CarbFix

Rapid CO$_2$ mineral sequestration in basalts

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Overview of talk

- What is CarbFix
- Timeline of project
- Injections carried out
- The CarbFix CCS method
- Results of project
  - Solubility storage and mineral storage
- Storage capacity
- Cost
- Upcoming activities
CarbFix: CO$_2$ turned to stone in less than two years
Permanent removal from the atmosphere

Animation: PBS
The chemical equation

Basalt + CO₂ dissolved in water = Carbonates
Imitate a natural process

Benign environmental impact

- Natural CO$_2$ storage in Hellisheidi geothermal field estimated to be 65.7 kg/m$^3$ and 1650 megatons in total$^1$

- 750-fold anthropogenic CO$_2$ emissions in Iceland (2.2 megatons$^2$)

$^1$ Weise et al., report Ísor-2008/003  
$^2$ UN Framework Convention on Climate Change, 2005
How it began
Back in year 2006

- President Ólafur Ragnar Grímsson invited Prof. Wallace Broecker to give a talk on the fight against climate change in 2006
- Wally presented CO₂ sequestration as an important tool for the fight
- A team began studying the feasibility of sequestering CO₂ in basalts in Iceland
- CarbFix formally founded in 2007
Brief project timeline

Preparation phase
- Idea born
- CarbFix founded
- Lab experiments
- Design of method and equipment
- Field hydrology study
- Hydrological and reactive transport modelling
- Development of monitoring methods
- Test injections

Pilot phase
- Monitoring
- 1st scale industrial operations
- Results on rapid mineralization
- Doubled capacity of industrial operations
- EU funding: Direct air capture and preparing for offshore

Industrial scale operations

Timeline:

Today
Injections carried out
CO₂ injected in CarbFix since 2011

- 2011: 800 kg test injection
- 2012: 285 tons pilot injection
  - Phase 1: pure CO₂
  - Phase 2: gas mixture
- Industrial scale capture and injection built up in stages from 2014
- Currently capturing and injecting about 1/3rd CO₂ and 2/3rd H₂S
The CarbFix1 method

Gislason and Oelkers, Science, 2014
Sigfússon et al., IJGGC, 2015
CO\textsubscript{2} and H\textsubscript{2}S gas mixed with conservative volatile tracers, SF\textsubscript{6} and SF\textsubscript{5}CF\textsubscript{3}.

Pilot gas separation station captures ~2% of gases from power plant.

Injected 175 tonnes of pure CO\textsubscript{2} in January-March 2012.

Injected 73 tonnes of CO\textsubscript{2}-H\textsubscript{2}S-H\textsubscript{2} gas mixture (75%-24%-1%) in June-August 2012.

Water pumped to the injection site. Conservative and non-volatile tracers added and the carbon was labeled with\textsuperscript{14}C.

2 kg/s of water pumped out of the first monitoring well.

Temperature 20-50°C. Distance ~100 m at ~500 m depth.
Reykjavík Energy injects about 25 million tonnes of geothermal brine into the rock each year at more than 700 m depth and 250 °C.

CO₂ and H₂S gas mixture has been continuously injected into this “down going stream” since June 2014.
“Pure” condensate “shower” at 20°C

“Insoluble gases” out: H₂, N₂, O₂, CH₄, Ar…

Out-going gas-charged condensate water at ≈ pH 4, 20°C and pressurised to 8 bars before injection

“Insoluble gases” out: H₂, N₂, O₂, CH₄, Ar…

“Pure” condensate “shower” in

In-going gas stream at 6 bars
CO₂ and H₂S are dissolved in condensation water in a scrubbing tower at the power plant and co-injected with the brine into the basaltic rocks. Conservative tracers arrive months after injection.
Results
Immediate solubility storage confirmed
Within injection well (pilot phase) and on surface (industrial scale operations)

- Eradicates risk of leakage towards surface due to buoyancy
- Surface and atmospheric gas flux measurements in vicinity of injection site showed no signs of leakage
- Bailer samples furthermore confirm complete dissolution

Sigfússon et al., IJGGC, 2015
Tracer results from pilot phase

- Increase in tracer concentration in HN04 signal for arrival of injectate
  - First arrival: 56 and 58 days
  - Peak: 406 and 350 days
- pH and DIC initially show same behavior as tracers
- DIC then levels off and remains more or less constant
Fate of injected CO$_2$

- Mass balance calculations show that measured and expected DIC and 14C concentrations differ significantly
  - Suggests a loss of DIC and 14C
  - Most plausible mechanism for this difference is carbonate precipitation
- Results indicate that >95% of injected CO$_2$ was mineralized through water-CO$_2$-basalt reactions within 2 years
• Submersible pump clogged with calcite 1.5 years after start of pilot phase injection
• Confirmed by 14C analysis that carbon originates from CarbFix (Matter et al., 2016)
Mass balance on the injected and observed tracer, CO\textsubscript{2} and H\textsubscript{2}S concentrations suggest that most of the gases are mineralised within a year of injection.

A dosing pump injected a concentrated 1-naftalenesulphonic acid tracer into the condensate stream.
Pilot injection phase
Which carbon minerals formed?

- Calcite only carbonate phase identified
- Fluid chemistry, modelling and lab experiments point towards*
  - precipitation of siderite and other Fe-rich carbonate solid solutions during low pH
    - expect Fe to go into sulfides during mixed gas injection
  - As fluid evolves above pH 5 carbonates become more Ca and Mg rich
  - Calcite dominant carbon phase to form when pH reaches 8

* Snæbjörnsdóttir et al, IJGGC, 2017; Clark et al. Goldschmidt, 2017; Snæbjörnsdóttir et al. GCA, 2018; Matter et al. Science, 2016; Aradóttir et al., IJGGC, 2012
Minerals precipitating
Saturation indices of monitoring samples

- Calcite strongly undersaturated initially but reaches saturation a few weeks after injections
  - Aragonite and carbonate solid solutions show same trend
- Siderite supersaturated shortly after injections but magnesite strongly undersaturated
- Ankerite supersaturated during whole monitoring period
Minerals precipitating
Reaction path modelling of first breakthrough

- Chalcedony first alteration phase to form
- Siderite first carbonate to form at pH 5
- Gradually, the carbonates become more Mg-, and Ca-rich with calcite dominating at the end

Snæbjörnsdóttir et al., GCA, 2018
Minerals precipitating
Reaction path modelling of main plume

- Aluminum hydroxides and chalcedony first minerals to precipitate
- Siderite first carbonate-phase to form
- As the fluid evolves above pH 5 the carbonates become more Mg-rich and Ca-rich
- Calcite is the dominant carbonate forming when the pH reaches 8
- Competing minerals for cations are the zeolites analcime and thomsonite along with smectite
Reactive transport modelling
Simulation of 1200 ton pilot injection

- Chalcedony and simple hydroxides first minerals to precipitate
- Calcite most dominant carbonate to form but dolomite and a Fe-rich magnesite–siderite solid solution also form to a lesser degree
  - Calcite precipitates over diffuse rock volume
  - Dolomite precipitates in large quantities at the front of traveling CO$_2$ plume but dissolves again as the plume passes by
  - Fe-rich solid solution precipitates within the CO$_2$ plume
- Zeolites compete with carbones for cations
- Horizontal zeolite zones reproduced in simulations (Walker, 1960)
- Figures apply to 5 years from injection

Aradóttir et al. IJGGC, 2012
Industrial scale operations
What minerals are precipitating and where

• Mass balance calculations indicate most of the gases to have precipitated within a year
• Simple dual porosity reactive transport models predict magnesite to act as the only CO$_2$ sink (Aradóttir et al, 2015) but we believe calcite is also forming
• Injectivity of injection well remains stable so precipitation not occurring in near vicinity of well
• Expect precipitation over a diffuse rock volume
  – Volume of current reservoir is ~1,5 m$^3$
  – Flow not radial and highly responsive to nearby injection
Storage capacity
- Storage capacity of current injection flow ~ 5 Mt CO₂ (150 years of power plant operation).
- For all Hellisheidi area, different analysis on storage capacity range from 0.4 to 5,744 Mt CO₂ with an average value of 1,348 Mt CO₂ and median value of 697 Mt CO₂.
- Storage potential of the basaltic formations at Hellisheidi is not a limiting factor for large scale, long term operations.
- Storage capacity of rift zone in Iceland 1000–2500 Gt CO₂ (Snæbjörnsdóttir et al., 2014).
Location of major basaltic terrains
5% of continents (Dessert et al. CG 2003)
Storage capacity of oceanic ridges

- Theoretical storage capacity of ocean ridges is ~100,000–250,000 Gt CO$_2$
  - Significantly larger than the estimated 18,500 Gt CO$_2$ stemming from burning of all fossil fuel carbon on Earth

- CarbFix is water intensive
  - The Atlantic Ocean contains $\approx 18.750.000.000.000.000$ tons of sea water
Cost
Cost of CarbFix

- Total cost of project ~25 million USD
  - All inclusive for all partners
    - Pre-injection studies at field site
    - Lab work
    - Modelling
    - Design and building of pilot and industrial scale infrastructure
    - Monitoring
    - Natural analogs
    - Outreach
    - Training of ~10 PhD students
    - ...

- Cost per ton injected ~US $ 1900/ton
Cost of industrial scale CCS at Reykjavik Energy ~US $ 30/ton

Cost of capture highest but monitoring lowest
Comparison of cost
Conventional carbon and sulfur removal methods

Cost of conventional CCS methods from Global CCS Institute, 2011
Cost of Conventional S methods based on consultancy work for OR
What next?
Upcoming activities in CarbFix

- Continued research on ongoing injection
  - Tracers, monitoring, reactive transport models, seismicity, ...

- Preparation for off-shore injection
  - Pre-feasibility assessment, reactive transport models, tracer study for hydrological research, laboratory work, development of a seawater-based CO$_2$-rich gas prototype capture system

- Direct capture of CO$_2$ from ambient air and injection into the CarbFix reservoir (negative carbon emissions)
  - Demonstration plant launched last month
Summary

• CarbFix has developed a safe, efficient and economical method for capturing, injecting and permanently storing CO$_2$ as minerals in basaltic formations

• Process has been demonstrated to work in shallow, relatively cold reservoirs (~500 m, 30°C) and in fractured hot reservoirs (~1500 m, 250°C)

• Precipitation of carbonates believed to proceed through Fe rich → Mg, Ca rich → Calcite as pH evolves
Thank you very much for your attention

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Induced seismicity at CarbFix2 injection site

- Induced seismicity occurred when the Húsmúli re-injection field was commenced in 2011
  - not in relation to gas injection
- About 4600 events during 8 months
  - The largest events close to 4.0
- Events over 2.5 were felt in the village of Hveragerði, 10 km away from the injection site
- The largest earthquakes were also felt in Reykjavík (distance of 20-30 km)
New traffic light process put in place
Based on AltaRock Energy’s Newberry EGS demonstration project

<table>
<thead>
<tr>
<th>Event</th>
<th>Field Operation</th>
<th>Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>Seismic monitors in place and active</td>
<td>Notify the Icelandic Civil Protection Department (ICPD), IMO and Reykjavik Energy’s public affairs.</td>
</tr>
<tr>
<td>No flow increase</td>
<td>M 2.0 til 2.5</td>
<td>Status report sent to IMO</td>
</tr>
<tr>
<td>Decrease flow</td>
<td>M 2.5 til 3.5</td>
<td>Status report sent to regulators, the ICPD, IMO and Reykjavik Energy’s public affairs.</td>
</tr>
<tr>
<td>Stop injection</td>
<td>M &gt; 3.5</td>
<td>Status report sent to regulators, the ICPD, IMO and Reykjavik Energy’s public affairs. Assess possible damage.</td>
</tr>
<tr>
<td>End</td>
<td>Reinjection stable</td>
<td>Notify the Icelandic Civil Protection Department (ICPD), IMO and Reykjavik Energy’s public affairs.</td>
</tr>
</tbody>
</table>

Injection started slowly. Pumping increased in stages with lag times in between.
No flow or pressure increase for two hours.
Injection is decreased by one step and a 12 hour stop on further injection changes.
Stop injection operation.
No action.
Outreach procedures have proven to be successful

- Media coverage and public opinion of the events of October 2011 was very unfavorable
- Traffic light procedure and outreach had been in effect for a few years when another wave of seismic activity occurred in September 2016
- Effects on society were minimal as reflected in content analysis of media coverage
- Indicative of the impact of OR’s public and stakeholder engagement following the event of 2011

Content analysis of news on Reykjavík Energy in two months when seismic activity connected to re-injection has occurred