



**CO₂ Fixation into Basalts
Hellisheiði
Iceland**

**Annual Status Report 2008
Hólmfríður Sigurðardóttir**

Contents

Prologue	3
Participants	4
Leadership	5
PhD Students	6
MSc Students	6
The Status of the CarbFix Project 2008	7
The CarbFix Field Site	7
Resource Characterisation	9
The Injection System	10
Licenses	11
Modeling	11
Monitoring	11
Plug Flow Reactor	11
Webpage	11
Meetings	12
Financial Status and Outcome 2008	13
Index I – Financial Information	14
Notes	15
Summary	16
Appendix I – List of Selected Publications 2008	17
Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory (LDEO)	17
The Centre National de la Recherche Scientifique, France (CNRS)	17
Orkuveita Reykjavíkur (OR)	18
The University of Iceland – Institute of Earth Sciences (IES)	19
Appendix II – CarbFix in the Media	23

Prologue

Mineral storage of CO₂ is a well known natural process in basaltic volcanoes that host geothermal systems. The primary goal of the CarbFix program is to accelerate these natural processes by developing methods for permanent fixation of CO₂ in basaltic rock, creating solutions for the global CO₂ problem and creating the human capital to address these problems in the future. The CO₂ gas from the geothermal steam at the Hellisheiði Geothermal Plant will be captured and dissolved in water at elevated pressures and then injected through wells down to 400-800 m, just outside the boundary of the geothermal system. The liquid will react with minerals such as magnesium and calcium from the basalt and form solid carbonates.

This report describes how the CarbFix research program advanced during the year 2008.

Participants

The CarbFix project was formally launched on September 29th 2007 when the following four Participants agreed to enter into an Agreement for the purpose of setting forth objectives, plans and undertakings with respect to the CarbFix project at Hellisheiði (Figure 1).



Figure 1 – The CarbFix signing ceremony at Hellisheiði geothermal plant

Orkuveita Reykjavíkur (OR)

OR is the main sponsor of the CarbFix project. As the owner of the geothermal plant and the infrastructure on Hellisheiði, OR plays a leadership role for the project. OR provides the infrastructure (land, pipelines, injection and monitoring wells), CO₂ source and helps in the logistics and management of the project. Many of OR's scientists, engineers and technicians work on this project. Additionally, OR has set up a science fund to support academics in several Icelandic Universities. A part of the annual budget has been reserved for the CO₂ studies.

Iceland Geosurvey (ISOR) is one of OR's primary consultants. ISOR maintains a database of important geologic, geophysical and geochemical data of the Hengill area. ISOR plays an important role in monitoring and verifying of the CO₂ injection and is designing a soil gas monitoring program to detect possible CO₂ leakage to the surface before, during and after the injection.

Mannvit Engineering, Iceland (Mannvit) is one of OR's primary consultants for the development of its power plants. Mannvit assists, among other things, the development and design of the CO₂ injection system.

Lawrence Berkeley National Laboratory USA (LBNL) is a long-term partner of OR for geothermal reservoir modelling. LBNL has adopted properties of Icelandic basalts into the reactive transport modelling code (TOUGHREACT), to predict the long-term success of CO₂ injection into basalts and to interpret field and experimental data.

The University of Iceland – Institute of Earth Sciences (IES)

IES develops and runs laboratory experiments and the plug flow reactor in collaboration with CNRS. The result of the laboratory experiments, kinetic and thermodynamic data are used for reactive transport modelling. The plug-flow reactor will be used to fine tune reactive transport models. IES in cooperation with LDEO, ISOR and OR administers the designing of the monitoring protocol and sampling equipment. IES has a leading role in systematic collection and analysis of the groundwater in the injection wells as well as in the monitoring wells.

Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory (LDEO)

LDEO has a leading role with OR and ISOR in monitoring and verifying the CO₂ injection. The work includes pre-injection characterization of the basaltic rocks and ground waters with geochemical and geophysical tools to assess the CO₂ storage capacity of the injection site, developing a monitoring program for the CO₂-water-rock interactions in the subsurface and validate the hydrological modelling with tracer studies in cooperation with IES and ISOR. LDEO develops a CO₂-water mixing system in collaboration with OR and Mannvit Engineering.

The Centre National de la Recherche Scientifique, France (CNRS)

CNRS through the Laboratoire des Mécanismes et Transferts en Géologie (LMTG - UMR 5563) evaluates kinetic and thermodynamic data for basaltic rocks that will be used to further the CO₂ storage process and reactive transport models. Laboratory efforts aim at characterizing the effect of surface coatings on mineral dissolution rates and the effect of solution compositions on precipitation rates, as well as the long-term evolution and consequences of these reactions on the porosity and permeability of the basaltic rocks.

LeadershipThe Scientific Steering Committee:

Sigurður Reynir Gíslason (Chairman). Research Professor at the Institute of Earth Sciences, University of Iceland. sigrg@raunvis.is

Wallace S. Broecker. Newberry Professor of Earth & Environmental Sciences, Lamont-Doherty Earth Observatory of Columbia University, USA. broecker@ldeo.columbia.edu

Eric H. Oelkers. Research Director - Chemistry and Earth Science, CNRS UMR 5563/Université Paul Sabatier, France. oelkers@lmtg.obs-mip.fr

Einar Gunnlaugsson. Research Director - Chemistry and Earth Science, Orkuveita Reykjavíkur, Iceland. einar.gunnlaugsson@or.is

The Management Team:

Jakob Sigurður Friðriksson (Chairman). Director of Production and Sales, Orkuveita Reykjavíkur, Iceland. jakob.fridriksson@or.is

Juerg M. Matter. Doherty Associate Research Scientist. Lamont-Doherty Earth Observatory of Columbia University, USA. jmatter@ldeo.columbia.edu

Andri Stefánsson. Associated Professor at the Institute of Earth Sciences, University of Iceland. as@hi.is

Project Manager:

Hólmfríður Sigurðardóttir. Head of Innovation and Development, Orkuveita Reykjavíkur, Iceland. holmfridur.sigurdardottir@or.is

PhD students

In 2008 eight PhD students were working on science projects, closely linked to the CarbFix project. In November 2008 one of the students quit her PhD thesis. The University of Iceland will hire a PhD student in 2009 to work on a thesis on “Large scale plug flow experiment on the carbon fixation in basaltic rocks”.

Name	Title of Ph.D. thesis	University	Start	Finish
Alexander Gysi	Experimental and numerical modelling of CO ₂ -water-basalt interaction	University of Iceland	Sept 2007	Sept 2010
Diana Fernandez de la Reguera	Monitoring and verification of geologic CO ₂ storage using tracer techniques	Columbia University	Sept 2008	2013
Edda Sif Aradóttir	Computational study of chemical changes in Icelandic geothermal areas: Coupling chemical reactions into reservoir models.	University of Iceland	Jan 2007	2010
Gabriella Stockmann	Experimental determination of the effect of precipitated mineral coatings on the rates of basaltic mineral and glass dissolution rates	University of Iceland	Sept 2007	Sept 2010
Guðmundur Bjarmi Ingvarsson	Bicarbonate metal complexation in aqueous solution at elevated CO ₂ pressures	The Centre National de la Recherche Scientifique, France and University of Iceland	Oct 2007	Quit Nov 2008
Helgi Arnar Alfreðsson	Characterization of the rocks and fluids, before and after CO ₂ injection, at the Hellisheidi Iceland site	University of Iceland	Sept 2007	Sept 2011
Snorri Guðbrandsson	Dissolution rates of crystalline basalt as a function of temperature, pressure and solution composition	University of Iceland	Sept 2007	Sept 2011
Therese Kaarbo Flaathen	Natural analogue for CO ₂ fixation in basalt and the effect of sulphur on the dissolution rate of basalt and precipitation rate of carbonates.	The Centre National de la Recherche Scientifique, France and University of Iceland	Sept 2006	Sept 2009

MSc students

In 2008 one MSc student was working on a science project linked to the CarbFix project and defended her thesis in the fall 2008. In December 2008 it was decided that one MSc student at the Reykjavik Energy Graduate School of Sustainable Systems (REYST) would work on a thesis in connection to the CarbFix project in 2009.

Name	Title of MSc thesis	University	Start	Finish
Mahnaz Rezvani Khalil Abad	Characterization of the Hellisheidi-Threngsli CO ₂ sequestration target aquifer by tracer testing	University of Iceland	Sept 2008	Sept 2009
Elísabet Vilborg Ragnheiðardóttir	Costs, Profitability and Potential Gains of the CarbFix Program	Reykjavik Energy Graduate School of Sustainable Systems	Jan 2009	Jan 2010

The status of the CarbFix project 2008

The CarbFix field site

The targeted field site for the injection of CO₂-charged water is close (3 km distance) to the Hellisheiði geothermal plant in SW Iceland.

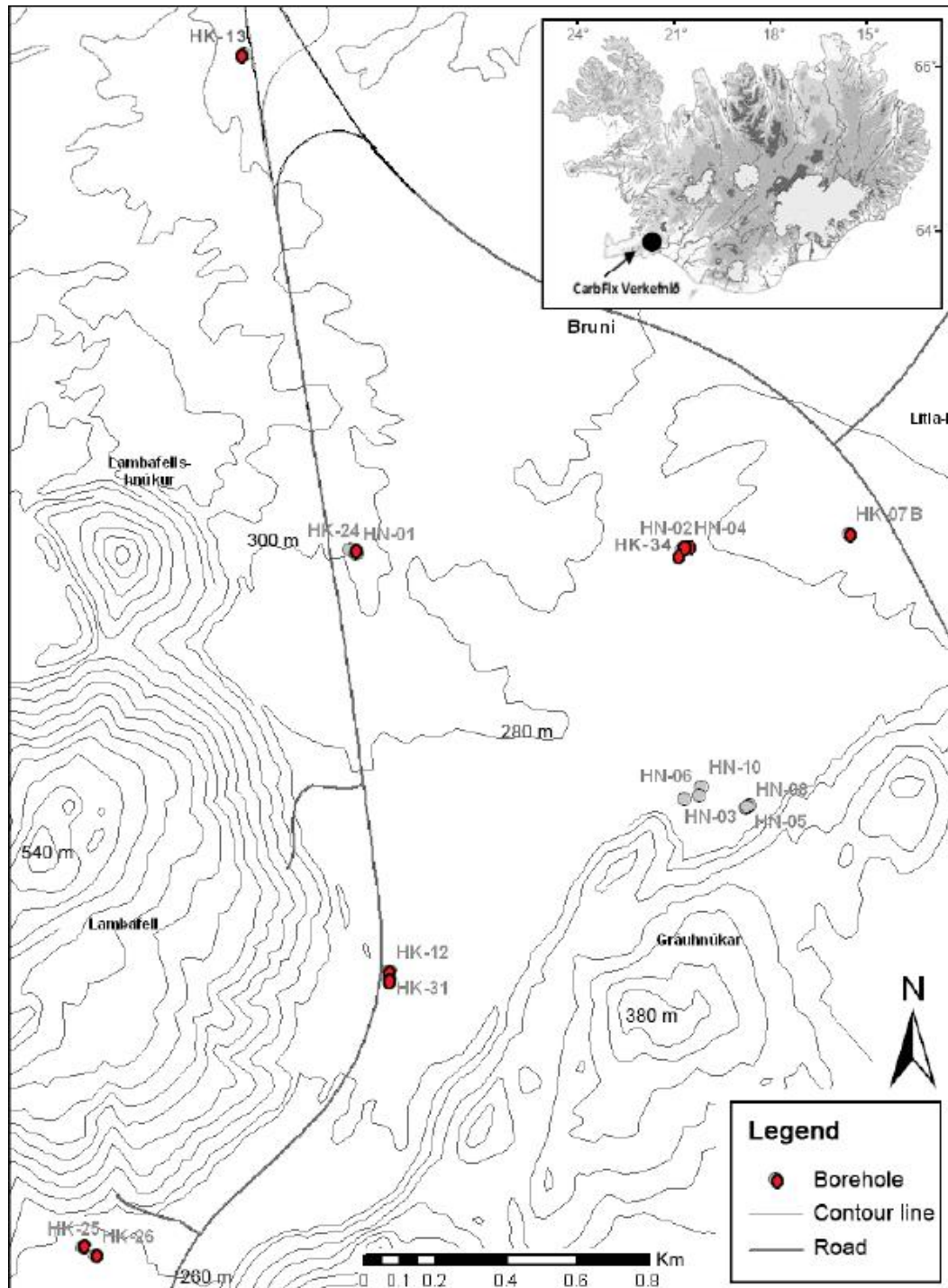


Figure 2 – The CarbFix field site. The CO₂ will be dissolved in water from well HN-1 and injected into well HN-2. Wells HN-4, HK-34, HK-31 and HK-26 are deep monitoring wells and wells HK-12, HK-25, HK-7 and HK-13 are shallow monitoring wells. *Map: Helgi Arnar Alfreðsson.*

The CO₂ gas. The source of the CO₂ is the geothermal gas from Hellisheiði geothermal plant. A pilot gas-processing plant is under construction. The gases from the power plant's condenser will be compressed and cooled. The CO₂ and the H₂S will be separated and the H₂S will be re-injected with brine into the reservoir. The remaining gas, a mixture of 98% CO₂ and 2% H₂S, will be the substance for the CarbFix project, which will be injected in the summer 2009.

The CarbFix wells. The CO₂ will be dissolved in water from well HN-1 and injected into well HN-2 (Figure 3). Wells HN-4, HK-34, HK-31 and HK-26 are deep monitoring wells and wells HK-12, HK-25, HK-7 and HK-13 are shallow monitoring wells (Figure 2).



Figure 3 – The CarbFix group at the injection well HN-2 in June 2008. Photo: Hólmfríður Sigurðardóttir

Infrastructure. The injection site was connected to the national electricity grid in February 2008. Installation of down-hole pumps for injection and monitoring wells was conducted in March and July 2008. Drilling of a new monitoring well HK-34 at the CO₂ injection site started early May 2008 and was finished 16 June (Figure 4). Reykjavik Energy's contractor was Ræktunarsamband Flóa og Skeiða. The well is approximately 700 m deep and is drilled at 30° angle from the surface.



Figure 4 – Drilling of a new monitoring well HK-34 at the CO₂ injection site in May 2008. Photo: Guðmundur Lárusson.

Resource characterisation

The project is currently addressing background fluid chemistries at the injection site and characterizing the target reservoir for CO₂ storage. Tracer tests have been launched in collaboration with scientists at LDEO and ISOR. These tests are part of a comprehensive research that is being conducted in order to understand and characterise the regional groundwater flow and to estimate the volume of reservoir available for CO₂ injection. In addition the tracer tests are intended to ensure that there is no loss of injected CO₂ to the surface.

A short-scale tracer test (forced-gradient test) using sodium fluorescein was launched in cooperation with ISOR on November 13th 2007 and was running until May 26th 2008. Sampling from monitoring well HN-4 was carried out at a rate of four samples per day for two weeks and one sample per day for the remaining period. Samples were also taken from wells HN-1. From March-May samples were taken once a week from wells HK-12 and HK-31.



Figure 5 – Sampling from HN-1 during winter. *Photo: Gretar Ívarsson.*

A large-scale tracer test. The short-scale test was followed with a large-scale tracer test (natural gradient test) using sulfur hexafluoride (SF₆) and sodium fluorescein. The test was launched on June 10th 2008 (Figure 6). This tracer test is still running. The first four weeks sampling from monitoring well HN-4 was carried out at a rate of two samples per week and samples from HK-12, HK-31 and HK-26 was carried out at a rate of one sample per week. From early July to late October 2008 sampling from the deep wells HN-4, HK-34, HK-31 and HK-26 was carried out at a rate of one sample per week. Sampling from HN-1 and the shallow wells HK-7, HK-12, HK-



Figure 6 – Tracer injection June 10th 2008. *Photo: Hólfríður Sigurðardóttir.*

13 and HK-25 was carried out once a month. From November to December 2008 samples were taken from wells HN-4 and HK-34 once a week and the rest of the wells once a month. In November and December 2008 it was not possible to take samples from the shallow well HK-13, HK-7, and HK-25 due to difficulties to install the portable pump and due to heavy frost.

OR, LDEO, and ISOR collaboratively conduct the large-scale test. Samples are taken from two monitoring wells nearby the injection well HN-2 once a week but once a month in seven monitoring wells further away. The SF₆ samples are shipped to LDEO for analysis and the sodium fluorescein samples are analysed at ISOR.

The chemistry of the ground waters at the CarbFix filed. Since July 2008 the chemistry of the ground water at the injection site has been studied regularly. Temperature, pH, alkalinity, conductivity, major and trace elements, dissolved organic carbon, nutrients, ¹⁸O, ¹³C, δD and ³⁴S isotopes have been measured and analysed. These activities are part of the resource characterization package.

Temperature log in well HN-2. In June 2008 ISOR interpreted temperature logs from the injection well HN-2 measured at the end of May 2008. This was done while waiting for the outcome of spinner logs planned in the fall 2008.

Spinner log in wells HN-4 and HK-31. In early 2008 ISOR made an attempt to set up a co-operative project with Robertson Geologging Ltd, which has provided the Icelandic geothermal industry with several logging tools in the past. A preliminary date for the logging project had been set in May 2008, but Robertson withdrew from the project at the last moment. Therefore a spinner tool was purchased by ISOR. The first attempt at spinner logging of CarbFix wells (HK-31) failed in November 2008 because of technical problems. In mid December 2008 well HN-4 was spinner logged. The logging as such was successful, but the results were vague.

The injection system

In summer 2008 Mannvit in cooperation with OR started developing and designing a set-up for the mixing of CO₂ and water. CO₂ gas will be moved under pressure from the gas purification plant by a 3 km long plastic pipeline to the injection well HN-2. Water from HN-1 will be pumped down the well through a pipe to dissolve the carbon dioxide to a partial pressure of ~25 bar. Several methods for mixing of the carbon dioxide and water were discussed during the fall 2008. The mixing can be problematic as the carbon dioxide might form gas bubbles that can escape to the surface. In December 2008 the design on the needed operation system for the gas and water mixing setup started. A decision concerning the design of the CO₂-water mixing system is needed in spring 2009.



Figure 7 – Technicians at Orkuveita Reykjavíkur at work at the CO₂ injection site. Photo: Guðmundur Lárusson.

Licenses

Iceland has no specified legal or regulatory frameworks for long-term storage of CO₂. Some relevant regulations for injecting chemicals underground do exist. For instance; regulations concerning prevention of groundwater contamination, health and safety regulations and planning and nature conservation acts. Environmental authorities have already granted one year permission for tracer use (SF₆ and sodium fluorescein) in the resource characterization project.

In August 2008 the National Planning Agency decided that the planned CarbFix pilot project with adjacent pipelines and infrastructure is not subject to Environmental Impact Assessment.

In September 2008 OR and EIS introduced the planned CO₂ injection to the Environmental Agency and the Public Health Authority in South Iceland. The authorities need a detailed monitoring plan of the injection facilities, the storage complex and where appropriate, the surrounding environment to be able to grant a licence for the CO₂ injection and the use of the tracers. In 2009 the licenses for the planned CO₂ injection will be proposed on basis of the CarbFix monitoring plan.

Modeling

Chemical modelling scenarios are being performed by the IES and CNRS. In addition, laboratory experiments are performed to evaluate the thermodynamics and reaction kinetics of basaltic rocks.. This is to ensure that future site activities can be modelled beforehand to be able to manage the CO₂ storage project better. A PhD student is using TOUGHREACT, a numerical simulation code developed at Lawrence Berkeley National Laboratory (LBNL) in California, to develop reactive fluid flow models of the CO₂ mineralization. The code requires vast amount of thermodynamic and kinetic data. Effort has been put into developing a consistent database with up to date parameters that are suitable for conditions at Hellisheiði. Two types of models have been constructed, a laboratory sized plug-flow model and a horizontal, two layer field model surrounding the injection site. Both models are currently being used to simulate different scenarios that are under consideration for the CO₂ fixation.

Monitoring

Careful monitoring of subsurface impact of injected CO₂ gas is essential for the project's success and validation. Various methods are to be tested on-site.

Monitoring methods. Early 2008 the opportunity was used to measure natural soil CO₂ flux while snow covered the rough surface lavas at the future injection site. Direct measurements on CO₂ capture will be used by injecting tracers with the gas and by systematic collection and analysis of groundwater downstream. Furthermore geophysical measurements like resistivity are up for consideration. The preparation for the monitoring plan started in the fall 2008.

Sampling. In November 2008 a design on the bailer, that will be used for down hole sampling during the CO₂ injection, started. The cost estimate of using down-hole pump for sampling in well HN-4 was carried out in December 2008.

Plug flow reactor

In November 2008 IES in collaboration with OR and CNRS started designing and developing a large laboratory plug flow reactor that will be filled with basaltic material. The experiments are scheduled in 2009. Reactive transport models will be implemented to model the replacement reactions within the plug.

Webpage

In the spring 2008 the outlook of the CarbFix website was redesigned. In April Marijo Murillo a Graphic Designer finalized designing of the CarbFix logo, (www.carbfix.is). In the fall 2008 the Icelandic part of the webpage was completed.

Meetings

The scientific Steering Committee and the Management team held the following joint meetings in 2008.

Conference Call: January 24th, February 12th and 19th, March 31st, April 28th, June 23th and 26th.

Physical meetings in Iceland 2008: June 12th-14th and October 16th-17th

Financial Status and Outcome 2008

In Index I (see next page) the financial outcome of year 2008 (in addition to 2006 and 2007) is presented as well as the estimated forecast for 2009 and 2010. As mentioned earlier the CarbFix project was formally launched in the fall 2007 when a project manager was employed. The four participants in the CarbFix project have been performing preliminary studies in the field since 2006. Therefore, the financial outcome for both year 2006 and 2007 is presented in Index I.

When the CarbFix project was formally launched in September 2007, the initial total budget for the project was estimated to be EUR 7.333.262 over a period of three years. The segmentation between participants was estimated to be: EUR 3.304.970 for Orkuveita Reykjavíkur, EUR 2.243.792 for the University of Iceland - Institute for Earth Sciences, EUR 1.097.974 for Columbia University USA – Lamont-Doherty Earth Observatory and EUR 691.526 for the Centre National de la Recherche Scientifique. The referent exchange rate was 90,0 ISK/EUR and 1,4 EUR/USD, observe the rate should have been 0,7 USD/EUR. Since September 2007 the exchange rate of the Icelandic króna (ISK) has significantly weakened compared to the euro. For further detail of the exchange rate see Note 1 on page 15.

In order to save space, the following abbreviations are used in Index I:

OR: Orkuveita Reykjavíkur

IES: The University of Iceland – Institute of Earth Sciences

LDEO: Columbia University USA – Lamont-Doherty Earth Observatory

CNRS: The Centre National de la Recherche Scientifique, France

It was decided to present profit or loss for each year as shown in Index I. Instead of moving it to a specific Balance sheet for each year the profit/loss is moved to a so-called “Balance“ that shows how the profit or loss moves between years.

Orkuveita Reykjavíkur does not credit the CarbFix project accessibility of land and wells at the Hellisheiði field site. Orkuveita Reykjavíkur has not credited the CarbFix project the cost of drilling the new monitoring well HK-34 at the CO₂ injection site in early summer 2008. The CarbFix project is a pilot project that is well defined both in time and space. It is a joint benefit for both Orkuveita Reykjavíkur and the CarbFix-project to grant the project this interest. For enlightenment the cost of drilling a well of the same size and type as the injection well HN-2 is approximately ISK 300 million (EUR 1.9 million). The cost of drilling a deep monitoring well is approximately ISK 50 million (EUR 0.3 million).

The CO₂ injection was planned in the fall 2008 but was delayed until 2009. Therefore the estimated cost of design and execution of the injection will be credited in 2009.

Index I – financial information

CarbFix - Budget	EUR					NOTES
	2006 EUR real number	2007 EUR real number	2008 EUR real number	2009 EUR estimated	2010 EUR estimated	
Income						
Contribution from OR	72.109	228.311	1.252.041	547.565	604.731	1
Contribution from IES	87.131	523.333	374.031	266.703	68.082	1,3
Contribution from LDEO	52.979	48.114	137.100	300.617	195.240	2
Contribution from CNRS	17.640	58.064	136.643	0	0	4
Total Contribution	229.859	857.821	1.899.815	1.114.885	868.053	
Expences						
Salaries and Wages - OR	45.848	114.048	106.685	192.072	223.238	5
Salaries and Wages - IES	49.075	163.180	181.838	186.593	207.353	
Salaries and Wages - LDEO	28.988	37.582	76.097	133.796	102.606	6
Salaries and Wages - CNRS	11.400	41.279	96.375	0	0	
Total Salaries/Wages	135.311	356.089	460.995	512.461	533.197	
Travel Cost - International - OR	0	9.835	1.535	5.034	5.594	
Travel Cost - International/Domestic - IES	16.961	34.930	32.698	0	0	
Travel Cost - International - LDEO	8.130	2.298	9.909	20.082	16.946	
Travel Cost - International - CNRS	2.500	5.020	9.870	0	0	
Total Travel Cost - International	27.591	52.083	54.013	25.116	22.540	
Operational and Equipment Cost - OR	26.261	97.776	266.288	689.079	227.691	7
Operational and Equipment Cost - IES	20.010	82.961	195.014	0	0	8
Operational and Equipment Cost - LDEO	12.489	1.958	33.211	112.251	50.694	9
Operational and Equipment Cost - CNRS	500	1.100	5.300	0	0	10
Total Operational and equipment cost	59.261	183.794	499.813	801.330	278.385	
Website and marketing-OR	0	7.741	3.626	11.506	5.000	11
Total Website and Marketing - RE	0	7.741	3.626	11.506	5.000	
Indirect cost recovery-IES	15.884	54.626	64.980	0	0	12
EI Cost Recovery (15%) - LDEO	3.371	6.276	17.883	34.488	24.994	13
Indirect cost recovery - CNRS	3.240	10.665	25.098	0	0	14
Other Operational cost	22.495	71.566	107.960	34.488	24.994	
Total Operational Cost-OR	72.109	229.400	378.134	897.691	461.522	
Total Operational Cost-IES	101.930	335.697	474.530	186.593	207.353	
Total Operational Cost-LDEO	52.979	48.114	137.100	300.617	195.240	
Total Operational Cost-CNRS	17.640	58.064	136.643	0	0	
Total Operational Cost	244.658	671.275	1.126.407	1.384.901	864.115	
Profit/loss						
Profit (loss)-OR	0	-1.090	873.907	-350.127	143.208	
Profit (loss)-IES	-14.799	187.636	-100.499	80.110	-139.271	
Profit (loss)-LDEO	0	0	0	0	0	
Profit (loss)-CNRS	0	0	0	0	0	
TOT Profit (loss)	-14.799	186.546	773.408	-270.017	3.937	
Balance						
Balance from previous year- OR		0	-1.090	872.817	522.691	15
Balance from previous year - IES		-14.799	172.837	72.338	152.448	
Balance from previous year- LDEO		0	0	0	0	
Balance from previous year- CNRS		0	0	0	0	
Total balance from previous year		-14.799	171.747	945.155	675.139	

Notes

Note

- | | | | |
|----|---|-----------------|----------------------------|
| 1 | Average Exchange Rate 2006 | 87,72 ISK/EUR | Central bank of Iceland |
| | Average exchange rate 2007 | 87,6 ISK/EUR | Central bank of Iceland |
| | Average Exchange Rate Jan-June 08 | 110,12 ISK/EUR | Central bank of Iceland |
| | Average Exchange Rate July-Sept 2008 | 125,59 ISK/EUR | Central bank of Iceland |
| | Average Exchange Rate Oct-Dec 2008 | 163,51 ISK/EUR | Central bank of Iceland |
| | Exchange Rate 2009 Forecast | 127 ISK/EUR | Glitnir Bank February 2009 |
| | Exchange Rate 2010 Forecast | 120 ISK/EUR | Glitnir Bank February 2009 |
| 2 | Average Exchange Rate 2006 | 0,79703 USD/EUR | |
| | Average Exchange Rate 2007 | 0,73082 USD/EUR | |
| | Average Exchange Rate 2008 | 0,68341 USD/EUR | |
| | Exchange Rate 2009 Forecast | 0,7242 USD/EUR | |
| | Exchange Rate 2010 Forecast | 0,7242 USD/EUR | |
| 3 | <p>In year 2007 and 2008 Orkuveita Reykjavíkur granted IES a substantial support through the Environment and Energy Research Fund and the Division of Innovation and Development. The proportion of this funding in IES's contribution to the CarbFix project was 57% each year. In year 2009 this support from Orkuveita Reykjavíkur is estimated to be 77%. In year 2007 and 2008 IES was granted a support from Hitaveita Suðurnesja and Norðurál that was 15 % of IES's contribution to the CarbFix project. The proportion of EU funds in the contribution from IES was 7% in 2006, 5% in 2007, 13% in 2008 and it is estimated the EU funds will be 12% in 2009 and 49% in 2010</p> | | |
| 4 | The estimated figures for CNRS in 2009 and 2010 did not arrive in due time for the Status Report | | |
| 5 | Salaries: Project Manager, Research Scientists, Lawyer and Technicians | | |
| 6 | Includes salary and wages for personnel and fringe benefits (30.8%) | | |
| 7 | Filed supply: Setup in boreholes, downhole pumps, containers, dieselmotors, connection to electricity grid, oil and electricity on site, equipment for sampling, heavy machinery, ISOR fieldwork and analysis and cost of designing and constructing the injection setup | | |
| 8 | Laboratory and filed supply and analyses | | |
| 9 | Laboratory and filed supply and analyses | | |
| 10 | Laboratory and filed supply and analyses | | |
| 11 | Cost of designing the CarbFix website and logo. Cost of the signing ceremony and CarbFix meetings | | |
| 12 | Overhead cost according to the Managing Director at the Science Institute of University of Iceland | | |
| 13 | ICR on direct costs for internally funded projects (not including permanent equipment) | | |
| 14 | Overhead cost | | |
| 15 | The CO ₂ injection was planned in the fall 2008 but was delayed until 2009. Therefore the estimated cost of design and execution of the injection will be credited in 2009 | | |

Summary

In the year 2008 the CarbFix project was addressing background fluid chemistries at the injection site and characterizing the target reservoir for the planned CO₂ injection in year 2009. Orkuveita Reykjavíkur completed the connection of the injection site to the national electricity grid early 2008 and installation of down-hole pumps for all monitoring wells was finalised in the summer of 2008 as well as drilling of a new monitoring well at the CO₂ injection site. Tracer tests have been launched in collaboration with scientists at Columbia University and Iceland Geosurvey. Numerous groundwater samples have been collected at the injection site the whole year and analysed at Iceland Geosurvey, Columbia University and Institute of Earth Sciences in Iceland. Several methods for mixing of the carbon dioxide and water have been discussed. The design of the set-up for the mixing of CO₂ and water has started in fall 2008. The preparation for the monitoring plan has started and meetings were held with the Environmental Authorities since fall 2008. Chemical modelling scenarios are being performed by the Institute of Earth Sciences in Iceland and the Centre National de la Recherche Scientifique, France, by lab experiments and numerical modelling and a numerical simulation code TOUGHREACT developed at Lawrence Berkeley National Laboratory in California has been used to develop reactive fluid flow models of the CO₂ mineralization. The outlook of the CarbFix website was finalized in the spring 2008. Eight PhD students and one MSc student were working on science projects, closely linked to the CarbFix project.

Appendix I – List of Selected Publications 2008

Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory (LDEO)

2008

Name	Talk	Poster	Abstract	Ext.Abs	Paper/Report	Book
W.S. Broecker						1
J. Matter	2	1			2	
M. Stute					1	
Summary	2	1			3	1

Wallace S. Broecker and Robert Kunzig (2008). **Fixing Climate: What Past Climate Changes Reveal About the Current Threat-and How to Counter It**. Farrar, Straus and Giroux. 272 pp.

Juerg Matter. The fifth meeting of the Global Roundtable on Climate Change, 12-13 February, 2008. Talk.

Juerg Matter. 2nd U.S. – China Symposium on CO₂ Emission Control Science & Technology, Hangzhou, China, May 28-30, 2008. Talk.

Juerg Matter. GHGT-9 (9th International Conference on Greenhouse Gas Control Technologies) in Washington, USA. 16-20 November, 2008. Poster.

Matter, J.M., Broecker, W.S., Stute, M., Gislason, S.R., Oelkers, E.H., Stefansson, A., Wolff-Boenisch, D., Gunnlaugsson, E., Axelsson, G. and Bjornsson, G. (2009). **Permanent Carbon Dioxide Storage into Basalt: The CarbFix Pilot Project, Iceland**. Energy Procedia. In Print.

Oelkers E.H., S.R. Gislason, and J. Matter (2008). **Mineral Carbonation of CO₂**, Elements, Vol. 4, 333-337.

The Centre National de la Recherche Scientifique, France (CNRS)

2008

Name	Talk	Poster	Abstract	Ext.Abs	Paper/Report	Book
E.H. Oelkers	1		1		3	
Summary	1		1		3	

E. H. Oelkers, T. K. Flaathen, S. R. Gislason, J. Schott, M. Hacini (2008). 30 YEARS OF PROGRESS IN PERFORMING REAL-TIME REACTIVE TRANSPORT CALCULATIONS? Abstract and talk.

Oelkers E.H., Gislason S. R. and J. Matter (2008). **Mineral Carbonation of CO₂**, Elements, 4, 333–337.

Oelkers, E. H and Cole, D.R. (2008) **Carbon Dioxide Sequestration: A Solution to a Global Problem**. Elements, 4, 305-310.

Flaathen, T.K., Gislason, S. R., Oelkers, E. H. and Á. E. Sveinbjörnsdóttir (2008). **Chemical evolution of the Mt. Hekla, Iceland, groundwaters: A natural analogue for CO₂ sequestration in basaltic rocks**. Applied Geochemistry, pending revision.

Orkuveita Reykjavíkur (OR)**2008**

Name	Talk	Poster	Abstract	Ext.Abs	Paper/Report	Book
E. Gunnlaugsson	1					
H. Sigurdardottir	16				1	
Summary	17				1	

H. Sigurdardottir (2008). **Nature Imitated in Permanent CO₂ Storage Project in Basalts in Iceland.** Greenhouse Issues, number 90, June 2008.

List of selected talks on the CarbFix project 2008:

Einar Gunnlaugsson. The Mayor of Los Angeles Antonio Villaraigosa met Olafur Ragnar Grimsson at Hellisheiði powerplant, 4 August.

H. Sigurdardottir. Carb-Fix, CO₂ fixation into basalt in Iceland. EU Sustainable Energy Week 2008. Geothermal Energy – Benefits and Potential, Brussels Belgium, 1 February.

H. Sigurdardottir. CarbFix, CO₂ fixation into basalt. Experiment at Hellisheiði Geothermal Plant, Iceland. ClimBus Workshop on CO₂ Capture, Utilization and Storage, Helsinki, Finland, 5 February.

H. Sigurdardottir and S.R. Gíslason. EFTA Surveillance Authority (ESA), Embassy of Iceland in Brussels and the Ministry for the Environment in Iceland, 13 March.

H. Sigurdardottir. The CarbFix project. Newsweek Daniel Gross Senior Editor, 17 March.

H. Sigurdardottir. A seminar on novel sustainable energies held on behalf of the British Embassy, Innovation Center Iceland, Ministry of Industries and Reykjavik Energy, 17 April.

H. Sigurdardottir. LULUCF (Land Use, Land-Use Change and Forestry), 7 May.

H. Sigurdardottir. The Norwegian Committee of Energy- and Environment, 14 May.

H. Sigurdardottir. Samorka's spring conference. Samorka is a federation of the Icelandic electricity industry, district heating, waterworks and sewage utilities in Iceland, 23 May.

H. Sigurdardottir. A group from the Environmental Defense Fund led by executive vice president David Yarnold, 25 June.

H. Sigurdardottir. Meeting with scientists who got a grant from Reykjavik Energy Environmental and Energy Research Fund, June.

H. Sigurdardottir and S.R. Gíslason. BBC Newsnight programme filming and interviewing on the carbon storage project at Hellisheiði, 4 July.

H. Sigurdardottir. The Minister of Energy and Water in Hungary visits Hellisheiði Geothermal Plant, 26 September.

H. Sigurdardottir. The Reykjavik Energy Graduate School of Sustainable Systems (REYST), 2. October.

H. Sigurdardottir. The Earth Institute of University of Iceland, 11 November.

H. Sigurdardottir. The Rotary Club Straumur, 4 December.

H. Sigurdardottir. A Norwegian Delegation of investors from the Energy Future Invest, Eidsiva and Statskraft, 16 December.

The University of Iceland – Institute of Earth Sciences (IES)**2008**

Name	Talk	Poster	Abstract	Ext.Abs	Paper/Report	Book
S.R. Gislason	5		3		1	
D. Wolf-Boenisch	2		1			
H.A. Alfredsson	5	2	2	1		
E.S. Aradottir*	1		1			
T.K. Flaaten	4	1	3	1	1	
S. Gudbrandsson	5	2	1	1		
A. Gysi	3	1	2	1		
G.J. Stockmann	3	2	2	1		
M. Rezvani Khalilabad	4	1	2	1	1	
A. Stefansson	2		2		1	
Summary	34	9	19	6	4	

* The University of Iceland – Department of Chemistry

H. A. Alfredsson, S. R. Gislason, B. S. Hardarson and H. Franzson, 2008. Permanent CO₂ fixation in basaltic rock: Characterization of the rocks at the injection site. Abstract and poster at the Natural Science Symposium 2008 at the University of Iceland.

H. A. Alfredsson, 2008. Permanent CO₂ fixation in basaltic rock: Characterization of the rocks at the injection site. Talk at the MIR-EST / MIN-GRO meeting in Carcassonne 2008.

H. A. Alfredsson, S. R. Gislason, B. S. Hardarson, 2008. CO₂ sequestration in basaltic rock at the Hellisheidi site in SW Iceland: Chemical composition of the rocks at the injection site. Abstract and talk at the CarbFix SSC/MT meeting, 12-14 June 2008 at Reykjavik Energy, Iceland.

H. A. Alfredsson, B. S. Hardarson, H. Franzson and S. R. Gislason, 2008. CO₂ sequestration in basaltic rock at the Hellisheidi site in SW Iceland: Stratigraphy and chemical composition of the rocks at the injection site. Mineralogical Magazine, February 2008, Vol. 72(1), pp. 1-5. Extended abstract for GES-8 conference, London.

H. A. Alfredsson, B. S. Hardarson, H. Franzson, S. R. Gislason 2008. CO₂ sequestration in basaltic rock at the Hellisheidi site in SW Iceland: Stratigraphy and chemical composition of the rocks at the injection site. Extended abstract and poster at the GES-8 conference, London 2008.

H. A. Alfredsson and Snorri Gudbrandsson, 2008. CarbFix - introduction. European Researchers' night in Iceland, 26. September 2008.

H. A. Alfredsson and S. R. Gíslason, 2008. CarbFix - CO₂ sequestration in basaltic rocks: The chemistry of the ground waters at the injection site. Talk at the CarbFix SSC / MT meeting, October 17th, 2008 at Reykjavik Energy.

H. A. Alfredsson and S. R. Gíslason, 2008. CarbFix - CO₂ sequestration in basaltic rocks: The chemistry of the rocks and ground waters at the injection site. Talk at the Folda seminar series, October 23rd, 2008, University of Iceland.

E.S. Aradottir (2008). Development of coupled reactive fluid flow models for mineral CO₂ capture. Abstract and talk at the CarbFix SSC/MT meeting, 12-14 June 2008 at Reykjavik Energy, Iceland.

Sigurður R. Gíslason (2008). Binding kolefnis í bergi. Rotaryklúbburinn Borgir, 3. apríl 2008.

Sigurður Reynir Gíslason, Einar Gunnlaugsson, Wallace S. Broecker, Eric H. Oelkers, Juerg M. Matter, Andri Stefánsson and Grímur Björnsson (2008). Permanent CO₂ sequestration into basalt: The Hellisheidi, Iceland project. Talk given at the Icelandic President's residency, Bessastadir during Al Gore's visit to Iceland in April 2008.

S. R. Gislason, W. S. Broecker, E. H. Oelkers, E. Gunnlaugsson, A. Stefansson, D. Wolff-Boenisch, J. Matter, G. Björnsson. Mineral CO₂ Sequestration into Basalt: The Carbfix Project. Abstract and Talk. Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract H11J-05.

S.R. Gislason, W.S. Broecker, E.H. Oelkers, E. Gunnlaugsson, A. Stefansson, J.M. Matter and G. Björnsson (2008). Mineral CO₂ sequestration into basalt: the Hellisheidi, Iceland project. Talk at the 33rd International Geological Conference, Oslo Norway, August 2008.

Sigurdur R. Gislason (2008). The carbfix project (www.carbfix.com). Talk at the International workshop in CO₂ sequestration into geothermal fields. University of Iceland, October 6th, 2008.

S.R. Gislason, W.S. Broecker, E.H. Oelkers, E. Gunnlaugsson, D. Wolff-Boenisch, A. Stefansson, J.M. Matter and G. Björnsson (2008). Mineral CO₂ sequestration into basalt: the Carbfix project. Fall Meeting of the American Geophysical Union, AGU, San Francisco, December 2008. (Talk given by DWB).

S. Gudbrandsson, 2008. Permanent CO₂ fixation in basaltic rock: Crystalline basalt dissolution rates as a function of temperature, pressure & solution composition. Talk at the MIR-EST / MIN-GRO meeting in Carcassonne 2008.

S. Gudbrandsson, D. Wolff-Boenisch, S. R. Gislason, E. H. Oelkers, 2008. Dissolution rates of crystalline basalt at pH 4 and 10 and 25°C to 75°C. Abstract and talk at the CarbFix SSC/MT meeting, 12-14 June 2008 at Reykjavik Energy, Iceland.

S. Gudbrandsson, D. Wolff-Boenisch, S. R. Gislason, E. H. Oelkers, 2008. Dissolution rates of crystalline basalt at pH 4 and 10 and 25 - 75°C. Mineralogical Magazine, February 2008, Vol. 72(1), pp. 155-158. Extended abstract at the GES-8 conference, London 2008.

S. Gudbrandsson, D. Wolff-Boenisch, S. R. Gislason, E. H. Oelkers, 2008. Dissolution rates of crystalline basalt at pH 4 and 10 and 25 - 75°C. Extended abstract and poster at the GES-8 conference, London 2008.

S. Gudbrandsson and H. A. Alfredsson, 2008. CarbFix - introduction. European Researchers' night in Iceland, 26. September 2008.

S. Gudbrandsson, 2008. Short introduction on findings, current activities and future experiments. Determination of crystalline basalt dissolution rates as a function of temperature, pressure and solution composition. Talk at the CarbFix SSC / MT meeting, October 17th, 2008 at Reykjavik Energy.

S. Gudbrandsson and D. Wolff-Boenisch, 2008. Determination of crystalline basalt dissolution rates as a function of temperature and solution composition. Talk at the Folda seminar series, November 27th, 2008, University of Iceland.

S. Gudbrandsson, 2008. AGU Fall meeting USA December 2008. Co-author.

A. Gysi and A. Stefansson, 2008. Numerical modeling of CO₂-water-basalt interaction. Abstract and talk at the CarbFix SSC/MT meeting, 12-14 June 2008 at Reykjavik Energy, Iceland.

A. Stefansson and A. Gysi. CO₂-basalt interaction - Numerical simulation and experimental study. Co-author, conference abstract, Goldschmidt, Vancouver 2008.

A. Stefansson, 2008. CO₂-basalt interaction. Disko-Nuussuaq, West-Greenland analogue. Talk at the CarbFix SSC/MT meeting, 12-14 June 2008 at Reykjavik Energy, Iceland.

A. Stefansson, (2008). **Numerical simulation of CO₂-water-basalt interaction**. Institute of Earth Sciences Report, RH-2-2008.

A. Gysi. CO₂-water-rock interaction: numerical modeling and experiments on the effects of CO₂ on basalt alteration. Talk at the MIR-EST / MIN-GRO meeting in Carcassonne 2008.

A. Gysi and A. Stefansson, 2008. Numerical modeling of CO₂-water-basalt interaction. Poster at the GES-8 conference, London 2008.

-
- A. Gysi and A. Stefánsson, 2008. Numerical modeling of CO₂-water-basalt interaction. *Mineralogical Magazine*, February 2008, Vol. 72(1), pp. 55-59. Extended abstract at the GES-8 conference, London 2008.
- A. Gysi, 2008. CO₂-water-basalt interaction, update. Talk at the CarbFix SSC / MT meeting, October 17th, 2008 at Reykjavik Energy.
- T. K. Flaathen, S. R. Gíslason, E. H. Oelkers, 2008. CO₂ sequestration in basalt. MIR-EST/MIN-GRO meeting in Carcassonne, France, May 2008.
- T. K. Flaathen, S. R. Gíslason, E. H. Oelkers, 2008. Can CO₂ be safely sequestered by carbonization of basalt? CarbFix SSC-MT meeting, Reykjavik Energy, Iceland, June 2008.
- T. K. Flaathen, E. H. Oelkers, S. R. Gíslason, 2008. An experimental study of the effect of sulphate on the dissolution rate of basaltic glass. CarbFix SSC-MT meeting, Reykjavik Energy, Iceland, June 2008.
- T. K. Flaathen, E. H. Oelkers, S. R. Gíslason, 2008. Can CO₂ be safely sequestered by carbonization of basalt? The 33rd international Geological Congress, Oslo.
- T. K. Flaathen, E. H. Oelkers, S. R. Gíslason, 2008. The effect of aqueous sulphate on basaltic glass dissolution rates. *Mineralogical Magazine* 72 (1), 39-41.
- Flaathen, T.K., Gíslason, S. R., Oelkers, E. H. and Sveinbjörnsdóttir Á. E. (2008). **Chemical evolution of the Mt. Hekla, Iceland, groundwaters: A natural analogue for CO₂ sequestration in basaltic rocks.** *Applied Geochemistry*, pending revision.
- Matter, J.M., Broecker, W.S., Stute, M., Gíslason, S.R., Oelkers, E.H., Stefánsson, A., Wolff-Boenisch, D., Gunnlaugsson, E., Axelsson, G. and Björnsson, G. (2009). **Permanent Carbon Dioxide Storage into Basalt: The CarbFix Pilot Project, Iceland.** *Energy Procedia*. In Print.
- Oelkers E.H., Gíslason S. R. and Matter J. (2008). **Mineral Carbonation of CO₂**, *Elements*, 4, 333–337.
- M. Rezvani Khalilabad, G. Axelsson and S. R. Gíslason, 2008. Aquifer characterization with tracer test technique: Permanent CO₂ sequestration into basalt, SW Iceland. *Mineralogical Magazine*, February 2008, Vol. 72(1). Pp. 121-125.
- M. Rezvani Khalilabad, G. Axelsson and S. R. Gíslason, 2008. Characterization of the intermediate level ground water system in Threngsli-Hellisheidi through tracer test application. Abstract and talk at the Natural Science Symposium, University of Iceland.
- M. Rezvani Khalilabad, G. Axelsson and S. R. Gíslason, 2008. Characterization of the intermediate level ground water system in Threngsli-Hellisheidi through tracer test application. Talk at the MIR-EST / MIN-GRO meeting in Carcassonne 2008.
- M. Rezvani Khalilabad (2008). **AQUIFER CHARACTERIZATION WITH TRACER TEST TECHNIQUE; Permanent CO₂ Sequestration into Basalt, SW-ICELAND.** University of Iceland 2008. M.sc. Thesis and talk.
- M. Rezvani Khalilabad, G. Axelsson, 2008. Characterization of The Threngsli CO₂ injection target zone through tracer testing. Abstract and talk at the CarbFix SSC/MT meeting, 12-14 June 2008 at Reykjavik Energy, Iceland.
- Stipp S.L.S., Oelkers E., Gíslason S., West K., Nissenbaum, J., Sand K.K., Makovicky E., Bjørnholm T. and Bechgaard K. (2008). Can we convert CO₂ back to rock form?
- G. Stockmann, D. Wolff-Boenisch, S. R. Gíslason & E. H. Oelkers, 2008. Dissolution of diopside and basaltic glass: the effect of carbonate coating. *Mineralogical Magazine*, February 2008, Vol. 72(1), p. 139-143.
- G. Stockmann & E. Sturkell (ed.), 2008. SSC/MT meeting, 12-14 June at Reykjavik Energy, Iceland, Book of Abstracts, 28 pp.
-

G. Stockmann, D. Wolff-Boenisch, S. R. Gíslason & E. H. Oelkers, 2008. Dissolution of diopside and basaltic glass, CarbFix SSC-MT meeting, Reykjavik Energy, Iceland, June 2008, Abstracts, page 16.

G. Stockmann, S. R. Gíslason, D. Wolff-Boenisch & E. H. Oelkers, 2008. Carbon dioxide sequestration into basalt. Natural Science Symposium 2008, University of Iceland, Abstracts, page 139.

G. Stockmann, 2008. Update on PhD project: Dissolution of diopside and basaltic glass. Talk at the CarbFix SSC-MT meeting, Reykjavik Energy, Iceland, October 2008.

G. Stockmann, 2008: Dissolution of diopside and basaltic glass. Talk at the CarbFix SSC-MT meeting, Reykjavik Energy, Iceland, June 2008.

G. Stockmann, 2008: Permanent CO₂ sequestration into basalt: Experimental determination of the effect of precipitated mineral coatings on the rates of basaltic mineral and glass dissolution rates. Talk at the Min-Gro workshop, Carcassonne, France, May 2008.

D. Wolff-Boenisch, G. Stockmann, S. Gudbransson, S. R. Gíslason, E. H. Oelkers, 2008. Laboratory Studies on the Potential of Using Basalt for Large-Scale Mineral Sequestration of CO₂. Abstract and Talk. Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract H11J-04.

Domenik Wolff-Boenisch, Gabrielle J. Stockmann, Snorri Gudbransson, Sigurdur R. Gíslason, Eric H. Oelkers (2008). RESULTS FROM LABORATORY STUDIES on the POTENTIAL of USING BASALT as INJECTION MEDIUM for PERMANENT LARGE-SCALE CO₂ SEQUESTRATION. Talk at the Fall Meeting of the American Geophysical Union, AGU, San Francisco, December 2008.

Appendix II - CarbFix in the media

June 11th 2008 the Icelandic National Broadcasting Service reported from the CarbFix field site and interviewed Juerg Matter and Martin Stute from Columbia University.

October 9th 2008 BBC Newsnight's Susan Watts Science Editor reports from Iceland on the CarbFix project along with radical new approaches to reducing carbon in the atmosphere involving algae and artificial trees. Susan together with Ming Tsang Producer and Mark Thompson Cameraman from BBC Newsnight visited the CarbFix project site at the Hellisheidi Geothermal Plant in July 2008. Susan Watts interviewed Wallace Broecker from Columbia University, Sigurður R. Gíslason from the University of Iceland and Hólmfríður Sigurðardóttir from Orkuveita Reykjavíkur

November 8th 2008 an interview with Wallace Broecker from Columbia University on the CarbFix project in the newspaper Morgunblaðið.