DOOSAN

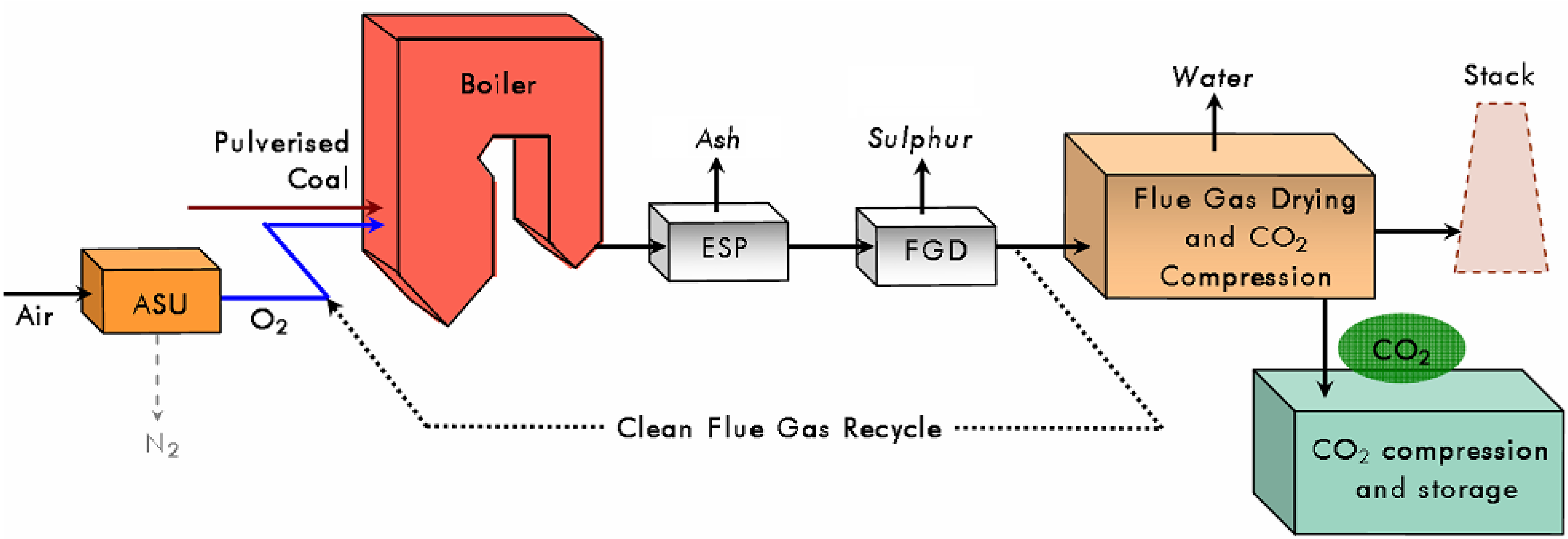
Doosan Babcock Energy

Oxyfuel Combustion

R&D Activities

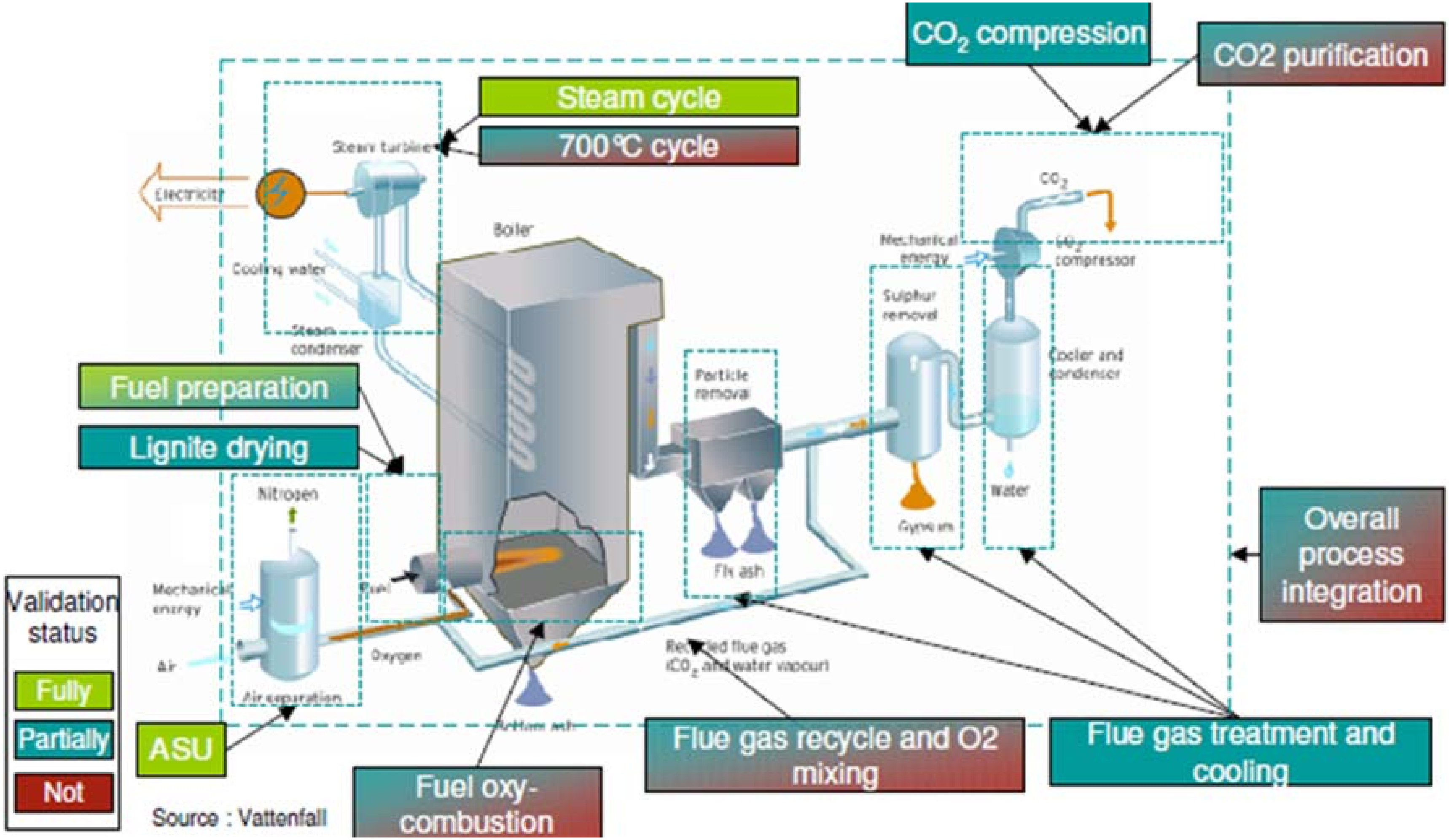
APGTF Workshop on Carbon Abatement Technologies - Development and Implementation of Future UK Strategy
London, 11-12 February 2009

Oxyfuel Technology - Introduction



- Air Separation Unit (ASU) to supply nearly pure O_2; N_2 is removed from the process prior to combustion to produce a flue gas that is mostly CO_2 and H_2O
- Fuel burned in O_2/CO_2 atmosphere
- Flue Gas Recycle (FGR) mitigates high temperatures from combustion in pure O_2 to maintain combustion and boiler thermal performance
- High CO_2 content allows simple compression cycle for CO_2 purification and capture

Oxyfuel Technology – Current Validation Status



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Source: ETP ZEP Technology Blocks Nov 2008, reproduced in APGTF draft strategy document, January 2009

Oxyfuel Technology – Current R&D Activities

Air Separation Unit (ASU)

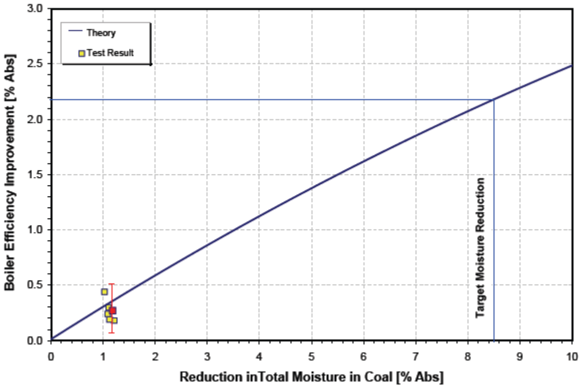
- Cryogenic air separation is a mature technology
  - Available now, but considerable power consumption
  - Drive to reduce specific power consumption from 200 kWh/tonne (current) to ~160 kWh/tonne (by 2012) – in-house R&D by suppliers
- New air separation technologies under development by suppliers – being evaluated in EPRI's "Coal Fleet for Tomorrow" programme
  - Ion Transport Membrane (Air Products)
  - Oxygen Transfer Membrane (Praxair)
  - Ceramic AutoThermal Reaction (Linde)

Fully Validated Improved processes being developed

Oxyfuel Technology – Current R&D Activities

Fuel Preparation

- Conventional coal handling / pulverising technology will be used for oxyfuel
  - Engineering issues associated with the use of hot flue gas in place of air
  - Addressed in FEED projects – not really R&D
- Lignite pre-drying
  - RWE's WTA process uses low grade heat to pre-dry lignite in a fluidised bed
  - Moisture content reduced to typically 12% before firing
  - Overall cycle efficiency significantly improved
  - Plant operating at
    - Frechen (WTA1) (53t/h)
    - Niederaussem (WTA1) (170t/h)
    - Frechen (WTA2) (27t/h)
    - Niederaussem (WTA2) (210t/h) – under construction
    - Hazelwood (WTA) (140t/h) – (planned)
  - Plant also operating in USA at Coal Creek (112t/h)
  - Technology is independent of oxyfuel, and will be adopted regardless
  - Technology is already in "large" demonstration stage



Fully Validated Improved processes being developed

Sources: RWE Brochure; EPRI Program 66 "Coal Fleet for Tomorrow"

Oxyfuel Technology – Current R&D Activities

Steam Cycle

- Oxyfuel can be applied to existing steam cycles, but improved cycles can mitigate the efficiency penalty associated with oxyfuel (and post-combustion) capture
  - Improvements to current steam cycle aim to improve cycle efficiency by increasing temperature and pressure
  - R&D activities are predominantly to develop the boiler and steam turbine materials to allow operation at elevated temperatures and pressures – e.g.
    - COST 536 Materials for Advanced Plant
    - COMTES 700 Demonstration of 700°C steam circuit at E.ON's Scholven PS, Germany
    - DTI Project 410 Materials and fabrication for 700°C power plant
    - TSB IMMP3 Improved modelling of materials properties for higher efficiency power plant
    - US DoE Com-Tes 1400 Materials for 1400°F (760°C) Ultra-supercritical boiler
  - The impact of oxyfuel on corrosion is also under investigation – e.g.
    - TSB OxyCoal-1 Fundamentals & underpinning studies
    - DTI Modelling of fireside corrosion of heat exchangers in advanced energy systems
- The continuing advances in steam cycles will happen, regardless of oxyfuel or post-combustion capture

Fully Validated Improved processes being developed

Oxyfuel Technology – Current R&D Activities

Fuel Oxy-Combustion

- Combustion is at the heart of the power plant
  - If it does not perform to expectation, the impact on the steam cycle can be considerable
- "Hey, we're mixing coal and oxygen. How difficult will it be to burn?"
  - Probably not too difficult, but what about….
    - Flame length
    - Flame luminosity
    - Radiant heat transfer in the furnace (combustion / heat transfer interaction)
    - NOx (does it matter anyway?)
    - SO_2 / SO_3
    - CO
    - Ash properties, slagging, fouling
  - Practical experience is required at a realistic scale

Oxyfuel Technology – Current R&D Activities

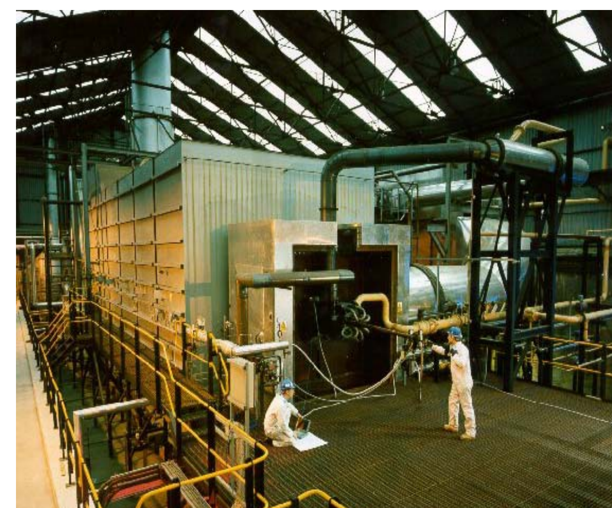
Fuel Oxy-Combustion

- Considerable laboratory scale experience
  - E.g. in the UK in OxyCoal 1
- Considerable pilot scale experience
  - In the UK at E.ON, RWE, Doosan Babcock (OxyCoal 1, JOULE, etc.)
  - In Europe at IVD, IFRF, Chalmers, etc. (ENCAP, JOULE, OxyMod, etc.)
  - In the rest of the world (e.g. US DoE)
- Large industrial scale experience is becoming available
  - Vattenfall's Schwarze Pumpe 30MWt test facility is operational (ENCAP LST)
  - Doosan Babcock's 40MWt burner test is planned for Q2/09 (OxyCoal 2)
  - B&W's 30MWt burner test facility is operational (US DoE)
- CFD and Engineering modelling capability is being developed
  - E.g. in Europe in RFCS OxyMod
- Advanced oxyfuel burner development (for utility application) is starting
  - TSB Q3092D "Optimised OxyCoal Combustion"

Partially / Not Validated

OxyCoal™ 2 Project

- £7.4M project
- Convert Doosan Babcock’s full-scale burner test facility to oxyfuel firing
  - Oxygen supply
  - Flue gas recycle system (fans, ducts, cooler, heater, etc.)
  - Instrumentation
- Design and build full-scale utility OxyCoal™ burner (40MW)
  - Derived from air-firing experience, CFD modelling and Oxyfuel R+D
- Demonstrate a full-scale utility OxyCoal™ burner
  - Flame stability, combustion efficiency, emissions, flame shape, and heat transfer characteristics as function of %CO_2 recycle and excess oxygen
  - Start-up, shut down, transition from air to oxyfuel, load change



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OxyCoal^{TM} 2 Project

The substantial contributions of: BERR | Department for Business Enterprise & Regulatory Reform

- the Prime Sponsor — Scottish and Southern Energy, energy made better
- Sponsors — Air Products, DONG energy, Drax Power Limited, EDF Energy, e.on UK, ScottishPower energy wholesale, Vattenfall
- University participants — Imperial College London, The University of Nottingham

are acknowledged by Doosan Babcock

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Oxyfuel Technology – Current R&D Activities

Flue Gas Recycle and O_2 Mixing

- Flue gas recycle is an established means of controlling reheat steam temperature, for gas tempering, and for gas/coal reburn systems in large coal-fired utility boilers
- Mixing of a gas into another (bulk) gas is a common process requirement

- While there is limited experience of flue gas recycle and O_2/flue gas mixing for oxyfuel, there is sufficient expertise to engineer the combustion system, as has been done for…..
  - Vattenfall's Schwarze Pumpe 30MWt test facility
  - Doosan Babcock's 40MWt burner test
  - B&W's 30MWt burner test facility
  - Numerous paper studies for full scale plant (e.g. DTI 407, ENCAP, IEA, etc.)

- However a full-scale oxyfuel plant has not been built

Partially / Not Validated

Oxyfuel Technology – Current R&D Activities

Flue Gas Treatment and Cooling

- Considerable air firing experience, but need to apply to oxyfuel
- ESP
  - Laboratory scale work at Korea Institute of Machinery & Materials (KIMM) indicates that dust collection efficiency will be lower in high CO_2 atmospheres
  - ESP performance will be investigated at Vattenfall's Schwarze Pumpe test facility (ENCAP LST)
- FGD
  - Suggestion that high CO_2 content will reduce SO_2 capture
  - Option to use lime (CaO) instead of limestone ($CaCO_3$)
  - Little ongoing R&D, most test facilities with SO_2 capture do not replicate large plant FGD
- SCR
  - Not thought to be necessary for oxyfuel (NOx captured in CO_2 compression plant)
- Flue Gas Cooler
  - Basic engineering capability exists
  - Little ongoing R&D, test facilities may not be replicating large plant (e.g. rigs tend to use direct spray cooling, whereas indirect cooling may be favoured in large plant for technical, economic, and environmental reasons)

Partially Validated

Sources: KEPRI International Workshop on Oxy-Fuel Combustion 2008
Power Plant Air Pollutant Control Mega-symposium 2008

Oxyfuel Technology – Current R&D Activities

CO_2 Compression

- CO_2 compression technology is required for oxyfuel, pre-combustion, and post-combustion capture technologies
- ASU equipment suppliers and operators already have considerable experience of large scale compression of gases
- There is already experience of CO_2 compression (and pipeline transportation & sequestration)
  - In the USA – CO_2 captured from the Beulah, Dakota gasification plant is compressed, transported 320km, and injected 1500m underground in the depleted Weyburn oil/gas fields
  - In Europe – the CO2SINK project is compressing and injecting CO_2 into the Ketzin, Germany saline aquifier
  - In Australia – CO_2 separated from natural gas is compressed and injected 2250m underground into the depleted Otway Basin gas field
- CO_2 compression of oxyfuel generated CO_2 is being undertaken at Vattenfall's Schwarze Pumpe test facility (ENCAP LST)
- However there is no demonstration of the compression of CO_2 arising from a full-scale oxyfuel plant

Partially Validated

Oxyfuel Technology – Current R&D Activities

CO_2 Purification

- CO_2 purification undertaken in conjunction with compression
  - Theoretical studies show effective NOx and SOx capture
  - A number of processes have been proposed by various parties
  - Process proven at laboratory and small scale, e.g.
    - Air Products (OxyCoal 1)
    - US DoE Albany Research Centre
  - Process being tested at larger scale
    - Vattenfall Schwarze Pumpe (Linde supply) (ENCAP LST)

- Capability to design the CO_2 purification process exists
  - Process will continue to be refined
    - FEED projects
    - Plant demonstrations
    - "n^{th} of kind"

Partially / Not Validated

Sources: GHGT-9 "Purification of Oxy-fuel Derived CO_2"

Oxyfuel Technology – Current R&D Activities

Overall Process Integration

- Vattenfall's Schwarze Pumpe test facility is the first large scale application of oxyfuel that combines the core elements of the ASU, the steam generator, and the CO_2 purification and compression plant (ENCAP LST project)
  - The plant is not highly integrated, and it is not optimised for efficiency

- There have been numerous paper studies investigating the options for process integration to maximise cycle efficiency (e.g. DTI 407, ENCAP, IEA, etc.)
  - Impact of integration on operability has not been considered to date (TSB Q3099G "Optimisation of Oxyfuel PF Power Plant for Transient Behaviour" starts to address this)
  - The optimisation of the overall process and the optimisation of the individual process operations should complement each other

- Process integration will continue to be refined
  - FEED projects
  - Plant demonstrations (next slide)
  - "n^{th} of kind"

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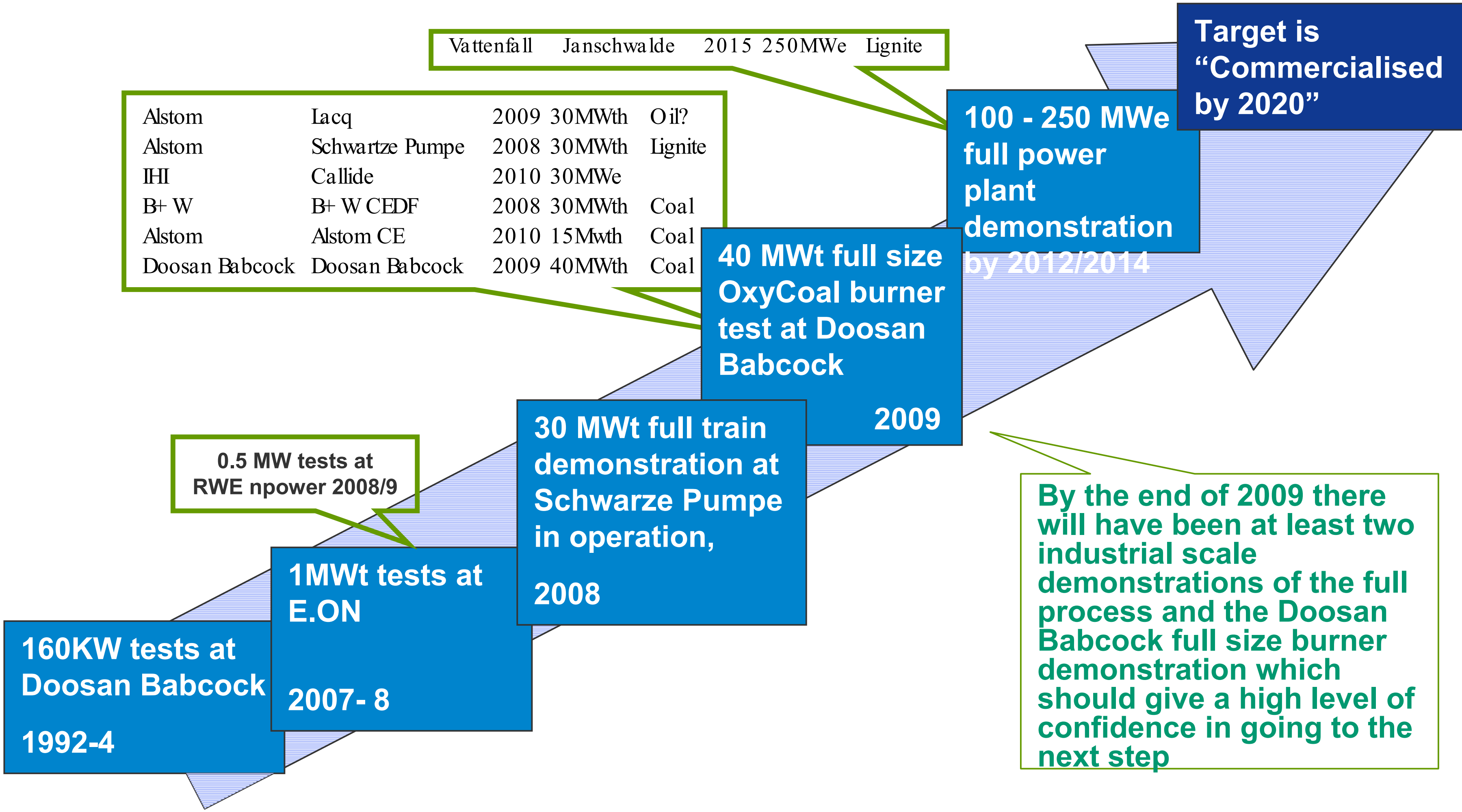
Oxyfuel Technology – Coal-Fired Demonstration Projects

Owner	Site	Size	Remarks
Doosan Babcock	Burner Test Facility Renfrew, Scotland	40MWt	Oxyfuel retrofit under construction, start operation Q2/09
Vattenfall	Schwarze Pumpe, Germany	30MWt	Operational
Vattenfall	Janschwalde Unit F, Germany	500MWe	Announced, start 2015
CS Energy	Callide, Australia	30MWe	Engineering, start late-2010
KOSEP/KEPRI	Youngdong, Korea	125MWe	Announced
Babcock & Wilcox	Burner Test Facility Alliance, Ohio, USA	30MWt	Operational
CUIDEN	Spain	20MWt	Engineering, start mid-2010
Orrville Utilities	Orrville, OH, USA	30MWe	Feasibility
Jamestown BPU	Jamestown, NY, USA	50MWe (CFB)	Feasibility, start 2013

Oxyfuel Technology – Scale-Up and Timescales



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Oxyfuel Technology – Coal-Fired Demonstration Projects

Real projects give us the essential experience to commercialise oxyfuel

- It is only by undertaking "real" projects that we learn to make the hard decisions
  - It is too easy to put off decisions in paper studies
  - From Doosan Babcock's perspective, we have gained valuable practical experience during the engineering of our test facility oxyfuel retrofit, and we haven't even finished construction
- It is only by undertaking "real" projects that we can gain confidence in a process
  - The prospect of massive quantities of nearly pure O_2 and CO_2 in a utility environment is a frightening one for the uninitiated
  - Experience of the process allows those fears to be rationalised and properly addressed
- It is only by undertaking "real" projects that we can commercialise the technology
  - No matter how much information and experience we gain from reduced scale facilities, there is always a degree of uncertainty in the performance of the "first-of-kind" full scale plant
  - Until we are fully confident in our design process it is impossible to deliver a plant under truly commercial conditions with performance guarantees

Oxyfuel Technology – R&D Needs

- First and foremost, we need a full-scale demonstration of the oxyfuel process (i.e. >100MWe) to…..

- Demonstrate
  - The operation of the process elements at full-scale
  - The integration of the process elements
  - The operation of the plant, and its ability to respond to grid requirements
  - The use of materials in an oxyfuel environment

- Validate
  - The engineering software / design methods, and refine them
  - The performance predictions

- Learn
  - The lessons of real experience, to make the next plant better

Oxyfuel Technology – R&D Needs

Equipment suppliers are capable of engineering a credible oxyfuel power plant today, but further R&D work is required to arrive at better designs and to have greater confidence in the performance

- From the APGTF Draft Strategy Document
  - Process optimisation, including start-up / shut-down / flexibility
  - Combustion chemistry and kinetics
  - Heat transfer prediction
  - Materials for the oxyfuel environment, corrosion
  - As properties – impact of oxyfuel on mineralogy, deposition, ash sales
  - Product gas clean-up
  - Safety
  - ASU's – selection, cycle optimisation
  - Novel processes such as gas separation membranes to reduce energy penalty

- From other sources
  - Process integration
  - Process optimisation, including load-following, turndown, excess O_2 reduction, etc.
  - Operating philosophies
  - Alternative hardware choices (e.g. tubular gas-gas heaters), flue gas cooling / heat recovery
  - Trace species – SO_3, Hg, etc.

Closing Remarks

- Considerable progress has been made in the development of oxyfuel CO_2 technology
  - The process is technically viable
  - The process is well understood
  - The process has been demonstrated at pilot scale
  - The process is being demonstrated at large scale (30MWt +)
  - Most of the individual components are in commercial operation at the required scale
- Oxyfuel combustion is economically competitive with alternative technologies
- Several utilities are making or planning significant investments in oxyfuel technology
  - Large-scale plant demonstration
- The time is right for the full scale demonstration of oxyfuel
  - Equipment manufacturers are ready to supply the technology