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SUCCEED: A CO_2 storage and utilisation project aimed at mitigating against greenhouse gas emissions from geothermal power production

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Abstract

The non-condensable gases in most geothermal resources include CO_2 and smaller amounts of other gases. Currently, the worldwide geothermal power is a small sector within the energy industry, and CO_2 emissions related to the utilisation of geothermal resources are consequently small. In some countries, however, geothermal energy production contributes significantly to their energy budget and their CO_2 emissions are relatively significant. SUCCEED is a targeted innovation and research project which aims to investigate the reinjection of CO_2 produced at geothermal power production sites and develop, test and demonstrate at field scale innovative measurement, monitoring and verification (MMV) technologies that can be used in most CO_2 geological storage projects. The project is carried out at two operating geothermal energy production sites, the Kızıldere geothermal field in Turkey and the CarbFix project site at the Hellisheiði geothermal field. Together with a brief description of the seismic monitoring technologies proposed in the project, this paper presents the details of the two field sites and the progress made in installing and testing of the surface fibre-optic cables at the Hellisheiði geothermal field in Iceland.

Keywords: Geothermal energy; CO_2 emissions; CO_2 utilisation and storage; distributed acoustic sensing; vibratory-type electric seismic source

1. Introduction and background

Although it is widely assumed that geothermal energy is clean, 'zero-emission', and renewable, most geothermal energy plants emit carbon dioxide. The non-condensable gases in geothermal resources include CO_2 and smaller amounts of ammonia, nitrogen, methane, hydrogen sulphide, and hydrogen [1]. CO_2 concentration in the non-condensable gases can be as high as 97.8% and, together, the non-condensable gases typically make up less than 5% by weight [2]. Currently, the worldwide geothermal power is a small sector within the energy industry and CO_2 emissions related to the utilisation of geothermal resources are consequently small. In some countries, however, geothermal energy production contributes significantly to their energy budget and the CO_2 emissions from geothermal power plants are relatively significant [3].

In Turkey, nearly all geothermal reservoirs are producing from carbonate rocks. One common feature of these systems is the presence of considerable dissolved carbon dioxide in the geothermal fluids, which is produced as non-condensable gas at the outlet pressure and temperature conditions of the turbines, or heat exchangers, and is usually exhausted to the atmosphere. The concentration of dissolved CO_2 can reach up to 4% by weight depending on site characteristics, which also is a valuable feature of the geothermal resource as it improves productivity. The spent geothermal fluid, depleted in CO_2, is generally re-injected into the reservoir.

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The world's first dedicated industrial CO_2 storage project was launched in 1996 at Sleipner in Norway. Since then, it has been demonstrated that CO_2 can be injected, at a rate up to ~ 1 M tonne per year per well, and be safely stored in deep saline (mainly sandstone) aquifers, through the implementation of a number of industrial scale CO_2 storage projects worldwide. Considerable experience of injection into carbonates has been gained in North America in association with CO_2EOR operations. An important concern closely related to CO_2 storage in carbonates is that the injected CO_2 may dissolve into formation brines, causing acidification and possible dissolution of carbonate minerals within the reservoir. To date, the only European pilot study to investigate monitoring of permanent storage of CO_2 in a fractured carbonate system has been the Hontomin research pilot in Spain [4]. Reinjection of produced CO_2 back into the geothermal fields has been proposed by several researchers [5, 6]. However, the harsh and high temperature downhole environments in geothermal reservoirs pose an added challenge for field implementation of CO_2 injection and downhole monitoring of its fate in the reservoir.

SUCCEED (Synergetic Utilisation of CO_2 storage Coupled with geothermal EnErgy Deployment) aims to research and demonstrate the feasibility of utilising produced and subsequently vented CO_2 for re-injection to the reservoir to improve geothermal performance, while also storing the CO_2. The project also aims at field testing and implementation of a new higher signal-to-noise ratio DAS (Distributed Acoustic Sensing) System by Silixa Ltd. and a new and innovative vibratory-type electric seismic source by Seismic Mechatronics BV to provide semi-continuous seismic monitoring capability for CCS and geothermal applications. In order to achieve its objectives, the project takes advantage of the already existing deep well infrastructure at the two partner geothermal field sites, Kızıldere in Turkey and the CarbFix project site at Hellisheiði in Iceland, which also provide different geological settings and two different techniques of CO_2 injection in the reservoir.

2. Seismic monitoring technologies used in the project

The main requirement for high-resolution images of the subsurface is a sufficiently dense placement of seismic sources and receivers at the surface and/or boreholes, which has always been a limiting factor. The new developments in recent years of fibre-optic sensing of acoustic and seismic wavefields addresses the challenge of sufficiently dense receiver sampling. Distributed Acoustic Sensing (DAS) technology offers dense spatial and temporal sampling, less than 1m and up to 100kHz, respectively, and measurements can be made on a single cable up to tens of km long. Another advantage of fibre-optic technology over traditional seismic instruments (geophones) is that cables with polyimide coatings enable DAS measurements in high-temperatures up to 300°C, as often experienced in geothermal environments. Fibre-optic sensing cables have been shown to be suitably robust for extended duration installations in geothermal fields [7], making them ideal to test and assess monitoring techniques at the Hellisheiði and Kızıldere geothermal fields.

DAS is based on digital optical detection of elastic Rayleigh backscattered light resulting from inhomogeneous variations of refractive index along a fibre. The system can record the full wavefield amplitude and phase at every point along the fibre over a wide frequency and dynamic range. Changes in strain on the fibre due to the passage of seismic wavefronts result in changes in the recorded signal and interrogators are able to measure changes in axial strain down to sub-nanostrain resolution [8]. Silixa's new intelligent Distributed Acoustic Sensors (iDAS) provide the latest achievements in the field of DAS technology available (Fig.1). Furthermore, the Carina Sensing System, which uses the new family of engineered Constellation fibres, provides 20dB (100 times) improvement in signal-to-noise performance [9] and, therefore, significantly improve the results of both passive and active seismic surveys. Fibre-optic cables can be installed in trenches at the surface, deployed into existing boreholes, or cemented behind casing in permanent installations to provide enhanced coupling. Once deployed the fibre provides a long-term and repeatable monitoring solution because the fibre can be left in place and data collected for up to tens of years.

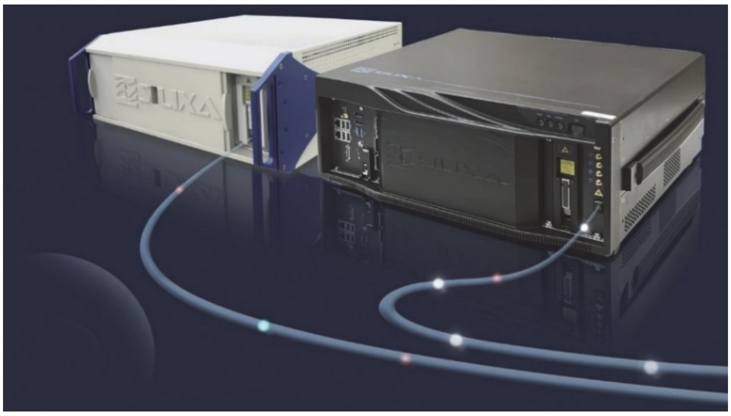
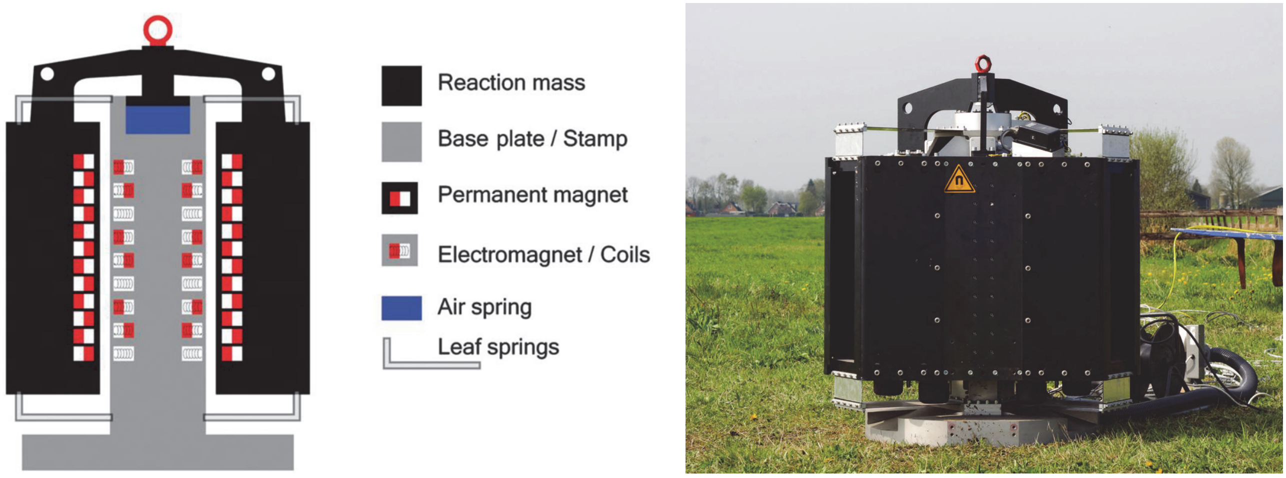


Fig. 1. Silixa's intelligent Distributed Acoustic Sensing (iDAS) interrogators. On the left is the iDAS v2 and on the right the iDAS v3 (Carina) interrogator. Light is emitted from the interrogator and the back scattered light from the fibre is recorded.

DAS measurements are only one-component as fibres are only sensitive to axial strain in the fibre direction. Therefore, linear fibres are insensitive to seismic P-waves arriving broadside to the cable. Although they decrease S-wave sensitivity, helically wound cables (HWC), which boost the P-wave sensitivity have been developed to address this issue.

Another challenge faced in seismic sensing is having active seismic sources with sufficiently broad spectrum, especially at lower frequencies, that emit a repeatable source signal. Mechanical vibroseis sources were invented to tackle the repeatability, but having mechanical driving mechanism limits their utilisation as broader-band sources. This is especially the case for broadening the spectrum of the emitted signal to the lower frequencies. The lower frequencies are required to perform a correct full-waveform inversion that finds the global minimum instead of finding a local minimum due to the cycle-skipping problem. The seismic vibrator driven by electric linear synchronous motors (LSM) developed by Seismic Mechatronics BV easily generates this low frequency content with high force, without suffering from low repeatability issues due to its frictionless design [10].

The functionality of the original LSM based vertical-type seismic vibrator (E-vib) was first demonstrated at a site in central Netherlands. The system weighed one tonne and its design involved six synchronised LSM's providing a flat amplitude response from 2-200 Hz with a peak force of 7 kN mass. As illustrated in Fig.2, an LSM is an electrically driven motor consisting of a magnet track and a coil track, that allows the generation of large controllable forces with a reduced amount of signal distortion [10]. In addition to the base plate, reaction mass, and LSMs, the unit also contained an air spring and a few leaf springs. The performance of an upgraded 7 kN version of the prototype weighing 1.65 tonne was recently used to obtain enhanced imaging of an iron-oxide deposits in Sweden [11]. Compared to the microspread seismic profile, the E-vib data have shown double the vertical resolution with similar penetration depth.



(a) (b)

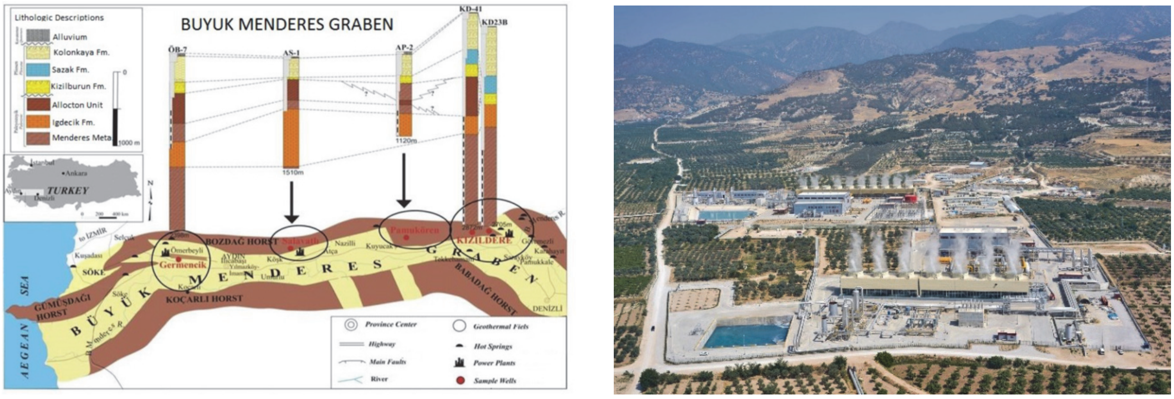
Fig. 2. (a) A 2D sketch showing the different components of the original prototype LSM vibrator, (b) Prototype vibrator deployed in the field [10].

Currently, Seismic Mechatronics is developing a new 10 kN E-vib for use in SUCCEED, the design of which reflects all the learnings from past experiments and also meets the specific requirements of the project. It is expected to deploy this unit in the project field sites in the second quarter of 2021 and carry out the first integrated seismic survey together with Silixa's iDAS system.

3. Project field sites

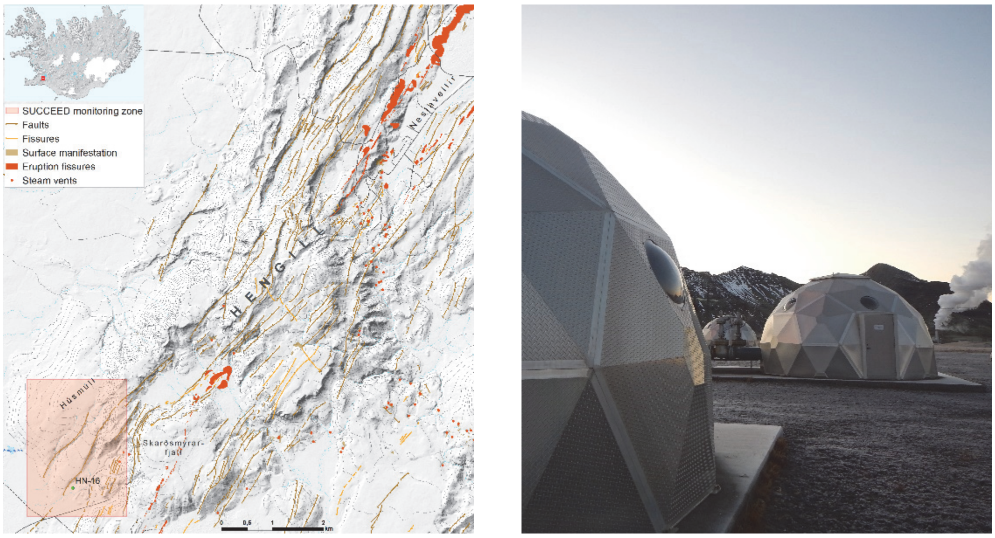
The Kızıldere geothermal field is located in the East of Büyük Menderes graben in Western Anatolia near Denizli (Fig.3). It was discovered in 1968 as the first site with potential geothermal energy source in Turkey. The geothermal field is made up of two main reservoirs: the upper reservoir within the Pliocene limestones of the Sazak Formation, and the 2nd reservoir which comprises the Palaeozoic marble–quartzite–schist intercalations of the Iğdecik Formation and the deeper gneisses and quartzites (Menderes Metamorphics) that are intercalated with, and underlie the schists [12]. The geothermal fluid at Kızıldere carries a significant amount of dissolved CO_2 (over 3% by weight depending on depth). Operated by Zorlu Energy, the Kızıldere geothermal site has 260 MWe installed capacity with 38 production and 24 re-injection wells drilled at depths from 500 to 3,500 m into carbonate rocks at 220 – 245 ^{o}C reservoir temperature. Through its long-term tracer monitoring experience and geochemistry monitoring, Zorlu Energy already has a very good database and understanding of the hydrothermal system at Kızıldere.

An existing well at the geothermal power generation site Kızıldere will be used to inject produced and captured, but mostly vented to the atmosphere, CO_2 into the reservoir at supercritical state. This is aimed at enhancing the pressure in the reservoir as the driving mechanism for the geothermal fluid and improve geothermal performance, as well as storing the produced CO_2, providing a low environmental impact and resource efficient coupled geothermal-CCUS technology.



(a) (b)

Fig. 3. (a) Location of Kızıldere geothermal field in Büyük Menderes Graben (Courtesy of Ş Şimsek, 2020), (b) the Zorlu Energy Kızıldere-III geothermal power plant (Courtesy Zorlu Energy, 2020).



(a) (b)

Fig. 4. (a) The Hengill volcanic system and the SUCCEED seismic monitoring zone around the HN-16 CO_2 injection well at the Hellisheiði site marked with a red rectangle (Courtesy of T.A. Thorgeirsson, Reykjavík Energy, 2020), (b) the Hellisheiði site brine and CO_2 injection wellfield.

The Hellisheiði geothermal field lies within the Hengill volcanic system of the western volcanic zone of Iceland, about 30 km east of Reykjavík (Fig.4). The reservoir temperature is between 260 – 320 °C in the main production zones within the basaltic rocks. Operated by Reykjavík Energy (OR), the Hellisheiði power plant started operation in 2006 and currently utilises the field production capacity of 303 MWe and 200 MWth energy. In total, 61 production and 17 re-injection wells have been drilled at depths from 1,500 to 3,300 m. Feasibility study on injecting CO_2 and H_2S produced with the geothermal fluid back in the geothermal reservoir at Hellisheiði started in 2012. The EU funded CarbFix project developed a technology to dissolve CO_2 in the reinjected brine, encouraging solubility trapping and carbonation of CO_2 in the subsurface. The storage formation consists of basaltic lavas of olivine tholeiitic composition. CarbFix2 project was set up in 2014 and the industrial scale injection of CO_2 started, which was scaled up in 2016, and later in 2017. Modelling and field geochemical monitoring results for basaltic rocks suggested that complete mineralisation of injected CO_2 takes less than two years [13]. During the SUCCEED project, it is planned to inject 12,000 tonnes/annum CO_2 at the Hellisheiði geothermal field.

The produced and utilised geothermal fluid, depleted in CO_2, is re-injected into the reservoir at both SUCCEED field sites, at a rate of 5,000 tonnes/hour at Kızıldere in Turkey and 3,800 tonnes/hour at Hellisheiði in Iceland, respectively. As a result, the geothermal fluid resource in the reservoir is gradually diluted and the field pressure is reduced over time, affecting well productivity. For example, at the Hellisheiði field in Iceland the mass flow of CO_2 has decreased from 120 tonnes/day to 100 tonnes/day since the early 2014 [14].

4. DAS survey designs for the two field sites and initial test data

The applications of DAS monitoring to be tested at the two project sites involve (i) passive seismic monitoring for natural or induced seismicity and (ii) seismic imaging using a new electric active seismic source and ambient noise recordings. A fibre-optic cable deployment has already been designed and carried out at the Hellisheiði field and is planned for the Kızıldere site during

2021. The overall monitoring objective is to image and understand the behaviour of CO_2 in the reservoir. A baseline survey will also be conducted before the injection of CO_2 begins at Kızıldere. The deployments at both sites provide the possibility for continuous and repeatable time-lapse seismic monitoring capability with permanently installed cables.

CO_2 charged water and the spent geothermal fluid are injected to a depth of 750 m at well HN-16 at the Hellisheiði geothermal field (Fig. 5a). It is allowed to mix until it enters the main feed zones at 1,900 m and 2,200 m depth in the injection well. To evaluate the capabilities of surface HWC for CO_2 injection monitoring, a 1.5km long cable was deployed in a 70-80 cm deep trench as close as possible to the injection point of the CO_2 injection well (Fig. 5b, c). At Hellisheiði, the HWC is also being tested for microseismic event detection capabilities. A regional seismic network is available for comparison purposes. Initial test data collected from the Hellisheiði site in July 2020 have shown clear recordings of regional natural seismicity on the surface cable (Fig. 6). During the seismic surveys planned, data will be recorded continuously along with the active source (E-vib) deployment.

(a) (b) (c)

Fig. 5. (a) Location of wells at the Hellisheiði site. HN-16 is the CO_2 injection well. The blue line is the helically wound cable deployment and the black line is the tactical cable joining the HWC to the DAS interrogator, (b), (c) installation of the HWC at the Hellisheiði geothermal site.

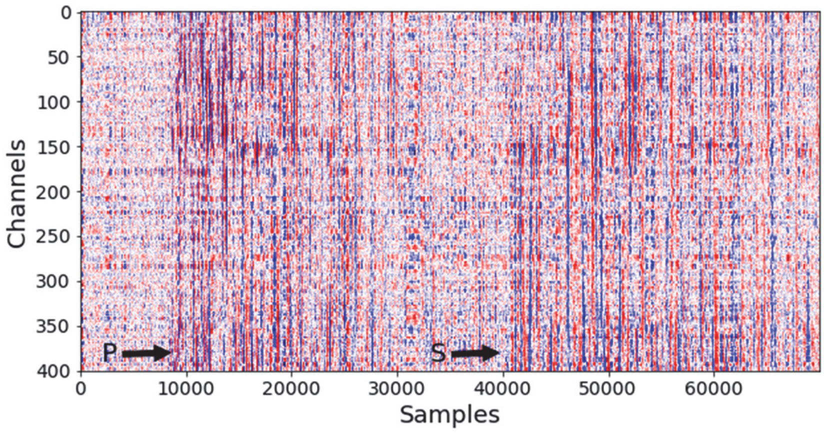


Fig. 6. A recording on the surface HWC of a M3.3 earthquake on 23 July 2020 with an epicentre approximately 100km from the Hellisheiði power plant. The time of P- and S-wave arrivals are indicated [15].

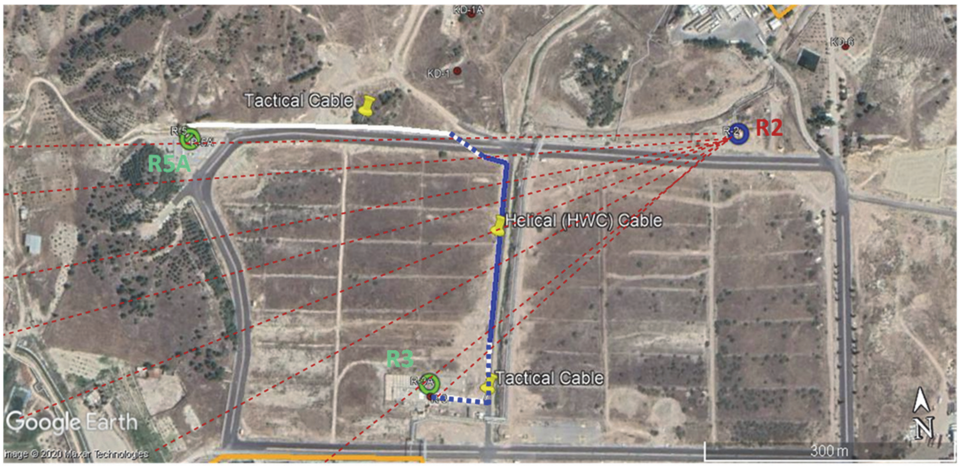


Fig. 7. Location of the planned CO_2 injection well R2 and the two monitoring wells R3 and R5A where the downhole Constellation fibres will be installed at the Zorlu Energy Kızıldere geothermal field. The blue line is the HWC deployment and the white line is the tactical cable joining the two downhole cables and the HWC to the DAS interrogator. The red dashed lines indicate the tracer flow paths from previous tests at the site.

The designs and deployment at the Kızıldere site is more complex than that employed at Hellisheiði. Approximately 500 m of HWC will be deployed on the surface in a trench connected to the downhole Constellation fibres in two wells (Fig. 7). As well as a background survey, which will be conducted before the CO_2 injection begins, passive and active seismic surveys will be conducted to evaluate the behaviour of injected CO_2 in the reservoir and the effectiveness of the use of fibre-optic monitoring techniques for carbonate reservoirs.

5. Conclusions

SUCCEED aims to research and demonstrate the feasibility of utilising produced and subsequently vented CO_2 for re-injection to the reservoir to improve geothermal performance, while also storing the CO_2. The project also aims at field testing and implementation of a new higher signal-to-noise ratio DAS (Distributed Acoustic Sensing) System by Silixa Ltd. and a new and innovative vibratory-type electric seismic source by Seismic Mechatronics BV to provide semi-continuous seismic monitoring capability for CCS and geothermal applications. In order to achieve its objectives, the project takes advantage of the already existing deep well infrastructure at the two partner geothermal field sites, Kızıldere in Turkey and the CarbFix project site at the Hellisheiði, which also provide different geological settings and two different techniques of CO_2 injection in the reservoir.

Besides the field based outcrop studies, sample collection for the laboratory experimental programmes designed to characterise mechanical and flow characteristics of the reservoir rocks and their seismic response, the project partners have selected the injection and monitoring wells at the two project sites, designed the seismic monitoring programmes to be implemented in the field, and installed and tested the surface HWC at the Hellisheiði geothermal site. Filed testing of the monitoring systems designed will start in 2021.

Acknowledgements

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References

[1] Holm A, Jennejohn D, Blodgett L. Geothermal energy and greenhouse gas emissions, Geothermal Energy Association 2012.
[2] Bloomfield KK, Moore JN, Geothermal electrical production CO_2 emissions study. Proc. Geothermal Resource Council Annual Meeting,. INEEL/CON-99-00655PREPRINT 1999: 6p.
[3] ESMAP. Greenhouse gases from geothermal power production., ESMAP Technical Report, 009/16 2016.
[4] Humphries M, Marin Vidal JA and de Dios JC. VSP monitoring for CO_2 migration tracking in fractured rock massifs. 78th EAGE Conference and Exhibition, Extended Abstracts 2016: 1-5.
[5] Pruess K. Enhanced geothermal systems (EGS) using CO_2 as working fluid—A novel approach for generating renewable energy with simultaneous sequestration of carbon. Geothermics 2006; 35(4):351-367.
[6] Salimi H, Wolf K-H. Integration of heat-energy recovery and carbon sequestration. Int J Greenhouse Gas Control 2012;6:56-68.
[7] Mondanos M, Coleman T. Application of distributed fibre-optic sensing to geothermal. First Break 2019;37:51-56.
[8] Parker T, Shatalin S, Farhadiroushan M. Distributed Acoustic Sensing – A new tool for seismic applications. First Break 2014;32:61–69.

[9] Naldrett G, Parker T, Shatalin S, Mondanos M, Farhadiroushan M. High-resolution Carina distributed acoustic fibre-optic sensor for permanent reservoir monitoring and extending the reach into subsea fields, First Break 2020;38:71 – 76.

[10] Noorlandt R, Drijkoningen G, Dams J, Jenneskens R. A seismic vertical vibrator driven by linear synchronous motors. Geophysics 2015;8(2):57–67.

[11] Pertuz T, Malehmir A, Brodic B, Bäckström E, Marsden P, de Kunder R, Bos J. Broadband seismic data acquisition using an E-vib source for enhanced imaging of iron-oxide deposits, Sweden. SEG Technical Program Expanded Abstracts 2020:81-85.

[12] SUCCEED project internal discussions with Zorlu Energy exploration team 2020.

[13] Snæbjörnsdóttir SÓ, Eric H, Oelkers EH, Mesfin K, Aradóttir ES, Dideriksen K, Gunnarsson I, Gunnlaugsson E, Matter JM, Stute M, Gislason SR. The chemistry and saturation states of subsurface fluids during the in situ mineralisation of CO_2 and H_2S at the CarbFix site in SW-Iceland. Int J Greenhouse Gas Control 2017;58:87-102.

[14] Sigfússon B, Þór Arnarson M, Ósk Snæbjörnsdóttir S, Rós Karlsdóttir M, Gunnarsson I. Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheiði power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals. Energy Procedia 2018;146:135-145.

[15] Stork A, Chalari A, Durucan S, Korre A, Nikolov, S. Fibre-optic monitoring for high-temperature Carbon Capture, Utilisation and Storage (CCUS) projects at geothermal energy sites. First Break 2020; 38:61-67.