience, for many of our environmental problems already have good, feasible solutions" (**S7**).

In January 2019, the Project Manager of CarbFix gave an invited presentation on CarbFix as a solution in the fight against climate change to the Prime Ministers and Ministers of the Nordic countries during the Nordic countries Climate Meeting in Helsinki. During this meeting, Prime Ministers signed the '**Declaration of Nordic Carbon Neutrality**', in which they emphasised that the Nordic countries have the political will and technical solutions to take a global lead against climate change (**S8)**. In Iceland, the pledge led to larger collaboration projects between the government and industry aimed at expanding CarbFix to help Iceland achieve carbon neutrality by 2040. In 2019, as part of the initiative, Reykjavík Energy, market leaders in the Aluminium and Silicon Industry (including Elkem, Fjarðarál, PCC and Rio Tinto), and government Ministries (including the Prime Minister of Iceland, the Ministry for the Environment and Natural Resources, the Ministry of Industries and Innovation and the Ministry of Education, Science and Culture) signed a Letter of Intent to investigate CarbFix as a viable option to safely store CO_2 emissions from other large emitters in Iceland (**S8**). A year later, a working group was tasked with drafting a bill of law aiming to ensure that CO_2 storage via CarbFix process complies with EU legislation and is included in EU Emissions Trading System (**S8**).

Inspiration for artists and new generations of scientists

Results of this successful CCS technology originating from UCL research inspired and interested people of all ages globally. CarbFix was featured by over **400 media sources worldwide**, including the New York Times, The Guardian, CNBC, Forbes, Japan Times, Los Angeles Times, The Washington Post, The Economist, Wired, MIT Technology Review, The Australian, Outside, the Conversation, Phys.org, BBC, Euronews, PBS Newshour, and National Geographic [I]. Most recently, the research has been featured in the latest Sir David Attenborough documentary, *Climate Change – The Facts*, which was broadcast on BBC One on 18 April 2019 and has been watched on various platforms by **3,560,000 people**, with many viewers defining it as a "wake up call" (**S9)**.

Following the worldwide media exposure, a teacher from New York (New York, US) arranged a teleconference for her 7th grade students to meet geologists on the CarbFix team, with the support of the *'Skype A Scientist'* initiative (**S10**). Additionally, an 11-year old girl from San Antonio (Texas, US) was inspired by the CarbFix project when she visited Iceland in 2016. The CarbFix team helped her design a small-scale experiment using basaltic rocks from both Iceland and Texas. The girl was awarded the first prize at the Science Fair at her school in February 2017 (**S10**).

The core that was drilled into the CarbFix pilot injection site in 2014 was part of the *Infinite Next* exhibition at the Living Art Museum in Reykjavík, specifically in the work entitled *Ten Thousand and One Years* of the artist Bjarki Bragason (of 7 participating artists in total). According to the Managing Director of the Living Art Museum, the exhibition "has been viewed by 600 visitors until 19th June 2016", and it was "well received, by other artists, art professionals, and students aged between 18-25". The exhibition was featured in the Icelandic newspaper Morgunblaðið, in the Visual Arts radio programme Víðsjá, and in Artzine – an online art magazine. This work was also presented at exhibitions in Los Angeles (USA), Auckland (NZ) and Vienna (AU) (**S10**).

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. CarbFix project website with information on project status corroborates CO_2 and H_2S capturing capacity; An article in Interface Focus (14/08/2020) and a case study from the U.S. Department

of Energy's Office of Energy Efficiency and Renewable Energy SBIR program (date not provided) corroborate cost of CO_2 and H_2S capture and storage.
S2. An article in Morgunbladid journal with statement from CEO at OR (23/03/2018) - corroborates the savings figures provided.
S3. Supporting statement from the CEO of CarbFix (12/06/2020) corroborates the role of underpinning research in the development and operation of CarbFix.
S4. Geotermal Emission Control website corroborates location of power plants that adopted CarbFix technology; CarbFix news website for the job adverts corroborate the positions created.
S5. Supporting statement from the Project Director at Amphos21 Consulting S.L. (10/06/2020) corroborates company's financial details.
S6. An article on CarbFix News website (03/11/2014) on Executive Secretary of the United Nations Framework Convention on Climate Change visit corroborates Executive Secretary view and comment on CarbFix.
S7. Twitter coverage of former president of Iceland on the joint venture between CarbFix and Climeworks corroborates the president statement; Climeworks news on CarbFix2 corroborates the joint-venture establishment; An article on CarbFix News website (09/04/2019) corroborates recognition of CarbFix2 and the National Energy Globe Award 2019.
S8. Declaration of Nordic Carbon Neutrality (25/02/2019) corroborate the impact on climate change policy in Finland, Iceland, Sweden, Norway and Denmark; Press releases (18/06/2019 and 29/04/2020) corroborate evaluation CarbFix technology for use by large emitters in Iceland and corroborates work towards compliance of CarbFix technology utilisation by large emitters with EU legislation.
S9. CarbFix2 Dissemination Report (30/01/2019) corroborates media coverage of CarbFix; Top programmes report (April 15-21, 2019) corroborates viewers figures on "Climate change: the facts"; An Article on RadioTimes website corroborates viewers' commentary on "Climate change: the facts".
S10. Twitter coverage (12/12/2018) corroborates the teleconference between 7th graders and a CarbFix geologist *via* the "Skype A Scientist" initiative; CarbFix News article corroborates a student's visit at CarbFix and her school (24/11/206) project; Supporting statement from Managing Director at the Living Art Museum (23/04/2019) and from the artist (01/07/2019) corroborate the exhibition, visitor figures and cultural impact.