Scoping study on oxy-fuel combustion for the Australian National Low Emission Coal R&D (ANLECR&D) program

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Executive summary

A scoping study for oxy-fuel combustion technology for the Australian National Low Emission Coal R&D (ANLECR&D) program is presented.

As one of the three major carbon capture technologies associated with carbon capture and storage (CCS), oxy-fuel technology is currently undergoing rapid development with a number of international demonstration projects commencing in the progression towards commercialisation. The study details the current international status of the technology; Australian prospects, needs and capability for early demonstrations; and project options for ANLECR&D.

At its current state of maturity oxy-fuel technology may be considered pre-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. This is because guarantees could not at present be provided for operating characteristics associated with mature technologies such as reliability, emissions, ramp rate and spray control. This is due to the maturity of the technology associated with the capability of vendors and associated design and operational uncertainties, associated with a lack of plant experience at scale. Two categories of international vendors are associated with the development of oxy-fuel technology, those being traditional power station designers and manufacturers and others being suppliers of ASUs and also developers of CO2 compression technology. In addition, the power station vendors have either developed large pilot plants to test burners at full scale, and other oxy-fuel components, or are associated with pilot plants.

The projected development of oxy-fuel technology for first-generation plant is provided, this using an ASU for oxygen supply, standard furnace designs with externally recirculated flue gas, and limited thermal integration of the ASU and compression plant with the power plant. This includes the currently announced pilot-scale and industrial scale plant and demonstrations with and without CCS.

Australia made an early start on oxy-fuel R&D compared to many countries. There are a number of aspects which characterise the Australian situation, including the characteristics of power stations, coal property and regulatory aspects, local skills and links with international programs. Oxy-fuel research and technology development is coordinated and progressed through international organisations and events, with Australian researchers continuing to play leading roles in these activities. Australian researchers have recognised skills. But a reduction in research effort since 2007 has resulted in Australian research falling behind international efforts. For example, the author is not aware of specific Australian research or Australian involvement in international programs regarding compression of CO2 or full scale burner testing.

The Australian research skill base clearly needs to be re-established and expanded for the projected ANLECR&D program.

The Callide Oxy-fuel Project (COP) will be the worlds first to use oxy-fuel technology fired with coal, generating electricity with CCS. The COP is a strength of the potential Australian oxy-fuel R&D effort, in that it is a world first, provides local knowledge and experience, establishes Australian oxy-fuel R&D efforts internationally, and provides an opportunity for related research driven by issues established as the project is developed and operated. It has been suggested that any contribution the COP makes to ANLECR&D will be assessed in the context of the ANLECR&D contribution of cash and in-kind. Issues and options are provided.

Projects for the ANLECR&D program on oxy-fuel technology are presented in the *R&D recommendations table: Projects to address barriers* which address the barriers to technology deployment identified. Consideration has been given to extracting value from the COP demonstration, establishing an appreciation of the technology and vendor status amongst generators, a reduction of high impact cost and risk technical barriers, while addressing market, legal, regulatory and public acceptance issues. High priority projects requiring immediate development are listed.

A sequence to progress the projects requiring development is suggested as follows, in order of priority:

Projects requiring research in 2009/10 include:

- Furthering the development of the relationship of Callide Oxy-fuel Project with ANLECR&D at both management and technical levels.

- Establishing a capability on gas quality impacts from oxy-fuel minor gases (O2, N2, SOx, NOx, Hg) and other trace element during CO2 compression, and removal or impact control.

- Clarifying brown coal oxy-fuel research for the oxy-fuel node.

- Progressing issues due to the impact of regulatory and legal barriers

Projects are also identified requiring development in 2009/10 which must be assessed for relevance, priority and cost, these include those requiring visits and interaction with international activities in the first half of 2010.

In addition, as the ANLECR&D program is developed the reestablishment of Australian capability and staff in oxy-fuel technology should be a priority.

R&D recommendations table: Projects to address barriers

Including

- Suggested ANLECR&D node for work, 1-Economics, 2-Fundamentals, 3-Brown Coal, 5-Oxy-fuel, 6-IGCC/CCS; with
- priority High/Medium/Low and H* for projects requiring immediate progression and development
- X - research recommended in Callide feasibility study
- Status of project definition, with indicative budget need for 2009/10 and 2010/11 – for project **D**evelopment or active **R**esearch

Barrier to oxy-fuel deployment and project aims	**Project**		**Year initiated**	**ANLEC R&D node**	**Priority, H/M/L**	**Recomm Callide study**	**Budget year**	
							09/10	**10/11**
1. Removing technical and economic barriers								
1.1 Design and operation verification from the Callide Oxy-fuel Project	Resolving issues arising from Callide demonstration Design verification R&D – heat transfer, burner performance, gas quality Operation protocols and dynamics R&D – air and oxy operation switching, load change, partial capture operation		2009/10	5	H*	X	R	R
	Other projects potentially associated with the COP, but could be conducted separately:. • Operation of oxy-fuel plant in an electricity market • Water generation from oxy-fuel • Testing of current Australian boiler plant anf future high nickel steels in an oxy-fuel environment		2009/10	5	M		D	R
1.2 Appreciation of oxy-fuel status and Australian relevance	International oxy-fuel demonstrations, status and vendor capability		2009/10	5	H*		D	
	High level techno-economic assessment of oxy-fuel process options and second generation options		2009/10	1 with input from others	H*	X	D	
	Assessment of the Australian pf fleet for candidates for oxy-fuel retrofit		2010/11					D
	Standards – codes of practice – for Australian oxy-fuel plant		2010/11					D
1.3 Reduction of high impact cost and risk technical barriers	Gas quality from oxy-fuel, minor gases (O2,N2, SOx, NOx, Hg) and other trace element removal or impact control, in power station, CO2 compression, transport and storage	Fundamentals of oxy-fuel gas quality issues and control SOx and NOx removal or control through the capture plant Trace element behaviour removal or control CO2 compression, optimisation of pressure/temperature and impurity impact on recovery and energy penalty	2009/10	5	H*	X, project combines and extends three recommendations from feasibility study	R	R

	O2 supply for reduced cost and energy penalty		2011/12	2, with 5/6	H	X		
	Furnace heat transfer for large furnaces		2011/12	5 with 3	H			
	Burner operation for oxy-fuel		2010/11	5 with 3	H	X		D
	Process modelling for efficiency of oxy-fuel processes for efficiency improvement and process integration		2009/10	5 with 3	H		D	
	Fireside tube decay and corrosion			5, links to project 1.1	H		D	
	Second generation oxy-fuel options for reduced cost and new technology (eg, chemical looping, ITM)		2012/13	5	H			
	Brown coal oxy-fuel technology	Understanding brown coal specific oxy-fuel issues	2009/10	3 with 5	H*		R	R
		Combustion behaviour of brown coals – both as pf and CFB						
		Fly-ash chemistry under oxy-fuel conditions						
		Quality of condensed water and its utilisation						
1.4 Establishing oxy-fuel research capability	The Australian oxy-fuel test facility		2009/10 for decision on need	5	H*		D	
2. Removing market barriers	Plant operation in a competitive environment with CO2 cost, related to 1.1		2001/11, links to project 1.1	1 with 5	H*			D
3. Establishing public knowledge and acceptance	Technology information for public outreach		2009/10	5 with others	M		D	
4. Removing legal and regulatory barriers	CO2 regulations – gas emissions, gas quality for transport and storage		2009/10	5 with others	H*		R	R
	Financial incentives for early movers		2010/11	1 with others	H		D	
	Capture ready oxy-fuel technology		2009/10	5	H*		R	

1. Introduction

ANLECR&D is developing an Australian national program for collaborative low emission coal R&D, and will oversee its implementation and operation. The program, initially funded by $75M each from the Federal Government and the Australian Coal Association, is for a seven year period. This R&D will be undertaken in ANLECR&D research nodes, which will be based on existing research centres or, if necessary, developed for the purpose.

The focus will be on facilitating early demonstration projects in the 2015 to 2020 timeframe. These projects will be entering Front End Engineering Design (FEED) within the next 2 years, and the R&D program will necessarily focus on building capacity for commercial deployment and optimising and adapting commercial technologies to local conditions and circumstances. While ANLECR&D will be focused on near term commercial scale deployment, identifying productive areas for near term capacity building and constructive linkages to fundamental R&D would be very useful.

The ANLECR&D construct has seven research nodes- economic studies, fundamentals, brown coal, three capture technologies - oxy-combustion (commonly called oxy-fuel), post combustion capture, gasification - and carbon storage.

An earlier report (Simento and Lowe, 2009) outlines Current Australian R&D on low emission coal technology. This scoping study is for the area of oxy-fuel technology and covers three aspects: the international status of the technology; Australian prospects, needs and capability for early demonstrations; and a recommended R&D program for the ANLECR&D Oxy-fuel node.

2. Oxy-fuel technology

Reduction of greenhouse gas emission from coal-fired power generation can be achieved by efficiency improvement, switching to lower carbon fuels and CO_2 capture and storage (CCS) (Wall 2005; Wall 2007). A report released by MIT indicates CO_2 capture and storage is necessary for the future use of coal when carbon costs are established (Katzer 2007).

There are several options for capture and storage of CO_2 from coal combustion and gasification, including:

- Post-combustion capture: CO_2 capture from conventional pulverized coal-firing plant with scrubbing of the flue gas by chemical solvents, solid minerals etc,
- Pre-combustion capture: Integrated gasification combined cycle (IGCC) with a shift reactor to convert steam and CO to make H2 (a fuel) and CO_2 (that can be stored) ,
- Oxy-fuel combustion: combustion in oxygen rather than air, with recycled flue gas,
- Emerging options such as chemical looping combustion: oxygen carried by solid oxygen carriers reacts with fuel to produce a high concentration CO_2 stream in the flue gas, oxygen carriers are then regenerated to uptake oxygen from air in a second reactor. This technology is not as advanced in development or scale as the others.

Conventional pf coal-fired boilers, i.e., currently being used in power industry, use air for combustion in which the nitrogen from the air (approximately 79 % by volume) dilutes the CO_2 concentration in the flue gas. During oxy-fuel combustion, a combination of oxygen (typically of greater than 95% purity) and recycled flue gas is used for combustion of the fuel. A gas consisting mainly of CO_2 and water vapour is generated with a concentration of CO_2 that can be purified if required for sequestration. The recycled flue gas is used to control flame temperature and make up the volume of the missing N_2 to ensure there is enough gas to carry the heat through the boiler. Figure 1 details the unit operations associated with the technology.

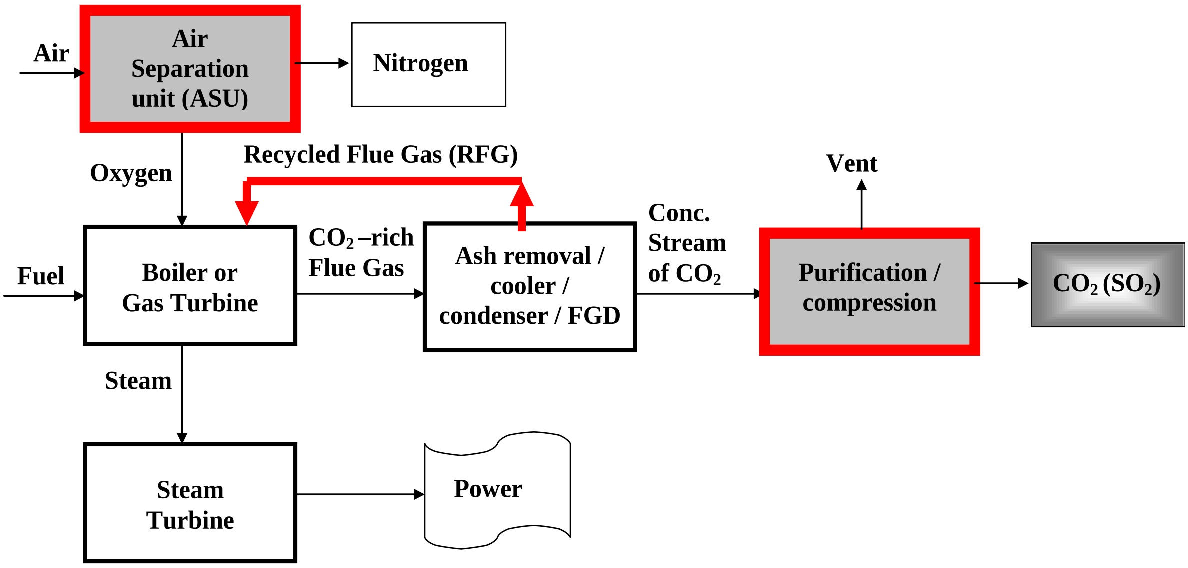

Figure 1: Simplified flowsheet for oxy-fuel technology, showing in bold the additional operations added to a standard pf plant

CO_2 capture and storage by the current technically viable options post-combustion capture, pre-combustion capture and oxy-fuel combustion will impose a 7%-10% efficiency penalty on the power generation process. The major contributors to this efficiency penalty are oxygen production and CO_2 compression, with regeneration of the solvent required for post combustion capture.

The literature contains many reviews of the development of the technology (Kiga 2001; Allam, White et al. 2005; Buhre, Elliott et al. 2005; Croiset, Douglas et al. 2005; Wall 2005; Santos, Haines et al. 2006). The state-of-the-art of oxy-fuel technology was reviewed in 2005 (Buhre, Elliott et al. 2005) and 2007(Wall 2007) respectively. Research has primarily been presented at international conferences and published as journal papers (Wall 2005; Gupta, Khare et al. 2006; Lundström, Eriksson et al. 2006; Rathnam, Elliott et al. 2006; Yamada, Tamura et al. 2006; Khare, Farida et al. 2007; Rathnam, Moghtaderi et al. 2007; Spero 2007; Wall 2007; Wall 2007; Wall et al 2009). A recent review (Wall et al 2009) made several contributions to knowledge, and identified critical issues including:

- New measurements in a pilot-scale oxyfuel furnace comparing temperatures, burnout, and gas compositions have been obtained simulating air firing retrofitted to oxyfuel, when furnace heat transfer is matched.
- The use of adiabatic flame temperature (AFT) commonly used as a design criterion for furnace design for an oxy retrofit was evaluated, and modified with a criterion of matching heat transfer being considered more appropriate.
- The emissivity of the gases in oxy-fired furnaces has been predicted by a new 4-grey gas model, which is required as a furnace model input for CFD predictions. However, the

model must be fitted to emissivity data, and this does not extend to the high multiple of partial pressure-beam length of oxy-fuel fired furnaces

- The first measurements of coal reactivity comparisons, including high-temperature volatile yields and coal burnout, at several O_2 levels in air and oxyfuel combustion conditions at pilot and laboratory-scale were given, showing a higher reactivity in oxyfuel at the same O_2 concentrations.
- Observed delays in flame ignition in oxy-firing were shown by mathematical modelling to be due to both gas property differences and aerodynamic effects, due to the differing momentum flux ratio of primary to momentum levels associated with a retrofit.

3. The status of oxy-fuel demonstrations and large pilot-plants

3.1 Oxy-fuel CCS technology development

Currently a number of oxy-fuel demonstrations are being progressed as the technology is developed from pilot scale (<5MWt), with the historical progression detailed on Figure 2. The oxy-fuel demonstrations and large pilot-plants of 5-250 MWe (~ 15-750 MWt) are listed in Table 1. The table gives the scale of plant as MWe, with MWt/3 for plants without electricity generation. The table includes projects which have commenced operation, through to projects which are at the feasibility study stage, and which await progression if the study is positive. Projects are classified and detailed in three categories:

1) Power plant with CCS, these being full demonstrations which are primarily coal fired, generate electricity, with associated carbon capture and storage;
2) Industrial scale demonstrations, without carbon storage;
3) Pilot-plant, with testing of combustion plant, possibly gas cleaning and carbon capture, but without electricity generation. Such plant may test full-scale burners, evaluate gas processing and carbon dioxide compression, and storage.

The projects listed in Table 1 are at different stages of development, with several being at pre-feasibility or feasibility stage. Six of the plants indicated have CCS. Not all are expected to proceed to financial close.

The projects are considered to contribute to particular aspects of oxy-fuel technology development, as follows;

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 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 oxy-fuel firing

The Callide 30 MWe oxy-fuel demonstration project – will be the first integrated plant, having power generation, carbon capture and CO_2 sequestration

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

New projects not indicated on Figure 1 which are in development have recently been announced, including:

B&W Black Hills Oxy-fuel project, Wyoming, USA. A project has now been submitted to DOE Restructured FutureGen to build a 100MWe oxy-fuel 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 Oxy-fuel 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 Oxy-fuel 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.

The Jamestown 50MWe project driven by Praxair is likely to be changed to a 78MWe project, again associated with a city generation plant in Holland in the USA, and again using CFB technology

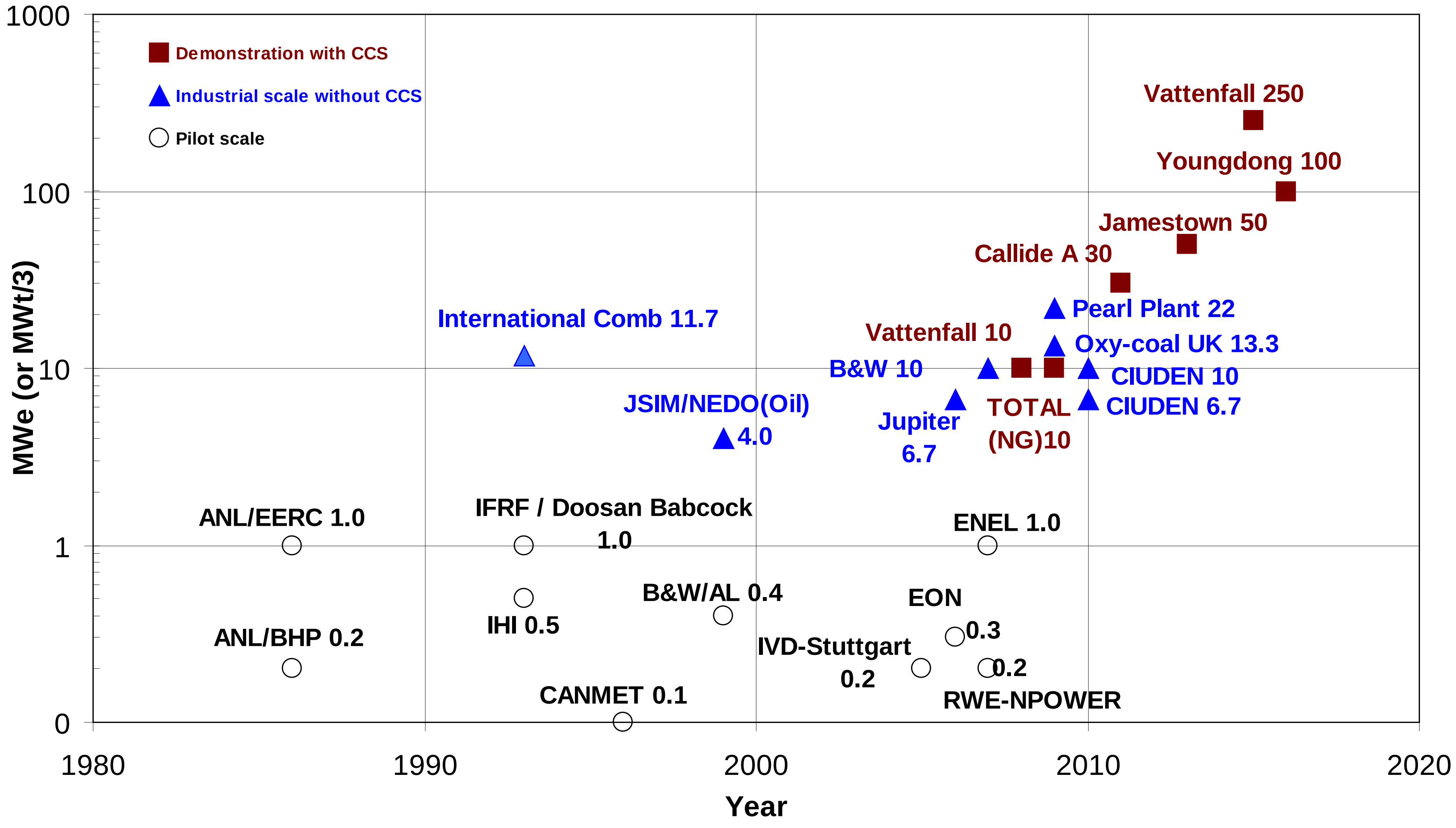

Figure 2. Historical progression of the scale of oxy-fuel pilot-plants and demonstrations

Table 1: List of large demonstration oxy-combustion plants, with some characteristics indicated

No	Demo/pilot-plant name	Scale (Demo/Pilot plant)	MW e	New Retrofit	Startup/ Duration	Main Fuel	Electricity generation Yes/No	CO2 Compression (Yes/No)	CO2 use/Seq	CO2 purity	Gas clean up
1	Vattenfall pilot plant, Germany	P	10	N	2008	Coal	N	Y	Y	99.90%	FGD ESP
2	Callide (CS Energy, Australia)	D	30	R	2011	Coal	Y	Y	Y		FF
3	TOTAL, Lecq, France	D	10	R	2009	NG	N	Y	Y	99.90%	
4	CIUDEN, Spain	P (PC/CFB)	17	N	2010	Coal	N	Y	Y		SCR FF FGD
5	Youngdong, South Korea	D	100	R	2016	Coal	Y		Y	98%	SNCR FF
6	Jamestown/Praxair Plant, USA	D(CFB)	50	N	2013	Coal	N	Y			
7	Jupiter Pearl plant, USA	D	22	R	2009	Coal	N	N			
8	Babcock&Wilcox pilot plant, B&W, USA	P	10	R	2008	Coal	N		N	70% dry	FGD ESP
9	Doosan Babcock, UK	P	30	N/A	2008	Coal	N		N		

2.1 Pilot plants

The Vattenfall 30 MWt plant (Anheden 2008). Vattenfall commenced a R&D project on oxy-fuel technology in 2001, leading to a commissioned 30 MWt Oxy-fuel pilot plant in August, 2008. The flow sheet diagram of the plant is shown in Figure 3 (Anheden 2008) indicating a focus towards combustion and assessing gas treatment options. These include options for the removal of NO_x, SO_x, H_2O and fly ash, with provision for direct limestone and ammonia addition. Objectives of the tests are to validate and tune commercially available technologies in oxy-fuel concepts to allow the launch of a demonstration project in commercial scale. A maximum of 240 t/day CO_2 is captured with a 90% capture proportion rate and the purified >99.7% CO_2 stream is expected transported by truck to the storage site.

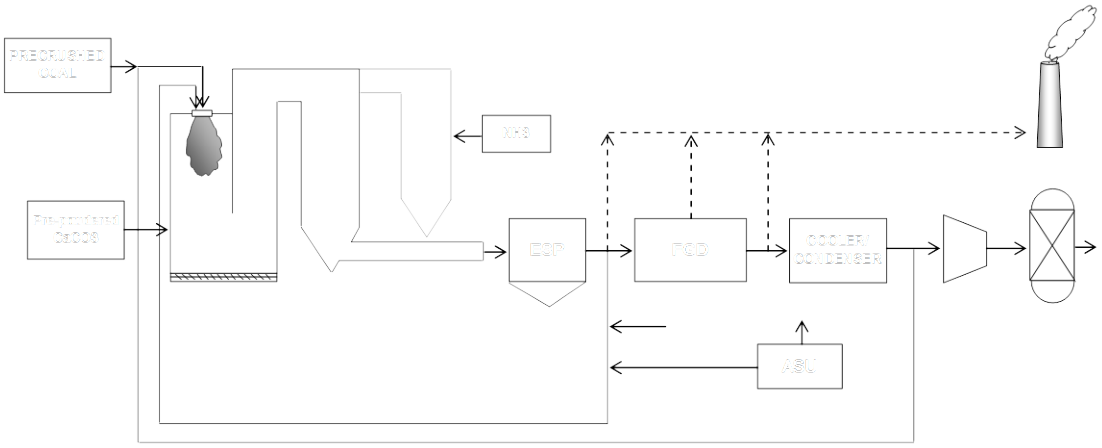

Figure 3: Flow sheet diagram of the Vattenfall's Oxy-fuel pilot plant, showing options for the removal of NO_x, SO_x, H_2O and fly ash, with provision for direct limestone and ammonia addition. (Anheden 2008)

CIUDEN test furnace (Cortes 2008). The CIUDEN test facility includes an oxy-fuel 20 MWt PC and 30 MWt CFB. Plans include provision for limestone preparation/feed system and optional SCR, FF and wet FGD. For air phase experiments, CO2 capture will occur through an absorption tower and be fed into a compression/cooling unit, which can be fed directly during oxy-fuel mode.

B*abcock and Wilcox USA project (McDonald, DeVault et al. 2007; McDonald, Flynn et al. 2008).* B&W's 30 MWt Test Facility is located in Alliance, Ohio (McDonald, DeVault et al. 2007; McDonald, Flynn et al. 2008). During 2007 and early 2008, B&W's existing 30 MWt Clean Environment Development Facility (CEDF) was modified to operate in the oxy-coal combustion mode. The flow diagram of the demonstration oxy-coal plant includes removal of fly ash, SO_x and water prior to CO2 cleaning and compression.

Oxy-coal UK project. Currently Doosan Babcock are retrofitting a 90MWt full-scale burner test facility with an oxy-fuel combustion firing system; operation with a 40MWt oxy-fuel burner commenced in mid-2009. The project, OxyCoal-UK 2, is sponsored by the UK Government The full-scale burner demonstration follows on from an earlier project which started in 2007 and involved ignition testing (in an ignition bomb apparatus), drop-tube furnace tests, CFD modelling, pilot-scale testing at 160kWt and 1MWt, corrosion tests, and engineering studies.

Testing of the 40MWt oxy-fuel burner, the largest burner planned to be tested to date, will be completed by the end of 2009.

Pearl Power Station (Jupiter Oxygen). A 22 MWe 4-burner oxy-fuel combustion system is proposed by Prairie Power Inc at Pearl Power Station in the USA and burner testing started in 2008. The flow diagram of the Jupiter Oxy-fuel combustion pilot plant includes power generation and a CO_2 compression train. Mercury is removed before CO_2 capture. In their proposal, the captured CO_2 will be transported by pipeline.

2.2 Demonstrations of power plants with CCS

The Callide oxy-fuel demonstration project (Spero 2005; Spero 2007). The Callide oxy-coal demonstration project was developed by a scoping study initiated in 2004 and is managed by CS Energy, an Australian utility.

Figure 4 gives the flowsheet. The focus is demonstrating a retrofit with electricity generation during oxy-fuel firing and storage of CO2. The plant design includes: 2×330 t/d ASU with 98% O2 purity, 4-year operation, 40% flue gas recirculation, slip stream compression – drying-CPU with two stage compression, Hg removal and ~99% CO_2 product quality. Stack emission modelling for lower stack velocities was also undertaken, giving ground level concentrations for SO_2. The design liquid CO_2 production rate is 75 tonnes/day with the target geosequestration rate being 60 tonnes CO2/day, over 3 years. Transport by truck to the storage site is expected. Start-up is expected in early 2011.

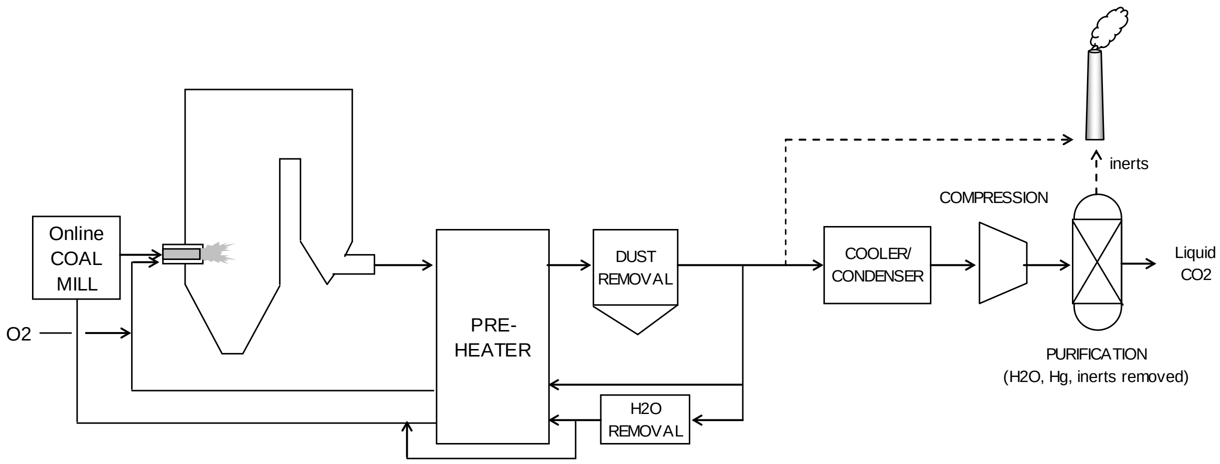

Figure 4 Flowsheet of the retrofitted oxy-coal firing power plant of the Callide A demonstration project (Spero 2005; Spero 2007)

TOTAL Lacq project. TOTAL Lacq CCS pilot-scale oxy-fuel project uses natural gas as fuel and aims to transport the CO2 via a 27km pipeline to the sequestration site. The unit has a capacity of 30MWt. The plant produces 92% purity CO_2 stream and the well reservoir to be monitored in the existing gas field has a 4500 m depth. This is a 2-year project with the start-up being scheduled in 2009.

Praxair Jamestown CFB oxy-coal project. Praxair has announced a near-zero emissions flue gas purification project for existing pulverized-coal power plants retrofitted with oxy-fuel combustion technology project in Jamestown, New York. Goals of this project are to cost-effectively capture more than 95% of CO_2 emissions from a CFB boiler. The plan is to capture up to 98% of the CO2, and transport by pipeline and injection into a local site.

Youngdong oxycoal demonstration project. A re-powered 100 MWe unit is planned replacing the Yongdong unit #1 boiler in Korea, which currently fires domestic anthracite. The oxy-coal plant will be designed by 2013 and to be constructed by 2015. High-volatile bituminous coal is the design coal, but sub-bituminous coal or lignite possibly imported from Indonesia may be used in the plant. The research phase led by the KEPRI group has been approved with the conceptual design over 3 years. The storage site of CO_2 produced from the demonstration plant is yet to be decided and has the greatest uncertainty.

Vattenfall 250 MWe oxy-fuel demonstration plant. In May 2008, Vattenfall announced its plans to build a demonstration plant for CCS technologies at one of the 500 MW blocks of the conventional lignite power plant in Jänschwalde in the State of Brandenburg, Germany. The investment for the demonstration is estimated to be € 1 billion. The Jänschwalde lignite power plant consists of six 500 MW blocks. For the demonstration plant, one of the blocks consisting of two boilers will be equipped with CCS facility. One boiler will be a new plant with oxy-fuel technology and the other will be retrofitted with a post-combustion technology.

4 International vendors and demonstrations

Two categories of international vendors are associated with the development of oxy-fuel technology, those being traditional power station designers and manufacturers and others being suppliers of ASUs and also developers of CO2 compression technology. Table 2 indicates the associations for the demonstrations.

Table 2 : Association of commercial technology vendors with CCS demonstrations of Table 1

No	Demonstration	Power station vendor	O2 supply/ CO2 compression vendor	CO2 storage expertise
1	Vattenfall	ALSTOM for design and initial burner, Doosan Babcock and Babcock Hitachi also to test burners in rig following ALSTOMS tests	LINDE	Schlumberger
2	Callide	IHI	Air Liquide	Schlumberger
3	TOTAL	ALSTOM	Air Liquide	
5	Youngdong	Doosan Babcock		
6	Jamestown	Foster Wheeler	Praxair	
7	Pearl Plant	Jupiter Oxygen aim to establish an association with a vendor based on their patents	The patented NTEL compression process is being tested under a DOE project by Jupiter Oxygen	

In addition, the power station vendors have either developed large pilot plants to test burners at full scale, and other oxy-fuel components, or are associated with pilot plants. Table 3 lists these associations.

Table 3 : Association of power station vendors with large combustion pilot plants

No	Large pilot-plant	Other associated vendors
4	CUIDEN	CBS (PC combustor), Foster Wheeler (CFB combustor)
8	B&W, USA	Air Liquide
9	Doosan Babcock, UK	Air Products

The B&W and Doosan Babcock pilot plants are funded by the vendors, based on their perceived need to test their oxy-fuel burner designs at full scale, and to develop their expertise in oxy-fuel technology driven by the business prospects as the technology is commercialised.

There are particular alliances formed between vendors as follows

- On PC technology: Doosan Babcock – Air Products
- On FBC technology: Foster Wheeler – Praxair

Air Liquide is associated with several power station vendors and demonstrations, including the Callide Oxy-fuel Project, B&W, and TOTAL projects.

A number of the demonstrations also have associations with research organisations, as follows:

- The Vattenfall Demonstration has involved many research organisations, with Chalmers University (Sweden) and The University of Newcastle in particular, and is leading funded projects involving many others.
- The Doosan Babcock, UK, pilot plant involves experimental research at Imperial College in the evaluation of the Air Products compression process and the impact of impurities in the CO2 compressed, and the University of Nottingham on coal and combustion issues.

The two most advanced demonstrations are led by generators, Vattenfall and CS Energy, as are other projects such as Jamestown, Youngdong and Pearl Plant.

Vattenfall’s aim is to drive technology development and the scientific understanding of oxy-fuel processes, so that a number of vendors can tender for commercial projects in the future - hence their support of R&D involving many vendors and research providers. CS Energy has the same aim, but their recent involvement in R&D, and in international oxy-fuel activities has been limited by resources, funding and the effort in establishing the Callide Oxy-fuel Project since mid 2007.

5 Progress towards commercial deployment

For oxy-fuel combustion, developments progress through the laboratory scale, pilot scale, demonstrations, pre-commercial demonstration (or industrial scale) and commercial scale. Most of the pilot-scale facilities detailed here do not include CCS while commercial scale plants and some pre-commercial demonstration plants have CCS integrated.

The anticipated cost of CCS technologies as they are researched, demonstrated and deployed is given on Figure 5 (Stu Dalton, EPRI, personal communication). Prior to demonstration, costs are underestimated. The first-of-a-kind demonstration plant may have a lower expected cost than those following, as some design and operational issues are not foreseen. After a small number of plants are operating, the experience gained reduces the cost, i.e., costs reduce as the technology is deployed and matures. The cost reduction will be associated with a lower capital cost of plant as well as competition due to the availability of technology suppliers.

On Figure 5 Oxy-fuel technology is seen to be in development, and entering the demonstration phase, whereas other CO2 capture technologies (PCC and IGCC-CCS) are being demonstrated. CO2 storage of the scale required for CCS is also under development. Advanced ultra supercritical PC plant is straddles several phases depending on the steam conditions. This is relevant to oxy-fuel technology as the higher efficiency of higher steam temperature plant will reduce the impact of efficiency reduction associated with oxygen supply and compression.

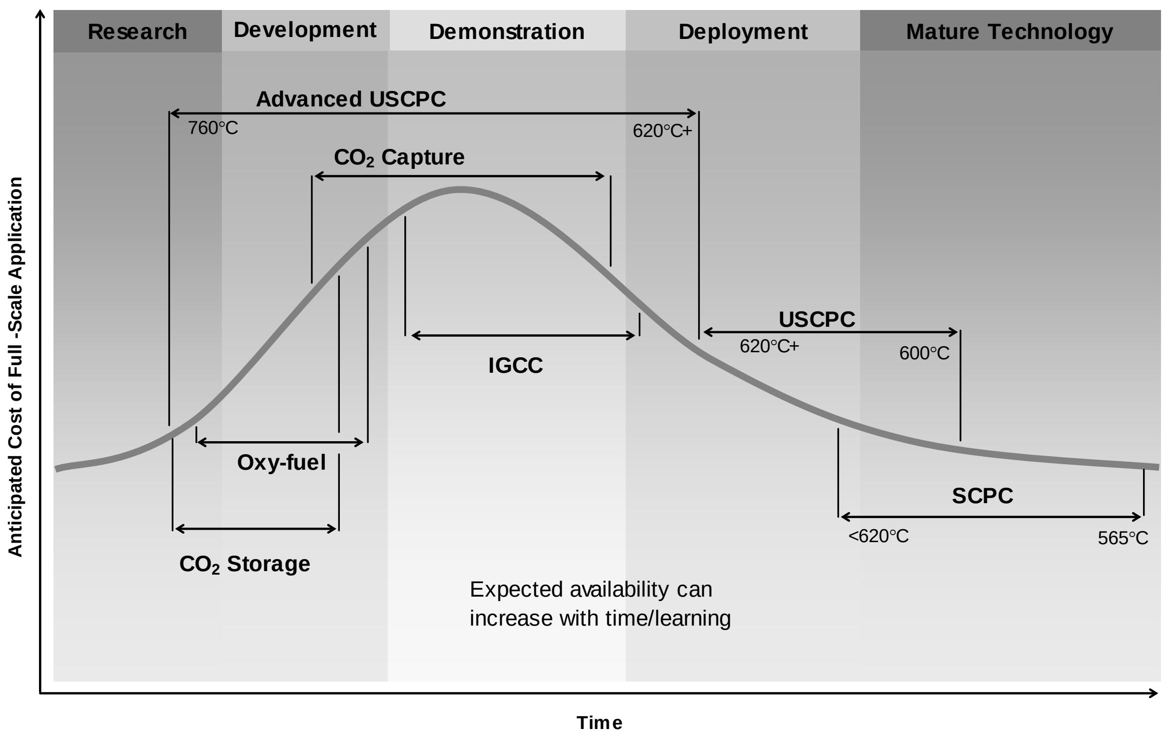

Figure 5: Anticipated cost of technologies as they are developed and applied, with current status of technologies indicated (Stu Dalton, EPRI, personal communication)

Operating experience and optimization of the demonstration plants are crucial for commercial oxy-coal combustion technology. Inputs of the demonstration plants through to the commercial plants provide guidelines not only to the operation of full-scale power plants, but also to the CO_2 handling (such as compressing and transportation) and storage (such as monitoring).

Table 4 presents illustrative times for the three phases of development of a 500 MW low emission coal power plant with geosequestration, in parallel to the development of such power plants, CO_2 disposal and permitting. A typical time from concept development through construction to handing over the plant by the contractor is 6-9 years. After each phase the project might not proceed, but one critical requirement is that a feasible CO_2 storage site must be validated at the end of phase 2, typically after 3-5 years. The illustrative costs of the phases are reasonable for the power plant, but highly variable for the CO_2 disposal geology, as this will be determined by the number of exploration holes required. For projects requiring exploration of a number of uncertain storage sites, the cost of establishing a suitable storage site can exceed the FEED cost. The times for project completion given in Table 2 and for storage site validation are used in establishing the roadmap for future oxy-fuel combustion technology deployment. Time may be reduced for 50 MW demonstration plant.

Table 4: Project components and sequence: Low emission coal power plant with geosequestration, based on a 500MW plant.

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

On the basis of the above overview, a sequence of the development of oxy-fuel technology for first-generation plant can be proposed, which is expected to use an ASU for oxygen supply, standard furnace designs with externally recirculated flue gas, and limited thermal integration of the ASU and compression plant with the power plant. This includes the currently announced pilot-scale and industrial scale plant and demonstrations with and without CCS. The suggested deployment of commercial plant is expected to overlap the pre-commercial plant.

The project development sequence for the commercial scale CCS plants suggested by the IEA and G8 Workshop states “The G8 must act now to commit by 2010, to a diverse portfolio of at least 20 fully integrated industrial-scale demonstration projects (>1 Mtpa), with the expectation of supporting technology learning and cost reduction, for the broad deployment of CCS by 2020”. For the IEA plants, the project development should commence prior to 2012, requiring that storage sites be proven prior to 2016. The EPRI roadmap of Wheeldon and Dillon (Novak 2007) (Dillon, Panesar et al. 2005) prepared in 2007 has the pre-commercial demonstrations running from 2012 to 2022.

Milestones and targets towards commercial deployment are therefore suggested as follows:

Research milestones:
By 2014 – Gas cleaning technology proven to meet regulatory requirements for CO_2 transport and storage.
After 2016 – Alternative oxygen supply technology to ASU such as membranes and chemical looping demonstrated at scale.
After 2020 – Second generation oxy-fuel plant applied using learnings from first generation demonstrations.

Regulatory milestones:
By 2014 – Regulatory framework established to allow permitting process to proceed for demonstrations to be operating by 2020.

Technology development
To 2014 – Further pilot-scale testing.
To 2016 – Testing of currently announced industry scale demonstrations without CCS.
To 2018 – Testing of currently announced industry scale pre-commercial demonstrations with CCS, with EPRI nominated period extending to 2022.
2020 – Yet to be announced integrated oxy-fuel industrial-scale demonstration plants (with CCS >1Mtpa) operating within the portfolio of 20 CCS plants set the IEA/G8 target.

Related deployment targets:
By 2020 - Improved efficiency of PF plants by more severe steam conditions, such that efficiencies for oxy-fuel with capture reaches 40-42% HHV, similar to PCC and IGCC.
By 2022 – Commercial availability of CO_2 storage, with new coal plants capturing and storing 90% of CO_2.
By 2030 – Further improvement in efficiencies with CCS, to above 45% HHV.

Based on the above targets a schematic representation of the development of oxy-fuel technology is given on Figure 9. The objective of 20 commercial scale CCS plants of scale >1Mtpa operating by 2020, requires several oxy-fuel plants. Currently, given the expected technology development, carbon costs justifying CCS, and appropriate regulations a number of oxy-fuel plants may be operating by this time, but the number is uncertain.

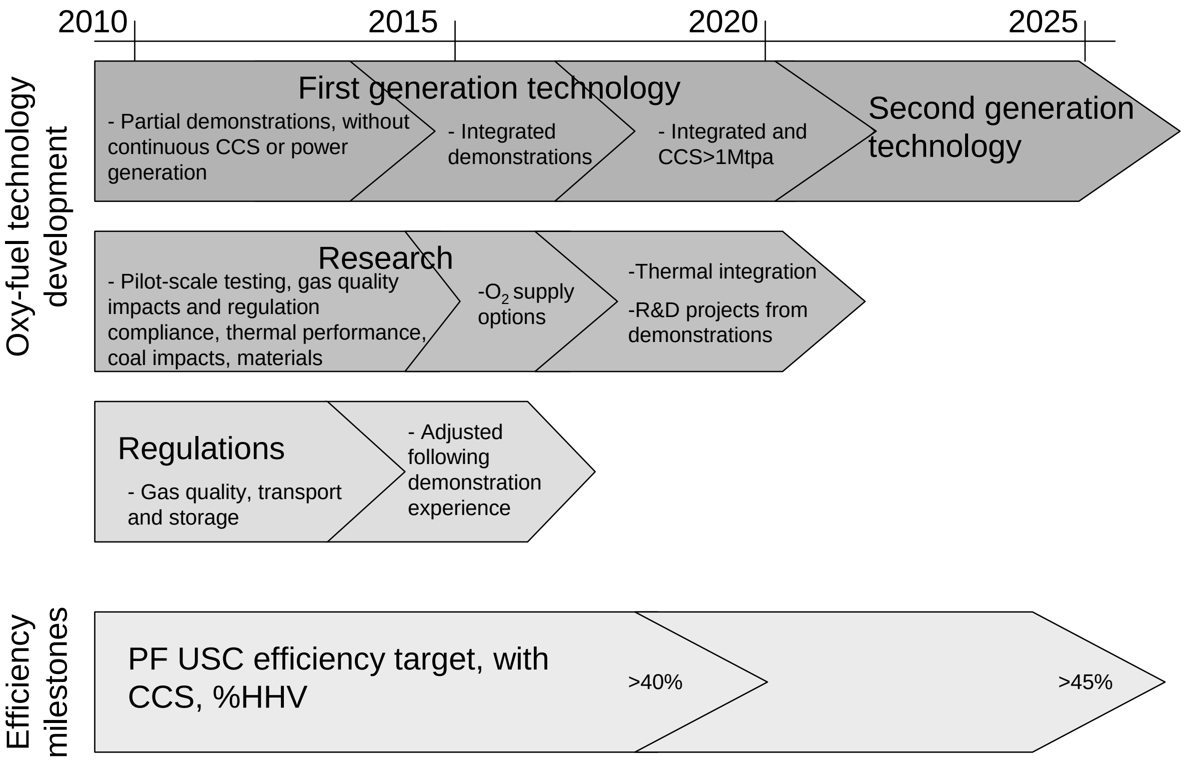

Figure 6: Phases and sequences of the projected development of oxy-fuel technology.

5 Issues preventing immediate commercial deployment

CCS technologies will be applied commercially for electricity generation once a future cost of CO2 emissions is established with certainty, and the cost of CCS is competitive with other generation options. Apart from cost, a regulated limit of CO2 emissions applied to generators would also drive application. In a carbon constrained future, CCS technologies will compete with other low carbon emission options, and oxy-fuel technology also with other CCS options.

At its current state of maturity oxy-fuel technology may be considered pre-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. This is because guarantees could not at present be provided for operating characteristics associated with mature technologies such as reliability, emissions, ramp rate and spray control. This is due to the maturity of the technology associated with the capability of vendors and associated design and operational uncertainties, associated with a lack of plant experience at semi-commercial and commercial scale.

The experience required for a mature technology is for units of a scale justifying high efficiency using high temperature steam conditions, typically >250MWe, rather than a number of demonstration units currently proposed of a scale of 100MWe. This is because the efficiency penalty has a greater impact on low efficiency units. In the recent past a 300MWe unit was being progressed by SaxPower, and a 100MWe unit is being progressed, both supplied by B&W. The first did not proceed on economic reasons based on the CO2 value for EOR, the second is a demonstration and requires government funding in a current proposal.

The cost of the mature technology will determine its future commercialization and will only be realized once it is demonstrated and deployed, as its cost establishes relative to the price of CO2 as shown on Figure 7. On the figure the economic gap separating CCS cost and CO2 price in the demonstration phase prior to early commercial deployment must be met by funds from government and industry.

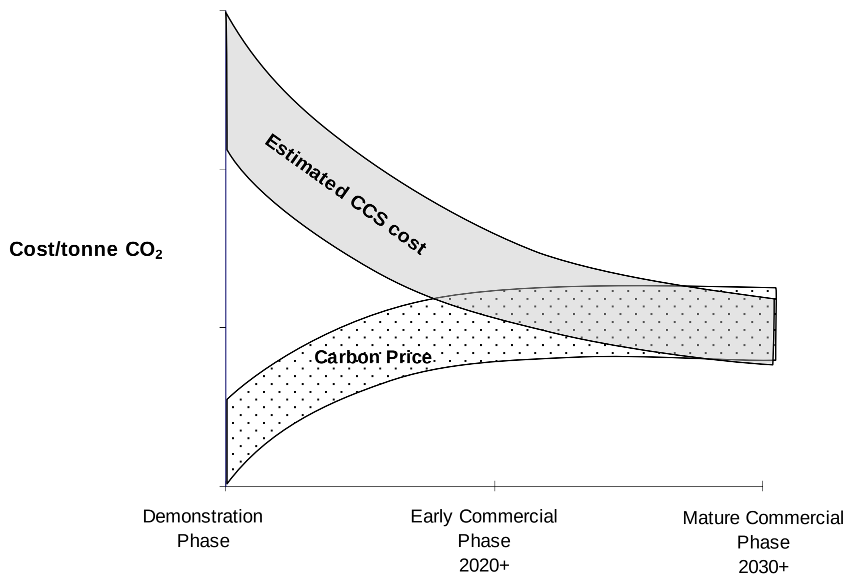

Figure 7: Development of CCS cost relative to CO2 price

In addition to cost and technology maturity, uncertainty regarding regulations on CO2 quality and storage site access and responsibility will delay deployment, as will public acceptance of CCS.

6 The potential technical, market, economic, public acceptability and legal barriers that need to be addressed

The current barriers to oxy-fuel technology deployment include:

a. Technical and economic barriers for capture plant. For CCS generally, the large capital and operating costs of CCS plant as the technologies progress through demonstration, increasing scale and technical development to commercialisation;

b. Market, economic and legal barriers. Uncertainty over costs determined by legal and regulatory frameworks, including future carbon emission costs, with plant operation impacts;

c. Public acceptability. Public knowledge and acceptance of CCS

d. Barriers specific to storage. Uncertainty over the availability and of long-term storage sites and the expense of establishing infrastructure to their access;

Market forces will not deliver the technology in the demonstration phase of Figure 7, and government, generator, coal industry and vendor support of R&D and demonstrations are necessary in this phase.

Commercial deployment of oxy-fuel technology requires cost and risk reduction. Compared to the other two CC technologies – PCC and IGCC-CCS, the economics of oxy-fuel is particularly affected by oxygen supply and the impacts of the CO2 gas quality required. This is because

- The O2 supply for oxyfuel is greater than that for IGCC technology

- The quality of CO2 passed from the power station to gas compression, and then to a transport by pipeline remains uncertain, and covers a greater range of impurities such as SOx, NOx, Ar, N2 and Hg than other CC options. . This quality determines the need for costly operations for SOx and NOx removal in the power station, the impact of air leakage in the power station, the design of the compression operation to remove these and other impurities, and the ability to comply with gas quality .regulations for pipeline transport and storage.

These issues provide a focus for part of the R&D program leading to future technical developments.

In summary, barriers are both specific to oxy-fuel technology and general to CCS, with a summary given on Table 5.

Table 5: Barrier categories and examples

Barrier	Specific to oxy-fuel technology	General to CCS technologies	Comments
Technical	High impact cost and risk technical barriers detailed in Section 8	Commercial vendors required able to offer performance guarantees	Requires engagement with demonstrations and vendors
Market	Plant operation to follow demand (load following)	Certainty in future carbon cost	Carbon tax or cap-and-trade scheme influences certainty
Economic	High cost operations, eg cost of oxygen supply Demonstrations to drive cost down	Economic incentives for early movers (demonstrations) Carbon emission credits for demonstrations	EU and USA currently developing incentives for early movers
Public acceptability		Public scepticism and knowledge of CCS technologies	
Legal	Regulation for gas quality as "overwhelmingly CO2" will have greater impact on oxy-fuel compared to other CCS options	State (onshore) and federal (offshore) regulations for storage site access, land for pipeline , liability following site use	Australian Federal legislation and some State legislation emerging, States not accepting liability. Session at September 2009 IEA Oxy-fuel Conference to address regulations.

7 Australian issues that need to be addressed for a successful demonstration program in the 2015 – 2020 timeframe

Australia made an early start on oxy-fuel R&D compared to many countries, has a demonstration starting in 2011 which will be a worlds first. There are a number of aspects which characterise the Australian situation, including coal property and regulatory aspects, local skills and links with international programs that are detailed here.

7.1 Australian advantages for deployment of oxy-fuel technology

Australia has a number of advantages relating to the future deployment of oxy-fuel technology, relating to coal properties, regulations and the current involvement in a first-of-a-kind demonstration. The advantages include:

- Suitability of oxfuel technology for low sulphur Australian coals. The partial pressure of SO_2 and SO_3 in the furnace gases is higher in oxy-fuel than in airfiring, by a factor of three or greater, to the extent that either low sulphur coals may be required to avoid impacts or sulphur gases removed in the recycle stream to avoid tube corrosion.
- Australian environmental regulations for gas emissions. The flowsheet for oxy-fuel is simplified if gas emissions for the expected operation on air during during start up and shut down, or during oxy-fuel operation without CCS, will not require gas cleaning for sulphur and nitrogen gases.
- Maturity of Australian legislation for CO_2 transport and storage. The relative maturity compared to several other countries for regulations relating to pipeline route development, storage site assessment and site liability after storage has ceased is an Australian advantage.

- A world's first-of-a-kind oxy-fuel demonstration. The Callide demonstration will be the first oxy-fuel CCS project combining coal firing and electricity generation, thus providing a basis for establishing Australian experience and interaction with international developments.

Australia has an involvement in the phases of the projected development of oxy-fuel technology of Figure 6.

If SO2 must be removed, either because of downstream corrosion issues or for regulation, there are several options available. An FGD unit may be installed after particulate removal, which will also co-capture Hg; a secondary separation of CO2 from SO2 and NO2 may be installed after the removal of non-condensable gases. Alternatively, Air Products are in the process of designing a recirculation system to strip both NOx and SOx out of the flue gas after compression. The system is novel and yet to be tested at full scale. Currently, the impacts of coal sulfur on plant and its control remain an area for future research.

Plant is likely to partially operate in the air fired mode. The overall goal is for oxy-fuel retrofitted utilities to fully operate in oxy-fuel mode. However, the practicalities of this may be determined by the cost of CO2 emission, with operation partially air fired and oxy-fired. The balance between air fired and oxy-fuel operation will be economically determined, but start-up and switching will also require air firing.

Regulations on transport and storing CO2 in geologic formations are emerging – both proposed and enacted at the national and regional level in the European Union, the United States, and Australia in late 2008 and 2009. This is a critical next step to CCS technology development. The development of Australian Federal (offshore) and State (onshore) regulations are currently further advanced than in many countries, although States have not assumed responsibility for storage sites after storage has ceased.

7.2 Unique or world class Australian skill sets

Australian oxyfuel researchers are internationally recognised :

- Australian oxy-fuel researchers have been involved in international developments for several years, primarily due to the Callide feasibility study and demonstration development.
- The research skills have been recognised in furnace heat transfer and coal reactivity for oxy-fuel technology by funded research contracts for Vattenfall.
- Researchers are continuing to be invited to give plenary talks in the most significant international oxy-fuel conferences and contribute to conference organising committees.
- The capacity of Australian storage research is internationally recognised, and of benefit to all CC technologies.
- At the first IEA Oxyfuel Conference in Cottbus, Germany in September 2009, two of the six panellists selected to summarisise the conference in the closing session were Australian, being Dr Spero and the author

Issues that currently need to be addressed include;

- A reduction in research effort since 2007 has resulted in Australian research falling behind international efforts. There is no research or involvement in international programs in some critical technology areas, such as CO2 compression or full scale burner testing

- The Australian research skill base needs to be re-established and expanded for the projected ANLECR&D program.
- With no local coal technology industry, engagement with international vendors is critical for Australian generators to be informed purchasers. This engagement needs to be expanded, potentially through involvement in collaborative projects.

7.3 Interfaces and linkages with international programs

Oxy-fuel research and technology development is coordinated and progressed through international organisations and events. Australian researchers are continuing to play leading roles in these activities.

The International Energy Agency (IEA) Greenhouse Gas R&D Programme has arranged three meetings through the Oxy-fuel Combustion Network, the first in Cottbus, Germany, on the site of the Vattenfall 30 MWt pilot-plant in 2005, the second in Windsor, Connecticut at the ALSTOM laboratories in 2007, and the third in Yokohama in 2008. The First Oxy-fuel Conference was held in Cottbus in September 2009. These meetings include the significant international players in oxy-fuel – demonstration leaders, technology providers and researchers, with the author involved in the Organising Committees of all events.

Some coal technology conferences have a major oxy-fuel focus, with the annual Clearwater Coal Conference in Florida, USA, having some 30 papers on oxy-fuel – the most on any CCS technology. This conference is the major international coal technology conference. Panels on the topic were included in 2006, 2007 and 2009, with the author invited as a panellist for all.

From 2008-2011, the Asia-Pacific Partnership has supported an Oxy-fuel Working Group (OFWG), led by the author to coordinate collaboration through information sharing, and joint projects, between international oxy-fuel demonstrations and support development of the technology towards commercialisation (OFWG, 2009). All organisations involved in the demonstrations listed on Table 1 participate. In 2009, work has developed collaboration, is preparing a technology status report, a roadmap towards commercialisation with IEA, addressing regulations faced by demonstrations, and has run an oxy-fuel course in Korea for Korean, Chinese and Indian delegates.

At a high level the linkages are considered satisfactory. Certainly the linkages have allowed an appreciation of the current status of the technology and international RD&D to be established. What is needed is involvement in international research projects at a working level.

8 ANLECR&D focus areas and priorities

8.1 Australian oxy-fuel R&D

Australian oxy-fuel research commenced in 2003, through CCSD. The research effort addressed issues of furnace and coal combustion performance, burner and furnace modelling.

The research led to the Australia-Japan Oxy-fuel feasibility study of 2004-2007, and then to the development of the Callide Oxy-fuel Project, which reached financial close in July 2008. The feasibility study included tests of three Australian coals in the IHI Aioi test furnace to compare air and oxy-fuel firing, and included emission measurement, start-up/shut-down, and burner operation.

The feasibility study, its related research and announced demonstration resulted in Australia's involvement in collaborative projects with Vattenfall – which is driving oxy-fuel R&D in Europe – and invitations to international coordinating events such as the IEA Oxy-fuel Network and panels of the Clearwater Coal Conference.

The Callide Oxy-fuel Project is the strength of the Australian oxy-fuel R&D effort, and provides an opportunity for related research driven by issues established as the project is developed and operated. A number of issues have emerged as the project has developed:

- A preoccupation due to the effort in establishing the project has resulted in limited interaction with other oxy-fuel demonstrations to date

- IP issues have restricted researchers interacting with the project proponents

- The CO2 product is taken to partial completion, to liquid CO2 rather than supercritical CO2 – the practical product – limiting the experience of the complete process

- The association with a single technology vendor for the power station and also for CO2 processing has limited the interaction with developments which have emerged in large oxy-fuel burner pilot testing and CO2 compression with gas cleaning undertaken by other vendors

Since the closing of CCSD in mid-2008, ACARP has supported oxy-fuel research in order to maintain research capability and to address a specific issue, that of sulphur impacts. The ACARP project objective is to maintain an Australian research capability in oxy-fuel technology in the transition period between the end of CCSD in June 2008 and the development of ANLECR&D. The project includes research on heat transfer, coal reactivity and flame ignition in air and oxy-fuel environments, and initiates Australian research on sulphur impacts in oxy-fuel.

A project funded by the Victorian Energy Technology Innovation Strategy from 2008 to 2010 Involving Monash University, HRL, and Victorian Power Generators aims to investigate the combustion behaviour of Victorian brown coal under the oxy-fuel combustion conditions. This will confirm the applicability, costs and risks of oxy-fuel combustion as a technology option to achieve drastic reduction of CO_2 emissions from power plants burning Victorian brown coal. Project activities include process integration and economic evaluation with experimental investigations of the oxy-fuel combustion behaviour of Victorian brown coal, fly-ash chemistry under oxy-fuel combustion conditions and utilisation options of condensed water from oxy-fuel operation.

APP funding from 2008-11 has established an oxy-fuel working group (OFWG) to coordinate collaboration of all international demonstrations through information sharing and joint projects, and support development of technology towards commercialisation (OFWG, 2009). The OFWG activities are based on the construct given on Figure 7 and includes the Annual OFWG Working Meeting involving organisations active in demonstrations, an educational program with an annual course for countries and organisations somewhat new to oxy-fuel. Discussions are commencing to ensure the OFWG continues beyond 2011.

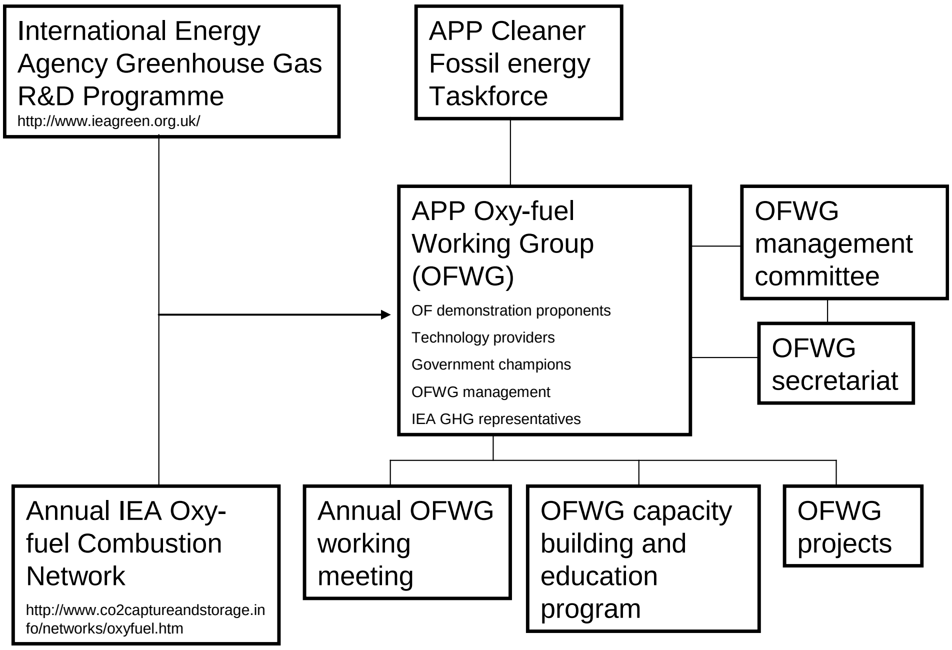

Figure 7: Structure of the APP OFWG project

Currently Australian oxy-fuel R&D is continuing, but at a reduced level and the effort will need to be expanded for the ANLECR&D program. The skill base has contracted, and building the research team is an immediate need.

8.2 The ANLECR&D Node / Callide Oxy-fuel Project interface

The Callide Oxy-fuel Project (COP) is structured as a Joint Venture involving:

- Australian members: CS Energy, Xstrata Coal, Carbon Storage Services (Schlumberger), and the Australian Coal Association.
- Japanese Members: IHI Corporation (technology vendor), JPower (generator) and Mitsui.
- JCoal is a supporting collaborator.
- Technology providers to the project under various contracts include: IHI, Air Liquide and GLP Pty Ltd (gas processing).
- The project is also supported financially by: Commonwealth Government and METI.

The CO2 capture/supply plant of the project is expected to be commissioned by January 2011, the CO2 compression plant by June, and the integrated plant by August 2011.

During the preparation of the scoping study, several informal discussions have been held with Dr Chris Spero of CS Energy, including the interaction of ANLECR&D and the COP, and in establishing the priority areas for research of Section 8.5.

During the design phase of the project, research expertise expected to be utilized for consulting needs and research areas critical for oxy-fuel technology have been identified, further needs may emerge during detailed design prior to commissioning, and others as the plant is commissioned and used.

Arrangements for involvement of ANLCR&D with the Callide Project must be agreed to by the Joint Venture Partners. The Project agreements allow only general information to be issued outside the Partners. The COP Joint Venture has therefore placed restrictions on confidentially and IP.

Within the COP organisation, Dr Spero will be responsible for managing the R&D program with support from a Technical & Investment Advisory Committee (TIAC). External experts will be invited to the TIAC forum as issues arise. The addition of a Research Manager for the Project under an arrangement with ANLECR&D is not considered to be appropriate at this stage.

Dr Spero suggests that any contribution the COP makes to ANLECR&D will be assessed in the context of the ANLECR&D contribution of cash and in-kind.

R&D opportunities discussed included:

Data and samples provision. Arrangements for ANLECR&D involvement could involve provision of data and samples as part of specific R&D activity or contract research, with contracts to protect IP. The COP will have boiler on-line monitoring and data collection systems with on-line continuous emissions monitoring (CO2, CO, NO, NO2, SO2, particulates, O2, Hg). Special test campaigns will also be run. Access to this kind of data for ANLECR&D may be limited because of confidentiality and its IP value.

Value of local expertise provided by ANLECR&D oxy-fuel node. The expertise developed by the ANLECR&D oxy-fuel node will be used to provide reviews of the state-of-knowledge of identified issues. A recent example would be mercury speciation and the implications for material corrosion in the compression plant. This is seen as a short term contract, rather than a research project. The preparation of technology status reports and updates of the status of active and proposed oxy-fuel projects, perhaps six monthly, could also be provided by the node.

Association or involvement of vendors not involved in the COP. External vendors are involved to a limited extent not withstanding existing confidentiality and IP constraints. Opportunity also exists for other vendors to be involved in new oxy-fuel projects that may be pursued by individual companies within the Callide Oxy-fuel Joint Venture.

Provision oxy-fuel technology information to other Australian generators. This is considered to be very difficult, and will be limited to the COP information released publicly. Generators can join COP as a "Further participant" with a significant financial contribution.

Collaboration with other (international) demonstrations. The COP is already collaborating with a number of other oxy-fuel projects but would like to further extend this collaboration not withstanding IP sensitivities.

At the ANLECR&D event conducted with EPRI in Brisbane in August 2009, other potential project areas involving the COP were identified. Further development of arrangements between ANLECR&D and the COP are necessary, and should consider specific ANLECR&D projects.

8.3 Other demonstrations

During the development of the scoping study, discussions were held with engineers of most of the Australian black coal generators, to access interest in CCS, and oxy-fuel technology in particular. Interest varied. Several indicated that interest involved a watching brief with the need to have an appreciation of the status of the technology. Several indicated that their Board appeared to be focussed on other issues at present. Others with involvement in other technologies

– PCC and IGCC-CCs – had a greater knowledge of CCS, and expressed interest in R&D to provide comparative economics of CCS technologies, operation in a competitive market, fuel quality impacts and capture ready aspects.

Several prospects for commercial Australian oxy-fuel projects have been identified:

The Callide Oxy-fuel demonstration project will assess potential commercial applications of the CCS technologies. CS Energy may therefore progress to commercial deployment in Queensland if the demonstration provides the technical and economic basis to do so.

AVIVA Corporation is developing the Coolimba Power Project in Central West WA, with a capture ready unit being considered which could be converted to oxy-fuel. The project is commercial. The unit may be a circulating fluidised bed, which accommodates coals with the ash and sulphur levels expected. The Simento and Lowe report (2009) indicated that oxy-fuel was the preferred technology option for this project, but currently PCC may be preferred as the technology can be applied partially and phased in. This option is driven by limitations of the identified storage CO2 capacity. Commissioned research by the CO2CRC has identified CO2 storage possibilities. The timing of a decision to proceed is uncertain, may depend on State and Federal financial support, and there is interest in research on capture ready plant.

Verve Energy of WA may consider the possibility of retrofit an existing unit to oxy-fuel, as the unit could become a stranded asset, as carbon costs emerge. Currently Verve is not actively involved in oxy-fuel development, but maintains an active watching brief, particularly on retrofit to oxy-fuel. The decision to proceed would be made after 2012.

8.4 Association with international oxy-fuel R&D

Oxy-fuel research and technology development is coordinated and progressed through international organisations and events. Australian researchers are continuing to play leading roles in these activities.

Australia is well aware of international developments, and their substantial funding and scope. As ANLECR&D develops, it may need to buy into targeted international research projects, commission external research and assessments, facilitate researcher/researcher interactions, and extended visits to international demonstrations.

8.5 Oxy-fuel ANLECR&D - Addressing the challenges facing Australian demonstrations and barriers to technology deployment

8.5.1 Research program

Options for the ANLECR&D program on oxy-fuel technology have been prepared which addresses the barriers identified in Section 6. Consideration has been given to extracting value from the Callide demonstration, establishing an appreciation of the technology and vendor status amongst generators, a reduction of high impact cost and risk technical barriers, while addressing market, legal, regulatory and public acceptance issues.

The *R&D recommendations table: Projects to address barriers* of the Executive Summary lists the program and projects, giving the ANLECR&D node responsible, the priority and whether the projects were recommended in the Callide feasibility study. Also indicated is the suggested

ANLECR&D node responsible for the project, with several projects of interest to more than one node listed.
The project priorities are also indicated, with nominated work over the first two years of ANLECR&D as requiring project **D**evelopment or projects with active **R**esearch. Projects requiring development may need further assessment of need, scoping or negotiation

8.5.2 Projects of high priority requiring immediate development

The projects noted H* in the *R&D recommendations table: Projects to address barriers a*re of high priority requiring immediate development will be discussed here.

- The project is considered to be of major significance in influencing future demonstrations and deployment

- The project requires building and further scoping, being of immediate impact and perhaps on a topic in which Australian skills and effort needs developing (eg, gas quality assessment and control, including during CO2 compression)

- If value is to extracted from the project, then it should be progressed now given the time required for development (eg, an oxy-fuel test-furnace)

8.5.1.1. Removing technical and economic barriers

Design and operation verification from Callide demonstration

Resolving issues arising from Callide demonstration. Although the Callide demonstration will not operate until 2011, arrangements and agreements to allow the measurements and interpretation of data must commence now. This includes contractual arrangements and consideration of measurement capability prior to operation. After operation commences, research needs will arise which can be undertaken by ANLECR&D.

Design verification R&D – heat transfer, burner performance, gas quality. This area requires establishing plant measurements and developing interpretative mathematical tools prior to the measurements being available from the plant

Operation protocols and dynamics R&D – air and oxy operation switching, load change, partial capture operation. This issue will be established by plant operation experience, with preparation of operational protocols required.

Appreciation of oxy-fuel status and Australian relevance

International oxy-fuel demonstrations, status and vendor capability. This area is facilitated by knowledge of, and interaction with, international oxy-fuel developments and would involve attendance at the major oxy-fuel events, and possibly involvement in international projects which need to be identified.

High level techno-economic assessment of oxy-fuel process options and second generation options. This area would be undertaken in conjunction with other capture technologies, in Node 1, with Node 5 providing flowsheet and operational variables. The novel aspects of the Australian situation are established here.

Reduction of high impact cost and risk technical barriers

Gas quality impacts. Amongst the capture technologies, the CO2 gas quality has the greatest potential variability, uncertainty and impact in oxy-fuel. This quality can be controlled either by cleaning in the power plant or the compression operation or both, and will be influenced by future regulations for CO2 quality for transport and storage. Cost and energy requirements should be minimised and CO2 recovery optimised, but at present the technical possibilities are still being established.

The lack of SOx and NOx control units and different regulations for these emissions make this issue of particular relevance to retrofits of Australian units.

Since the COP feasibility project the impact of mercury on cryogenic operations has also been identified. Expertise in this area resides in the international gas vendors (eg, Air Products, Air Liquide and Praxair), but some research has been established in laboratories (eg, Chalmers University and Imperial College) which provides a collaborative opportunity. Local knowledge needs to be established. There is little knowledge of impurity impact and removal during compression in Australia, so this high priority area must be developed quickly. Although gas quality impacts nodes 4, 6 and 7, it has greater impact on the cost and energy penalty of oxy-fuel CCS, which will involve higher impurity levels, hence a major involvement of node 5 is needed. Three areas are suggested: SOx and NOx removal or control through the capture plant; trace element behaviour removal or control; and CO2 compression, optimisation of pressure/temperature and impurity impact on recovery and energy penalty.

Brown coal oxy-fuel technology. The brown coal research areas have been identified through discussion with HRL and Monash University

Establishing oxy-fuel research capability - The Australian oxy-fuel test facility. The oxy-fuel test facility is of the second type of the categories above, the need must be established, The Callide Project does not see the need for the facility, but discussions with the brown coal node indicates their need for it.

8.5.1.2. Removing market barriers

This links with item 1 of Section 8.5.1.1

8.5.1.3. Establishing public knowledge and acceptance

This project is required for CCS deployment and must be managed centrally.

8.5.1.4. Removing legal and regulatory barriers.

Preparing for the future deployment of technologies for carbon dioxide capture and storage (CCS) is currently driving the development of guidelines and regulations to ensure that CCS projects are conducted safely and effectively. Regulations on transport and storing CO2 in geologic formations are emerging – both proposed and enacted at the national and regional level in the European Union, the United States, and Australia in late 2008 and 2009. Due to its potential gas quality variability, oxy-fuel is impacted by regulations to a greater extent than other capture technologies, and so the involvement of node 5 is required here, with the project managed centrally.

8.6 Developing project-specific design and costing

The scoping study has given R&D priorities. With a suggested annual budget of M$1 for oxy-fuel research, the research effort will be selective, and must be prioritised. Here, a sequence to progress the projects requiring development is suggested as follows, in order of priority:

Projects requiring **R**esearch in 2009/10 in the *R&D recommendations table: Projects to address barriers:*

Further the development of the relationship of Callide Oxy-fuel Project with ANLECR&D on both management and technical levels. The development of this aspect of the scoping study has focussed on technical issues and involved discussions between Dr Spero and the author. The COP/ANLECR&D negotiations should be broadened. Currently the possibility of an Imbedded Research Manager (or Research Officer) has not been supported by the COP, but should be progressed during negotiations. Consideration of measurement capability prior to operation must be progressed, such as for sampling and for coupons to test material/gas impacts. The staff and ANLECR&D budget for the work will then be established.

Local knowledge must be established on gas quality impacts from oxy-fuel minor gases (O2, N2, SOx, NOx, Hg) and other trace element during CO2 compression, and removal or impact control needs to be established. This justifies a research project with theoretical (thermodynamic) and experimental components, focussed on impacts on CO2 recovery, energy needs, and also plant aspects. This research is relevant to other capture technologies, but with a greater impact for oxy-fuel, due to higher impurity levels, and is also most relevant to Australian oxy-fuel technology deployment compared to international developments.

Brown coal oxy-fuel research. Details of cost and distribution of research between nodes 3 and 5 on brown coal needs to be resolved.

The impact of regulatory and legal barriers need to be progressed. The oxy-fuel working group is running a session at the IEA Oxy-fuel Conference in Cottbus in September, and a resource document has been prepared on regulations of different countries. This issue needs immediate action as regulations are now emerging.

Projects requiring **D**evelopment in 2009/10 in *R&D recommendations table: Projects to address barriers.* The table also lists a number of projects which should be assessed for relevance, priority and cost, these include those requiring visits and interaction with international activities in the first half of 2010.

In addition, as the ANLECR&D program is developed the reestablishment of Australian research capability in oxy-fuel technology should be a priority.

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Glossary

Sym	Description
APP	Asia Pacific Partnership
CCS	Carbon Capture and Storage
CEDF	Clean Environment Development Facility
CFB	Circulating Fluidized-Bed
CSLF	Carbon Sequestration Leadership Forum
DOE	US Department of Energy
EPRI	Electric Power Research Institute
FF	Fabric Filter
GHG	Green House Gases
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel for Climate Change
OCS	Oxygen Combustion System
OFWG	Oxy-fuel Working Group
PCC	Post-Combustion Capture
PF/PC	Pulverized Fuel
PIC	Production of Incomplete Combustion
RFG	Recycled Flue Gas

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