Lecture 14: Coal based oxy-fuel technology - progress to deployment

APP OFWG Capacity Building Course, Monday/Tuesday
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Xijiao Hotel, Beijing, China

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OFGW Project Leader and
University of Newcastle, Australia
Content

Summary of Oxy-fuel demonstration projects

Issues delaying deployment

Roadmap to commercialisation
Historical development of oxyfuel technology, at December 2009

Recent proposals

- Vattenfall 250
- Youngdong 100
- Jamestown 50
- Callide A 30
- Oxy-coal UK 13.3
- CIUDEN 10
- CIUDEN 6.7

- International Comb 11.7
- ANL/EERC 1.0
- IFRF / Doosan Babcock 1.0
- B&W 10
- Jupiter 6.7
- TOTAL (NG) 10
- ANL/BHP 0.2
- IHI 0.5
- B&W/AL 0.4
- CANMET 0.1
- IVD-Stuttgart 0.2
- EON 0.3
- RWE-NPOWER 0.2

- ANL/EERC 0.2
- ANL/EERC 1.0
- IFRF / Doosan Babcock 1.0
- B&W 10
- Jupiter 6.7
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- B&W/AL 0.4
- CANMET 0.1
- IVD-Stuttgart 0.2
- EON 0.3
- RWE-NPOWER 0.2
## Demonstration details

<table>
<thead>
<tr>
<th>No</th>
<th>Demo/pilot-plant name</th>
<th>Scale (Demo/Pilot plant)</th>
<th>MW&lt;sub&gt;e&lt;/sub&gt;</th>
<th>New Retrofit</th>
<th>Startup/Duration</th>
<th>Main Fuel</th>
<th>Electricity generation</th>
<th>CO2 Compression</th>
<th>CO2 use/Seq</th>
<th>CO2 purity</th>
<th>Gas clean up</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vattenfall pilot plant, Germany</td>
<td>P</td>
<td>10</td>
<td>N</td>
<td>2008</td>
<td>Coal</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>99.90%</td>
<td>FGD ESP</td>
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<tr>
<td>2</td>
<td>Calide (CS Energy, Australia)</td>
<td>D</td>
<td>30</td>
<td>R</td>
<td>2011</td>
<td>Coal</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<td>FF</td>
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<tr>
<td>3</td>
<td>TOTAL, Leq., France</td>
<td>D</td>
<td>10</td>
<td>R</td>
<td>2009</td>
<td>NG</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>99.90%</td>
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<tr>
<td>4</td>
<td>CIUDEN, Spain</td>
<td>P (FC/CFE)</td>
<td>17</td>
<td>N</td>
<td>2010</td>
<td>Coal</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>SCR FF FGD</td>
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<tr>
<td>5</td>
<td>Youngdong, South Korea</td>
<td>D</td>
<td>100</td>
<td>R</td>
<td>2016</td>
<td>Coal</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>98%</td>
<td>SNCR FF</td>
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<tr>
<td>6</td>
<td>Jamestown/Prairie Plant, USA</td>
<td>D (CFE)</td>
<td>50</td>
<td>N</td>
<td>2013</td>
<td>Coal</td>
<td>N</td>
<td>Y</td>
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<tr>
<td>7</td>
<td>Jupiter Pearl plant, USA</td>
<td>D</td>
<td>22</td>
<td>R</td>
<td>2009</td>
<td>Coal</td>
<td>N</td>
<td>N</td>
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<tr>
<td>8</td>
<td>Babcock &amp; Wilcox pilot plant, B&amp;W, USA</td>
<td>P</td>
<td>10</td>
<td>R</td>
<td>2008</td>
<td>Coal</td>
<td>N</td>
<td>N</td>
<td></td>
<td>70% dry</td>
<td>FGD ESP</td>
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<tr>
<td>9</td>
<td>Doosan Babcock, UK</td>
<td>P</td>
<td>30</td>
<td>N/A</td>
<td>2008</td>
<td>Coal</td>
<td>N</td>
<td>N</td>
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</tbody>
</table>
Vattenfall flowsheet

- PRECRUSHED COAL
- Pre-powdered CaCO3
- ESP
- FGD
- COOLER/CONDENSER
- Compression
- Purification
- Liquid CO2
  15-20bar
  -15-50°C

Components:
- de-NOx
- NH3
- ASU
- O2
- N2
- AIR

Process steps:
- Hot Secondary Recirculation
- Cool Primary Recirculation

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The University of Newcastle Australia
Callide flowsheet

Online COAL MILL → PRE-HEATER → DUST REMOVAL → COOLER/CONDENSER → COMPRESSION

O2

H2O REMOVAL

Liquid CO2

inerts

(PtO, Hg, inerts removed)
Demonstration contributions

*The Vattenfall 30 MWt pilot plant* – this is the first comprehensive project and it involves evaluation of burner operation, with key testing of boiler impacts, emissions and impacts on CO2 compression. The plant also allows evaluation of possible operations such as limestone addition for sulfur capture, and ammonia addition for NOx reduction.

*The Callide 30 MWe oxy-fuel demonstration project* – will be the first integrated plant, having power generation, carbon capture and CO2 sequestration

*The Doosan Babcock Oxy-coal UK project and B&W USA plants* – these demonstrations have comprehensive burner testing, with burner operational envelopes, stability, turndown, start-up and shut-down, with transition between air and oxyfuel firing

*The CIUDEN and Jamestown plants* - these evaluate CFB oxy-fuel technology, which is suited to coal/biomass cofiring and to direct sulphur removal using sorbents.

*The TOTAL, Pearl and Youngdong plants* – evaluate the technology in a commercial context
Recently announced oxyfuel project prospects

**B&W Black Hills Oxyfuel project, Wyoming, USA**

A project has now been submitted to DOE Restructured FutureGen to build a 100MWe oxyfuel plant with CCS as a greenfield plant for the Black Hills Corporation in Wyoming, with the plant commencing in 2015.

Plant simulations for a SC unit have included thermal integration to reduce the efficiency penalty for the ASU and CO2 compression to less than 6%.

**FORTUM Meri-Pori Oxyfuel Project, Finland**

Fortum aims to start a CCS demonstration project jointly with Teollisuuden Voima (TVO) at the Finnish Meri-Pori power plant, a 565MW plant. Due to lack of suitable storage locations in Finland, the CO2 from Meri-Pori will be shipped abroad.

**ENEL Oxyfuel CCS2 Demonstration, Italy**

The project goal of the CCS2 project is to build by 2012 a 50MWe zero emission coal fired power plant based on a pressurized oxy-combustion technology which has been developed at pilot scale.
### Announced Timelines and Phases of Demonstrations with CCS

<table>
<thead>
<tr>
<th>Feed Type</th>
<th>Location</th>
<th>Design Phase</th>
<th>Construction Phase</th>
<th>Operation Phase</th>
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</thead>
<tbody>
<tr>
<td>Black Coal</td>
<td>Coolimba</td>
<td>Announced</td>
<td>Operation with CCS after 2020</td>
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<td></td>
<td>Compostilla/Endesa</td>
<td>Announced</td>
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<td></td>
<td>Yongdong</td>
<td>Design</td>
<td>Construction</td>
<td>Operation</td>
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<tr>
<td></td>
<td>Black Hill</td>
<td>Design</td>
<td>Construction</td>
<td>Operation</td>
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<tr>
<td></td>
<td>Jamestown</td>
<td>Design</td>
<td>Construction</td>
<td>Operation</td>
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<td>ENEL</td>
<td></td>
<td></td>
<td>Operation</td>
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<tr>
<td></td>
<td>Callide</td>
<td>Construction</td>
<td>Operation</td>
<td>Commercialisation</td>
</tr>
<tr>
<td>Brown Coal</td>
<td>Janschwalde/Vattenfall</td>
<td>Design</td>
<td>Construction</td>
<td>Commerical Operation</td>
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<tr>
<td></td>
<td>Schwarze Pumpe</td>
<td></td>
<td></td>
<td>Operation</td>
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<tr>
<td>Gas Fired</td>
<td>Lacq</td>
<td>Operation</td>
<td></td>
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</tr>
</tbody>
</table>

- Cost/tonne CO₂
- Estimated CCS cost
- Cost barrier
- Carbon Price

Deployment phases:
- Demonstration Phase
- Early commercial Phase
- Mature commercial Phase

- Phase 2020+
- Phase 2030+
## Project times and sequence: Low emission coal power plant with geosequestration, based on a 500MW plant, time halved for 50 MW demonstration

<table>
<thead>
<tr>
<th>Time, yrs</th>
<th>Power plant, PP</th>
<th>CO2 disposal geology</th>
<th>Permitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1  1-2</td>
<td>Concept, pre-feasibility and site selection – cost 1% of PP project</td>
<td>Basin scoping, exploration and appraisal- &lt;$100M</td>
<td>Access to land, exploration licence</td>
</tr>
<tr>
<td>Phase 2  2-3</td>
<td>Feasibility and FEED (Front-End Engineering and Design) - 5%</td>
<td>Site validation and feasibility- &lt;$250M</td>
<td>Environmental impact statement. Permitting process and times very location dependant</td>
</tr>
<tr>
<td>Phase 3  3-4</td>
<td>Financial close, construction and commissioning - 95%</td>
<td>Storage site and injection licence confirmed</td>
<td></td>
</tr>
</tbody>
</table>

**Decision to proceed**
Issues preventing immediate commercial deployment

Cost of electricity and CO2 avoidance

**Oxyfuel technology is semi-commercial**, in that even if a unit was economically viable and could be provided by a vendor, the generator and vendor would need to share the technical risk.

The experience from demonstrations to reduce risk is for units of a scale justifying high efficiency using high temperature steam, typically 300MWe, rather than a number of units proposed of a scale of 100MWe. This is because the efficiency penalty has a greater impact on low temperature units.

... demonstrations require government, vendor and generator support as these issues are resolved.
Anticipated cost of CCS-related technologies as they are developed and applied

Expected availability can increase with time/learning
## Towards a CO2 cost: current status of ETS developments, with the world's top 5 CO2 emitters shown bold

<table>
<thead>
<tr>
<th>Country</th>
<th>Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>ETS unlikely to pass Congress, President likely to change options</td>
</tr>
<tr>
<td>China</td>
<td>No ETS</td>
</tr>
<tr>
<td>Japan</td>
<td>ETS planned</td>
</tr>
<tr>
<td>India</td>
<td>No ETS</td>
</tr>
<tr>
<td>Australia</td>
<td>ETS not likely to pass Senate, extensive debate and other options emerging</td>
</tr>
<tr>
<td>Canada</td>
<td>No ETS, awaiting USA developments</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Only non-EU ETS, operating with fixed carbon cost to 2013</td>
</tr>
<tr>
<td>EU, 27</td>
<td>ETS in operation as the EU Greenhouse Gas Emission Trading Scheme</td>
</tr>
<tr>
<td>Russia</td>
<td>No ETS</td>
</tr>
</tbody>
</table>
## Vendor associations with demonstrations

<table>
<thead>
<tr>
<th>No</th>
<th>Demonstration</th>
<th>Power station vendor</th>
<th>O2 supply/ CO2 compression vendor</th>
<th>CO2 storage expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vattenfall</td>
<td>ALSTOM for design and initial burner, Doosan Babcock also to test burners in rig</td>
<td>LINDE, with evaluation of Air Products compression process</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Callide</td>
<td>IHI</td>
<td>Air Liquide</td>
<td>Schlumberger</td>
</tr>
<tr>
<td>3</td>
<td>TOTAL</td>
<td>ALSTOM</td>
<td>Air Liquide</td>
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<tr>
<td>5</td>
<td>Youngdong</td>
<td>Doosan Babcock</td>
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<tr>
<td>6</td>
<td>Jamestown</td>
<td>Foster Wheeler</td>
<td>Praxair</td>
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<td>7</td>
<td>Pearl Plant</td>
<td>Jupiter Oxygen managed</td>
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</table>

<table>
<thead>
<tr>
<th>No</th>
<th>Large pilot-plant</th>
<th>Other associated vendors</th>
</tr>
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<tbody>
<tr>
<td>4</td>
<td>CUIDEN</td>
<td>CBS (PC combustor), Foster Wheeler (CFB combustor)</td>
</tr>
<tr>
<td>8</td>
<td>B&amp;W, USA</td>
<td>Air Liquide</td>
</tr>
<tr>
<td>9</td>
<td>Doosan Babcock, UK</td>
<td>Air Products</td>
</tr>
</tbody>
</table>
**Funding bodies aims**

Government –

- Accelerate deployment

Industry-

- Generators/utility – want vendors to develop expertise, to provide future commercial plants
- Coal industry – prove coal fired CCS, eg COAL21 fund

Vendors-

- Generate future business
The needs of vendors and generators

Generators/utilities

- Require economic and technical certainty
- Would like competition between vendors, to drive down “maturing” cost of technology
- Would like distributed expertise

Vendors

- Would like demonstration to generate information restricted to their business
- Require design, performance and operational protocols
  - eg, reliability, emissions, ramp rate and spray control
What research is needed

Gas quality impacts and control

- Plant impacts - S, Hg
- Air leakage – N2 compression energy and capture recovery
- Emerging (regulated) CO2 quality for storage
- Pipeline transport - O2, S
- Compression and gas cleaning

O2 supply

- Scale and energy penalty

Furnace

- Radiative heat transfer
- Burner operation
- Coal combustion
Gas property differences result in differing operations to air firing

Property/ratio

<table>
<thead>
<tr>
<th>Property</th>
<th>CO₂ Value</th>
<th>N₂ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (thermal conductivity)</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Cₚ (molar heat capacity)</td>
<td></td>
<td>1.6</td>
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<tr>
<td>ρ (density)</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>ρCₚ (energy volume⁻¹)</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>α (thermal diffusivity)</td>
<td>0.6</td>
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</tr>
<tr>
<td>D_{CH₄} (mass diffusivity)</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

Impact for air to oxyfuel retrofit

- Higher O₂ thru burner
- Lower burner velocity, higher coal residence time in furnace
- Slower flame propagation velocity

Gas property ratios for CO₂ and N₂ at 1200 K

Properties from Shaddix, 2006
Simplified roadmap to deployment of first-generation oxyfuel technology, suggested by Wall and Stanger

First generation technology
- Partial demonstration, without CCS or power generation
- Integrated demonstration
- Integrated and CCS>1Mtpa

Second generation

Research
- Pilot-scale testing and gas cleaning
- O$_2$ supply
- Thermal integration

Regulation
- Gas quality, transport and storage

Efficiency milestones
PF USC efficiency target, with CCS, %HHV
- 40-42%
- >45%
More detailed roadmap, suggested by Wall and Stanger

**Oxy-fuel Technology Deployment Roadmap - Barriers and Targets**

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<tbody>
<tr>
<td>Process modelling for energy penalty reduction - continuous development</td>
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<td>Heat transfer performance prediction - at large scale</td>
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<td>Coal reactions in oxy-fuel environments - reactivity and minor species formation</td>
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<tr>
<td>Gas quality control option assessment - in unit and during compression</td>
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<td>Materials impact of environment - furnace and transport</td>
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<td>O2 production options for reduced cost and energy penalty - membranes and chemical looping</td>
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<tr>
<td>R&amp;D projects from issues established from demonstrations and operating plant</td>
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**Demonstration and Deployment Targets** (reducing risk barriers and establishing commercial scale deployment)

<table>
<thead>
<tr>
<th>Demonstration and Deployment Targets</th>
<th>(reducing risk barriers and establishing commercial scale deployment)</th>
<th>2010</th>
<th>2012</th>
<th>2014</th>
<th>2016</th>
<th>2018</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
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<tbody>
<tr>
<td>Pilot-scale coal testing capability</td>
<td></td>
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<tr>
<td>Full-scale burner testing, first generation technology</td>
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<tr>
<td>Demonstrations with CCS</td>
<td>subcritical</td>
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<tr>
<td>IEA Oxy-fuel deployment targets</td>
<td>post demonstration</td>
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<td>Demonstration of second generation technology</td>
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**Cost and Capture Targets** (reducing market barriers)

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<tbody>
<tr>
<td>Establishing plant operation for generation flexibility in an electricity market</td>
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<tr>
<td>Overall efficiency targets with CCS, HHV basis</td>
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<tr>
<td>Oxy-fuel CCS penalty</td>
<td>8-11%</td>
<td>6-8%</td>
<td>&lt;6%</td>
<td></td>
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<td></td>
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<tr>
<td>Capital cost targets with CCS, US$/kW</td>
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<tr>
<td>CO2 capture targets (IEA total for all capture technologies, annual Gt sequestered)</td>
<td>2500-3100</td>
<td>2300-2600</td>
<td>0.6</td>
<td>2.6</td>
<td>3.8</td>
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**Regulations** (removing legal and regulatory barriers)

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<td>Capture ready specification</td>
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<tr>
<td>Gas quality defined for transport and storage</td>
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<tr>
<td>Financial incentives for early movers</td>
<td>Project financial support</td>
<td></td>
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**Notes:**

- **R & D Targets:** Requires immediate progression
- **Demonstration and Deployment Targets:** Demonstrations with CCS
- **IEA Oxy-fuel deployment targets:** Commercial Scale >250MWe
- **Oxy-fuel CCS penalty:** <6%
- **Capital cost targets with CCS, US$/kW:** 2500-3100
- **CO2 capture targets (IEA total for all capture technologies, annual Gt sequestered):** 0.6
- **Regulations:** Capture ready specification
- **Financial incentives for early movers:** Project financial support, Provision of CO2 credits, Initial operational incentives $/t sequestered
- **Storage site responsibility post sequestration:** Adjusted following demonstration experience, Commercially viable with carbon market

**Commercial Scale Targets:***

- 150-200 GW
- >40
- >45%
- >50
- >55%
- >60
- >65%
- >80
- >85%
- >90
- >95%
- >100

**Technology Types:**

- subcritical
- supercritical
- post demonstration

**Capacities:**

- <100MWe
- 250-500MW each
- 5 - 10 GW
- 50 - 100 GW
- 150 - 200 GW

**CO2 Capture Targets (IEA total for all capture technologies, annual Gt sequestered):**

- 0.6
- 2.6
- 3.8

**Subcritical Supercritical Post demonstration Commercially viable with carbon market Adjusted following demonstration experience Project financial support Provision of CO2 credits Initial operational incentives $/t sequestered Storage site responsibility post sequestration Capabilities at early movers**

**Commercially viable with carbon market Adjusted following demonstration experience Project financial support Provision of CO2 credits Initial operational incentives $/t sequestered Storage site responsibility post sequestration Capabilities at early movers**
Final comments

Oxyfuel is entering a process leading to commercial deployment

Deployment depends on

– Technology development through demonstrations, with cost and efficiency penalty reduction
– A future cost for carbon emissions
– Establishing regulatory framework
– Establishing CO2 storage sites