Large scale pilots “worldwide” for CO$_2$ geological storage

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Monitoring objectives

- Regulation and operational performance:
  - Health, safety and environment: no significant irregularities
  - Proof that CO$_2$ is within the reservoir/storage complex
  - Mass balance verification: controlled storage into target formations for emission trading (ETS requirements)
  - Proven understanding of future behaviour of CO$_2$ plume (transfer of responsibility)
  - Effectiveness of corrective measures

- Research and engineering:
  - Testing monitor techniques and methodologies

- Public engagement
  - Making storage more understandable for the public
Conclusion

➔ ECCSEL can play a determining role in developing and testing CCS technology for commercial deployment in the next 5 to 15 yrs from now

➔ Research should preferably be CCS implementation driven

➔ Research on monitoring:
  ➔ To recognize the proper spatial and temporal scales
  ➔ Provide reliable measurements over long time periods
  ➔ Provide the proper resolution

➔ Collaborate with implementers in government and industry in ‘real life’ conditions

➔ Engage all stakeholders including NGOs and public
Implementing CCS – any need for pilot sites?

Technical readiness level

Hontomin
~ 10 kt CO₂?

Ketzin
~ 67 kt CO₂
~ 0.01 Mt/a

Illinois Basin
Decatur Project
~ 1 Mt CO₂
~ 0.33 Mt/a

Sleipner
~ 3.8 Mt CO₂
~ 0.5 Mt/a

In Salah
~ 16 Mt CO₂
~ 0.8 Mt/a

Otway Project
~ 65 kt CO₂
~ 0.04 Mt/a

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Svelvik,
FRS
< 1 kt CO₂

Nagaoka
~ 10 kt CO₂
20~40 t/d

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~ 65 kt CO₂
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Boundary
Dam
~ 1 Mt/a

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field tests 0.01 Mt
pilot sites 0.1 Mt
demo projects 1 Mt
industrial sites

storage size

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Implementing CCS – any need for pilot sites?

**LSIPs – all stages (44 projects)**

- only 15 operating LSIPs (~28 Mt CO₂/a)
- out of these 11 with EOR (~25.4 Mt CO₂/a)
- only 4 dedicated storage LSIPs (~2.6 Mt CO₂/a)
- projects are highly uneven distributed globally

**LSIPs – operate (15 projects)**

- it’s not only lack of business case (although this would help)
- it’s a lack of knowledge, awareness and acceptance ➔ **pilot sites**!

**LSIPs – operate, dedicated storage (4 projects)**

(GCCSI)
The Ketzin case – representative for pilot site

- first European and only national on-shore CO\textsubscript{2} storage project
- as R&D site limited to maximum amount of 100 kt CO\textsubscript{2}

Main objectives:
- Study complete life-cycle
- Show feasibility of on-shore CO\textsubscript{2} storage in saline aquifer
- Increase confidence in CO\textsubscript{2} storage

Main tasks:
- Successful site operation
- Monitoring & modelling
- Public outreach

April 2004
Start project

July 2007
Operation permit

June 2008
Start injection

August 2013
End injection

December 2017
Transfer liability

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The Ketzin pilot site

- located in the North East German Basin
  - large Permo-Mesozoic sedimentary basin -
- Ketzin-Roskow double anticline above salt pillow

**cap-rock:**
- Upper Triassic shales, >165 m

**reservoir:**
- saline aquifer
- sandstones of Upper Triassic Stuttgart Formation
- fluvial system
- lateral and vertical heterogeneous
- 620 – 650 m depth
The Ketzin pilot site

- unique, fully equipped research infrastructure for field experiments

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The Ketzin pilot site

- Start of injection: June 30, 2008
- End of injection: August 29, 2013

**Total mass injected: 67 kt CO₂**

**CO₂ sources and quality:**
- Food-grade CO₂ (Linde), > 99.9%
- May to June, 2011: 1,515 t CO₂ from oxyfuel pilot plant, > 99.7%

**Field experiments:**
- 2012: “coring the reservoir”, drilling of well 203
- March to June, 2013: “cold injection” experiment
- July to August, 2013: 650 t CO₂-N₂ (95/5) co-injection experiment, isotopically labeled CO₂
- October, 2014: “CO₂ back-production” in the frame of Carbon Capture Utilization and Storage
- October 2015 to January 2016: “brine injection” experiment
Monitoring concept Ketzin

- Surface
- Overburden
- Cap rock >165 m shale
- CO₂ storage reservoir
- Reservoir

**Permanent:***
- Temperature (DTS)
- Pressure
- Passive seismic
- Geoelectric (cross-hole)
- InSAR

**Periodic:***
- Well inspection/
depth fluid sampling
- Active seismic
  (2D, 3D, VSP, MSP)
- Geoelectric
  (surface-downhole)
- Surface (soil flux)

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Monitoring concept Otway project

- Injection into depleted gas field @ ~ 2100 m, 2008 - 2011
- One injection, one observation well
- 65 kt CO₂ injected
- Monitoring observations consistent with modelled predictions
- No evidence of leakage
- Planning for stage II, injection into saline aquifer
Geophysical monitoring concept Ketzin

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Geophysical monitoring concept Ketzin

subsurface coverage
3D sismics:
- baseline
- repeat

lines for 2D, VSP, MSP

concentric orientation of surface dipoles
r = 800, 1500 m

isobaths [m]
top Stuttgart
710 m isobath
top Stuttgart = lateral extension of storage complex

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Geophysical monitoring concept Ketzin

normalized time-lapse amplitude changes:
Baseline – 2009; 22 kt CO₂
~ 0.08 km²
Baseline – 2012; 61 kt CO₂
~ 0.15 km²

• CO₂ plume indicate preferred WNW – ESE extension
• centered @ injection site, far from spill-point and central fault zone
  • 3rd repeat autumn 2015 on plume stabilization

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Geophysical monitoring concept Ketzin

integrated state-of-the art geoelectrical monitoring

- correlation between operational parameters and geophysical monitoring data
- hydrogeophysical modelling
"coring the reservoir"

Ktzi 203 – drilled through the reservoir to study effects of four years of CO$_2$ injection on petrophysics, mineralogy, geochemistry,

- 91 m (caprock and CO$_2$ reservoir) core samples provide unique data base
- sharp rise in CO$_2$-concentration in the reservoir (green area)
- significant shift of $\delta^{13}$C values to negative values in the reservoir (red line)
“coring the reservoir”

Pre-post-injection comparison indicative of changes in porosity and permeability?
"coring the reservoir"

Evidence for the formation of new carbonates and alteration of pre-existing Fe-oxides

Temporal crystallization sequence of new carbonate species:
(A) ankerite-rich dolomite
(B) calcite-rich siderite
(C) Mg–S-bearing (hydro-)calcite
(D) Sr–Na-bearing (hydro-)calcite

Partial transformation of hematite \(\text{Fe}_2\text{O}_3\) into goethite \(\alpha\)-FeOOH

X-ray photoelectron spectroscopy (XPS) for iron-oxides/hydroxides
"cold" injection experiment

- Bottom hole pressure
- Wellhead pressure
- Shut-in due to workover Ktzi 203
- Shut-in due to operational reasons
- Bottom hole temperature
- Wellhead temperature
- Set-point temperature

Flow rate [l/h]

- 0.9
- 1.1
- 1.3
- 1.5
- 1.7
- 1.9

Dates:
- 23.3.13
- 4.5.13
- 15.6.13
- 27.7.13

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“cold” injection experiment

Decreased wellhead temperature near l/v equilibrium but still single phase gas

- Despite larger variations in wellhead P-T and flow-rate, two-phase conditions did not pose any problems on injection process
**CO₂/N₂ co-injection experiment**

- Co-injection of 613 t CO₂ and 32 t N₂
- CO₂:N₂ ratio ~ 95:5
- δ¹³C = -3.4±0.2‰ vs. -30.6±0.4‰
- Kr tracer prior to regular experiment

**Injection rates of N₂ and HersteCO₂**

25.07.2013 - 18.08.2013
**CO₂/N₂ co-injection experiment**

- Gas mixture arrived after about 4 days at Ktzi 203 ~20 m from injection well Ktzi 201
- Increasing Kr concentrations correlate with increasing N₂ concentrations and δ¹³C values
- δ¹³C data indicate in-reservoir mixing between industrial CO₂ and Herste CO₂
- In-reservoir gas and C-isotope mixing are studied by post-injection back-production experiment
Back-production experiment

- Eddy covariance (BGR)
- Open-path FTIR (UFZ)
Back-production experiment

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~ 240 t CO$_2$

~ 55 t H$_2$O
Back-production experiment

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Public engagement: Making storage more understandable for the public

- Regular information of local politicians (started already prior to injection)
- Cooperation with local schools
- Weekly visitor day
- Yearly open-house day
- Close cooperation with mining authority
- Close cooperation with federal state government

Information of general public

Open-house days at Ketzin

Sports...

Beer, sausages, discussions...

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Implementing CCS – any need for pilot sites?

• General feasibility of CO$_2$ storage proven
  - no need for pilot sites
  - urgent need for integrated demo projects

• Perform specific field tests (leakage tests, risk of loosing a well)
  - only possible at pilot sites

• Monitoring tool development
  - pilot sites not essential but an advantage

• Provide first-hand experience on CO$_2$ storage
  - pilot sites are essential (even subcontractors from natural gas storage learnt from Ketzin)

• Build confidence in CO$_2$ storage
  - pilot sites form a first, essential step

Successful pilot sites are essential to implementation of CCS

but

they do not guarantee implementation of CCS