Innovation in geothermal energy

Turning CO$_2$ into rock

Hólmfríður Sigurdardóttir
Head of Environmental Affairs, Reykjavík Energy
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This is Reykjavík Energy

Water

Electricity

Hot water

Sewerage

Fiber optics
It matters how we do things
OR and subsidiaries serve ¾ of Icelanders
Climate goals of the OR group
We are partner to commitments initiated by The City of Reykjavík and Festa-Icelandic Center for CSR

Examples of reduction targets by 2020

<table>
<thead>
<tr>
<th>Activity</th>
<th>Target</th>
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</thead>
<tbody>
<tr>
<td>On-site electricity for steam-drilling</td>
<td>95%</td>
</tr>
<tr>
<td>Reduced office waste</td>
<td>80%</td>
</tr>
<tr>
<td>Reduced on-site waste</td>
<td>75%</td>
</tr>
<tr>
<td>Staff’s travels to and from work</td>
<td>50%</td>
</tr>
<tr>
<td>Fixation of geothermal gases</td>
<td>50%</td>
</tr>
<tr>
<td>Reduced food-waste</td>
<td>40%</td>
</tr>
<tr>
<td>Reduced air travels</td>
<td>5%</td>
</tr>
</tbody>
</table>
Benefits of geothermal in Iceland
Economic, environmental, social ...

- Households and companies
  - Affordable electricity and heating
  - Public health
- Economic
  - In 2010 Iceland’s total economic benefit from geothermal was calculated to be about $600 million
- Environmental
  - Reduced carbon footprint
Primary energy use in Iceland 1940-2015

Data: IEA, 2016
Relative primary energy use in Iceland 1940-2015

- 12% renewables 1940
- 85% renewables 2015

Data: IEA, 2016
How we utilize the geothermal resource

- **Space Heating**: 43%
- **Electric generation**: 40%
- **Agriculture/aquaculture/industry**: 9%
- **Bathing and Swimming**: 4%
- **Others**: 4%
Environmental benefits
Avoided CO₂ emissions through Iceland’s capital area’s district heating 1944-2014

Data: Einar Gunnlaugsson, 2015
CO₂ footprint of electric generation by source in grams of CO₂ equivalents per kWh

Data: International panel on climate change (IPCC) 2014
Not without challenges
Geothermal energy and geothermal gas emissions

• Emissions besides H₂O
  – CO₂, H₂S
  – H₂, N₂, CH₄, Ar
  – Environmentally significant
    • GHG, corrosive, toxic, flammable, smelly

• Origin
  – Magmatic
  – Meteoric/precipitation
  – Water rock reactions
Geothermal power plants by the Hengill central volcano

Nesjavellir

Commissioning 1990-2005
120 MW<sub>e</sub> and 400 MW<sub>th</sub>
H<sub>2</sub>S: ≈ 9,000 tons
CO<sub>2</sub>: ≈ 16,000 tons
30 km. from the Capital area

Hellisheidi

Commissioning 2006-2011
303 MW<sub>e</sub> and 133 MW<sub>th</sub>
H<sub>2</sub>S: ≈ 11,000 tons
CO<sub>2</sub>: ≈ 40,000 tons
20 km from the Capital area
Social acceptance
Geothermal utilization met its most serious challenge for decades

- In 2006 complaints and demands for cleaning the H$_2$S gas from the Hellisheidi Power Plant
- In 2007 a team of experts began the development of injecting H$_2$S into the basaltic bedrock
Complaints reflected in regulation

Icelandic regulation 514/2010 on atmospheric concentration of $\text{H}_2\text{S}$

- Stricter than WHO guidelines
- Requires the geothermal industry in Iceland to reduce atmospheric concentration
- Power companies obliged to conduct measurements in cooperation with authorities
- Non-compliance punishable by a 4-year prison term

<table>
<thead>
<tr>
<th>Guidelines and regulation on atmospheric $\text{H}_2\text{S}$ concentration</th>
<th>Averaging period</th>
<th>Value $\mu\text{g/m}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHO Air quality guidelines, 2nd Edition</td>
<td>24 hour</td>
<td>150</td>
</tr>
<tr>
<td>Icelandic regulation 514/2010</td>
<td>24 hour</td>
<td>50*</td>
</tr>
<tr>
<td></td>
<td>3 hour</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>5</td>
</tr>
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* Allowed instances of surpassing limit are 3 per year
United front against the challenge

- The largest environmental challenge OR was facing
- Formal collaboration between Iceland’s three largest geothermal companies
  - OR
  - Landsvirkjun
  - HS Orka
- OR rightfully was in the driver’s seat
During the debate scientists had been working...

CO₂ abatement and subsurface sequestration

- In 2006 Wallace Broecker was invited to Iceland by the President to give a talk on climate change
  - Removing CO₂ from the air and sequestering it in the subsurface
- CarbFix initiated in 2007
  - International experts investigate the feasibility of CO₂ sequestration in basalt
- Hellisheidi was an ideal laboratory
  - Stream of CO₂ and ample basalt
Imitation of natural processes

- Natural CO\textsubscript{2} storage in Hellisheidi geothermal field estimated to be 65,7 kg/m\textsuperscript{3} and 1650 megatons in total\textsuperscript{1}

- 750-fold anthropogenic CO\textsubscript{2} emissions in Iceland in 2003 (2.2 megatons\textsuperscript{2})

\textsuperscript{1} Weise et al., report Ísor-2008/003
\textsuperscript{2} UN Framework Convention on Climate Change, 2005
OR’s pilot stations at Hellisheidi
-capture, transporting and injection 2007-2012
CO$_2$ fixation manifested
Important results in October 2014

- $\approx 95\%$ sequestration in mineral form within two years from re-injection
- Theory confirmed
- The project receives attention in the scientific community
- A boost for the ongoing H$_2$S removal

Calcite from a core of $\sim$420 m depth. The green color is calcite marked by tracer.
Gas is turned into rock
Same basic processes

Basalt + CO$_2$ dissolved in water = Carbonates

Basalt + H$_2$S dissolved in water = Sulfur and Sulfides
R&D cost and cost of full scale gas abatement

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<td>Million USD</td>
<td>3.1</td>
<td>9.2*</td>
<td>1</td>
</tr>
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</table>

* Grants from EU, US DoE, GEORG etc: USD 6.8 million

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<tr>
<th>Full scale gas abatement</th>
<th>Hellisheidi $H_2S+CO_2$</th>
<th>Conventional CCS $CO_2$</th>
<th>Conventional $H_2S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>USD/tons</td>
<td>25</td>
<td>62-131</td>
<td>356**</td>
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</table>

** Cost of abatement
Dissemination of knowledge
Lessons learned and implications

- When pushed, the industry responds
- Collaboration of industry and academia can be very fruitful
- A new method has been developed
  - Economic
  - Environmentally friendly
  - Green energy has become even greener

Photo: www.nasa.gov