Zero Emission Platform

$CO_2$ Capture and Storage (CCS) – Matrix of Technologies

« Technology Blocks »

15 October 2008 FINAL (V9)
Agenda

• Overview of CO₂ value chain
• CO₂ capture technologies
• Efficiency improvement
• Transport & Storage
• Conclusion
• Appendix
CO₂ capture, transport and storage value chain

Power plant

- Power production & CO₂ capture
  - Several technologies
    - Pre-combustion
    - Post-combustion
    - Oxyfuel
  - CO₂ stream cleaning

Transport infrastructure

- Onshore pipeline
- Offshore pipeline
- Ships
- Rail/road tankers

Storage infrastructure

- Enhanced Oil/Gas Recovery
- Depleted oil/gas fields
- Deep saline aquifers
# CO₂ capture technology principles

<table>
<thead>
<tr>
<th>CO₂ capture technologies</th>
<th>CO₂ capture principle</th>
<th>Combustion principle</th>
<th>Power plant definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxyfiring</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>High concentration CO₂ stream production</td>
<td>O₂ combustion of coal/gas</td>
<td>Oxy-firing plant (Boiler-based)</td>
</tr>
<tr>
<td><strong>Post-combustion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>Exhaust gas CO₂ scrubbing</td>
<td>Air combustion of coal/gas</td>
<td>Pulverised Coal (PC) or Circulating Fluidised Bed (CFB)</td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td>Natural Gas Combined Cycle (NGCC)</td>
</tr>
<tr>
<td><strong>Pre-combustion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>Inlet gas CO₂ cleaning</td>
<td>Air combustion of H₂</td>
<td>Integrated Gasification Combined Cycle (IGCC)</td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td>Integrated Reforming Combined Cycle (IRCC)</td>
</tr>
</tbody>
</table>

Note: Coal includes all types of coal and biomass co-firing
Other technologies are not assessed due to low technical maturity or limited market potential (see appendix for details)
CO₂ capture, transport and storage value chains

Power production & CO₂ capture

Downstream

Oxy-fuel
O₂ separation

Post-combustion

Pre-combustion
O₂ separation

PC / CFB / NGCC

CO₂ Capture

CO₂ Capture

Purification

Purification

Compression

Compression

Land/sea pipeline Ship

Land/sea pipeline Ship

EOR/EGR Depleted fields
Saline aquifers

EOR/EGR Depleted fields
Saline aquifers

Power generation
Agenda

• Overview of CO₂ value chain
• CO₂ capture technologies
• Efficiency improvement
• Transport & Storage
• Conclusion
• Appendix
Validation status definition

<table>
<thead>
<tr>
<th>Validation status</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not validated</td>
<td>Not tested / Less advanced than pilot scale</td>
</tr>
<tr>
<td>Partially validated</td>
<td>Ready for large demo project</td>
</tr>
<tr>
<td>Fully validated</td>
<td>Commercially available</td>
</tr>
</tbody>
</table>
Oxyfuel technology blocks (boiler-based) – current validation status

Significant R&D and demonstration work required

Source: Vattenfall
Oxyfuel technology blocks – current validation status

O2 production → Oxy power plant → Purification & Compression

ASU → CO2 purification → CO2 compression

Fuel preparation → Fuel oxy-combustion → Flue gas recycle and O2 mixing → Steam cycle → Flue gas treatment and cooling

Overall process integration

Significant R&D and demonstration work required
Oxyfuel technology blocks – expected performance improvement

<table>
<thead>
<tr>
<th></th>
<th>Current validation</th>
<th>Expected by 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel preparation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignite drying</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel oxy-combustion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue gas recycle and O2 mixing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700°C cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue gas treatment and cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall process integration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ purification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ compression</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Major steps on lignite drying, oxy combustion and flue gas recycle and treatment

Advances to be done mainly on high rank coal and gas

Validation status:
- Fully
- Partially
- Not
Post-combustion (boiler-based) – current validation status

Fuel combustion

Fuel preparation

Lignite drying

Flue gas treatment and heat recovery

CO2 capture

Overall process integration

Steam cycle

700°C cycle

CO2 compression

CO2 purification

Validation status:
- Fully
- Partially
- Not

Source: Vattenfall
Post-combustion (GT-based) – current validation status

- CO2 capture
- CO2 compression
- CO2 purification
- Overall process integration
- Flue gas treatment and heat recovery
- CO2 enrichment in flue gas
- Fuel combustion
- Steam cycle

Source: Vattenfall
Capture blocks to be validated (Amines, Ammonia…)

Boiler-based process more advanced
Work on power island technology blocks mainly on low rank fuels and steam cycle performance enhancement

Main focus to be put on validation of capture and process integration blocks

<table>
<thead>
<tr>
<th>Post-combustion technology blocks – expected performance improvement</th>
<th>Current validation</th>
<th>Expected by 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel preparation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignite drying</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas turbine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal PC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignite PC</td>
<td></td>
<td></td>
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<tr>
<td>CFB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ enrichment in flue gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700°C Cycle</td>
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<td>Flue gas treatment and heat recovery</td>
<td></td>
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<tr>
<td>CO₂ capture</td>
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<td></td>
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<tr>
<td>Overall process integration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ purification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ compression</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Validation status:
- Fully
- Partially
- Not
Pre-combustion technology blocks – current validation status

- Gasification (coal)
- Gasification (Lignite)
- Reforming (gas)
- Dust removal
- CO2 capture and desulphurization
- CO2 purification & compression
- H2 coproduction
- Fuel handling (Lignite/Biomass)
- ASU
- CO shift
- H2 gas turbine
- Overall process integration

Validation status:
- Fully
- Partially
- Not

Source: Vattenfall
Validation more advanced than on Oxyfuel or Post-combustion capture
Validation of high efficiency H2 GT desirable
Future focus on integration and scale-up of already proven blocks
Pre-combustion technology blocks – expected performance improvement

<table>
<thead>
<tr>
<th>Technology Block</th>
<th>Current Validation</th>
<th>Expected by 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reforming (gas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasification (coal)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasification (Lignite)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ capture and desulphurization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$ coproduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$ gas turbine</td>
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<td>Overall process integration</td>
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</tr>
<tr>
<td>CO$_2$ purification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ compression</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Validation more advanced than on other technologies

– Lignite/Biomass fuels only partially validated for the different technology blocks

Limited validation expected by 2012

Focus to be put on process integration
Current validation initiatives – Oxyfuel

- **Upstream**
  - ASU
    - 250MW PC / 150MW CFB

- **Power production & CO₂ capture**
  - Fuel preparation
    - Lignite drying
      - 250MW PC / 150MW CFB
  - Fuel oxy-combustion
    - Lacq (10MW)
    - Vattenfall (10MW)
    - Ciuden (10MW)
    - 250MW PC / 150MW CFB
  - Flue gas recycle and O₂ mixing
    - 10MW
    - 250MW PC / 150MW CFB
  - Steam cycle
    - 700°C cycle
    - 10MW
  - Flue gas treatment and cooling
    - 250MW PC / 150MW CFB

- **Purification & Compression**
  - CO₂ purification
    - 10MW
    - 250MW PC / 150MW CFB
  - CO₂ compression
    - 10MW
    - 250MW PC / 150MW CFB

Overall process integration
- 250MW PC / 150MW CFB

Validation status:
- Fully
- Partially
- Not

Industry initiatives (existing or potential)
- Required large scale Demo projects

- **A few validation initiatives operating or under construction.**
- **Need for a set of large demos for ASU, boiler and components scale-up and integration**
Current validation initiatives – Post-combustion (boiler-based)

- **A few validation initiatives operating or under design and construction.**
- **Need for a set of large demos for capture scale-up and integration.**

### Overall process integration

<table>
<thead>
<tr>
<th>Fuel preparation</th>
<th>Power production &amp; CO₂ capture</th>
<th>Purification</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite drying</td>
<td>Coal PC</td>
<td>Steam cycle</td>
<td>CO₂ purification</td>
</tr>
<tr>
<td></td>
<td>Lignite PC</td>
<td>700°C cycle</td>
<td>10MW</td>
</tr>
<tr>
<td></td>
<td>CFB</td>
<td>Flue gas treatment and heat recovery</td>
<td>100MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO₂ capture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100MW</td>
</tr>
</tbody>
</table>

**100MW**

- **COMTES**
- **Castor/Esbjerg (2MW)**
- **Amines**
  - 10MW
  - 100MW
- **Ammonia**
  - 10MW
  - 100MW
- **Others**
  - 10MW
  - 100MW

### Validation status

- **Fully**
- **Partially**
- **Not**

### Industry initiatives

- (existing or potential)
- Required large scale Demo projects

**All capacities are expressed in MW Gross electrical**
Current validation initiatives – Post-combustion (GT-based)

- A few validation initiatives operating or under construction.
- Need for a set of large demos for capture scale-up and integration.

Overall process integration

All capacities are expressed in MW Gross electrical
**Current validation initiatives – Pre-combustion**

- **Upstream**
  - ASU

- **Power production & CO₂ capture**
  - Reforming
  - Gasification (coal)
  - Gasification (Lignite)
  - Dust removal
  - CO shift
  - CO₂ capture and desulphurization

- **Purification**
  - H₂ coproduction

- **Compression**
  - H₂ gas turbine

**Overall process integration**

- **450MW**

---

- **Fuel handling**
  - 450MW

- **Reforming**
  - 450MW

- **Gasification (coal)**
  - 450MW

- **Gasification (Lignite)**
  - 450MW

- **Dust removal**
  - 450MW

- **CO shift**
  - 450MW

- **CO₂ capture and desulphurization**
  - 450MW

- **H₂ coproduction**
  - 450MW

- **H₂ gas turbine**
  - 450MW

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- **Validation status**
  - Fully
  - Partially
  - Not

- **Industry initiatives**
  - (existing or potential)

- **Required large scale**
  - Demo projects

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- **No further validation initiatives for the moment**
- **Need for a set of demos to validate integration and components scale-up**

---

All capacities are expressed in MW Gross electrical

450MW is based on diffusion technology
CO₂ capture – synthesis

• Difference in validation status within the different CO₂ capture technologies
  – Pre-combustion technology blocks more advanced than for Post-combustion and Oxyfuel
  – Overall integration is the less advanced technology block
• Additional work needed on non-capture technology blocks to enhance plant performances and ease integration of CO₂ capture systems
• A number of large demonstration projects are under evaluation in the industry

Need for a large number of demo projects to validate technology blocks and integration
Agenda

• Overview of CO₂ value chain
• CO₂ capture technologies
• Efficiency improvement
• Transport & Storage
• Conclusion
• Appendix
Efficiency improvement through steam parameter increase should ease CO₂ capture validation in Post and Oxy
## Efficiency gains potential

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Potential efficiency gains compared to current state-of-the-art* (Additional % points)</th>
<th>Impact on CO2 emissions and/or CCS efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASU</td>
<td>+ 0.5 to 2 points</td>
<td>IGCC &amp; Oxy Medium</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>+ 0.5 to 2 points</td>
<td>Low / Medium</td>
</tr>
<tr>
<td>Boiler Steam Cycle</td>
<td>+ 2 to 4 points</td>
<td>Strong</td>
</tr>
<tr>
<td>Fuel preparation Lignite/Biomass</td>
<td>+ 1 to 4 points</td>
<td>IGCC &amp; Oxy Strong</td>
</tr>
<tr>
<td>Plant integration</td>
<td>+ 1 to 4 points</td>
<td>Post Medium</td>
</tr>
</tbody>
</table>

*Combining several potential sources of gains does not necessarily lead to the addition of % points. 4pts of efficiency is equivalent to 10% gain in overall performance.

**Focus to be on Boiler/Steam cycle and Plant integration**
Agenda

• Overview of CO₂ value chain
• CO₂ capture technologies
• Efficiency improvement

• Transport & Storage

• Conclusion
• Appendix
**CO₂ capture, transport and storage value chain**

- **Power plant**
- **Transport infrastructure**
- **Storage infrastructure**

**Pipelines**
- Onshore pipeline (already operational)
- Offshore pipeline (already operational)

**Ship**
- Comparable to ship transportation of liquefied petroleum gas (LPG)
- Already operational

**Rail/truck tankers**
- Already operational (CO₂ for beverage)

**Preferred options**

**Difficult option for large-scale operation**

**Not considered as attractive option for large-scale transport**
Transport processes explanation

Pipelines
- From plant compression
- Pipeline
- Booster/Pumping stations
- Injection site

Shipping
- Temporary storage
- Loading terminal
- Ship
- Offload system buoy or other
- Offshore unloading terminal
- Onshore unloading terminal
- Onshore injection site
- Offshore platform
- Offshore injection site
Pipeline transport technology blocks – current validation status

- **Mature technology**
- **Only work on integration with large power plant required – all else proved**

<table>
<thead>
<tr>
<th>Location</th>
<th>Validation status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortez (US)</td>
<td>Fully</td>
</tr>
<tr>
<td>Sheep Mountain (US)</td>
<td>Partially</td>
</tr>
<tr>
<td>Val Verde (US)</td>
<td>Not</td>
</tr>
<tr>
<td>Canyon Reefs Carriers (US)</td>
<td>Fully</td>
</tr>
<tr>
<td>Bravo (US)</td>
<td>Partially</td>
</tr>
<tr>
<td>Weyburn (US/Canada)</td>
<td>Not</td>
</tr>
<tr>
<td>Bati Raman (Turkey)</td>
<td>Fully</td>
</tr>
<tr>
<td>Snohvit (Norway)</td>
<td>Partially</td>
</tr>
<tr>
<td>Croatia EOR</td>
<td>Partially</td>
</tr>
<tr>
<td>South Arne (Denmark)</td>
<td>Not</td>
</tr>
<tr>
<td>Lacq (France)</td>
<td>Not</td>
</tr>
<tr>
<td>Weyburn (US/Canada)</td>
<td>Not</td>
</tr>
<tr>
<td>Snohvit (Norway)</td>
<td>Partially</td>
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<tr>
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</tr>
<tr>
<td>South Arne (Denmark)</td>
<td>Not</td>
</tr>
<tr>
<td>Lacq (France)</td>
<td>Not</td>
</tr>
</tbody>
</table>

Integration with CO₂ capture power plant and injection site
Ship transport technology blocks – current validation status

- Less mature technology, although close to LPG
- Strong work on integration with capture and storage required
- Ship flow vs. CO$_2$ generated from large plant
Transport processes work flow – current validation status

- **Pipelines**
  - Design basis
    - Network design
    - Safety review
  - Conceptual design
    - Mechanical design
    - Stability design
    - Protection against corrosion
    - Trenching
  - Monitoring
    - External monitoring
    - Instrumentation and control
  - Operation
    - Daily maintenance
    - Scheduled inspecting and repairing
    - Cleaning

- **Ships**
  - Design
    - Design/construction close to LPG carrier
    - 4 small CO2 carrier already in operation
  - Construction
  - Operation
    - CO2 carriers fleet management not experienced

- **Terminals**
  - Design
    - Design/construction/operation close to LPG terminals
  - Construction
  - Operation

- **Workflow of transport options well-advanced**
- **Main work will be on network definition**
**CO₂ transport – synthesis**

- **Technology blocks more advanced than capture**
  - Pipeline transport is commercially mature
  - Shipping transport already operating but at small scale
- **Main challenge will be network definition and transport infrastructure organisation**
  - Pipeline network (backbone) in densely populated areas
  - Ship fleet management/integration with capture and storage
- **No validation initiative on ship transport**

**Need for validation initiatives in shipping and CO₂ pipeline network definition**
**CO₂ capture, transport and storage value chain**

- **Power plant**
- **Transport infrastructure**
- **Storage infrastructure**

### Depleted Oil and Gas fields
- Onshore or offshore depleted oil and/or gas field

### Deep saline aquifers
- Permeable sedimentary rock formation saturated with water

### Enhanced Coal Bed Methane
- Coal Bed Methane extraction through injection of CO₂

### Enhanced Oil or Gas Recovery (EOR/EGR)
- Already operational (several large projects, US, Brazil, Turkey…)

#### Options in development

#### In development, limited potential

#### Mature option
**CO₂ storage process explanation**

**Depleted fields/Deep saline aquifers**

- **Outcome**
  - Ranked list of potential storage sites
  - Identification of data and knowledge gaps

- **Basin wide screening**
  - Identification and test of one or more viable storage sites

- **Site maturation and testing**
  - Definition monitoring and verification process
  - Barrier modelling

- **Baseline monitoring and verification**
  - Design and location of injection wells
  - Drilling and completion wells
  - CO₂ injection
  - Well integrity assurance

- **Operation**
  - Closing down injection and facilities leaving only monitoring equipment in place
  - Post-injection monitoring

- **Storage infrastructure**
  - Transport infrastructure
  - Power plant

- **Site closure**
**CO₂ storage overall validation status**

**Depleted fields/Deep saline aquifers**

- **Tools & Technology**
  - Basin wide screening
  - Site maturation and testing
  - Baseline monitoring and verification
  - Operation
  - Site closure

- **Work flow**
  - Power plant
  - Transport infrastructure
  - Storage infrastructure

- **Validation status**
  - Fully
  - Partially
  - Not

- **Tools and technology almost ready**
- **Work on workflow definition required**
**CO₂ storage detailed validation status**
Depleted fields/Deep saline aquifers (1/5)

- Tools and technology ready
- Work on workflow definition required

<table>
<thead>
<tr>
<th>Tools &amp; Technology</th>
<th>Identification of sedimentary basin</th>
<th>Compilation of data</th>
<th>Screening of storage prospect</th>
<th>Screening for storage system</th>
<th>Storage system interaction</th>
<th>Storage system interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work flow</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Validation initiatives</td>
<td>UK competition for CCS demos, EU Demo network, CENIT CO₂, Ciuden</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Validation status:
- Fully
- Partially
- Not
CO₂ storage detailed validation status
Depleted fields/Deep saline aquifers (2/5)

- Tools almost ready except for existing wells
- Strong work on workflow required for almost all blocks except for monitoring and verification
CO₂ storage detailed validation status
Depleted fields/Deep saline aquifers (3/5)

- **Strong work on workflow required for containment, economical screening of monitoring and regulatory requirement**
- **Validation initiatives more on theoretical definition**
CO₂ storage detailed validation status
Depleted fields/Deep saline aquifers (4/5)

- **Strong work several workflow**
- **Validation initiatives more on workflow definition, to be adapted on real projects**
### CO\textsubscript{2} storage detailed validation status

**Depleted fields/Deep saline aquifers (5/5)**

- **Tools & Technology**
- **Work flow**
- **Validation initiatives**

- **Basin wide screening**
- **Site maturation and testing**
- **Baseline monitoring and verification**
- **Operation**
- **Site closure**

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Transport infrastructure</th>
<th>Storage infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2} plume position &amp; monitoring parameters</td>
<td>History matching and forward modelling</td>
<td>Definition of criteria for operator's obligations</td>
</tr>
<tr>
<td>Observation wells</td>
<td>Regular monitoring &amp; verification performance</td>
<td>CO\textsubscript{2} containment monitoring &amp; verification</td>
</tr>
<tr>
<td>Terminal procedure</td>
<td>Relinquishment</td>
<td></td>
</tr>
</tbody>
</table>

**Tools & Technology**
- Sleipner

**Work flow**
- Strong work on workflow required
- More limited validation initiatives

**Validation initiatives**
- Sleipner
- Ketzin
CO₂ storage process explanation
ECBM

Outcome
- Evaluation of ECBM production
- Proof of long-term injectivity of CO₂
- Assessment of CO₂ effect on ECBM

Pattern test
- Well site space identification
- Prevention of corrosion

Upgrade Facilities
- Drilling and completion of wells
- Integration of compression site and well site designs

New facilities
- Detection of leakage both concentration and flux
- Detection of CO₂ / CH4 presence in water

Monitoring & validation (M&V)
- Closing down injection and facilities leaving only monitoring equipment in place
- Post-injection monitoring

Closure methodology

Post closure M&V

Power plant
Transport infrastructure
Storage infrastructure
CO$_2$ storage overall validation status ECBM

- Tools and technology almost ready
- Work on workflow definition required
CO₂ storage – synthesis

• Technology and tools are well advanced
  – Very few are not validated at all
  – Focus is more on adaptation and capability enhancement

• Main challenge will be work flow definition
  – Safe process definition
  – Adaptation of standard to CCS
  – Monitoring, verification requirement and operator’s obligations definition

• Majority of validation initiatives are not backed by practical demo projects

Need for basin wide screening and practical validation projects
Agenda

• Overview of CO$_2$ value chain
• CO$_2$ capture technologies
• Efficiency improvement
• Transport & Storage
  • Conclusion
• Appendix
**CO₂ capture, transport and storage demo project requirements**

Coverage of validation gaps by existing validation initiatives

- **Power production & CO₂ capture**
  - Oxy: Very partial
  - Pre: None
  - Post: Very partial
  - Demo project requirements: 13-15 projects

- **Purification & compression**
  - None

- **Transport**
  - Very partial on pipelines
  - None on shipping
  - 1-2 projects per transport options
  - Workflow development
  - Very partial in terms of projects

- **Storage**
  - 5-6 projects with priority on saline aquifer and DOGF

**10-12 demo projects, potentially combining capture, transport and storage as a means of addressing 80% of technological validation gaps**
Agenda

• Overview of CO₂ value chain
• CO₂ capture technologies
• Efficiency improvement
• Transport & Storage
• Conclusion

• Appendix
## CO₂ capture, transport and storage value chain

<table>
<thead>
<tr>
<th></th>
<th>Combustion reaction</th>
<th>Principle</th>
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<tr>
<td><strong>Post-combustion</strong></td>
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<tr>
<td>Coal</td>
<td>C + Air =&gt; CO₂</td>
<td>Exhaust gas CO₂ cleaning</td>
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<tr>
<td>Gas</td>
<td>CH₄ + Air =&gt; CO₂ + H₂O</td>
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<td><strong>Pre-combustion</strong></td>
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<td>C + O₂ =&gt; CO</td>
<td>C-free syngas burning</td>
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<td></td>
<td>CO + H₂O =&gt; CO₂ + H₂</td>
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<td>Gas</td>
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<td>C + O₂ =&gt; CO₂</td>
<td>High concentration CO₂ stream production</td>
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<td>Gas</td>
<td>CH₄ + O₂ =&gt; CO₂ + H₂O</td>
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</table>
Not selected CO$_2$ capture technologies

**CO$_2$ capture technologies**
- Natural gas-fired boiler
- Oxy GT
- Chemical looping
- High pressure oxy reactor
- Membranes
- Anti-sublimation
- Enzymes
- Algae

**Rational for exclusion**
- Very limited market
- Not mature enough, require additional R&D and pilot testing to qualify for large-scale demonstration by 2012
### Oxyfuel – detailed expected evolution of validation status

<table>
<thead>
<tr>
<th>Fuel preparation</th>
<th>Lignite drying</th>
<th>Liquid/Gas combustion</th>
<th>Flue gas recycle system</th>
<th>O2 supply to burner</th>
<th>O2/Fluegas mixing system</th>
<th>Flue gas treatment and flue gas cooling</th>
<th>CO₂ purification</th>
<th>CO₂ compression</th>
<th>Overall process</th>
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#### Current validation

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<th>Process</th>
<th>Coal</th>
<th>Lignite</th>
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<th>Off-gases</th>
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#### Expected by 2012

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#### Validation status

- **Fully**
- **Partially**
- **Not**
# Oxyfuel – capacity and performance (1/3)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Parameters</th>
<th>Proven performance</th>
<th>Expected by 2012</th>
<th>Flagship demo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASU (for PC)</td>
<td>Integrated multi-train</td>
<td>O2 flow (t/d)</td>
<td>4,300</td>
<td>7,000</td>
<td>3,500</td>
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<td></td>
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<td>Power consumption (kWh/t)</td>
<td>250</td>
<td>&gt;220</td>
<td>200</td>
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<td>Power consumption O2 compression (kWh/t)</td>
<td>50</td>
<td>50</td>
<td>10-15</td>
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<td>Pressure out (Bar abs)</td>
<td>5</td>
<td>5</td>
<td>1.3</td>
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<td>Temperature out (°C)</td>
<td>Ambient</td>
<td>Ambient</td>
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<td></td>
<td></td>
<td></td>
<td>Gross PG level (MWe)</td>
<td>One train</td>
<td>One train</td>
<td>250MWe</td>
</tr>
</tbody>
</table>

Membranes

Membranes assumed not available in Flagship demo timeframe

## Fuel preparation

| Liquid/Gas combustion | With Steam w/o flue gas recycle | Dryer throughput (t/h) | 80 | 200 | n x 200 |

## Fuel oxy-combustion

| Pulverized fuel firing | Including mill, commercial size burners (>40MWe), O2 mixing/ flue gas recycle | Gross PG level (MW) | 0.5-1MWth | 30MWth | 250MWe |
| Circulating Fluidized Bed | With flue gas recycle and O2 mixing | | 0.1-1MWth | 10sMWe | 150MWe |
## Oxyfuel – capacity and performance (2/3)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
<th>Parameters</th>
<th>Proven performance</th>
<th>Expected by 2012</th>
<th>Flagship demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam cycle</td>
<td></td>
<td>Increase steam cycle efficiency</td>
<td>Scoring factor (% LHV, without CCS)</td>
<td>43</td>
<td>46</td>
<td>Scoring</td>
<td></td>
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<tr>
<td>Flue gas recycle system</td>
<td>Flue gas recycle fan, reheat depending on T of recycle, O2 preheater</td>
<td>Gross PG level (MWe)</td>
<td>0.1-1MWth</td>
<td>30MWth</td>
<td>250MWe</td>
<td></td>
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</tr>
<tr>
<td>O2/Fluegas mixing system</td>
<td>O2 supply to burner or grid</td>
<td>Gross PG level (MWe)</td>
<td>eq. 0.1-1MWth</td>
<td>eq. 30MWth</td>
<td>eq. 250MWe</td>
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<tr>
<td></td>
<td></td>
<td>Different technologies are under development for O2 supply to burner and burner gas streams. Differences are due to technology, different design philosophy depending on supplier. Different designs to be tested</td>
<td>Gross Power (MWth)</td>
<td>-</td>
<td>eq. 30MWth</td>
<td>eq. 40MWth</td>
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</tr>
<tr>
<td>Technology blocks</td>
<td>Technology</td>
<td>Scope</td>
<td>Performances</td>
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<tr>
<td>Flue gas treatment and cooling (for PC)</td>
<td>DeNOx</td>
<td>Current technology to be improved with respect to needs of downstream steps for NOx, SOx, dust, trace elements ESP and/or baghouse depending on fuel</td>
<td>Gross PG level (MWe)</td>
<td>0.1-1MWth</td>
<td>30MWth</td>
<td>250MWe</td>
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<tr>
<td>Flue gas desulphurization</td>
<td>Particle removal before recycle</td>
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<td>Flue gas condenser</td>
<td>Water separation</td>
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<tr>
<td>CO₂ treatment (for PC)</td>
<td>CO₂ purification</td>
<td>Depending on compression technology, transport (corrosion?), storage option (geology), different limits to be considered (N2, O2, NOx, SOx, H2O, trace elements, dust)</td>
<td>Gross PG level (MWe)</td>
<td>-</td>
<td>30MWth</td>
<td>250MWe</td>
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<tr>
<td>Compression train</td>
<td>Supercritical compression</td>
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<tr>
<td>Overall process</td>
<td>Flexibility</td>
<td>Plant flexibility to increase positive commercial &amp; technical impacts: e.g. enabling dual air &amp; oxy modes</td>
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<tr>
<td>Process integration</td>
<td>Load change flexibility, start up, shut down and partial load behaviour of all components which are highly dependent on each other</td>
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<tr>
<td>Low grade heat use</td>
<td>Recovery of waste heat from ASU or CO₂ compression in steam cycle</td>
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### Post-combustion technology blocks – current validation status and expected evolution

#### Current validation

<table>
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<tr>
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<td>Lignite drying</td>
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<td>Gas turbine</td>
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#### Expected by 2012

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**Validation status**

- **Fully**
- **Partially**
- **Not**

---

53
## Scope of technology blocks for Post-combustion – capacity and performance (1/6)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
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<tr>
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<td>Parameters</td>
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<tr>
<td>CO₂ enrichment in flue gas</td>
<td>Drying</td>
<td>Lignite</td>
<td>Capacity (t/h)</td>
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<td></td>
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<td>Biomass</td>
<td>Share of cofiring by mass (%)</td>
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<tr>
<td></td>
<td>Flue gas recycle (FGR)</td>
<td>FGR system should be working in the scope of actual GTCC products, GT efficiency, lifetime and dynamic response; FGR connection to GT blowers and piping</td>
<td>SC Gross power (MWe)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SC Gross efficiency (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CC Gross power (MWe)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CC Gross efficiency (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lifetime vs. corrosion (kEOH)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Flue gas recycle ratio (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>System pressure loss (mbar)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operating window (ratio)</td>
</tr>
<tr>
<td></td>
<td>Supplementary firing</td>
<td>Supplementary firing to use all O2 available before HRSG</td>
<td>Exhaust O2 mol fraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exhaust temperature (°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Turbine exhaust mass flow</td>
</tr>
</tbody>
</table>
## Scope of technology blocks for Post-combustion – capacity and performance (2/6)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Parameters</td>
<td>Proven performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Gross power (MWe)</strong></td>
<td>266</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Efficiency (%) (NGCC)</strong></td>
<td>36.6 (57.5)</td>
</tr>
<tr>
<td></td>
<td>Gas turbine</td>
<td>Liquid/gas fired air combustion, GT combustor chamber</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulverized fuel</td>
<td>Dry/Raw lignite</td>
<td>Gross power (MWe)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bit. coal</td>
<td>Gross power (MWe)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CFB</td>
<td>Gross power (MWe)</td>
</tr>
<tr>
<td></td>
<td>Steam cycle</td>
<td>Steam generator</td>
<td>Efficiency for lignite (% LHV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Highest available efficiency is recommended for CCS</td>
<td>Efficiency for coal (% LHV)</td>
</tr>
<tr>
<td></td>
<td>Steam turbine</td>
<td>LP steam extraction to supply CO2 scrubber</td>
<td>Steam temperature (°C)</td>
</tr>
</tbody>
</table>
**Scope of technology blocks for Post-combustion – capacity and performance (3/6)**

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Parameters</td>
</tr>
<tr>
<td><strong>Flue gas treatment and heat recovery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>For amine capture technologies needs, usage of optimum desulfurization technology required (for economic reasons) Desulfurization down to the measurement limits (c.1ppm) has been demonstrated with 660MW. DeNOx &lt;0.5ppm has been demonstrated as well. For Alstom chilled ammonia scrubbing state-of-the-art is (more than) sufficient. Current state-of-the -art NOx levels are sufficient for CO2 scrubbing. Particulate levels as after Wet ESP are ok.</td>
<td>Gross power (MWe)</td>
</tr>
<tr>
<td></td>
<td>Flue Gas Desulphurization</td>
<td></td>
<td>SOx concentration in flue gas (ppmv)</td>
</tr>
<tr>
<td></td>
<td>Particulate removal</td>
<td></td>
<td>Particulate matters level (mg/Nm3)</td>
</tr>
<tr>
<td></td>
<td>DeNOx</td>
<td></td>
<td>NOx concentration in flue gas (ppmv)</td>
</tr>
</tbody>
</table>
### Scope of technology blocks for Post-combustion – capacity and performance (4/6)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amine</td>
<td>Basic assumptions: 1) removal rate for coal: c.20t/d and MW, removal rate for gas c.10t/d and MW, 2) min power level calculated on this basis, 3) Power level defined for CO2 capture process can also be slipstream</td>
<td>Removal rate (t/d) (400MWe appr. 7500tpd)</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td></td>
<td>Proven performance: 25 (CASTOR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Expected by 2012: 75 (NGCC); 200+ (coal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flagship demo: -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Removal rate (%): -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gross power (MWe): 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;100</td>
</tr>
<tr>
<td></td>
<td>Other physical absorption</td>
<td></td>
<td>Removal rate (t/d): -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;60 (NGCC); 200+ (coal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Removal rate (%): -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gross power (MWe): 0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;100</td>
</tr>
<tr>
<td></td>
<td>Scrubbing with solids</td>
<td></td>
<td>Removal rate (t/d): 10</td>
</tr>
<tr>
<td></td>
<td>membranes (carbonate loops,</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>others)</td>
<td></td>
<td>Removal rate (%): -</td>
</tr>
<tr>
<td></td>
<td>Membranes</td>
<td></td>
<td>&gt;90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gross power (MWe): ?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

Assumed not available in Flagship Demo time frame, need further RD&D
# Scope of technology blocks for Post-combustion – capacity and performance (5/6)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>CO₂</strong> purification</td>
<td>Depending on compression technology, transport (corrosion?), storage option (geology), different limits to be considered (N₂, O₂, NOx, SOx, H₂O, trace elements, dust)</td>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td></td>
<td><strong>CO₂</strong> compression</td>
<td>to produce supercritical CO₂; for 100MW coal plant 25kgCO₂/s is sufficient</td>
<td>Capacity (t/d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Capacity (kg/s)</td>
</tr>
</tbody>
</table>
## Scope of technology blocks for Post-combustion – capacity and performance (6/6)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Parameters</td>
</tr>
<tr>
<td>Overall process</td>
<td>Power loss compensation</td>
<td>Net power Loss Compensation and flexibility can be discussed to increase positive commercial and technical impacts. Ex: Enabling dual oxy and air combustion.</td>
<td>Level of integration</td>
</tr>
<tr>
<td></td>
<td>Process integration</td>
<td>Load change flexibility, start up, shut down and partial load behaviour of all components which are highly dependent on each other</td>
<td>Penalty of retrofit (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum Load (%)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency shutdown behavior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Load change velocity (%)</td>
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</table>
### Pre-combustion – detailed expected evolution of validation status

<table>
<thead>
<tr>
<th>Validation status</th>
<th>Coal</th>
<th>Lignite</th>
<th>Petcoke/Anthracite</th>
<th>Biomass</th>
<th>Natural gas</th>
<th>Off-gases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current validation</strong></td>
<td></td>
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<tr>
<td>Air Separation Unit</td>
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<tr>
<td>Fuel handling</td>
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<tr>
<td>Gasifier</td>
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<tr>
<td>Reformer</td>
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<tr>
<td>Dust removal</td>
<td></td>
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<tr>
<td>CO shift</td>
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<td></td>
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<tr>
<td>CO₂ capture and desulphurization</td>
<td></td>
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</tr>
<tr>
<td>H₂ coproduction</td>
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<tr>
<td>H₂ gas turbine</td>
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<tr>
<td>CO₂ purification</td>
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<tr>
<td>CO₂ compression</td>
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<tr>
<td>Process integration</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Expected by 2012</strong></th>
<th>Coal</th>
<th>Lignite</th>
<th>Petcoke/Anthracite</th>
<th>Biomass</th>
<th>Natural gas</th>
<th>Off-gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Separation Unit</td>
<td></td>
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<td></td>
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<tr>
<td>Fuel handling</td>
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<tr>
<td>Gasifier</td>
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<tr>
<td>Reformer</td>
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<td></td>
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<tr>
<td>Dust removal</td>
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<tr>
<td>CO shift</td>
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<tr>
<td>CO₂ capture and desulphurization</td>
<td></td>
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<tr>
<td>H₂ coproduction</td>
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<tr>
<td>H₂ gas turbine</td>
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<tr>
<td>CO₂ purification</td>
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<tr>
<td>CO₂ compression</td>
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<tr>
<td>Process integration</td>
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</tbody>
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### Scope of technology blocks for Pre-combustion – capacity and performance (1/5)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Parameters</th>
<th>Performances</th>
<th>Expected by 2012</th>
<th>Flagship demo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Separation Unit</strong></td>
<td>Cryogenic train</td>
<td>Single train integrated with F class turbine proven. Air and N2 integration levels determine ASU concept and overall efficiency. Development required for higher distillation &amp; Oxygen pressure levels. Fuel independent. Integration of compressor drive system to be considered</td>
<td>Capacity (t/d)</td>
<td>4,300</td>
<td>7,000</td>
<td>Demos will stick to single train concept. (2 or 3 turbines on one ASU - not proven. But is a matter of RAM vs, CAPEX. Start up part load may be an issue)</td>
</tr>
<tr>
<td>Membranes</td>
<td>Membranes ASU assumed not available in Flagship demo timeframe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel handling</strong></td>
<td>Fuel drying, grinding and mixing</td>
<td>Fuel pre-treatment particularly for fuels with high water content or difficult to grind to size required for feeding to gasifier (lignite, biomass). For more variable fuel feed online fuel analysis required.</td>
<td>Capacity (t/d)</td>
<td>WTA pilot plant 600t/d DWT test plant for lignite</td>
<td>600t/d</td>
<td>2500-7000 t/d Improvement in integration to enhance efficiency</td>
</tr>
</tbody>
</table>
## Scope of technology blocks for Pre-combustion – capacity and performance (2/5)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasifier</strong></td>
<td>Fuel dry feeding</td>
<td>Relevant for high overall efficiency.</td>
<td>Parameters</td>
</tr>
<tr>
<td></td>
<td>Gasifier optimized for CCS</td>
<td>Energy and cost optimized system targeting high carbon conversion rate and CO shift. Very fuel specific - e.g. ash melting point, ash content, reactivity. Steam integration to be adapted in CCS layout. Operational flexibility for capture and non capture mode.</td>
<td>Capacity (t/d)</td>
</tr>
<tr>
<td><strong>Reformer</strong></td>
<td>Capacity proven. Integration in water steam cycle is relevant and very IRCC specific</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dust removal</strong></td>
<td>Depending on gasifier concept. Venturi wash, ceramic filter or metal filter. Relevant are primarily availability, then CAPEX, O&amp;M and pressure loss. Availability issues with some types. Adsorbents for mercury capture may gain importance.</td>
<td></td>
<td>Operating temperature (°C)</td>
</tr>
</tbody>
</table>

**Integration in Water Steam Cycle**
### Scope of technology blocks for Pre-combustion – capacity and performance (3/5)

<table>
<thead>
<tr>
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<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
<th>Parameters</th>
<th>Proven performance</th>
<th>Expected by 2012</th>
<th>Flagship demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO shift</td>
<td>Optimized plant integration of steam production and steam / water demand. Size for F-class engine supply is proven. Sour or sweet shift - depending on concept for desulphurization and specification for delivered CO2.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Advanced thermal integration concepts to be proven.</td>
</tr>
<tr>
<td>CO₂ capture and de-sulphurization</td>
<td>Can be combined with desulphurization or separate. Based on absorption. Membrane processes not expected to be commercially available until 2015. Optimized for IGCC application (heat integration, pressure levels). Rest sulphur content dependent on GT requirements and NOx limits (SCR fouling from SO3 based aminosalts). CO-Shift requirements relevant. Some fuel specific aspects: sulphur content, chlorides, hazardous compounds.</td>
<td>MDEA, RECTISOL, Selecso, Genosorb, ... (other processes not expected in full scale) Optimization with regard to heat requirement, pressure loss, consumption of catalysts, aux.-power. Quality of delivered CO₂</td>
<td>Proven in full scale in chemical industry, advanced integration to be proven</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ coproduction</td>
<td>Avoid N₂ and steam feed into the fuel gas stream. Adapted fuel feed system. Meet pressure requirements for H₂ process.</td>
<td>downstream for 99,999% purity PSA required - proven</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very few references based on solid fuels</td>
</tr>
</tbody>
</table>
### Scope of technology blocks for Pre-combustion – capacity and performance (4/5)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Parameters</td>
</tr>
<tr>
<td>H2 GT</td>
<td>F class gas turbine</td>
<td>Syngas and hydrogen rich gases are diluted with waste nitrogen and/or steam to comply with combustion requirements. High dilution levels have been proven already in the nineties. However there is some rationale for reduced dilution levels in terms of efficiency and cost. Optimization efforts are under way for high availability, efficiency, low NOx emissions.</td>
<td>-</td>
</tr>
</tbody>
</table>

- CO2 purification
- Depends on CO2 capture process on one hand and requirements from compressor train and transport and storage infrastructure on the other hand. Can be a major issue depending on solvent technology. Uncertainties with regard to regard to requirements. Topic is common to oxy-fuel and post-combustion. However it should be easier to comply in pre-combustion with upstream purification in place.
- Depending on requirements: H2O, SO2, H2S, CO, ...
- According to ENCAP WP 1.1 requirements are fulfilled in per-combustion capture
- Final purification could be required for some contaminant according to CO2 specification
### Scope of technology blocks for Pre-combustion – capacity and performance (5/5)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
</table>
| **CO₂ compression** | Multi stage compression. Pressure ratio validated. Considerable upscale required (factor 3-4). Plant integration of intercooling. Corrosion resistance. Control concept. Drive concepts other than electrical to be considered. Topic is common to oxy-fuel and post-combustion. However it should be easier to comply in pre-combustion with upstream purification in place. | Parameters: Pressure level 100 - 200 bar  
Proven performance: Weyburn project; single train multi shaft compressor, ebd pressure 187 bar, 60000 m³/h, 13,5 MW  
Expected by 2012: -  
Flagship demo: Single train compressor, high efficiency, high availability, low O&M. |
| **Integration** | Overall plant not be scaled below 350 MW net - has to match F-class gas turbines. Optimised balance of degree of integration and redundancy to achieve low life cycle cost and high availability. Covers multiple areas such as heat, N2, air, steam. | Must not be judged on basis of net efficiency, but on LCC.  
Proven in full scale in chemical industry  
Target of the entire Flagship program is to reduce risk premium in EPC and thus foster market penetration.  
Expected by 2012: -  
Flagship demo: - |
Scope of technology blocks for efficiency improvement – capacity and performance (1/3)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology/ Main function</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Parameters</td>
</tr>
<tr>
<td>Steam cycle</td>
<td></td>
<td></td>
<td>Turbine inlet pressure (bar)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature Main steam/Reheat (°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Efficiency (% LHV)</td>
</tr>
<tr>
<td>Fuel combustion</td>
<td>Increasing efficiency would permit to decrease fuel consumption and CO₂ emissions</td>
<td></td>
<td>Coal consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO₂ emissions</td>
</tr>
<tr>
<td></td>
<td>Pulverized coal</td>
<td></td>
<td>Gross power (MWe)</td>
</tr>
<tr>
<td>Boiler</td>
<td>Boiler efficiency</td>
<td></td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td></td>
<td>Water wall</td>
<td></td>
<td>100,000 hours of creep rupture strength (Mpa)</td>
</tr>
<tr>
<td></td>
<td>Superheater</td>
<td></td>
<td>Resistance against high temperature corrosion</td>
</tr>
<tr>
<td></td>
<td>Reheater</td>
<td></td>
<td>Resistance against steam oxidation</td>
</tr>
</tbody>
</table>
Scope of technology blocks for efficiency improvement – capacity and performance (2/3)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology/ Main function</th>
<th>Scope</th>
<th>Performances</th>
<th>Parameters</th>
<th>Proven performance</th>
<th>Expected by 2012</th>
<th>Flagship demo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boiler</strong></td>
<td>Material welding</td>
<td>Welding of pipes with different material grade (P92, T24, A617…)</td>
<td>Welding qualification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reaction</td>
<td>Reaction</td>
<td>Gross power (MWe)</td>
<td>1,000</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turbine</strong></td>
<td>HP module</td>
<td>High steam temperature require Ni-based Alloy for inner casing and rotor. Rotor welding with different material grade is required</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>IP module</td>
<td></td>
<td>High steam temperature require the use of Ni-based Alloy is needed</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>HP bypass valve</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start-up valve</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Stop valve</td>
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</tr>
</tbody>
</table>

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### Scope of technology blocks for efficiency improvement – capacity and performance (3/3)

<table>
<thead>
<tr>
<th>Technology blocks</th>
<th>Technology/Main function</th>
<th>Scope</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plant</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material identification</td>
<td>High steam temperature requires new material for main steam path and hot reheat steam path. Using Ni-based Alloy is needed</td>
<td>100,000 hours of creep rupture strength (Mpa)</td>
</tr>
<tr>
<td></td>
<td>Material qualification</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piping design</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HP bypass valve</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piping flexibility</td>
<td>High steam temperature and pressure require high thickness Ni-based Alloy material. Flexibility must be taken into account piping routing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant layout</td>
<td></td>
<td>High cost Ni-based alloys require optimisation of the plant layout to limit the use of those materials</td>
</tr>
<tr>
<td><strong>Overall process</strong></td>
<td>Process integration</td>
<td>Load change flexibility, start up, shut down and partial load behaviour of all components which are highly dependent on each other. Full integration required</td>
<td>Start up length (hours)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cold</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Warm</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Hot</td>
</tr>
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</table>

<table>
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</thead>
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<tr>
<td>Gross power (MWe)</td>
<td></td>
<td>1,000</td>
<td>500</td>
</tr>
</tbody>
</table>
Main technology options to transport CO₂ captured in power plants

**Onshore pipelines**
- Already operational (>3,000 km worldwide, mainly in the US for EOR)
- CO₂ pipelines very similar to existing natural gas pipelines
- CO₂ transported in supercritical phase (100-150 bar)
- Densely populated area deployment issues

**Offshore pipelines**
- Offshore pipeline technology operational, as large natural gas pipelines have been built at depths over 2,000 meters

**Shipping**
- Comparable to ship transportation of liquefied petroleum gas (LPG)
- 4 small CO₂ ships already active, transporting liquefied CO₂ for food usage
- Limited capacity

**Rail/truck tankers**
- Already operational (CO₂ for beverage)
- Not considered as attractive option for large scale transport:
  - Costly
    - Non compatible with GHG reduction goal
    - Very limited capacity

Source: IPCC, O&G Journal, IEA GHG, L.E.K. Analysis
Pipeline transport process explanation

**Process**

- **Initial compression**
- **Booster/Pumping stations**
- **Pipeline**
- **Injection site**

**Description**

- **CO₂ is compressed over supercritical pressure** (i.e. 75 bars), generally up to 100 to 150 bars
- **Compression also increases temperature to about 150°C**
- **Cooling needed before transport**

- **Optimal CO₂ state is supercritical**
  - Minimizes volume
  - Most “fluid” state: minimizes friction losses

- **Within pipelines, friction causes pressure loss**: 4 to 15 bars per 100 km in most conditions

- **However, for large diameter pipelines, losses are limited and should not require booster stations**
  - Weyburn (14 inches) loses 7 bars per 100 km
  - In normal conditions, larger pipelines should have limited losses

- **Additional compression may be needed for storage**, depending on formation characteristics and CO₂ usage (e.g. EOR)
Significant CO$_2$ pipelines already exist

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Location</th>
<th>Operator</th>
<th>CO$_2$ flow (Av. 000 t / d)</th>
<th>Length (km)</th>
<th>Year finished</th>
<th>Origin of CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortez</td>
<td>USA</td>
<td>Kinder Morgan</td>
<td>53</td>
<td>808</td>
<td>1984</td>
<td>Mc Elmo Dome (largest known natural accumulation of pure* CO$_2$)</td>
</tr>
<tr>
<td>Sheep Mountain</td>
<td>USA</td>
<td>BP Amoco</td>
<td>26</td>
<td>660</td>
<td>-</td>
<td>Sheep Mountain (smallest CO$_2$ source field serving the Permian Basin)</td>
</tr>
<tr>
<td>Bravo</td>
<td>USA</td>
<td>BP Amoco</td>
<td>20</td>
<td>350</td>
<td>1984</td>
<td>Bravo Dome (natural CO$_2$ source with 225 Bn m3 reserves)</td>
</tr>
<tr>
<td>Canyon Reefs</td>
<td>USA</td>
<td>Kinder Morgan</td>
<td>14</td>
<td>225</td>
<td>1972</td>
<td>Shell Gas plants (natural gas processing plants)</td>
</tr>
<tr>
<td>Carriers</td>
<td>USA</td>
<td>Kinder Morgan</td>
<td>14</td>
<td>225</td>
<td>1972</td>
<td>Val Verde Gas plants (purification operations at 4 natural gas plants**)</td>
</tr>
<tr>
<td>Val Verde</td>
<td>USA</td>
<td>Petrosource</td>
<td>7</td>
<td>130</td>
<td>1998</td>
<td>Val Verde Gas plants (purification operations at 4 natural gas plants**)</td>
</tr>
<tr>
<td>Bati Raman</td>
<td>Turkey</td>
<td>Turkish Petroleum</td>
<td>3</td>
<td>90</td>
<td>1983</td>
<td>Dodan Field (natural resource of carbonates)</td>
</tr>
<tr>
<td>Weyburn</td>
<td>USA &amp; Canada</td>
<td>North Dakota Gasification Co.</td>
<td>5</td>
<td>328</td>
<td>2000</td>
<td>Gasification plant (Synfuel Plant, which manufactures synthetic natural gas from lignite)</td>
</tr>
<tr>
<td>Snohvit</td>
<td>Norway</td>
<td>Statoil</td>
<td>2</td>
<td>160</td>
<td>2006</td>
<td>Gas plants (purification operations)</td>
</tr>
</tbody>
</table>

Note: *98% purity level; **This CO$_2$ contains H2S contamination and is thus only suitable for use in sour gas fields
Source: Statoil, Sonatrach, IPCC, IEA GHG, DTI, DOE, L.E.K. Analysis
Pipeline construction process

**Preparation**
- Pipeline itinerary is planned and permits granted
- Right of way is cleared and terrain prepared
- Pipe sections are brought along the pipe route
- A trench is excavated (generally 1m deep)

**Pipe welding / coating / bending**
- Pipes are welded along the pipe route
- Coating is applied at the end of the pipes
- Pipeline is bent to match geographic characteristics of the route (hills, curves, etc)

**Completion**
- Pipeline is lowered in the trench
- Trench is filled and vegetation restored
- For offshore pipelines, pipes are welded to the end of the pipeline on a barge, then lowered down to the seabed as the barge advances

*Process well-mastered, potential issues in densely populated areas*
Technical aspects of pipeline CO₂

Materials
- With appropriate CO₂ drying and purification, regular carbon steel can be used
- Stainless steel can be used in some specific pipe sections to avoid corrosion

Pressure
- Natural gas is generally transported around 90-100 bars in large “backbone” pipelines (lower in small distribution pipelines)
- Pressure range is comparable to what would be required for CO₂ transport (100-150 bars)

Monitoring
- Pipeline monitoring consists in supervision by personnel (on the ground or by air), by metering devices (pressure, temperature, etc) and periodic inspection by robotic “pigs”
- Comparable for CO₂, with possible increase in frequency depending on local regulations

Equipment and processes very comparable to natural gas pipeline transportation
**Transport processes explanation**

**Process**
- Temporary storage
- Loading terminal
- Ship
- Offload system buoy or other
- Onshore unloading terminal
- Temporary storage
- Offshore platform
- Offshore injection site
- Onshore injection site

**Description**
- Liquid CO₂ (-50°C and 7 bars) is temporary stored in tank to align continuous capture with discrete flow of ships
- Liquid CO₂ is charged to the ship with pump adapted to high pressure
- Liquid CO₂ is transported in ship
- Heat transfer from the environment through the wall of the tank will boil CO₂ and raise pressure
  - Necessity to refrigerated this gaseous CO₂ to liquefy it
- Return to loading terminal with tank filled with dry CO₂ gas
- Special offloading technology is developed for safe on- and offshore operations
- Unloading of the liquid CO₂ in temporary storage or directly on underground storage site
  - Additional compression may be required
## Technical aspects of CO₂ transportation – ships

<table>
<thead>
<tr>
<th>Characteristics of ship transportation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ phase and purity requirements</td>
<td>Liquid state at -50°C and 7 bars</td>
</tr>
<tr>
<td>Maximum ship capacity</td>
<td>230,000 tonnes in a 200,000 m³ supertanker</td>
</tr>
<tr>
<td>Technical maturity of ship transport</td>
<td>4 active ships (20,000 m³) Comparable to LNG tankers</td>
</tr>
<tr>
<td>Construction timing of a ship</td>
<td>2 years for large tankers</td>
</tr>
</tbody>
</table>

- Comparable to semi-refrigerated LPG ships, but unlike large LNG tankers, which are around -160°C and atmospheric pressure
- This would only cover between 20 and 25 days of CO₂ from one high-efficient 800MW coal plant
- 4 small ships are in operation today, bringing food-grade CO₂ from plants to terminals in consuming regions
- Latest LNG tankers carry over 200,000 m³; the same yards could build CO₂ tankers
- Building time estimated between 1 and 2 years depending on ship size (closer to 2 years for supertankers)

CO₂ transportation ships built on the model of LPG tanker
Depleted oil and gas field storage process explanation

Schematic drawing of a depleted oil/gas field CO\(_2\) storage site (In Salah project)

- Processing facilities

As for other storage options, minimum depth of the field is about 800m for CO\(_2\) to remain in supercritical phase over 31°C.

The CO\(_2\) is injected in supercritical phase in the water, saturating the depleted oil and gas field.

Depending on acceptable injection rates and field characteristics, more or less injection wells will be required.

Site preparation and monitoring are particularly important for depleted fields, because oil production and abandoned wells can have created leakage risks.
EOR/EGR process explanation

CO₂ is injected in a specific well, separated from the oil extraction well. Minimum optimal depth of the field is about 800m for CO₂ to remain in supercritical phase (natural earth temperature above 31°C at that depth).

2 EOR mechanisms:
- CO₂ “chases” the oil by flooding the formation
- In optimal temperature and pressure conditions, part of the CO₂ also dissolves in the oil (miscible zone), making it more fluid.

Part of the CO₂ stays in the oil formation, the rest being re-extracted with the oil and partly recycled. Quantity of CO₂ staying in the formation depends on CO₂ and oil characteristics (20%-70%).
A deep saline aquifer is a permeable sedimentary rock formation saturated with water. Depth is generally between 800m and 3 km. Thickness and geological characteristics of aquifers (in particular permeability, which defines how “easily” CO₂ can enter) are highly site specific.

CO₂ is injected in supercritical phase in the saline water of the aquifer. Surface equipment, injection equipment and wells are comparable to EOR and depleted field storage. The number of required wells depends on geological characteristics.

Significant uncertainty exists on the share of aquifer volume that can be filled with CO₂ (between 2 and 70% estimates), because the speed and importance of CO₂ dissolution and precipitation is not yet well known.
## Scope of technology blocks for storage (1/19)

<table>
<thead>
<tr>
<th>Technology Block function</th>
<th>Technology</th>
<th>Scope</th>
<th>Capacity and Performance (specification parameters)</th>
<th>Proven</th>
<th>Expected proven by 2012</th>
<th>Expected for Flagship Demo (minimum perform)</th>
<th>Tools</th>
<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basinwide Screening (site options)</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Identify sedimentary basin, stratigraphical sequence</td>
<td>Standard industry systems</td>
<td>Identify the components that support storage (reservoir, seal, structure)</td>
<td>Having access to data that allows an evaluation of the principal components of a storage system and preferably a ranked assessment of storage sites within a basin.</td>
<td>Tools proven and in common industry use. Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices (e.g. as in reserves assessment for petroleum and minerals).</td>
<td>Alignment of peer reviewed work flows for screening</td>
<td>Documented and published screening procedures for each flagship demo Motivates the funding of the AQUACO2 project proposal under assessment by EU commission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compile DATA</td>
<td></td>
<td>Seismic, wells, license, geography, petrophysical, fluid, pressure, current regulatory constraints; identify data availability and gaps</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Screen for STORAGE PROSPECT</td>
<td></td>
<td>For each storage site screen for capacity, injectivity and containment through structure, faults &amp; fractures, cap rock, reservoir, pressure, fluids, mineralogy, legacy wells, surrounding resources, potable aquifers, surface features</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Screen for STORAGE SYSTEM</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Storage System INTERACTION</td>
<td></td>
<td>Define the storage system in the context of other economic interest (Hydrocarbons/minerals), potable water, biosphere/marin biosphere, atmosphere (environmental, HSE, population)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Shortlist of potential storage sites</td>
<td></td>
<td>Rank potential storage sites against capacity, injectivity and life-cycle containment criteria and demonstrate viable linkage to source</td>
<td></td>
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</tbody>
</table>
## Scope of technology blocks for storage (2/19)

<table>
<thead>
<tr>
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<th>Technology</th>
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<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Maturation (preferred sites)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Evaluate Storage features</strong></td>
<td>DATA availability is a key issue for all activities below</td>
<td>Confirm that the storage sites(s) is large enough to hold full life-cycle CO2 volumes. Sustained injection rates over the lifetime of the project can be achieved. Model and predict distribution of CO2 in the subsurface and demonstrate credible mechanisms for long term containment.</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices. Need to improve capability to predict caprock properties/continuity in areas with sparse data (characteristic for many aquifers). Need to be able to build a complete well model describing the wellbore integrity and flux rates. Reactive flow: Need modelling tools that fully couple all processes or can interface to specialised reactive flow modelling tools (e.g. Petrel, PVTesim which supply input to flow models).</td>
<td>Improved industry capability to evaluate cap rock properties and predict sealing potential an lateral continuity</td>
<td>Focus data acquisition strategies on improved understanding of cap rock properties and begin shared database</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Seal</td>
<td>Standard industry systems Improve lab experiments and numerical modelling capacity</td>
<td>Evaluation the primary and ultimate sealing capacity of cap rock for CO2</td>
<td></td>
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</tr>
<tr>
<td>Faults and Fractures</td>
<td>Standard industry systems Improve capability to model CO2 flux through faults and fractures</td>
<td>Assessment of safe operation pressure envelope including safety margin for fracture propagation pressure, fault reactivation pressure, fault reactivation pressure, fault reactivation pressure and seal capillary entry pressure which govern maximum safe bottomhole injection pressure</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Well integrity (existing wells)</td>
<td>Full wellbore integrity model; numerical model of wellbore geomechanics; tools to assess integrity of old/abandoned wells</td>
<td>Identify all old wells, location and condition of wells. Review well completion &amp; abandonment reports, surveys, cement practice &amp; zonal isolation. Summarise basin-wide well failure data (frequency and causes). Identify potential to re-enter to repair or abandon old wells.</td>
<td>Industry capability to build full wellbore model for integrity and to incorporate CO2 flux rates into risk project assessment</td>
<td></td>
<td>Test emerging modelling capability and acquire real data to mature capability further.</td>
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## Scope of technology blocks for storage (3/19)

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<tbody>
<tr>
<td>Reservoir capacity</td>
<td>Standard industry systems</td>
<td>Thorough estimation of primary and subsequent storage capacity, including assessment of structure, flow behaviour and trapping mechanisms (single phase CO2 dissolution, residual trapping and mineral trapping)</td>
<td>Confirm that the storage sites (s) is large enough to hold full life-cycle CO2 volumes. Sustained injection rates over the life-time of the project can be achieved. Model and predict distribution of CO2 in the subsurface and demonstrate credible mechanisms for long term containment.</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices. Need to improve capability to predict caprock properties/continuity in areas with sparse data (characteristic for many aquifers). Need to be able to build a complete well model describing the wellbore integrity and flux rates. Reactive flow: Need modelling tools that fully couple all processes or can interface to specialised reactive flow modelling tools (e.g. Petrel, PVTsim which supply input to flow models)</td>
<td>Alignment of peer reviewed work flows</td>
<td>Quantification of storage redundancy requirement and CO2 storage impact on regional aquifers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal flow</td>
<td>Standard industry systems</td>
<td>Static and dynamic model of plume migration with time within primary reservoir and model migration within secondary containment system as part of risk scenarios. Assess flow sensitivities on plume extent and pressure distribution by varying input data (e.g. reservoir heterogeneity, fracture distribution, PVT). Assess potential for impact onto regional aquifer.</td>
<td>Alignment of peer reviewed work flows</td>
<td>Defining key sensitivities that constrain plume migration and pressure modelling. Publishing workflows for operational and extended time scales for modelling.</td>
<td></td>
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</tbody>
</table>
### Scope of technology blocks for storage (4/19)

<table>
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<th>Expected for Flagship Demo (minimum perform)</th>
<th>Tools</th>
<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive flow (CO2 + any contaminants)</td>
<td>Standard industry systems need integration with emerging modelling codes/databases to handle complex geochemical/geomechanical processes. Lab experiments with critical liquids at operating conditions.</td>
<td>Predictive modelling of time dependent processes and their impact on flow, capacity and containment (chemical and physical rock-fluid and fluid-fluid interaction)</td>
<td>Confirm that the storage sites(s) is large enough to hold full life-cycle CO2 volumes. Sustained injection rates over the life-time of the project can be achieved.</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices. Need to improve capability to predict caprock properties/continuity in areas with sparse data (characteristic for many aquifers). Need to be able to build a complete well model describing the wellbore integrity and flux rates. Reactive flow: Need modelling tools that fully couple all processes or can interface to specialised reactive flow modelling tools (e.g. Petrel, PVTsim which supply input to flow models)</td>
<td>Emerging consensus on key reactive flow issues and in which geological settings these may be significant. Improved interfaces between flow modelling simulators and specialised modelling tools.</td>
<td>Assess for reactive flow issues prior to site selection and acquire data during field demo operation and post-operation phase to validate reactive flow components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffusion</td>
<td>Standard industry systems</td>
<td>Establish mechanisms and rates of diffusion through cap rock, faults/fractures wellbore annuli</td>
<td>Model and predict distribution of CO2 in the subsurface and demonstrate credible mechanisms for long term containment.</td>
<td>Alignment of peer reviewed work flows. More cap rock cores available for diffusion measurements and modelling</td>
<td>Focus data acquisition on cap rock cores and analysis</td>
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<tr>
<td>Injectivity</td>
<td>Standard industry systems for natural injectivity - advances in compression and pumping technology required for some projects</td>
<td>Geo-system: Assesment of potential for sustained injectivity into the reservoir through assessment of critical pressures, reservoir heterogeneity, compartmentalisation, brine displacement, reactive flow and wellbore impairment. Engineered system: Sustained injectivity requires high up-time for compression/pumping equipment, pipeline, capture plant</td>
<td>Confirm that the storage sites(s) is large enough to hold full life-cycle CO2 volumes. Sustained injection rates over the life-time of the project can be achieved.</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices. Need to improve capability to predict caprock properties/continuity in areas with sparse data (characteristic for many aquifers). Need to be able to build a complete well model describing the wellbore integrity and flux rates. Reactive flow: Need modelling tools that fully couple all processes or can interface to specialised reactive flow modelling tools (e.g. Petrel, PVTsim which supply input to flow models)</td>
<td>Emerging consensus on key reactive flow issues and in which geological settings these may be significant. Improved interfaces between flow modelling simulators and specialised modelling tools.</td>
<td>Assess for reactive flow issues prior to site selection and acquire data during field demo operation and post-operation phase to validate reactive flow components</td>
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</table>
## Scope of technology blocks for storage (5/19)

<table>
<thead>
<tr>
<th>Technology Block function</th>
<th>Technology</th>
<th>Scope</th>
<th>Capacity and Performance (specification parameters)</th>
<th>Proven</th>
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<th>Tools</th>
<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evaluate Leakage Potential</strong></td>
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<tr>
<td>Risk analysis</td>
<td>Adapted systems are emerging but as yet immature</td>
<td>Iterative assessment of major leak features that can be avoided through design and identification of residual risk to design a monitoring and verification plan and mitigation strategy. Agree performance with regulator.</td>
<td>Confirm that the storage sites (s) is large enough to hold full life-cycle CO2 volumes. Sustained injection rates over the life-time of the project can be achieved. Model and predict distribution of CO2 in the subsurface and demonstrate credible mechanisms for long term containment.</td>
<td>Risk assessment methodologies are emerging at a project level that require regulatory consensus to move to standardised and accepted practices</td>
<td>Alignment of peer reviewed work flows. Consensus on main principles that underpin robust risk assessment. Emerging regulatory frameworks.</td>
<td>Full performance assessment of each demonstration project to include life-cycle containment risk assessment including risk mitigation strategies and clear linkage to monitoring and verification programme.</td>
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<td>Features</td>
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### Scope of technology blocks for storage (6/19)

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<th>Technology Block function</th>
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<th>Tools</th>
<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define Storage License Parameters</td>
<td></td>
<td>Identify a site or a combination sites which can contain the full life-cycle project CO2 volume.</td>
<td>Defining the boundaries of the storage complex and agreeing operating performance with regulatory bodies</td>
<td>Within Europe all current activities operate license exceptions from existing regulations on a project-by-project basis. Only some of these projects have defined lateral and vertical boundaries prior to commencement</td>
<td>Increased project base with agreed license parameters and emerging national regulations</td>
<td>Documented and published criteria for regulatory definition of project boundaries for each flagship demo in order to establish first regulatory practice</td>
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<tr>
<td>Identify containment boundaries</td>
<td></td>
<td>Define and agree vertical and lateral boundaries for a licensed containment complex with regulatory authorities</td>
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<tr>
<td>Define separation distances</td>
<td></td>
<td>Define spatial and temporal separation margins between CO2 plume and identified leak features or sensitive zone (e.g. potable water, other licenses or national boundaries)</td>
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<tr>
<td>Define operation volume</td>
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<td>Agree licensed volume and pressure with regulator.</td>
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<tr>
<td>Define operation pressure</td>
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<tr>
<td>Define baseline M&amp;V requirements</td>
<td></td>
<td>Demonstrate geological storage of CO2 is effective and poses no unacceptable HSE or economic risk. To be effective this has to be against an agreed baseline. Setting external conditions informed by a combination of risk assessment, regulatory requirements and external stakeholder expectation (NGO, public).</td>
<td>Defining the baseline work and the monitoring &amp; verification programme, including thresholds for monitoring and inventory. Set the criteria for closure and agree post-closure monitoring with the regulator.</td>
<td>Not yet consensus on definition of a baseline for CO2 M&amp;V. Extensive and mature toolkit exists, but no standards for M&amp;V requirements (accuracy, areal extend, frequency). Criteria for definition of post-closure phase poorly defined. Different M&amp;V requirements for storage security, HSE and ETS credit.</td>
<td>Alignment of baseline definition of storage system, particularly around threshold. Need for consensus regarding the key parameters for monitoring and verification</td>
<td>Integrate M&amp;V procedures and plans as part of full storage system approach, showing clear linkages to risk assessment, containment, safe operation and CO2 credits.</td>
<td>Ok for seismic, wellbore and petrophysical, not for surface baseline &amp; CO2 monitoring</td>
<td>But need integration with definition of threshold s and project economics</td>
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</tbody>
</table>
### Scope of technology blocks for storage (7/19)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Site Testing</strong></td>
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<tr>
<td><strong>Site Maturation Plan</strong></td>
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<tr>
<td>Data acquisition</td>
<td>As per 'Evaluate Storage Features' above</td>
<td>Iterative loop of site maturation activities to close data gaps and mature preferred site(s)</td>
<td>Confirm that the storage sites (s) is large enough to hold full life-cycle CO2 volumes. Sustained injection rates over the lifetime of the project can be achieved. Model and predict distribution of CO2 in the subsurface and demonstrate credible mechanisms for long term containment.</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices.</td>
<td>Lack of subsurface data will limit maturation of some potential sites by 2012</td>
<td>Will take place on data rich sites/areas or sites with accelerated data acquisition and appraisal activities</td>
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<tr>
<td>maturation planning</td>
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<tr>
<td>Baseline surveys (MMV)</td>
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<tr>
<td>geosphere</td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. marine biosphere)</td>
<td>Establish initial conditions for all storage system components and map fluxes (if any) for each domain</td>
<td>Determine the parameters and thresholds of measurements per domain and to establish the project reference baseline which will be used for future performance validation.</td>
<td>Tools exist today for general application, but CCS thresholds and parameters have yet to be established</td>
<td>Application of tools modified to CCS activities. Convergence on thresholds and key parameters, and recognition of technology gaps.</td>
<td>Agreed baseline executed and shared for all flagship projects; matching thresholds and parameters to regulator expectations</td>
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<td>hydrosphere</td>
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<td>biosphere</td>
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<tr>
<td>atmosphere</td>
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## Scope of technology blocks for storage (8/19)

<table>
<thead>
<tr>
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<th>Tools</th>
<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage site and integration</td>
<td>CO2 source integration</td>
<td>ability to model variability</td>
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<tr>
<td>CO2 flow stream variability</td>
<td># CHECK</td>
<td>Matching of time dependent variable CO2 output (rate and composition) to transportation and storage facility, including flow regime, phase envelopes, compression/pumping and operating envelope.</td>
<td>Constraining the time dependent flow rate of CO2</td>
<td># CHECK</td>
<td># CHECK</td>
<td># CHECK</td>
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<tr>
<td>CO2 composition</td>
<td># CHECK</td>
<td>Constrained time dependent composition of CO2 and contaminants</td>
<td></td>
<td># CHECK</td>
<td># CHECK</td>
<td># CHECK</td>
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<tr>
<td>CO2 phase behaviour</td>
<td># CHECK</td>
<td>Establishing the operating envelope for transport, compression and storage</td>
<td></td>
<td># CHECK</td>
<td># CHECK</td>
<td># CHECK</td>
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<tr>
<td>Existing wells</td>
<td>survey/monitor for leakage &amp; corrosion</td>
<td>Existing technologies for live/suspended wells with a need for more sensitive and diagnostic tools for wellbore integrity. Lack of full wellbore modelling technology.</td>
<td>Identify any wells or zone that might be impacted by injected CO2 and establish a workover/abandonment plan.</td>
<td>Establish a basis for evaluation of leakage potential from old wells. Setting standards for remediation and/or abandonment.</td>
<td>Toolkit for live/suspended wells</td>
<td>Numerical modelling capability for full wellbore and improved downhole diagnostics for wellbore integrity. Emerging consensus on whether to remediate poorly abandoned wells or design site to avoid plume contact.</td>
<td>Gather data that will support full wellbore modelling and provide reference wellbore integrity data. Need to share experience between demonstration projects (i.e. through IEA Wellbore Integrity network)</td>
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<td></td>
<td>remEDIATE or abandon</td>
<td>Existing remediation and abandonment standards require updating for CCS</td>
<td>Industry standards for production/injection operations (hydrocarbon development)</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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<td>For CCS</td>
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## Scope of technology blocks for storage (9/19)

<table>
<thead>
<tr>
<th>Technology Block function</th>
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<th>Tools</th>
<th>Work flow</th>
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</thead>
<tbody>
<tr>
<td><strong>Baseline Monitoring and Verification</strong></td>
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<tr>
<td><strong>Identify M&amp;V parameters and thresholds for each domain for a specific storage system</strong></td>
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<tr>
<td>HSE</td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. marine biosphere)</td>
<td>Safeguarding the environment, population and work force</td>
<td>Agree with regulators the parameters and thresholds and frequency of measurements.</td>
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<tr>
<td>Containment</td>
<td>Setting performance standards and operating practices with regulatory bodies</td>
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<tr>
<td>Verification</td>
<td>Assuring credit under the EU ETS and any national system. Verification that CO2 storage operation does not expose operator to external liability (e.g. contamination of ground water, other operator's hydrocarbons)</td>
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<tr>
<td><strong>Forward Model Leakage - ‘what ifs’ for</strong></td>
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<tr>
<td>Atmosphere</td>
<td>Standard industry systems</td>
<td>Modelling plume migration beyond primary seal to identify leakage pathways to other domains. The intent is to mature M&amp;V programme and demonstrate storage system integrity.</td>
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<td>Biosphere</td>
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### Notes
- **Tools**
  - For free phase CO2
  - For individual storage system component but not for whole system
  - For primary containment but not for entire storage system
### Scope of technology blocks for storage (10/19)

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<tr>
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<tbody>
<tr>
<td><strong>Economical screening of MMV programme</strong></td>
<td>Work process</td>
<td>Place economic constraints on M&amp;V programme in the operation phase and to agree with regulator structures for M&amp;V post-closure</td>
<td>Site-specific requirements against corporate screening criteria and project economics</td>
<td>Existing industry approaches to economic screening require adaptation to extended CCS project time scales and to emerging EU and national regulations.</td>
<td>Formative screening models at a project-by-project level constrained by emerging regulations</td>
<td>Systematic economic screening, shared through IEA networks</td>
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<tr>
<td><strong>Regulatory MMV requirements</strong></td>
<td>Regulatory dialogue and approval</td>
<td>Define MMV plans with regulators (features, accuracy, time) for all phases of project</td>
<td>Capability to work with regulators to shape regulatory requirements for MMV incorporating and adapting experience from active CCS and other relevant projects (e.g. natural gas storage, waste water injection)</td>
<td>Exist for oilfield operations but not matured for CCS</td>
<td>Adapted procedures to fit CCS and as licensed by national regulators deriving monitoring guidelines from CO2 Storage Directive</td>
<td>Develop common approach to future CCS project MMV requirements based on experience from flagship programme demos</td>
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<tr>
<td><strong>Define requirements for forward modelling based on MMV data.</strong></td>
<td>Work process</td>
<td>Agree long-term modelling programme supported by M&amp;V data that demonstrates performance (storage security) against agreed baseline, to guide future choice of tools and frequency of measurements.</td>
<td>Model and predict distribution of CO2 in the subsurface and demonstrate credible mechanisms for long term containment.</td>
<td>Modelling capability proven today but modelling capacity for full storage system limits capability</td>
<td>Increased modelling capacity and alignment on the requirement to model beyond primary containment</td>
<td>Forward model leakage beyond the primary containment to fully identify leakage pathways and so mature M&amp;V strategy.</td>
<td>But only sparsely applied to date</td>
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</table>
## Scope of technology blocks for storage

### (11/19)

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<tr>
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<tr>
<td><strong>OPERATION</strong></td>
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<tr>
<td>Design wells</td>
<td>Standard industry systems working to revised standards. Increased emphasis on material selection, cementing practices, zonal isolation and contracting and procurement standards</td>
<td>Establish design criteria for injection (and observation) wells (well geometry, completion intervals, materials choice, cement and cementing practices, contracting and tendering procedures - in line with life-cycle containment objectives.</td>
<td>Establish agreed design standards and contracting and procurement practices for sequestration wells</td>
<td>Industry standards for production/injection operations (hydrocarbon development); emerging practices for CCS activities</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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</tr>
<tr>
<td>Locate injecton wells + patterns</td>
<td>Standard industry systems</td>
<td>Siting injection wells to allow even distribution of CO2 in subsurface, providing separation distance from recognised leak features and including redundancy injection capacity to optimise operational flexibility</td>
<td>Model injection patterns to assure an even distribution of CO2 in the subsurface and manage pressure distribution within licensed limits</td>
<td>Industry standards for production/injection operations (hydrocarbon development);</td>
<td>Alignment of peer reviewed work flows/criteria for locating wells and defining injection patterns</td>
<td>Documented and published work flows/criteria for each flagship demo</td>
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<tr>
<td>RemEDIATE and/or abandon old wells</td>
<td>Standard industry systems working to revised standards.</td>
<td>Minimise risk of CO2 migration outside containment system by remediating and/or abandoning old wells to a revised CCS standard</td>
<td>Workover and or abandon existing wells; assure integrity to revised standards.</td>
<td>Industry standards for production/injection operations (hydrocarbon development);</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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## Scope of technology blocks for storage (12/19)

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<th>Work flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill &amp; complete wells</td>
<td>Standard industry systems working to revised standards.</td>
<td>Drill and complete injection (and observation) wells to revised CCS standards</td>
<td>Drill and complete wells to revised standards; acquire adequate baseline data to monitor life-cycle integrity.</td>
<td>Industry standards for production/injection operations (hydrocarbon development); emerging practices for CCS activities</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
<td>Documents and share near-well bore clean-up practices for each flagship demo through appropriate networks.</td>
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</tr>
<tr>
<td>Cement integrity and zonal isolation</td>
<td>Standard industry systems working to revised standards.</td>
<td>Demonstrate wellbore material and cement integrity and effective zonal isolation</td>
<td>Assure cement integrity and zonal isolation to revised standards</td>
<td>Industry standards for production/injection operations (hydrocarbon development) - large variations in operating standards and practices resulting in variable but widespread well integrity issues</td>
<td>Revised standards for CCS activities addressing extended storage life requirement; revised regulatory requirements for contracting and procurement procedures for CCS activities (integrity assurance not cost driven)</td>
<td>Documented and share cement and zonal isolation practices for each flagship demo through appropriate networks.</td>
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<tr>
<td>Manage near-wellbore clean-up</td>
<td>Standard industry systems working to revised standards.</td>
<td>Maximise injectivity without compromising wellbore integrity</td>
<td>Clean-up the near well-bore region to: - optimise injection capacity - minimise well integrity problems - not compromise containment - condition the near well bore region for CO2 injection (if required)</td>
<td>Industry standards for production/injection operations (hydrocarbon development); emerging practices for CCS activities</td>
<td>Alignment of peer reviewed practices and work flows</td>
<td>Documented and share near-well bore clean-up practices for each flagship demo through appropriate networks.</td>
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</tr>
<tr>
<td>Inject dense phase CO2</td>
<td>Standard industry systems working to revised standards &amp; potentially extending existing operating envelopes.</td>
<td>Initiate injection activities within the agreed operating envelope</td>
<td>Inject dense phase CO2 within licensed limits and across selected injection intervals</td>
<td>Capacity at the scale of existing demonstrator projects and within restricted operating envelopes</td>
<td>Alignment of peer reviewed practices and work flows</td>
<td>Document and publish practices for each flagship demo.</td>
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</table>


## Scope of technology blocks for storage (13/19)

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Manage injection P + T</strong></td>
<td>Standard industry systems working within agreed licensed limits</td>
<td>Maintain injection activities within the agreed operating envelope</td>
<td>Confirm and maintain injection within licensed limits and across selected injection intervals</td>
<td>Industry standards for production/injection operations (hydrocarbon development); emerging practices for CCS activities</td>
<td>Alignment of peer reviewed practices and work flows</td>
<td>Document and share PT management practices for each flagship demo through appropriate networks</td>
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</tr>
<tr>
<td><strong>Manage CO2 input into reservoir</strong></td>
<td>Standard industry systems adapted to the variable throughput from different CCS projects</td>
<td>Maintain CO2 flow within defined operating envelope</td>
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<tr>
<td>rate</td>
<td>Standard industry systems working within agreed licensed limits and adapted to the variable throughput from different CCS projects</td>
<td>Manage plant load variation as part of reservoir management strategy to maintain down-hole pressure control. Model near-wellbore effects.</td>
<td>Forward model and manage/optimise variations in CO2 throughput into subsurface</td>
<td>Emerging practices for CCS activities but not yet across a wide-range of operating scenarios</td>
<td>Alignment of peer reviewed practices and work flows</td>
<td>Selection of demos across a range of operating envelopes; document and share subsurface CO2 management practices for each flagship demo through appropriate networks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>areal and vertical distribution</td>
<td>Standard industry systems</td>
<td>Model plume distribution and manage injection patterns/intervals to ensure an even distribution of CO2 vertically (i.e. in layered reservoirs) and laterally (i.e. even distribution of plume under cap)</td>
<td>Monitor injection intervals and plume migration/pressure evolution within reservoir</td>
<td>Emerging practices for CCS activities but not yet across a wide-range of operating scenarios</td>
<td></td>
<td></td>
<td>Not validated for specific demonstrator types with highly variable throughput</td>
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</table>
## Scope of technology blocks for storage (14/19)

<table>
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<tr>
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<tbody>
<tr>
<td>Lifecycle well integrity assurance</td>
<td>logging</td>
<td>Standard industry systems but with more sensitive and diagnostic downhole tools for wellbore integrity</td>
<td>Logging well/cement integrity during the operational period to identify workover/maintenance requirements</td>
<td>Utilise sensitive and diagnostic downhole tools for wellbore integrity, conduct numerical model of leakage for a full well bore; develop a statistical basis for the evaluation of wellbore performance</td>
<td>Standard industry logging capability but with limited capability/experience in modelling full wellbore integrity - including flux rates</td>
<td>Numerical modelling capability for full wellbore and improved downhole diagnostics for wellbore integrity</td>
<td>Gather data that will support full wellbore modelling and provide reference wellbore integrity data. Need to share experience between demonstration projects (i.e. through IEA Wellbore Integrity network)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>workovers</td>
<td>Standard industry systems working to revised standards.</td>
<td>Execute workover activities and manage simultaneous operations (SIMOP’s)</td>
<td>Workover and or abandon wells; assure integrity to revised standards.</td>
<td>Industry standards for hydrocarbon development and CO2 EOR; little/no experience for CCS activities</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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</tr>
<tr>
<td></td>
<td>maintenance</td>
<td>Standard industry systems working to revised standards.</td>
<td>Manage existing well stock</td>
<td>Maintain existing well stock and ensure data quality to assess integrity against agreed baseline</td>
<td>Industry standards for hydrocarbon development and CO2 EOR; little/no experience for CCS activities</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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## Scope of technology blocks for storage (15/19)

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<tbody>
<tr>
<td><strong>Select wells near injection end-life cycle</strong></td>
<td>Standard industry systems working within agreed licensed limits</td>
<td>Determine appropriate number and distribution of wells to convert to observation wells</td>
<td>Forward model plume distribution and determine appropriate wells to convert to observation wells</td>
<td>Adapted modelling workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices; absence of regulatory definition of post-closure observation well standards</td>
<td>Emerging consensus on key forward modelling issues and on emerging regulatory requirements.</td>
<td>Clarify and share license requirements/criteria for observation wells. Execute forward modelling prior to selection of abandonment/observation wells.</td>
<td></td>
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<tr>
<td>convert to observation</td>
<td>Standard industry systems working to revised standards.</td>
<td>Workover selected wells and convert to observation wells</td>
<td>Workover and convert wells; assure integrity to revised standards.</td>
<td>Industry standards for hydrocarbon development and CO2 EOR; emerging experience for CCS activities</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Incorporate experience to date from active demonstrator projects. Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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</tr>
<tr>
<td>abandon to agreed standards</td>
<td>Standard industry systems working to revised standards.</td>
<td>Abandon remaining well-stock to revised standard</td>
<td>Abandon wells; assure integrity to revised standards.</td>
<td>Industry standards for production/injection operations (hydrocarbon development);</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Review and update corporate standards for CCS activities, providing input for updated regulatory standards and practices.</td>
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# Scope of technology blocks for storage (16/19)

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<tr>
<td><strong>Storage</strong></td>
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<tr>
<td><strong>Closure</strong></td>
<td></td>
<td></td>
<td>Closing down injection and facilities leaving only monitoring equipment in place. It is anticipated that post-injection monitoring may be required for as long as the injection period (i.e. 30-40 years) or shorter if stability can be proven</td>
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<tr>
<td><strong>Define at end-of-injection</strong></td>
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<tr>
<td>CO2 plume position</td>
<td>Standard industry systems</td>
<td>Establish reference against which future CO2 dense phase plume is to be held.</td>
<td>Establish reference point for future comparison.</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices. Reactive flow: Need modelling tools that fully couple all processes or can interface to specialised reactive flow modelling tools (e.g. Petrel, PVTsim which supply input to flow models)</td>
<td>Alignment of peer reviewed work flows</td>
<td>Defining key sensitivities that constrain plume migration and pressure modelling. Publishing workflows for operational and extended time scales for modelling.</td>
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<tr>
<td>Establish &quot;baseline&quot; for all monitoring parameters</td>
<td>Make full inventory of all monitored parameters</td>
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<tr>
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<tr>
<td><strong>History matching and forward models</strong></td>
<td>Standard industry systems need integration with emerging modelling codes/databases to handle complex geochemical/geomechanical processes. Lab experiments with critical liquids at operating conditions.</td>
<td>Match against performance history and forward model plume behaviour and fate of CO2 dissolved in brine. Model 'what if' scenarios.</td>
<td>Use accumulated performance experience over 20-30 years for history matching and make predictions for the post-injection monitoring period as well as long term (100 to 1000's of years)</td>
<td>Adapted workflows are emerging at a project level but require peer review and alignment to move to standardised and accepted practices. Reactive flow: Need modelling tools that fully couple all processes or can interface to specialised reactive flow modelling tools (e.g. Petrel, PVTsim which supply input to flow models)</td>
<td>Emerging consensus on key forward modelling issues and on emerging regulatory requirements.</td>
<td>Assess for reactive flow issues prior to site selection and acquire data during field demo operation and post-operation phase to validate reactive flow components</td>
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<tr>
<td><strong>Define criteria for operator's obligations</strong></td>
<td>Regulatory dialogue and approval</td>
<td>Define convergence and stabilisation criteria with regulators; i.e. when can operator leave site</td>
<td>Define criteria for containment of CO2 within storage system</td>
<td>Criteria for definition of post-closure phase poorly defined. Different M&amp;V requirements for storage security, HSE and ETS credit.</td>
<td></td>
<td>Obligations agreed with regulator. Executed for all flagship projects; monitoring results shared amongst all ZEP demonstrators (e.g. through IEA Monitoring Network)</td>
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</tbody>
</table>
## Scope of technology blocks for storage (18/19)

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<tbody>
<tr>
<td><strong>Observation wells</strong></td>
<td>Standard industry systems working to revised standards.</td>
<td>Demonstrate wellbore material and cement integrity and effective zonal isolation.</td>
<td>Assure cement integrity and zonal isolation to revised standards</td>
<td>Industry standards for production/injection operations (hydrocarbon development)</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td>Clarify and share license requirements/criteria for observation wells. Execute forward modelling prior to selection of abandonment/observation wells. Acquire data late injection period to modelling and selection.</td>
<td></td>
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</tr>
<tr>
<td><strong>Perform regular MMV</strong></td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. passive seismic))</td>
<td>Review and update with regulators MMV activities (features, accuracy, frequency) and storage performance &amp; security against agreed baseline.</td>
<td>Repeatedly determine monitoring parameters at specified thresholds of measurements per domain and compare to establish the project reference baseline for performance validation.</td>
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<tr>
<td><strong>geosphere</strong></td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. passive seismic))</td>
<td>Review and update with regulators MMV activities (features, accuracy, frequency) and storage performance &amp; security against agreed baseline.</td>
<td>Repeatedly determine monitoring parameters at specified thresholds of measurements per domain and compare to establish the project reference baseline for performance validation.</td>
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<tr>
<td><strong>hydrosphere</strong></td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. passive seismic))</td>
<td>Review and update with regulators MMV activities (features, accuracy, frequency) and storage performance &amp; security against agreed baseline.</td>
<td>Repeatedly determine monitoring parameters at specified thresholds of measurements per domain and compare to establish the project reference baseline for performance validation.</td>
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<tr>
<td><strong>biosphere</strong></td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. passive seismic))</td>
<td>Review and update with regulators MMV activities (features, accuracy, frequency) and storage performance &amp; security against agreed baseline.</td>
<td>Repeatedly determine monitoring parameters at specified thresholds of measurements per domain and compare to establish the project reference baseline for performance validation.</td>
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<tr>
<td><strong>atmosphere</strong></td>
<td>Standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. passive seismic))</td>
<td>Review and update with regulators MMV activities (features, accuracy, frequency) and storage performance &amp; security against agreed baseline.</td>
<td>Repeatedly determine monitoring parameters at specified thresholds of measurements per domain and compare to establish the project reference baseline for performance validation.</td>
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## Scope of technology blocks for storage (19/19)

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<tr>
<td>Post Closure M&amp;V</td>
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<tr>
<td>CO2 containment M&amp;V</td>
<td>Simplified standard industry systems combined with standard surface monitoring technologies and emerging technologies (e.g. passive seismic))</td>
<td>Define with regulators and certification agency need - if any - for long term monitoring to ensure storage integrity and collation of documentation</td>
<td>Identify robust method for scientific monitoring over the following decades</td>
<td></td>
<td>Some procedures emerging at pilot sites</td>
<td></td>
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</tr>
<tr>
<td>Termination procedure</td>
<td>Standard industry systems working to revised standards.</td>
<td>Removal of all surface and monitoring equipment, including any observation wells.</td>
<td>How to leave site</td>
<td></td>
<td>Exists in oil and gas operations</td>
<td>Revised standards for CCS activities addressing extended storage life requirement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relinquishment</td>
<td>Regulatory dialogue and approval</td>
<td>Specification of when and to what specifications the operator can return license area to the regulators</td>
<td>Hand-over of liability to regulator</td>
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</table>
## Scope of technology blocks for storage – ECBM (1/4)

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<tbody>
<tr>
<td><strong>Pattern test</strong></td>
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<tr>
<td>Evaluate Enhanced CBM production</td>
<td>5 spot pilot</td>
<td>In mature CBM field, which is in decline, a new injector is drilled or producer converted into an injector to conduct a 5 spot pilot. Here the main objective is to enhance the methane production and postpone the decline of the field. The CO2 storage is a bonus.</td>
<td>Increase of methane production in producers</td>
<td>Technology to conduct pilot exists (Ref pilots in San Juan in 90s)</td>
<td>Commericially proven after pilot successfully completed in field (ready for scale up)</td>
<td>Successful pilot in mature field (stop decline in production and ready for scale up)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CO2 storage in coal injection test</td>
<td></td>
<td>A depleted CBM well is converted into an injector to test CO2 injectivity and storage potential of coal. The main objective is CO2 storage</td>
<td>Prove long-term injectivity of CO2: reduction in injectivity may mean less CO2 can be stored)</td>
<td>Technology to conduct pilot exists (RECOPOL pilot, etc.)</td>
<td>Commericial concept depends on CO2 credits and regulation</td>
<td>Successful injection in depleted field (continuous injection at acceptable rate and ready for scale up)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Flue gas injection lab evaluation followed by 5 spot test</td>
<td></td>
<td>The CO2 footprint of a CBM operation is largely due to the own use (fuel gas) for compression. Capturing the flue gas and usage for ECBM may be attractive option to reduce own CO2 at compressor stations. The effect of oxygen (in flue gas) on ECBM is unknown. Need better understanding before conducting field trails</td>
<td>Establish effect of oxygen on ECBM</td>
<td>not proven</td>
<td>Prove concept of flue gas injection</td>
<td>Ready to conduct commercial field pilot + integration with compressor sites</td>
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</tbody>
</table>
### Scope of technology blocks for storage – ECBM (2/4)

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</tr>
</thead>
<tbody>
<tr>
<td>Upgrade facilities</td>
<td>space for CO2 equipment</td>
<td>If producer is converted to injector changes are required to well site</td>
<td>sufficient space, footprint</td>
<td>proven</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>prevention corrosion</td>
<td>standard tech</td>
<td>CBM gas already contains CO2, but now more CO2 can be expected in produced gas (low pressure sep)</td>
<td>no corrosion</td>
<td>proven</td>
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</tr>
<tr>
<td>CO2 separator</td>
<td>standard tech</td>
<td>efficiency separation process</td>
<td>proven</td>
<td></td>
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<tr>
<td>New Facilities</td>
<td>standard CBM drilling</td>
<td>Volumes injected per well are relatively modest so low tech wells are sufficient</td>
<td>Completion of well</td>
<td>proven</td>
<td></td>
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<tr>
<td>Well site</td>
<td>standard well site prep CBM</td>
<td>If new injector is drilled, new site needs to be prepared</td>
<td>space, footprint</td>
<td>proven</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 transport</td>
<td>standard piping</td>
<td>Need to evaluate whether low pressure (plastic) or high pressure (steel) pipes will be used (compression at well-head or central compression)</td>
<td>pipe capacity + integrated design with compression</td>
<td>proven</td>
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<tr>
<td>CO2 storage at site</td>
<td>CO2 storage tanks</td>
<td>CO2 storage buffer is required for pilot</td>
<td>Sufficient storage space to conduct pilot</td>
<td>proven</td>
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### Scope of technology blocks for storage – ECBM (3/4)

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<tr>
<td>CO2 separation</td>
<td>standard tech</td>
<td>Extra separation may be required. Separation is possible and proven. Moreover, there are almost no compression losses, because CBM gas is produced at low pressure (few bars).</td>
<td>efficiency separation process</td>
<td>proven</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>CO2 compression</td>
<td>standard tech</td>
<td>New compressors can be build at compression station or at well site depending on economics</td>
<td>integrated design compression site and well site meeting injection specs.</td>
<td>proven</td>
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<tr>
<td>M&amp;V operational</td>
<td></td>
<td>Risk of leakage of CO2 comparable or smaller than risk of methane leakage. Monitoring similar as CBM, but include CO2 sensors. Also, there is standard mining technology to monitor methane and CO2 in mines.</td>
<td>detect leakage both concentration and flux</td>
<td>proven</td>
<td></td>
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<tr>
<td>Well</td>
<td>Standard Sensors</td>
<td>In CBM field migration of methane to surface always poses a risk when de-watering. CO2 leakage is less likely because it adsorbs stronger to the coal. Monitoring program in conjunction with existing methane monitoring program.</td>
<td>detect leakage both concentration and flux</td>
<td>proven</td>
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## Scope of technology blocks for storage – ECBM (4/4)

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<th>Tools</th>
<th>Commercial</th>
<th>Workflow</th>
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<tbody>
<tr>
<td>Ground water</td>
<td>Standard Sensors</td>
<td>Again risk of methane contamination due to CBM operation is higher, comparable monitoring techniques for CO2</td>
<td>detect CO2 or CH4 contamination of water</td>
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<td><strong>Closure methodology</strong></td>
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<td>Facilities</td>
<td>Standard abandonm ent CBM</td>
<td>Re-use of facilities (compressors etc.) recommended</td>
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<td>wells</td>
<td>Standard abandonm ent CBM</td>
<td>RECOPOL showed that it is difficult to get CO2 out of the coal</td>
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<tr>
<td>CO2 containment M&amp;V</td>
<td>Standard monitoring techniques</td>
<td>Risk CH4 leakage due to CBM at well site larger than CO2 leakage.</td>
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<td>Post Closure M&amp;V</td>
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<tr>
<td>CO2 containment M&amp;V</td>
<td>sensors surface and water</td>
<td>Similar to post monitoring mining areas (CH4 leakage)</td>
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<td>Termination procedure</td>
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<td>Relinquishment</td>
<td>legal</td>
<td>Mining rights: Coal needs to be classified as storage medium to avoid conflict with future mining</td>
<td>legal issues need to be resolved</td>
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