Coal based oxy-combustion for carbon capture and storage: status, prospects, research needs and roadmap to commercialisation

Purdue University Energy Center Invited Lecture
on Coal Based Energy

May 28, 2009

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Australia

Content

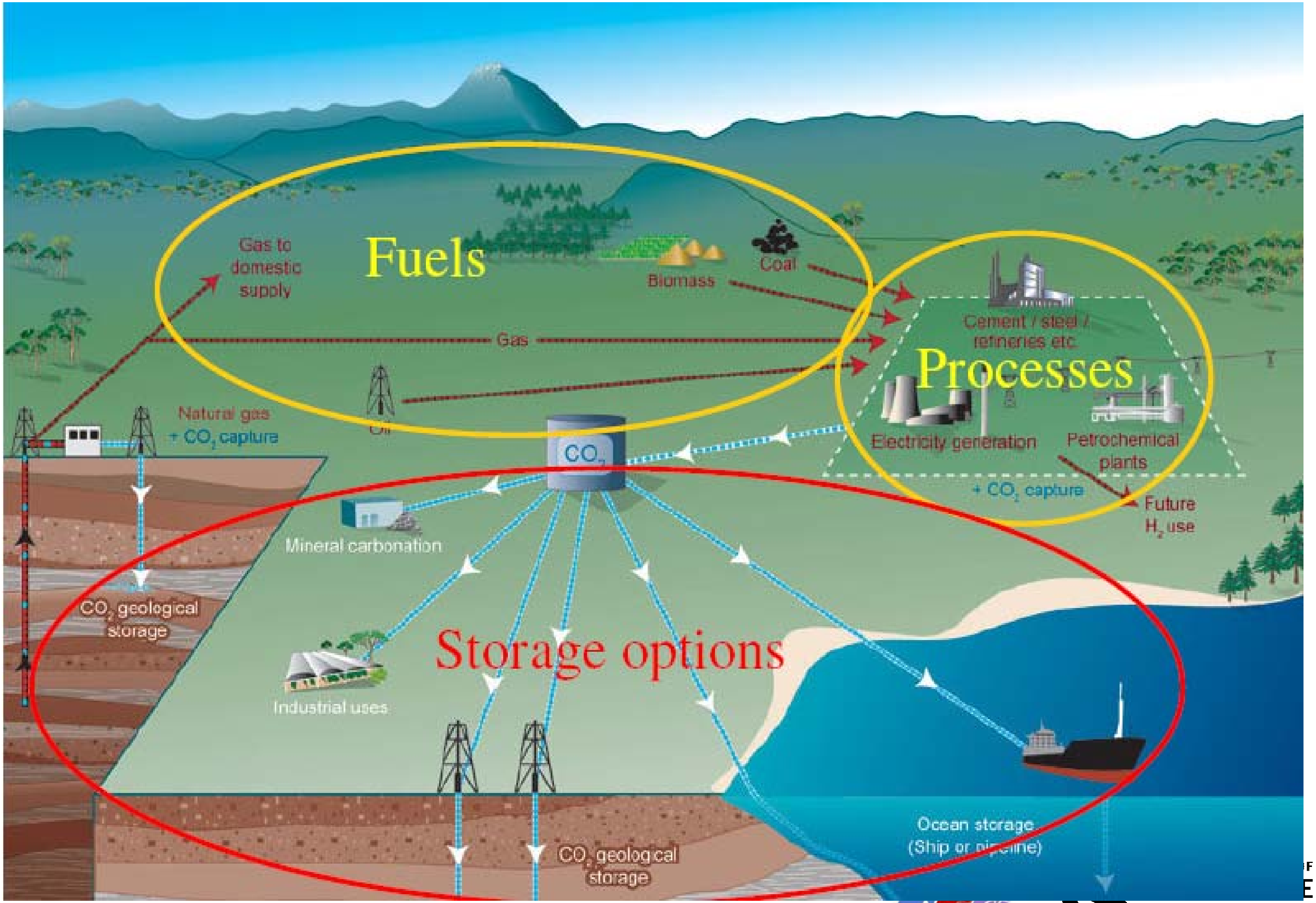
Technology status

Underpinning science

Technology prospects

Technology status and demonstration outlines

Low Emission Coal Technologies (or CCTs) ....



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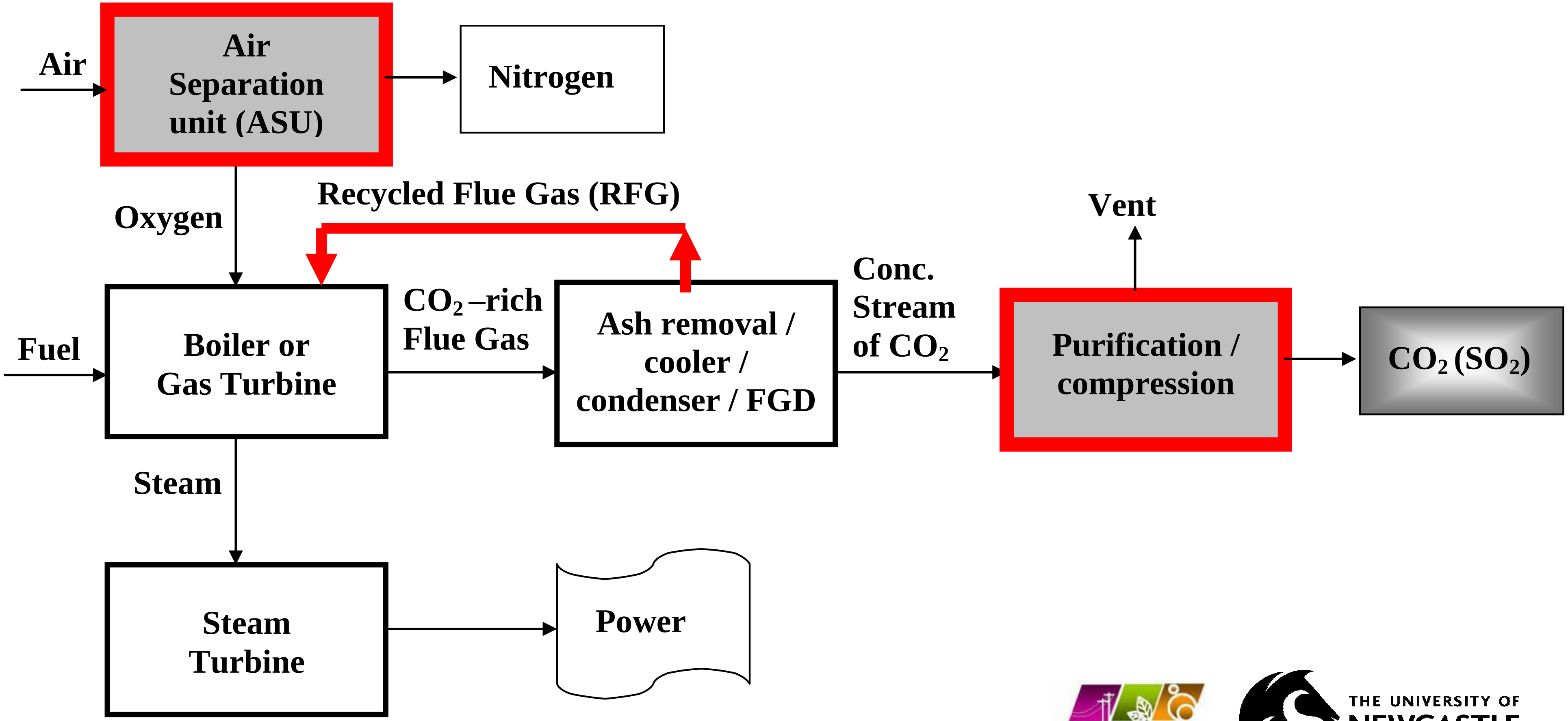
Oxy- fuel


Air
Air Separation unit (ASU)
Nitrogen
Oxygen
Recycled Flue Gas (RFG)
Vent
Fuel
Boiler or Gas Turbine
CO_2 –rich Flue Gas
Ash removal / cooler / condenser / FGD
Conc. Stream of CO_2
Purification / compression
CO_2 (SO_2)
Steam
Steam Turbine
Power

Low emission technologies

……. applicable at the scale required, using pulverised coal in entrained flow

PCC: CO_2 capture by scrubbing of the flue gas, here called ***post-combustion capture***

IGCC-CCS: Integrated gasification combined cycle (IGCC) with a shift reactor to convert CO to CO_2, which is often called ***pre-combustion capture***

Oxyf: ***Oxy-fuel combustion***, with combustion in oxygen rather than air

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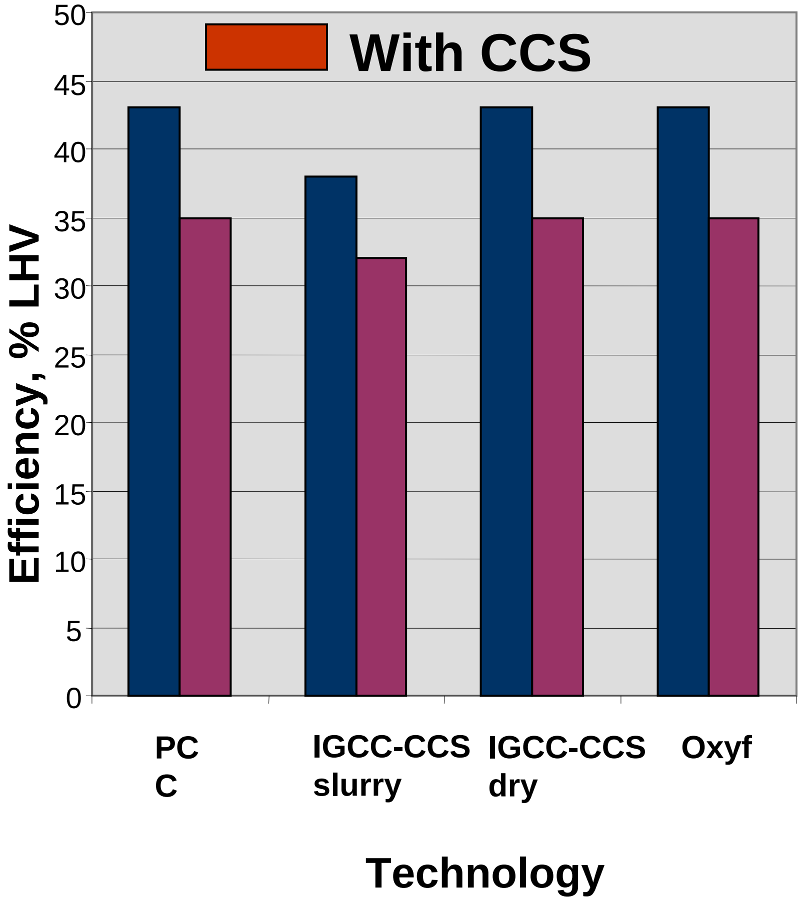
Technology comparisons



Data from IEA studies, 2005-7

“At the current level of development, our analysis indicates that the choice of a specific technology (eg pre-combustion, post-combustion, or oxy-fuel) does not significantly affect the cost of a “reference” large-scale plant, even though the relative shares of capex, opex and fuel costs within the total may vary markedly”.

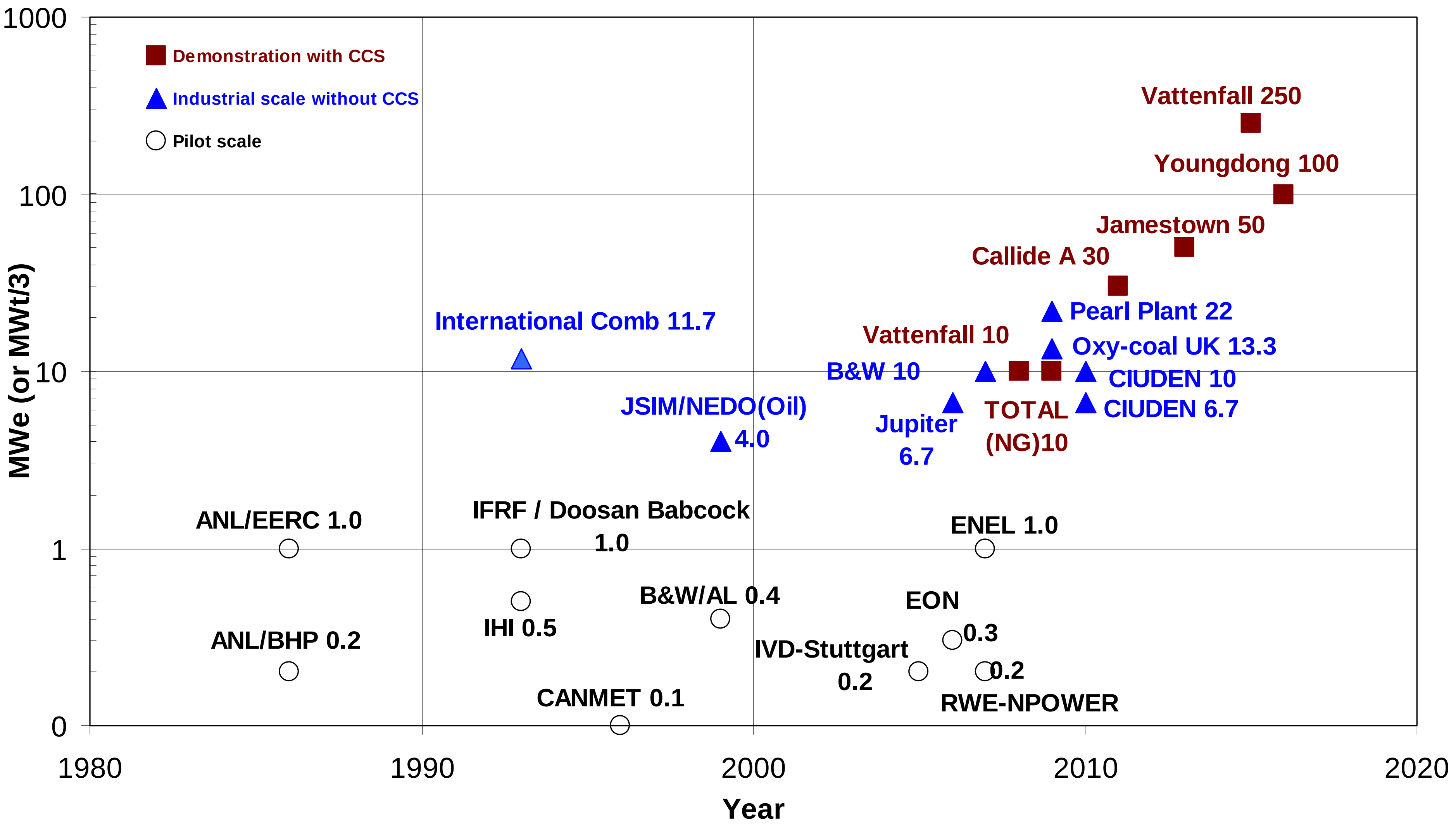
McKinsey&Company, CCS: Assessing the economics, 2008

CCS options, with desirable characteristics indicated X

Option	Demonstrated	For retrofit	Can be applied to slip-stream	No O_2 supply *	No CO_2 capture	Gives H_2
PCC		X	X	X		
IGCC-CCS						X
Oxyf		X			X	

* IGCC-CCS can be air fired

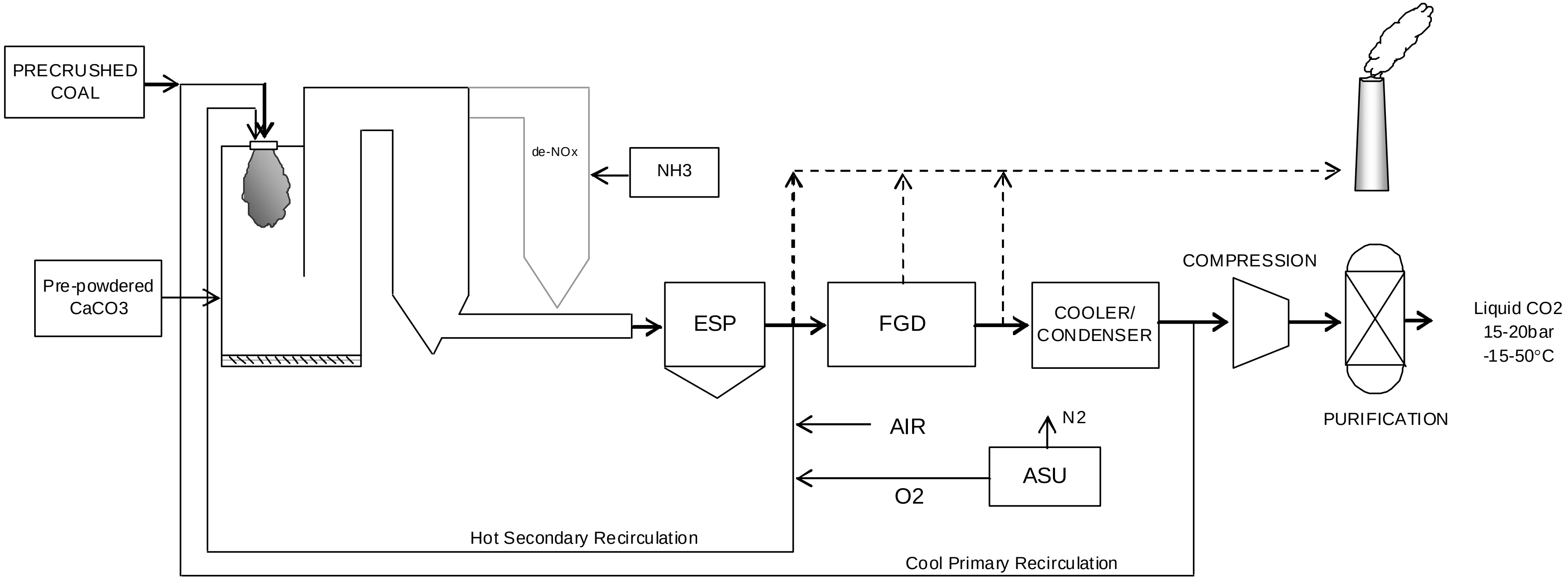
Historical development of oxyfuel technology



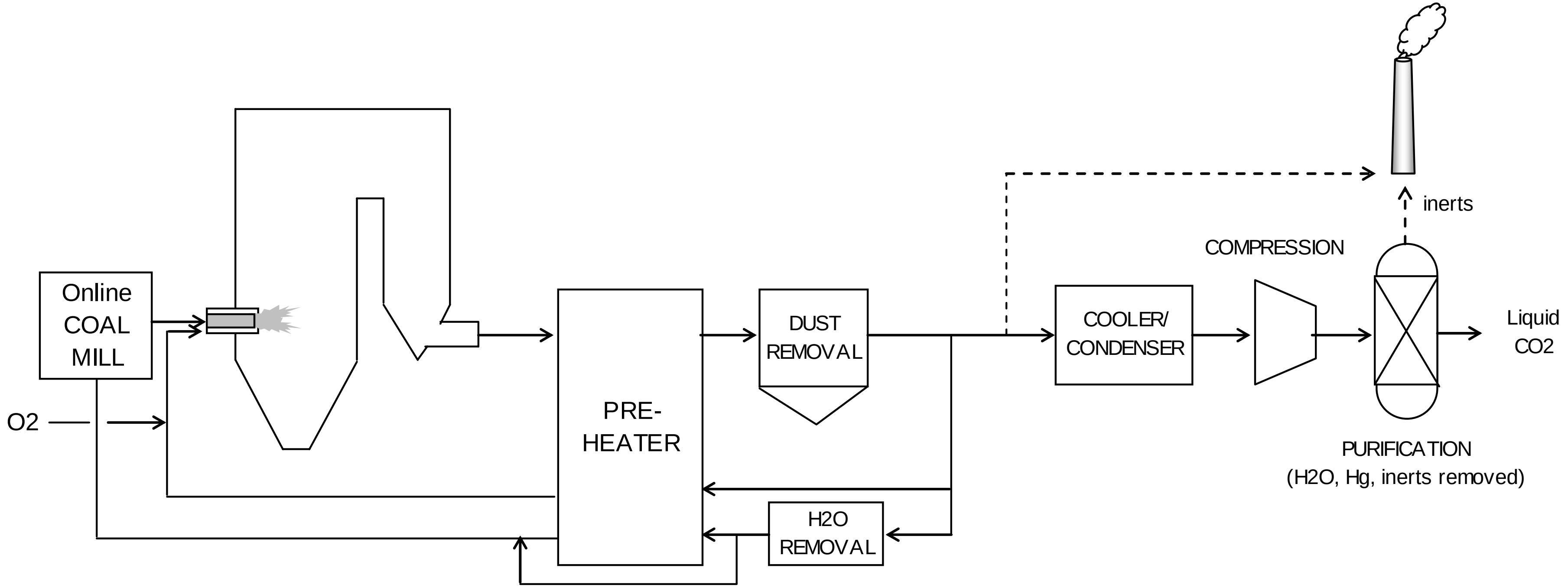
Current demonstrations

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		

Vattenfall flowsheet



Callide flowsheet



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.

Pathway to implementation

Oxyfuel technology implementation pathway

Implementation should be progressed at several levels:

1. Retrofit to existing units – generally as the 1st phase of implementation
2. Construction of new plants - generally as the 2nd phase of implementation, with application of new burners
3. 2nd generation oxyfuel plants could involve higher levels of thermal integration, new furnace designs, optimised gas cleaning ……
4. Parallel development of more efficient and lower cost oxygen plants – will be a key factor in the success of oxyfuel technology
5. Development of CO2 storage regulations, CO2 transport infrastructure and proving up of large CO2 storage reservoirs – necessary to underpin large projects

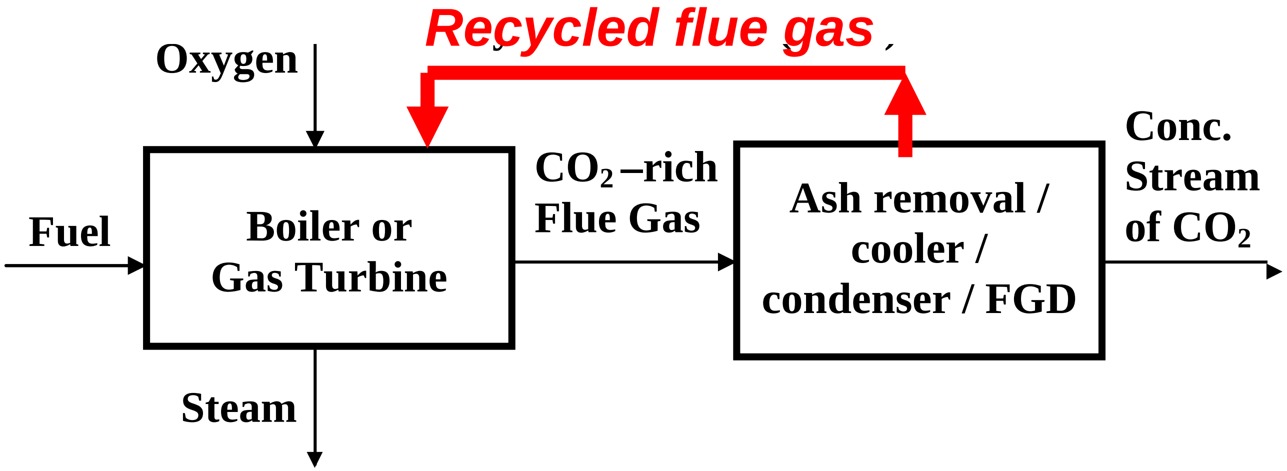
Oxy-fuel combustion – Underpinning science

B. J. P. Buhre et al, Oxy-Fuel Combustion Technology For Coal-Fired Power Generation, Prog. Energy Comb. Sci. 31 (2005) 283-307

T. F. Wall, Combustion processes for carbon capture, Proceedings of The Combustion Institute, 31, 31-47, 2007

Terry Wall et al, An overview on oxyfuel coal combustion—state of the art research and technology development, Chemical Engineering Research and Development, in press, 2009

……. and detailed here by comparison with air firing


Recycled flue gas

Oxygen

Fuel

Boiler or Gas Turbine

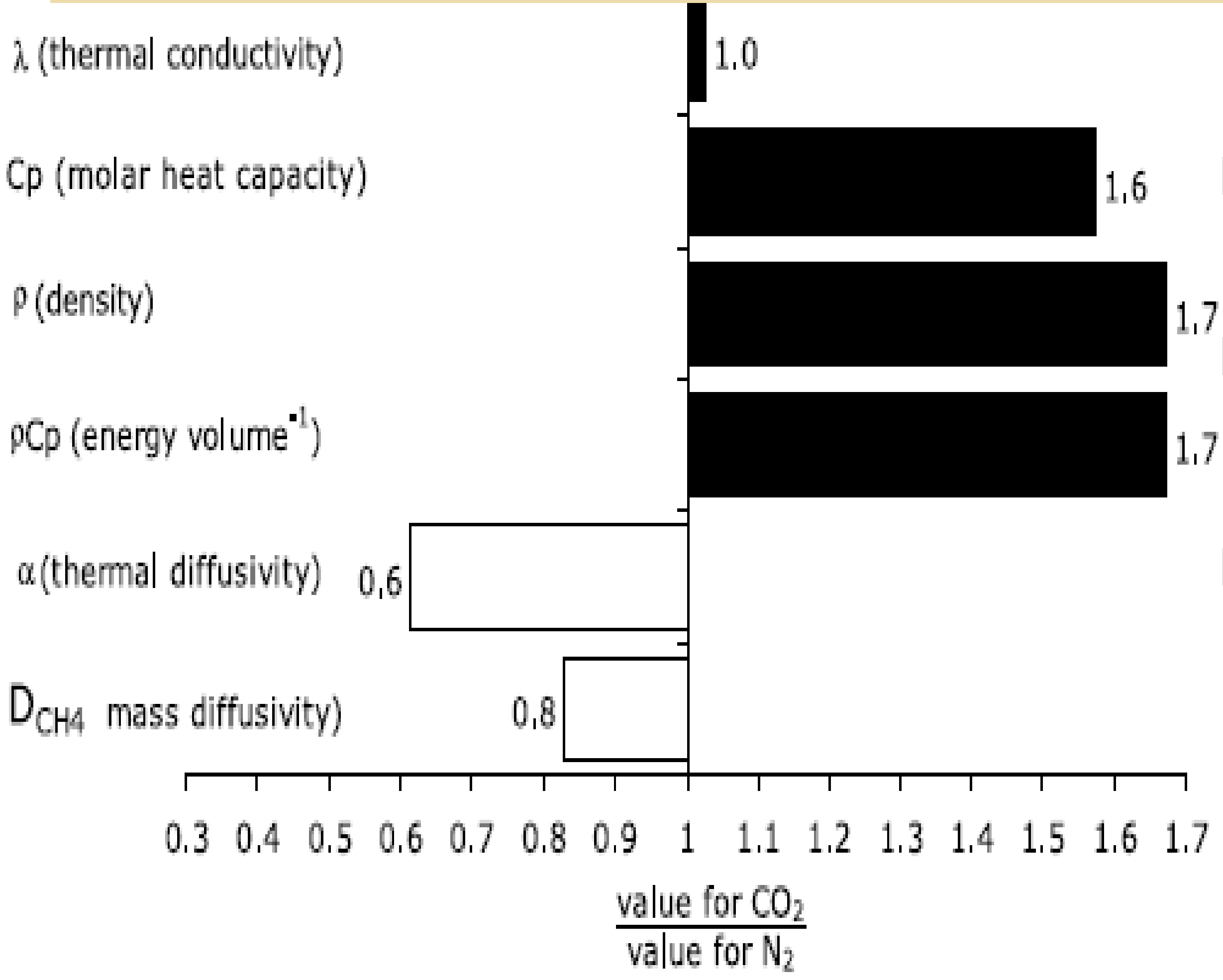
Steam

CO_2–rich Flue Gas

Ash removal / cooler / condenser / FGD

Conc. Stream of CO_2

Gas property differences



Impact for air to oxyfuel retrofit

➡ Higher O2 thru burner

➡ Lower burner velocity, higher coal residence time in furnace

➡ Slower flame propagation velocity

Properties from Shaddix, 2006

Gas property ratios for CO_2 and N_2 at 1200 K

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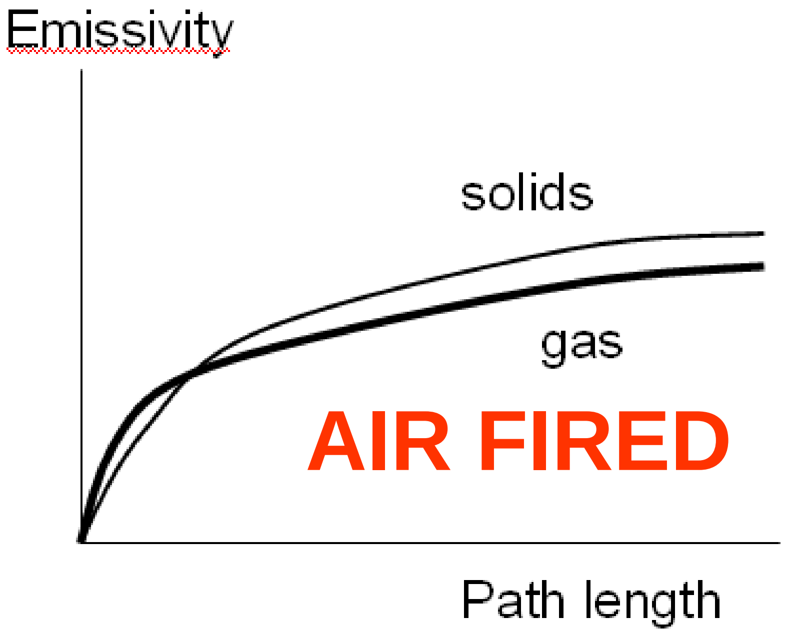
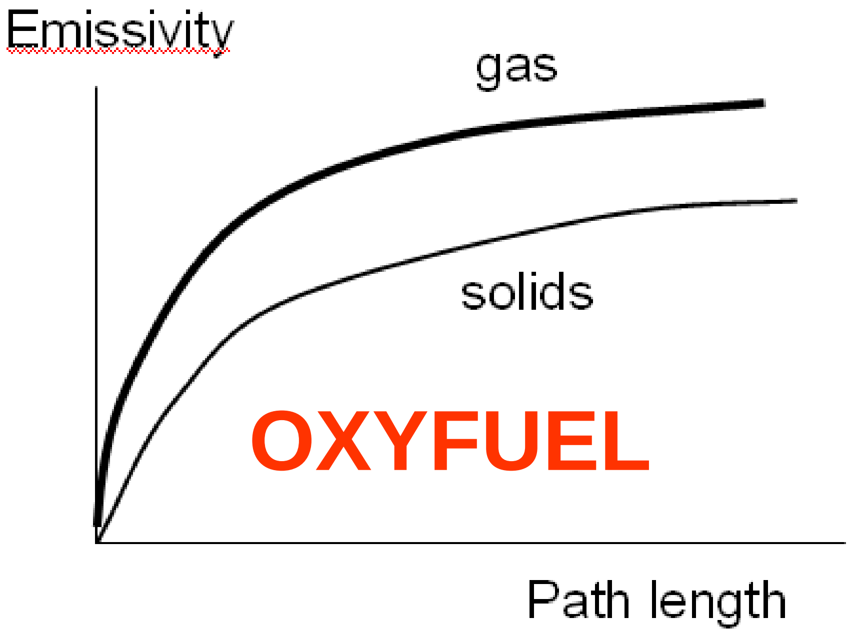
Emissivity


Emissivity
solids
gas
AIR FIRED
Path length


Emissivity
gas
solids
OXYFUEL
Path length

Oxy-fuel: differences of combustion in O_2/CO_2 compared to air firing

- To attain a similar AFT the O_2 proportion of the gases through the burner is 30%

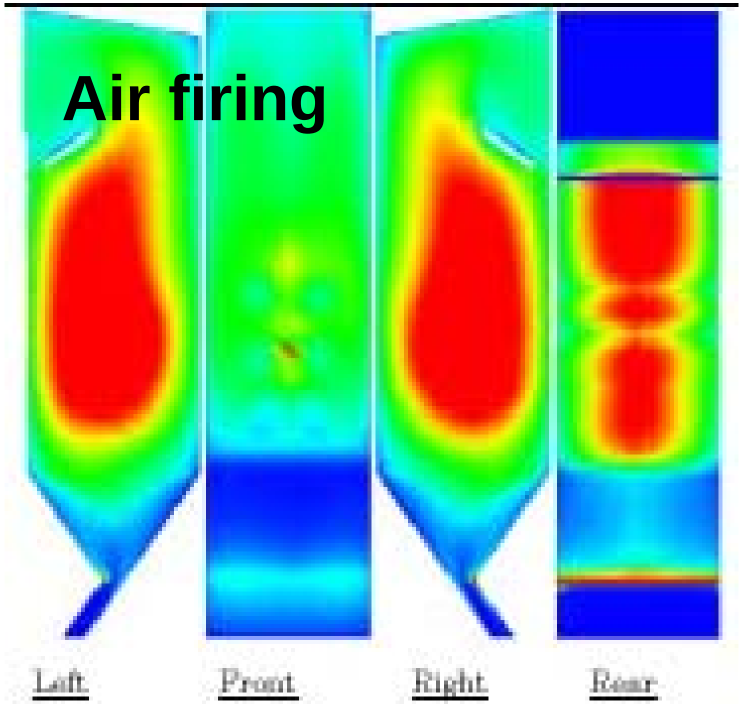
- The high proportions of CO_2 and H_2O in the furnace gases result in higher gas emissivities

- The volume of gases flowing through the furnace is reduced

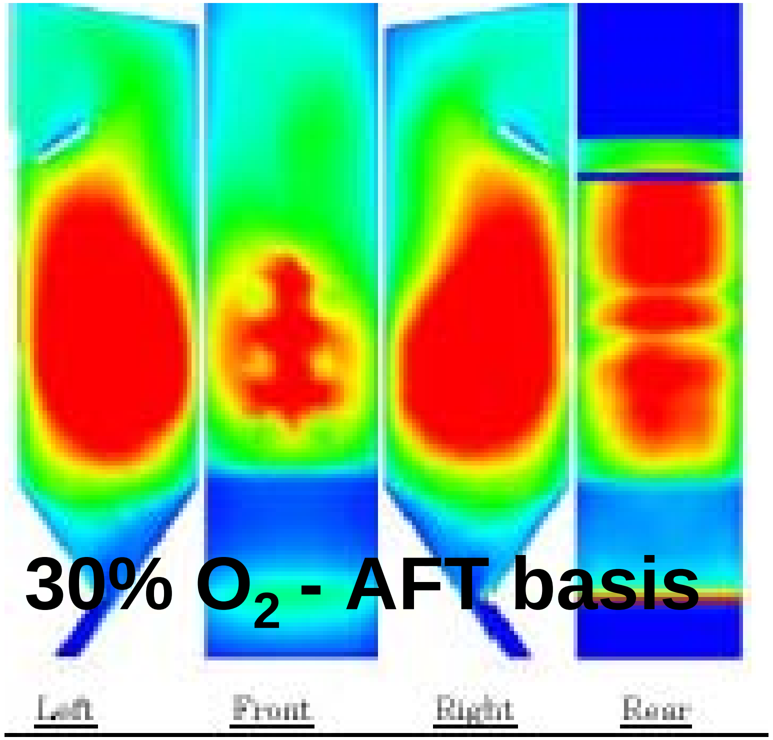
- The volume of flue gas (after recycling) is reduced by about 80%.

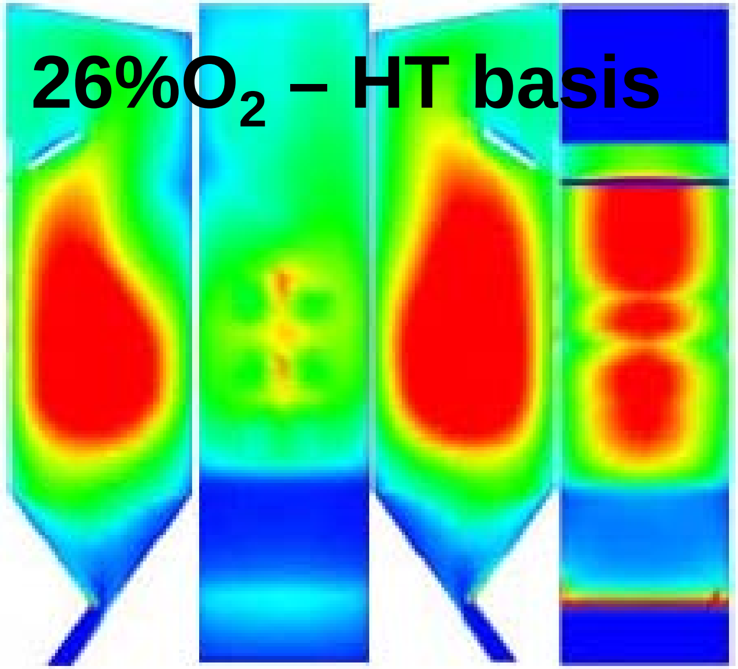
- Recycle gases have higher concentrations in the furnace

Oxy-fuel: furnace heat transfer comparisons, 30 MW_e, with predicted absorbed wall heat flux, by cfd


Air firing

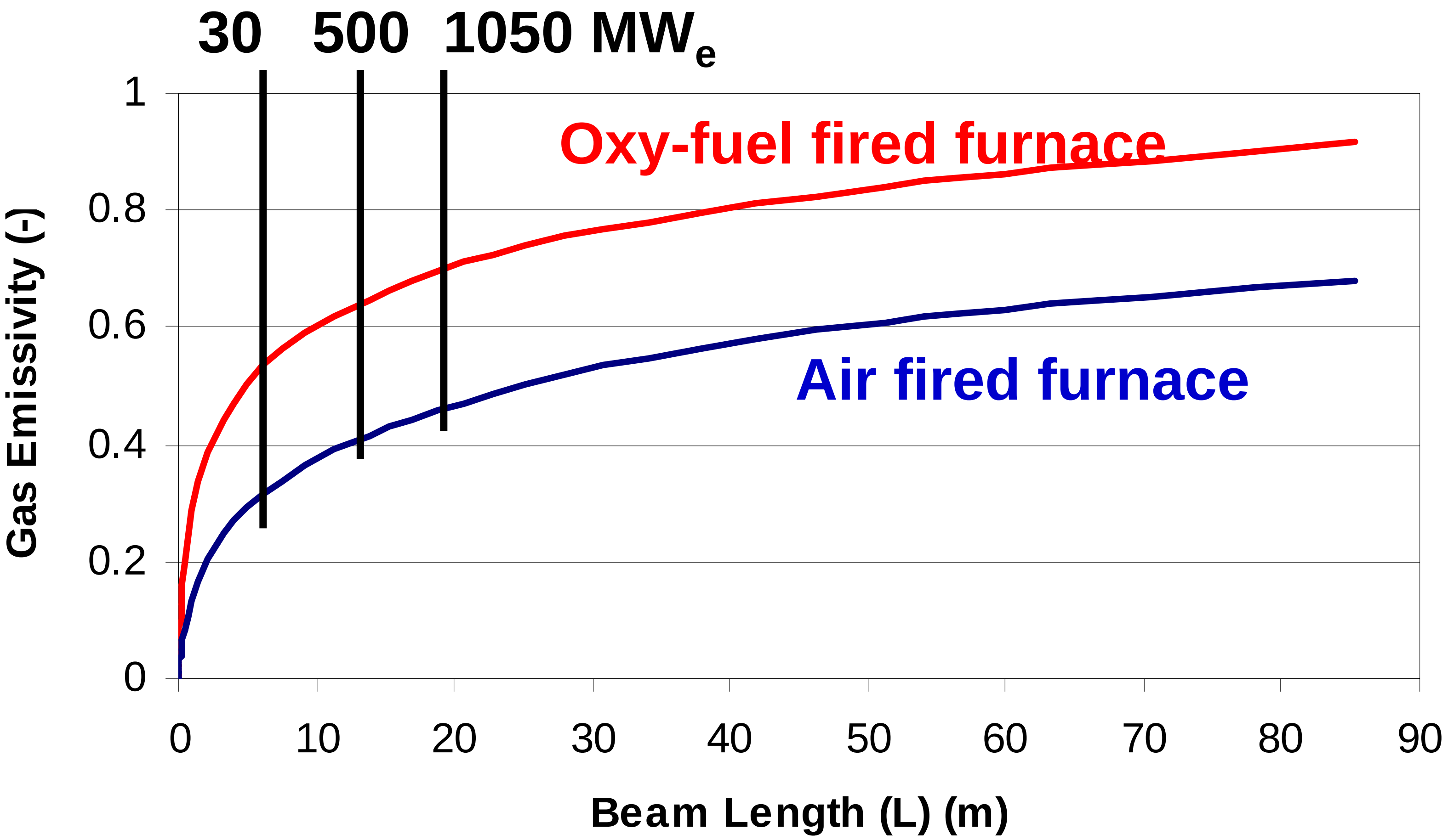
Oxy-firing, with different O_2 proportions thru' the burners, wet recycle


30% O_2 - AFT basis


26%O_2 – HT basis

IHI, personal communication, 2005

Oxy-fuel: Triatomic gas (H_2O+CO_2) emissivity ~ beam length comparisons



Gupta et al (2006)

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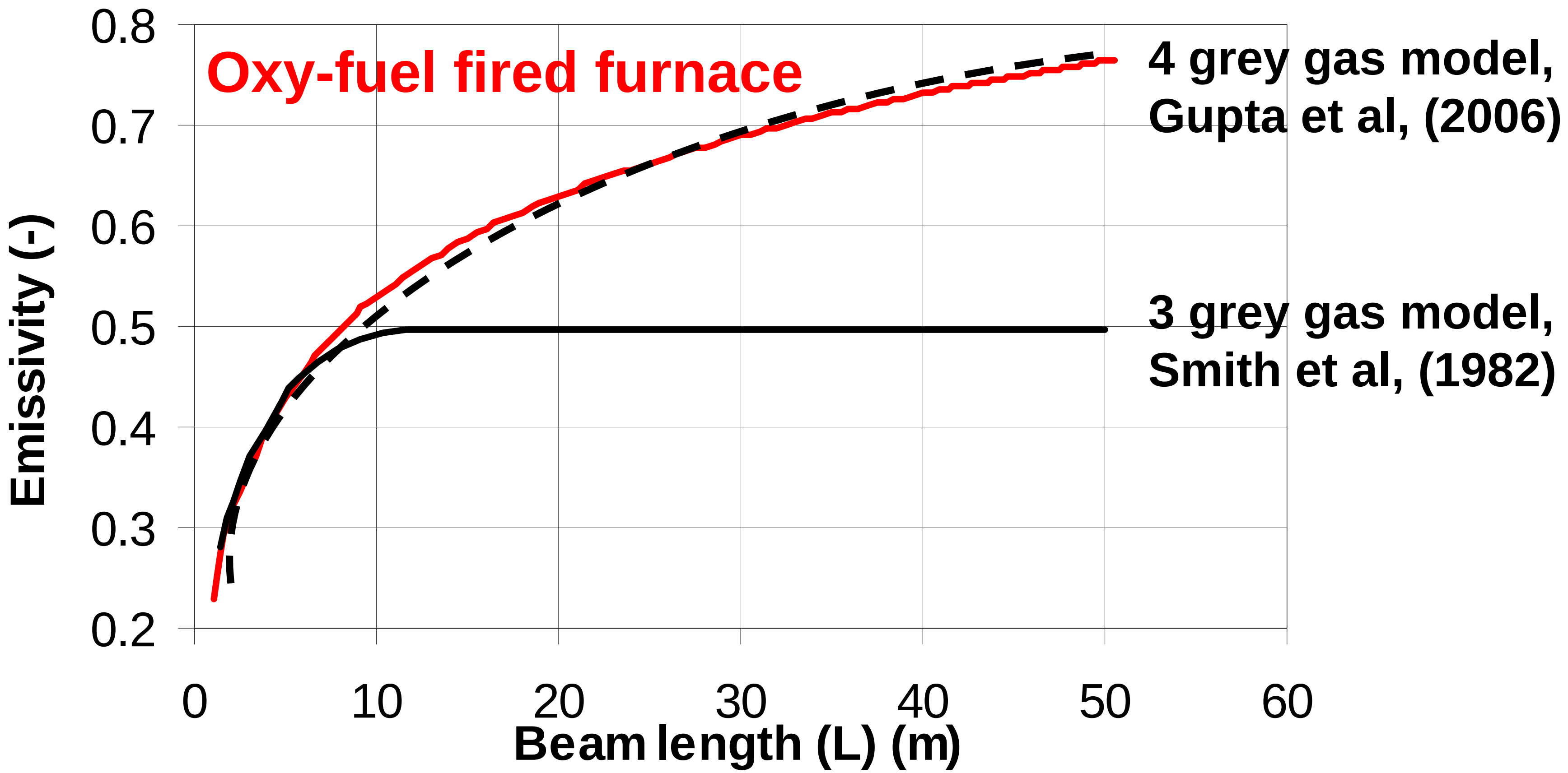
Oxy-fuel: CFD radiative transfer inputs



$$\varepsilon = \sum_{i=0} a_{\varepsilon,i}(T)\,[1 - e^{-k_i (p_{CO2} + p_{H2O}) L}]$$

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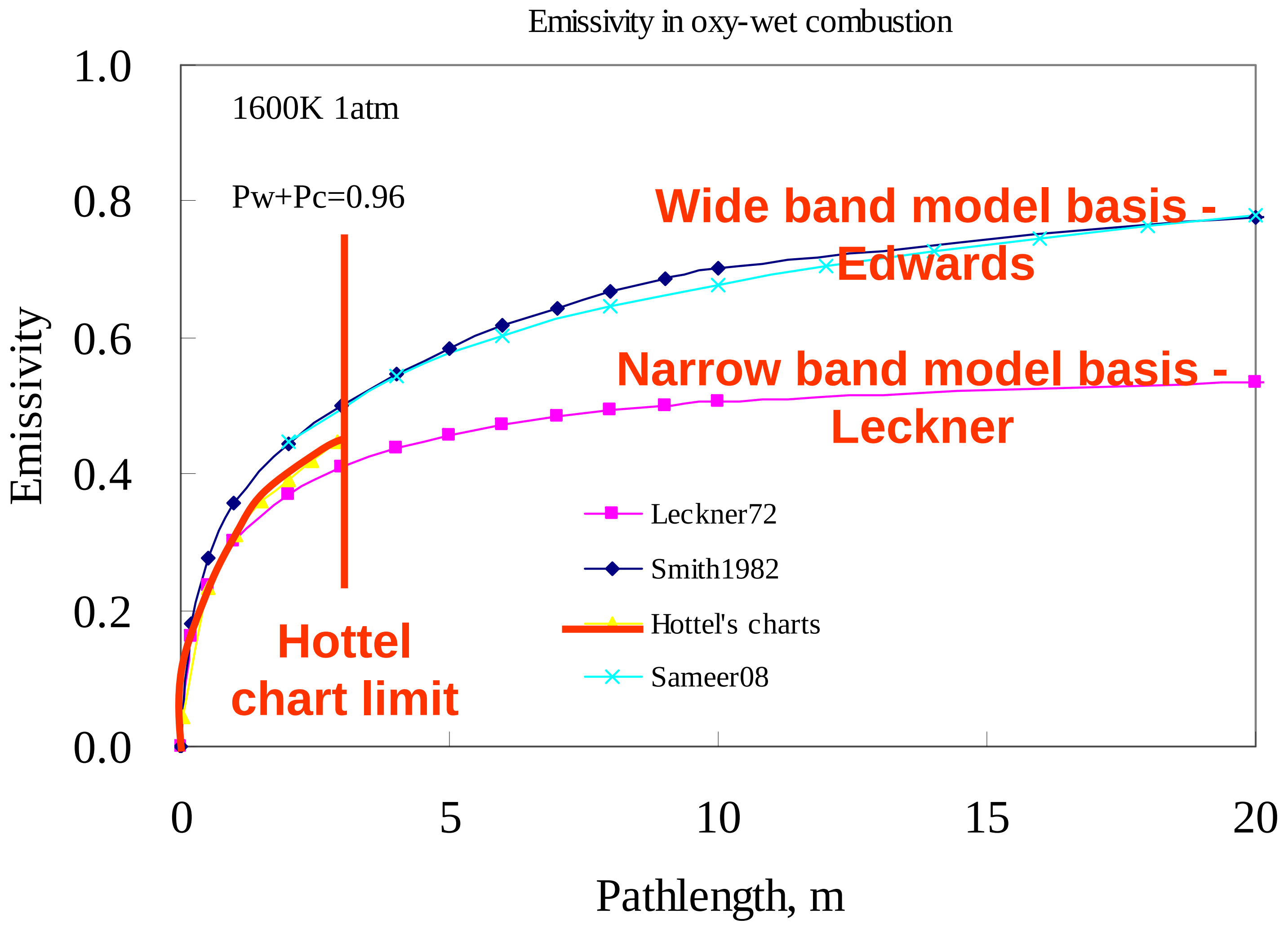
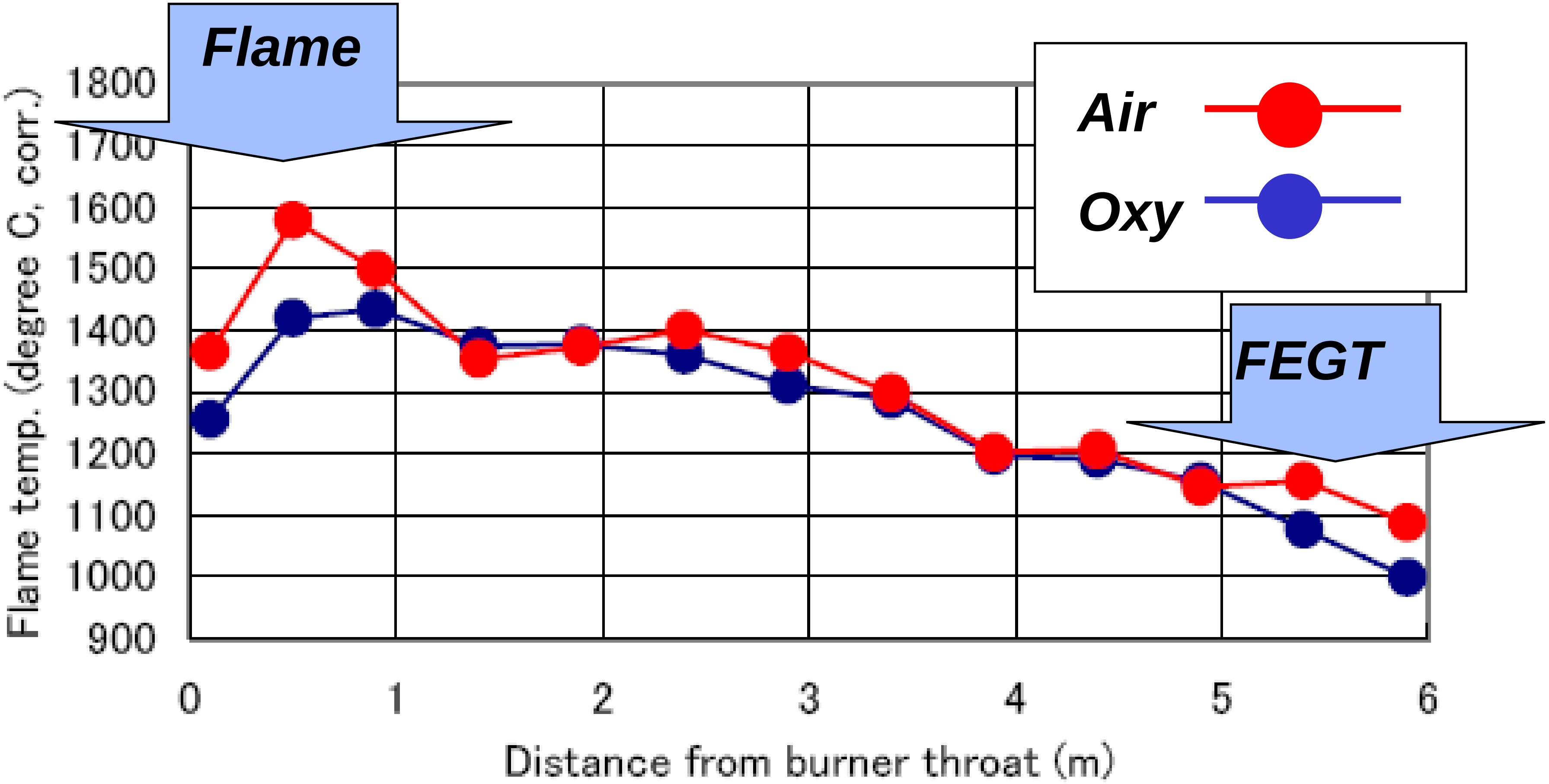
But gas emissivity predictions are uncertain for large oxy-fired furnaces



Oxyfuel: Pilot-scale measurements for oxy-fuel when furnace heat transfer is matched



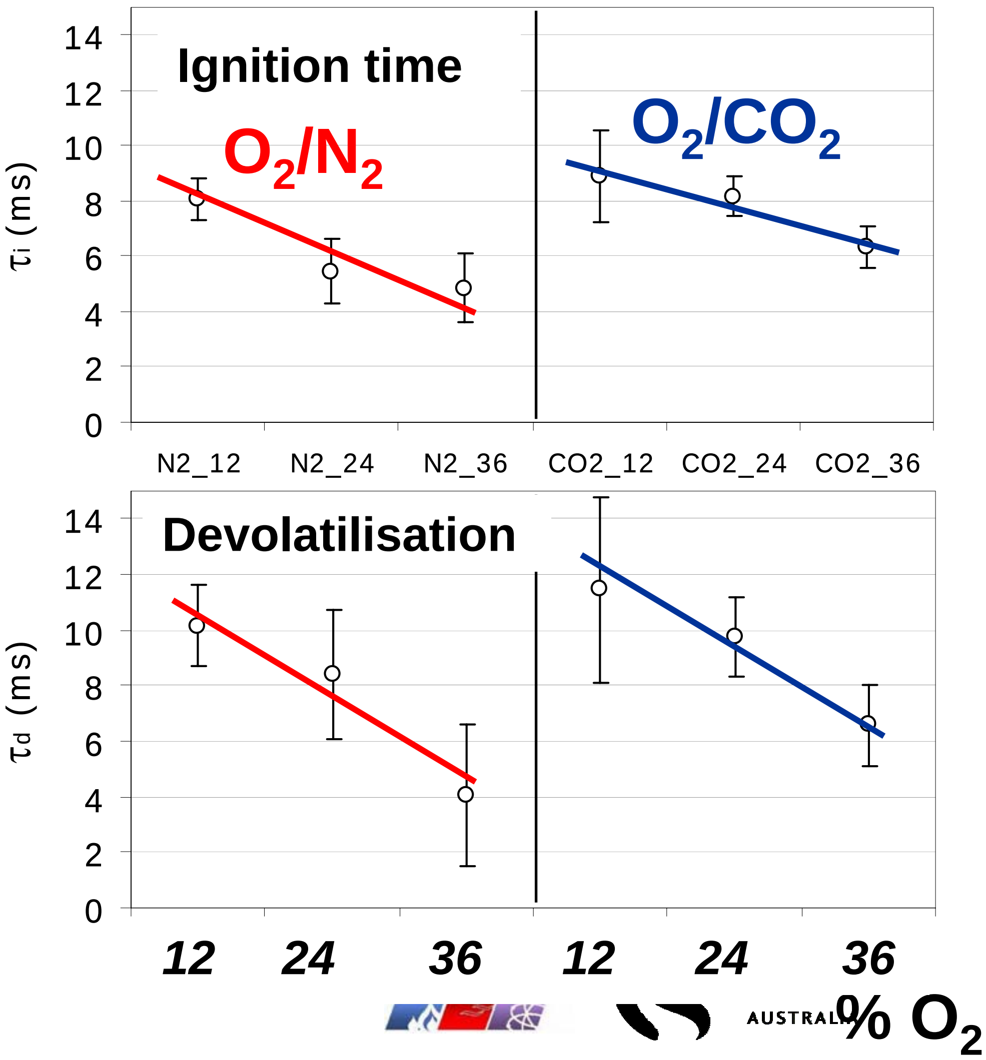
Yamada et al (2006)

Oxy-fuel: Combustion developments, ignition, burner operation, burner and furnace development

Pilot-scale tests reveal flame ignition is delayed in oxyfuel environments

Suda et al (2006) report measured laminar pf flame propagation velocities in O_2/CO_2 to be 1/3 ~ 1/5 of those in air

Shaddix (2006) has quantified differences in ignition and devolatilisation times in O_2/N_2 and O_2/CO_2



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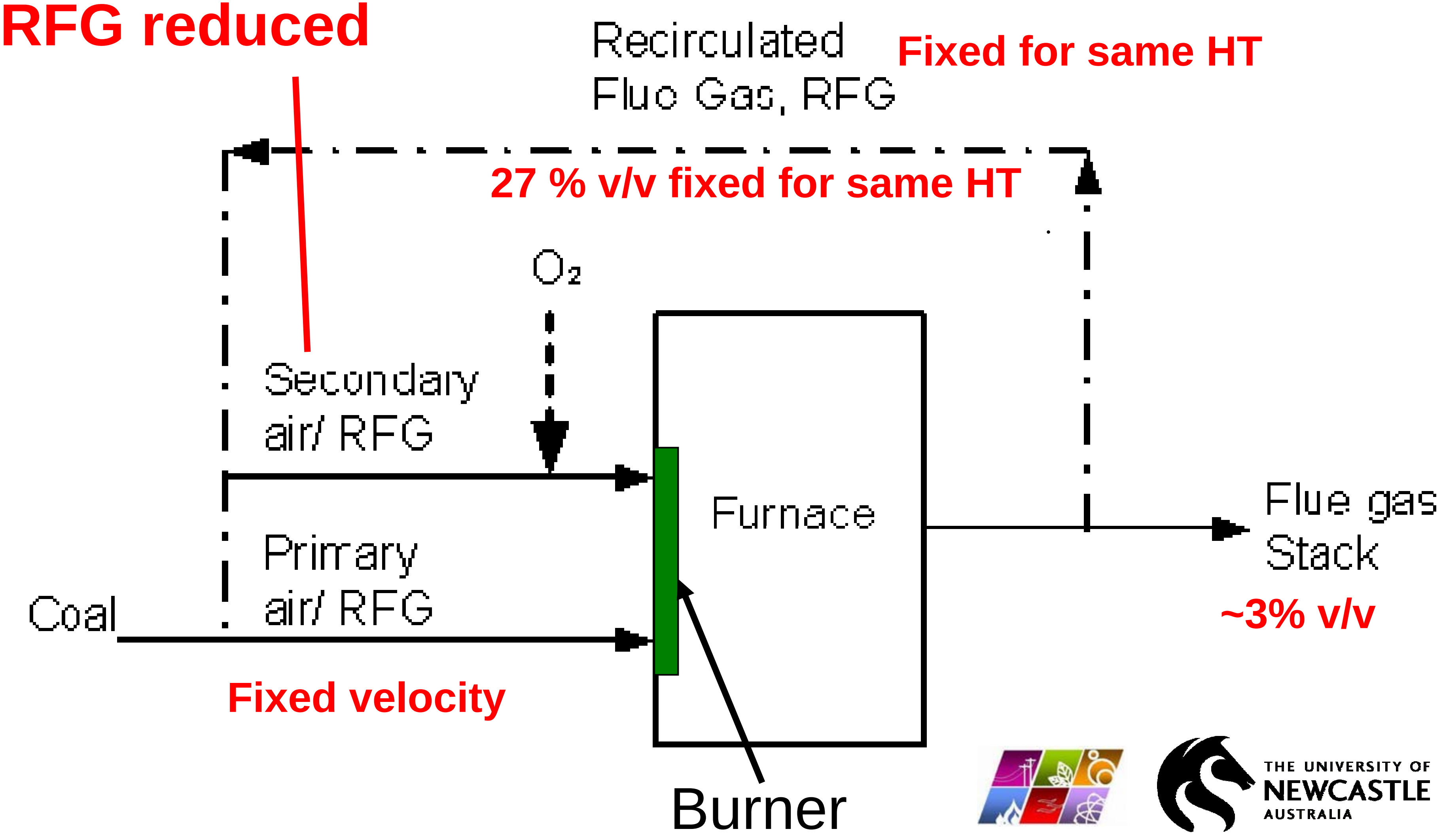
Burner flow comparisons for a retrofit



Therefore secondary RFG reduced

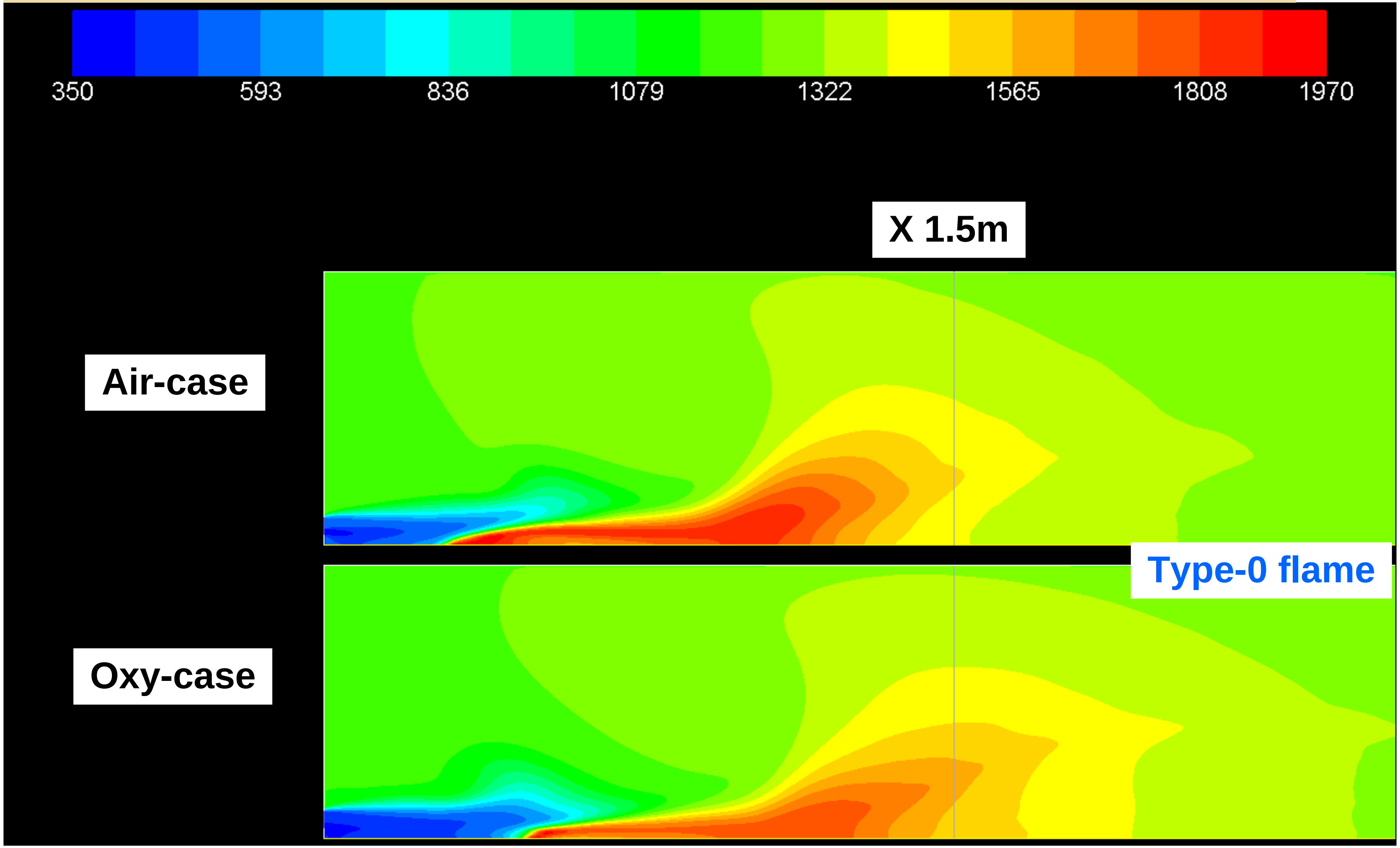
Fixed for same HT

27 % v/v fixed for same HT

Fixed velocity

~3% v/v

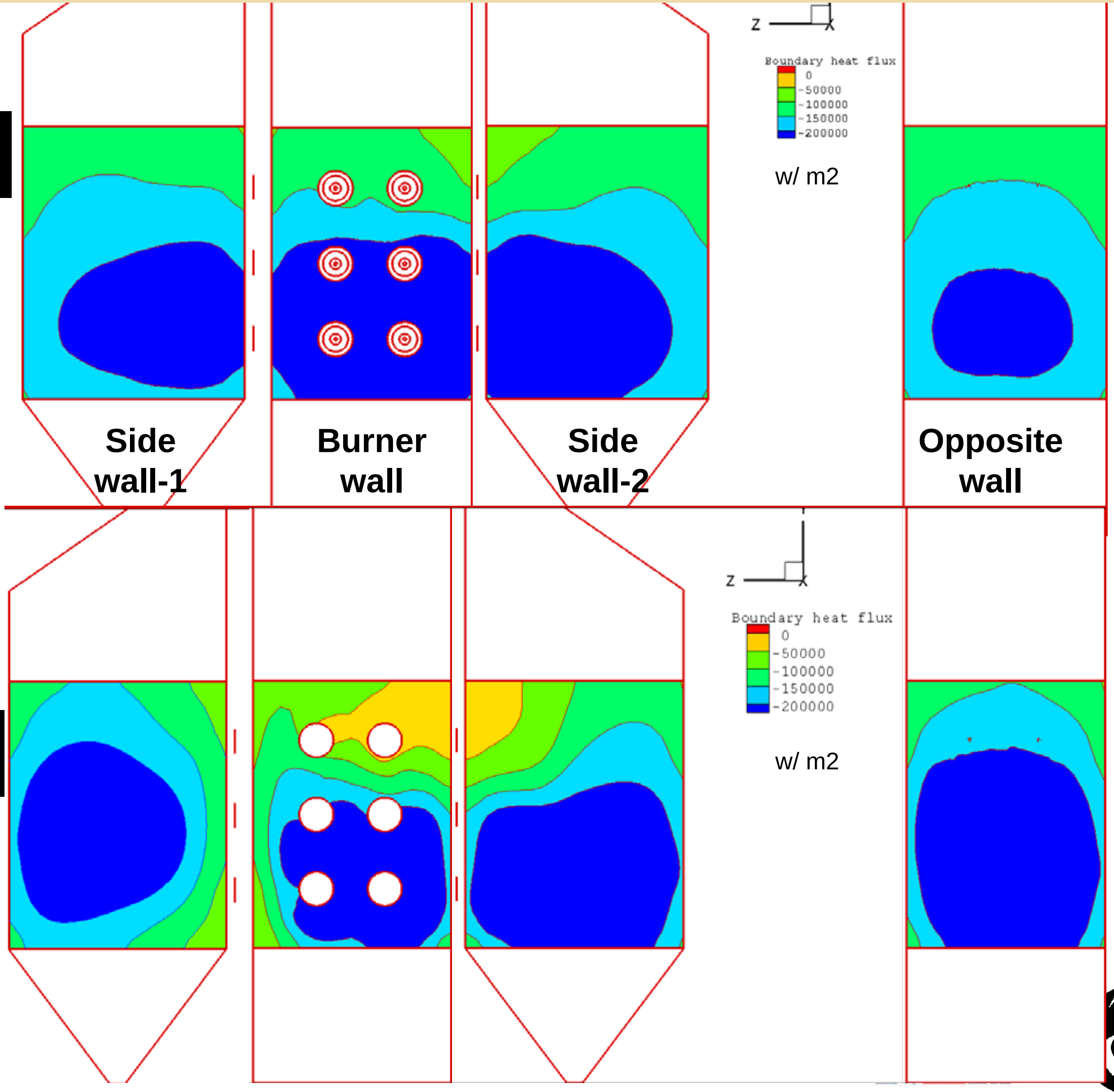
1 MWt – Temperature contours at full load



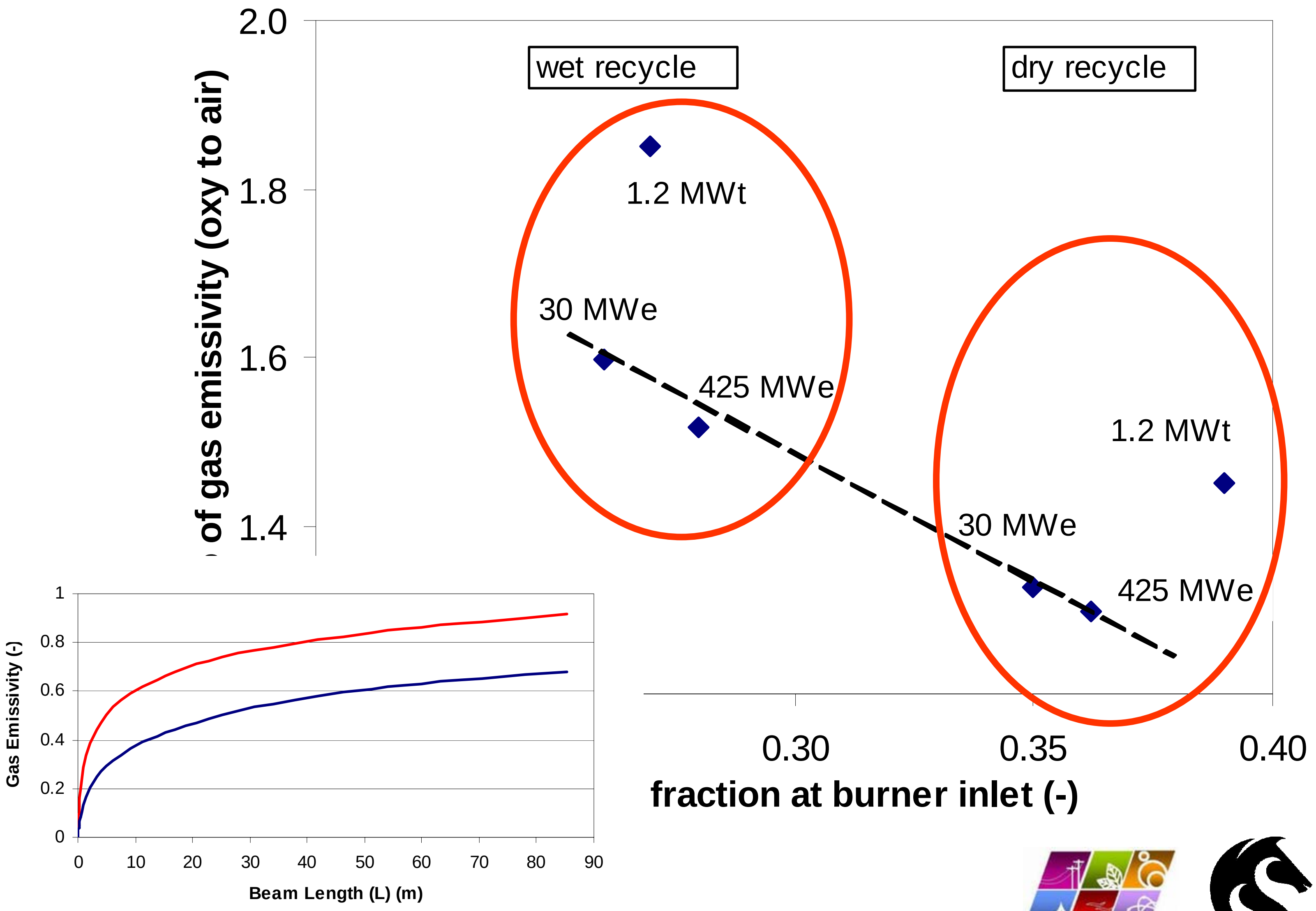
30 MWe Heat flux contours

Air case

Oxy case



Summary plot relating gas emissivity changes to burner oxygen ……



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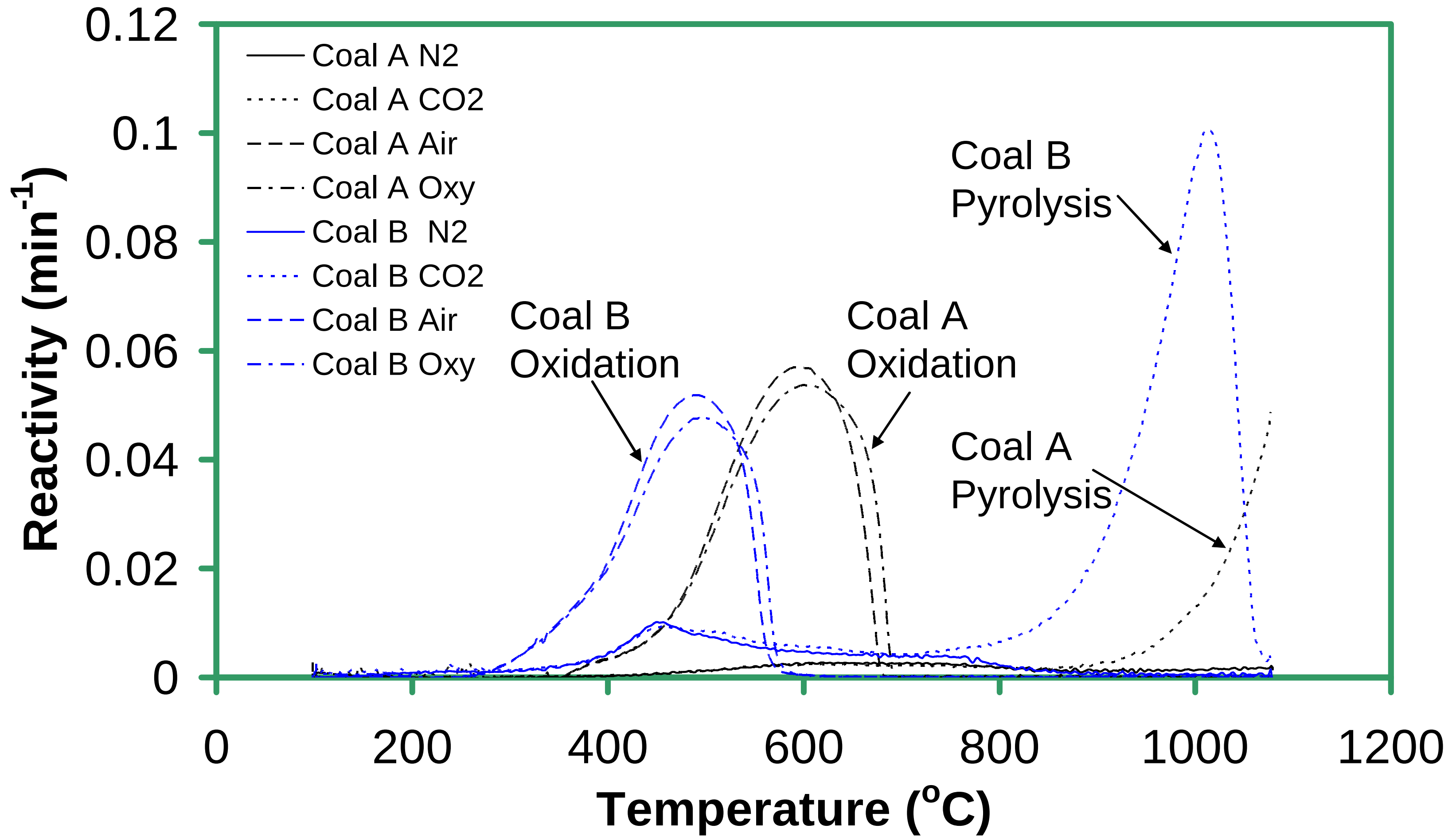
Illustrative differences in air and oxyfuel which influence burnout

For matched furnace heat transfer:

Oxyfuel has longer furnace residence time, ~20%	**Good**
Oxyfuel has lower temperatures, ~ 50 oC	**Bad**
In oxyfuel, coal experiences an environment with higher O2	**Good**

Pyrolysis and oxidation reactivities of Coal A & Coal B in heating TGA experiments



Volatile yields in DTF at 1400 oC

….. Estimated by pyrolysis in N2 and CO2

	Coal B	Coal C	Coal D
V* (N_2)	36.7	30.9	53.5
Q factor (N_2)	1.52	1.43	1.76
V* (CO_2)	43.3	32.2	66.2
Q factor (CO_2)	1.79	1.49	2.18

V* - Volatile yield at 1400 ^{o}C
Q factor – Ratio of V* and volatile yield obtained by proximate analysis

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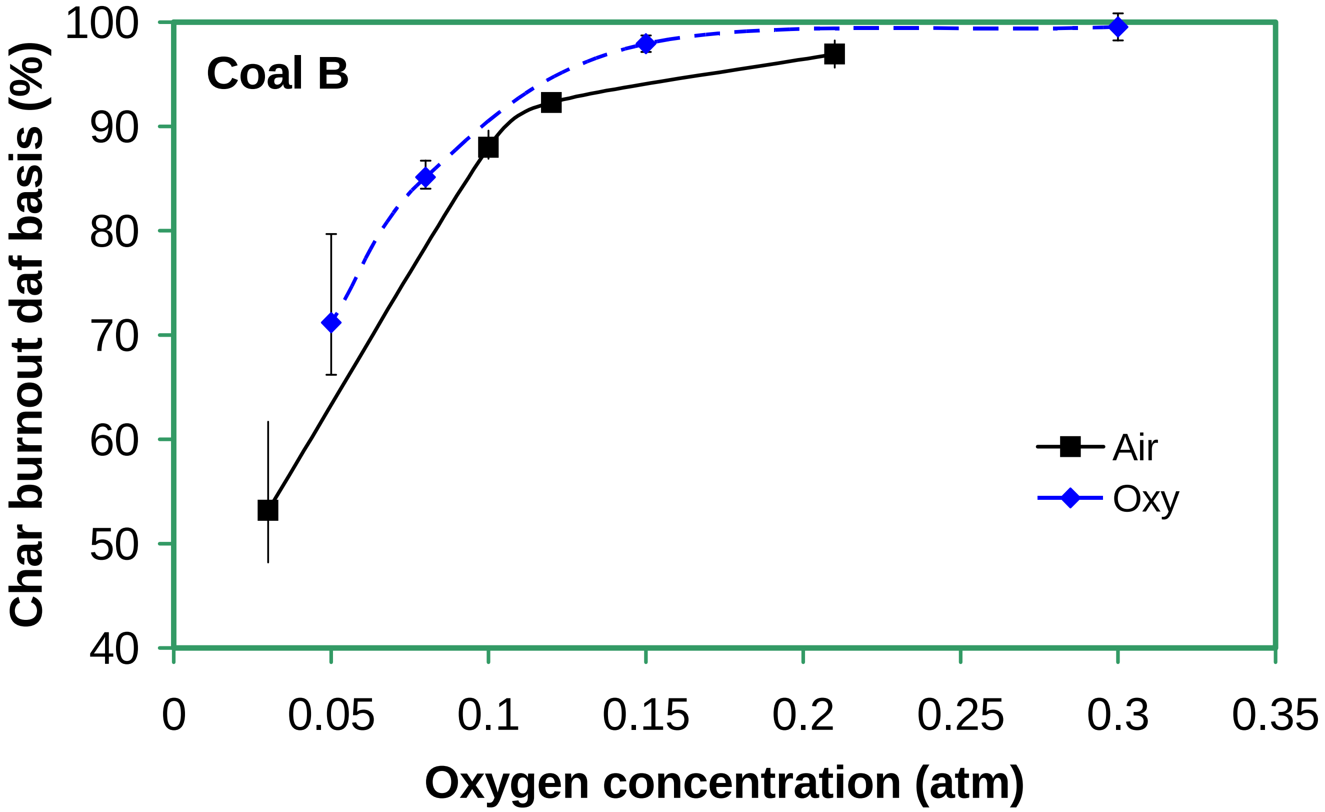
Char burnout in DTF taking $V^*(N_2)$ to estimate char yield



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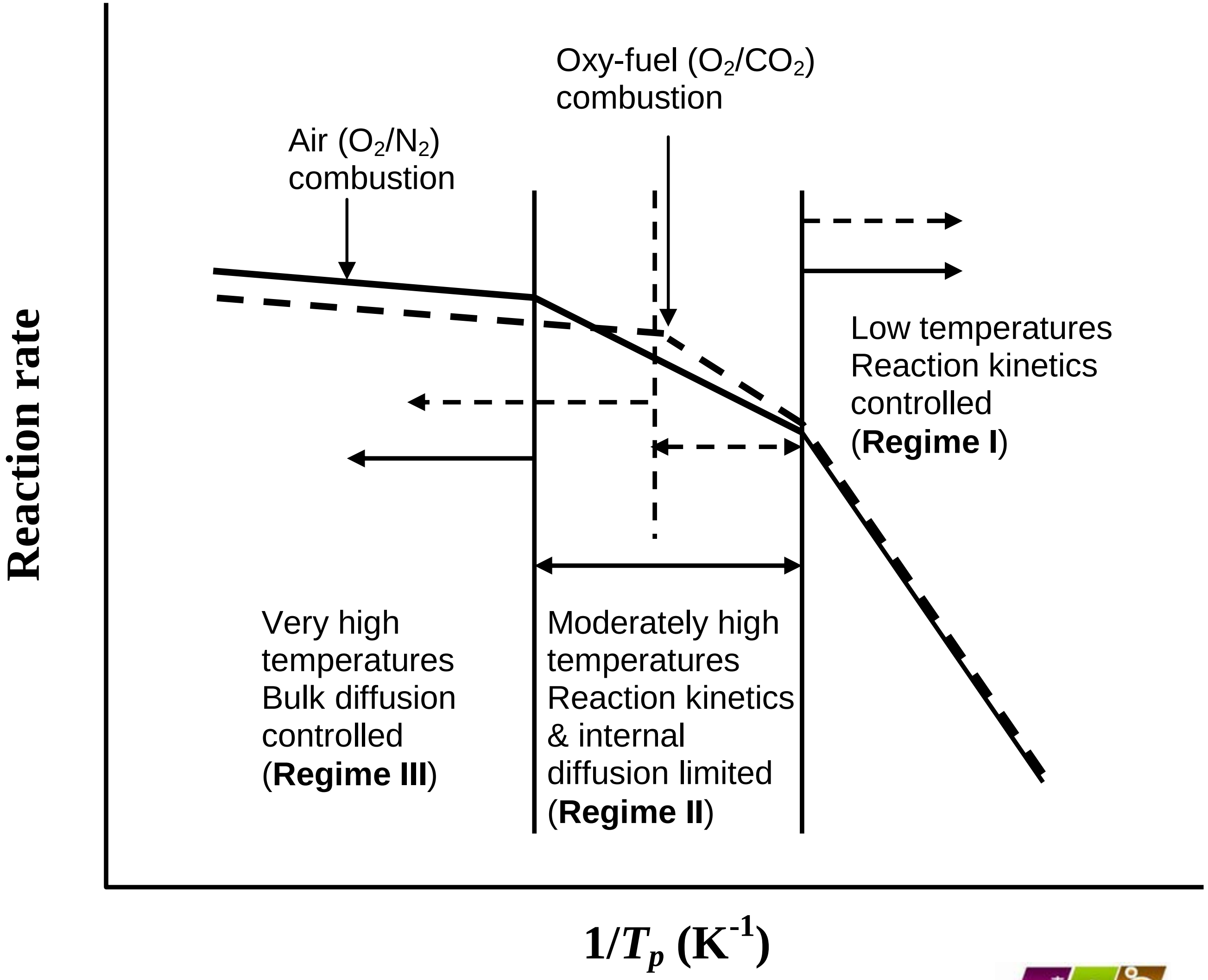
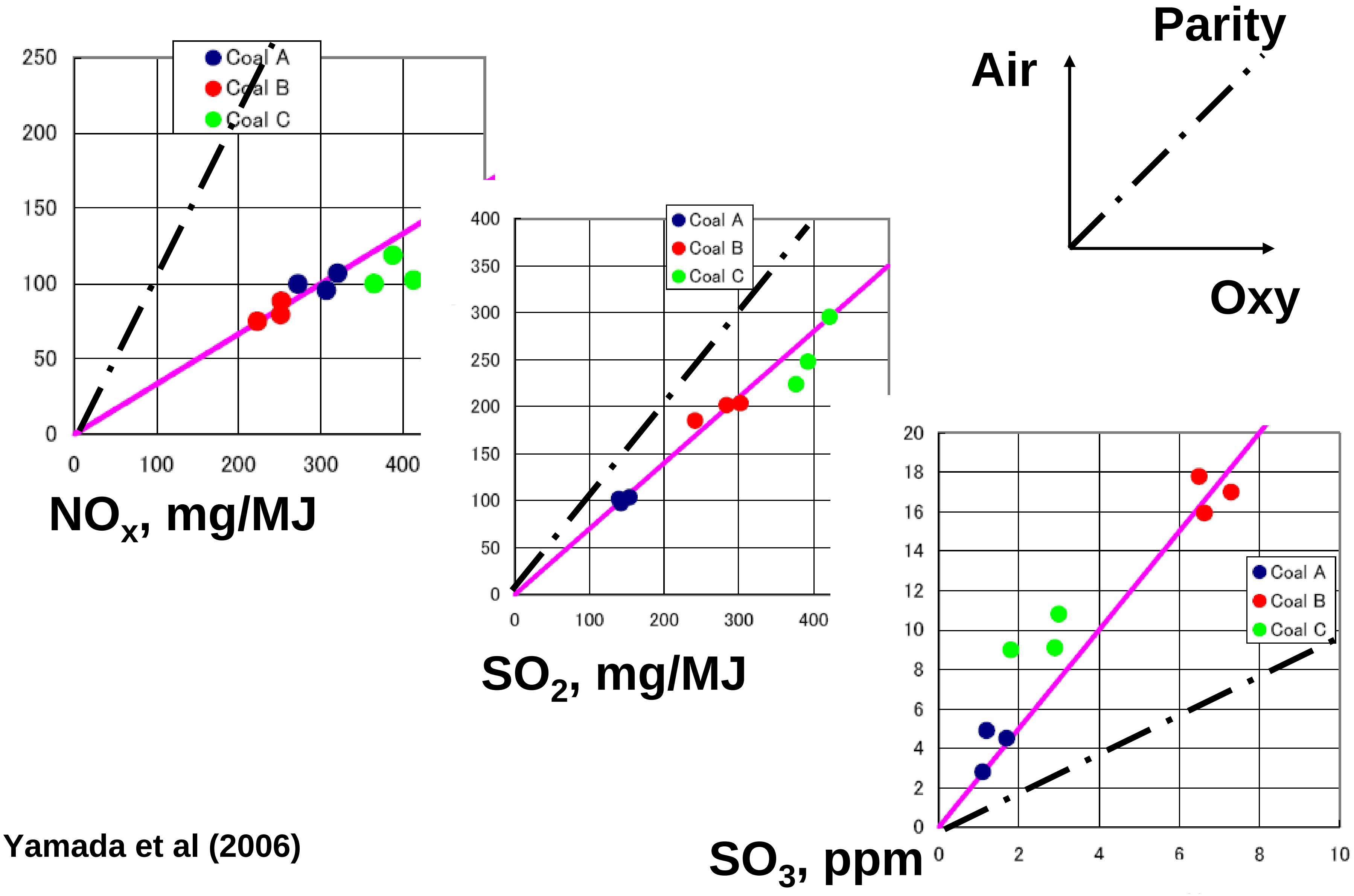
Char reactivity comparison for air and oxyfuel conditions at the same O2 level

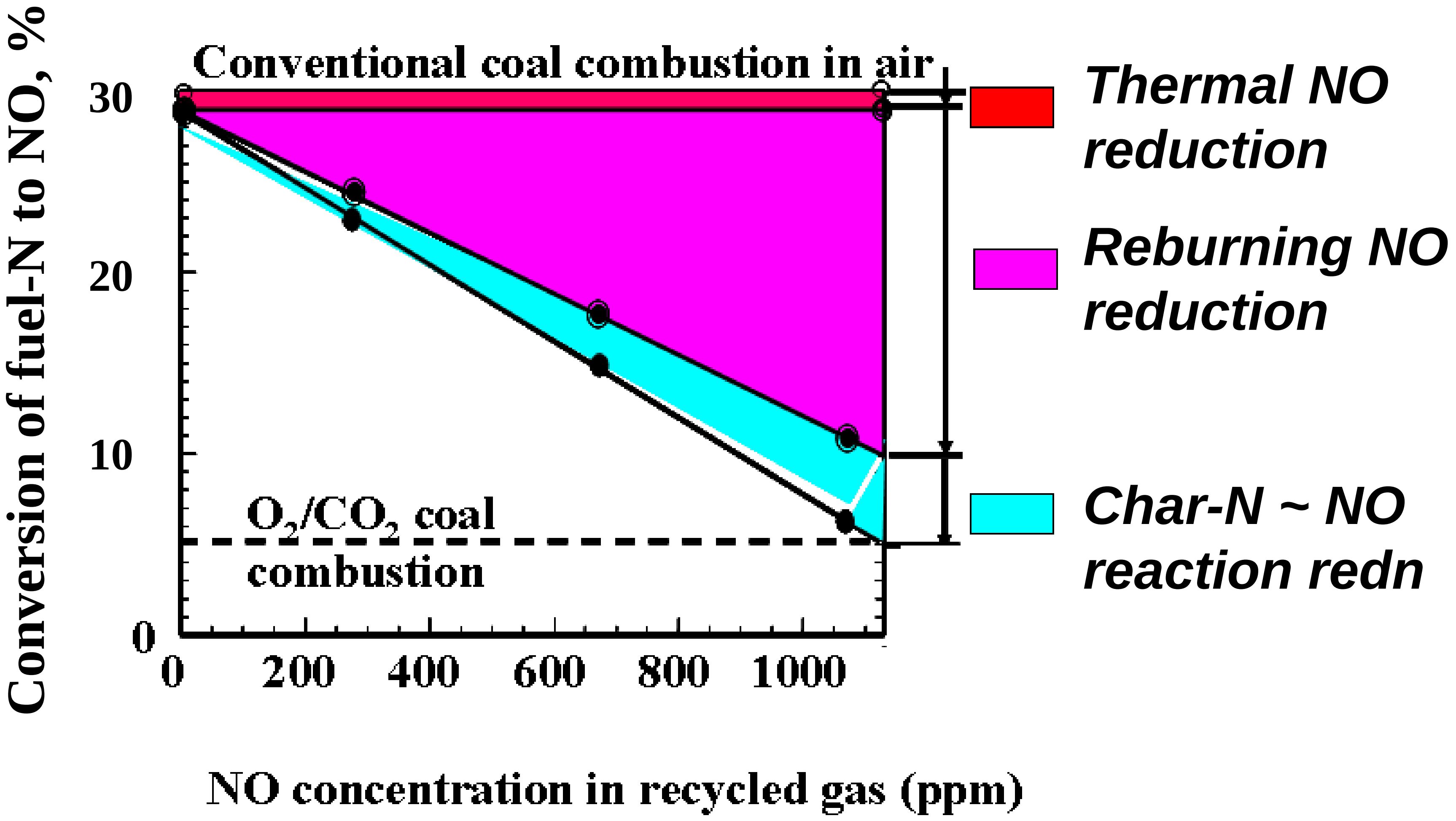


Oxyfuel: Pilot-scale emission comparisons for three coals



Yamada et al (2006)

Oxyfuel: Simulation of recycled CO_2 and NO and fuel-N conversion to NO – the “system” effect



Okazaki and Ando (1997)

Roadmap development

Scales for deployment

Laboratory Scale:

Research that investigates and aims to discover fundamental relationships or test new ideas through experiments and measurements at a small scale.

Pilot Scale

Research undertaken to optimise processes and provide design, process and cost related scale-up rules for application at commercial scale.

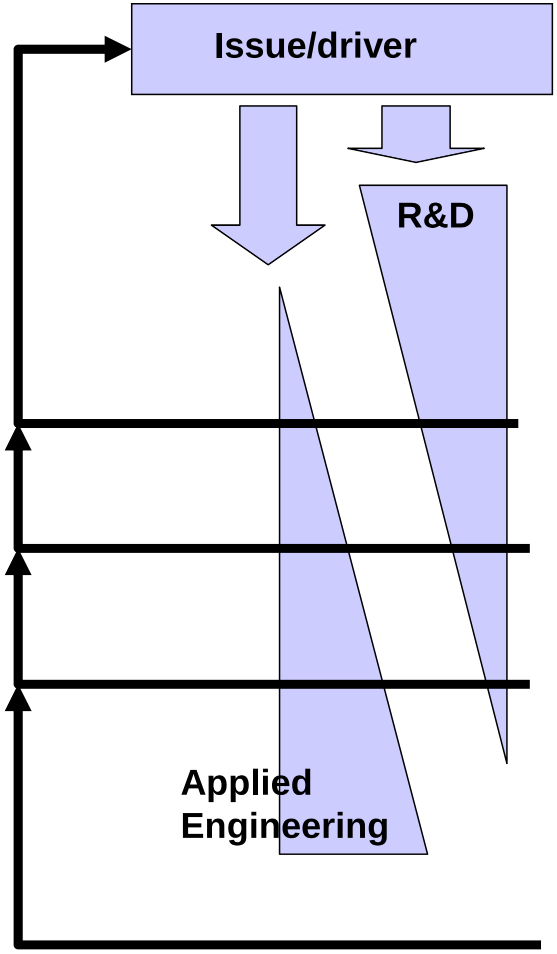
Pre-Commercial Demonstration

First-of-a-Kind (FOAK) plant deployed at Commercial or near Commercial scale where design, process and cost models can be validated for future application in commercial markets.

Commercial Scale

Deployment that is motivated by commercial investment and operates competitively in a fully commercial market

Pathway and drivers of technological development of oxyfuel combustion technology



Issue/driver

R&D

Applied Engineering

Research

Scientific Understanding

Concept development

Laboratory testing

Concept validation

Pilot testing

scaling , commercial understanding,

Demonstration

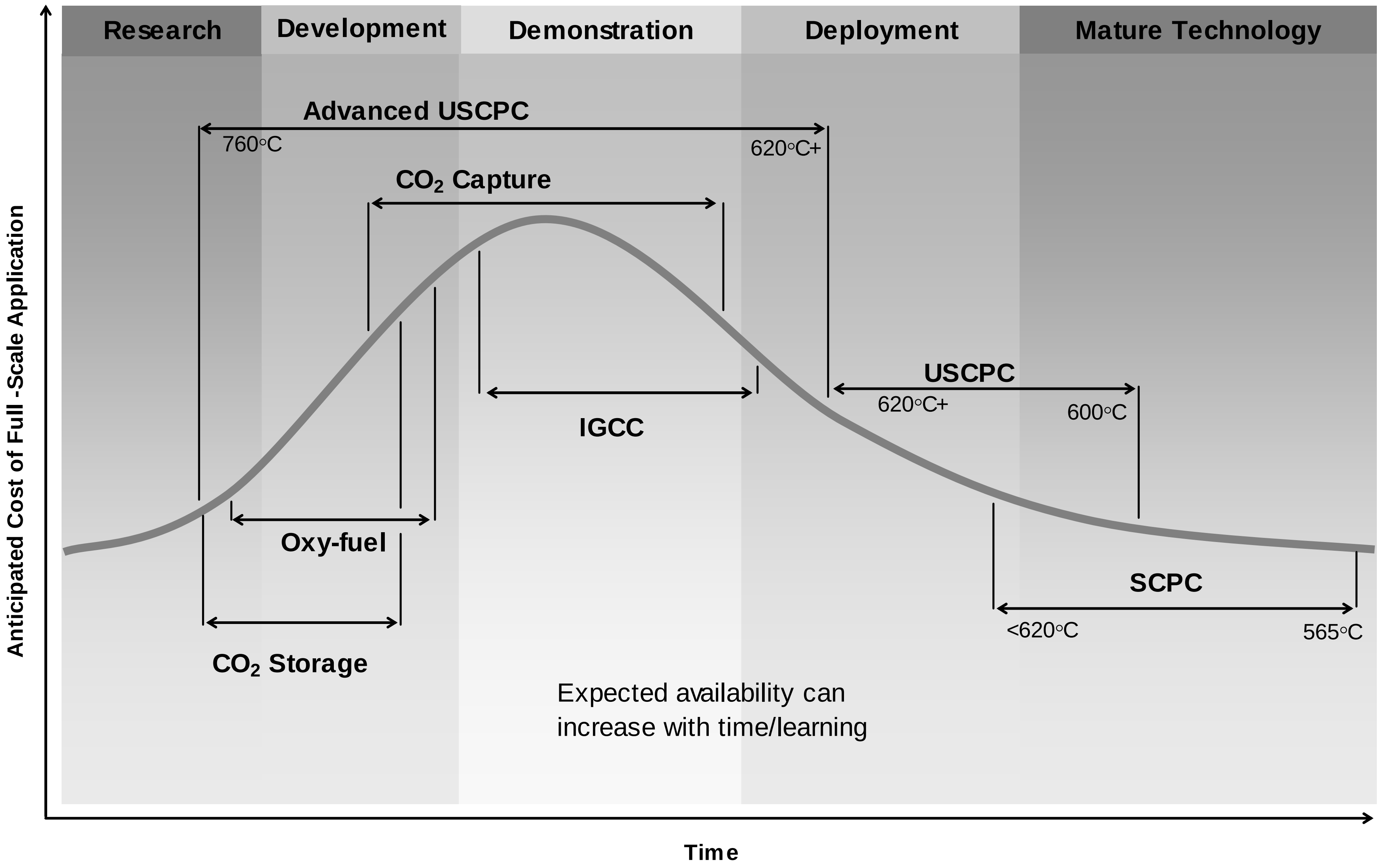
Commercial Validation

Technical validation

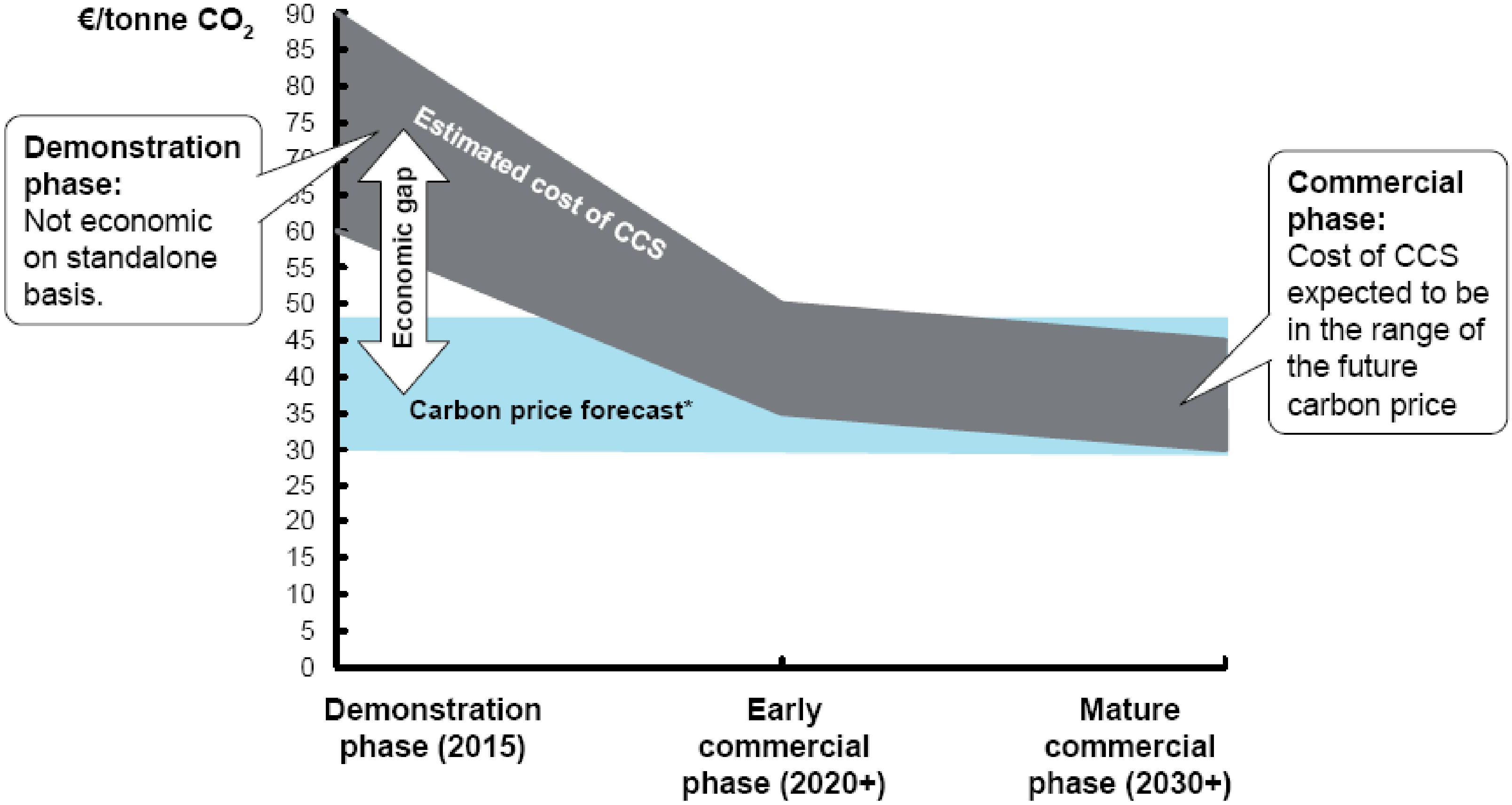
Performance assessment

Commercial deployment

Anticipated cost of CCS-related technologies as they are developed and applied



Indicative CO2 costs to drive development: McKinsey&Company, CCS: Assessing the economics, 2008



Demonstration phase:
Not economic on standalone basis.

Commercial phase:
Cost of CCS expected to be in the range of the future carbon price

* Carbon price for 2015 from 2008-15 estimates from Deutsche Bank, New Carbon Finance, Soc Gen, UBS, Point Carbon, assumed constant afterwards

Source: Reuters; Team analysis

IEA and G8 Workshop recommendation

"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".

http://ccsassociation.org.uk/docs/2007/Press release on G8 workshop 29 Nov 2007.pdf

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Project components and sequence: Low emission coal power plant with geosequestration, based on a 500MW plant, time halved for 50 MW demonstration

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	

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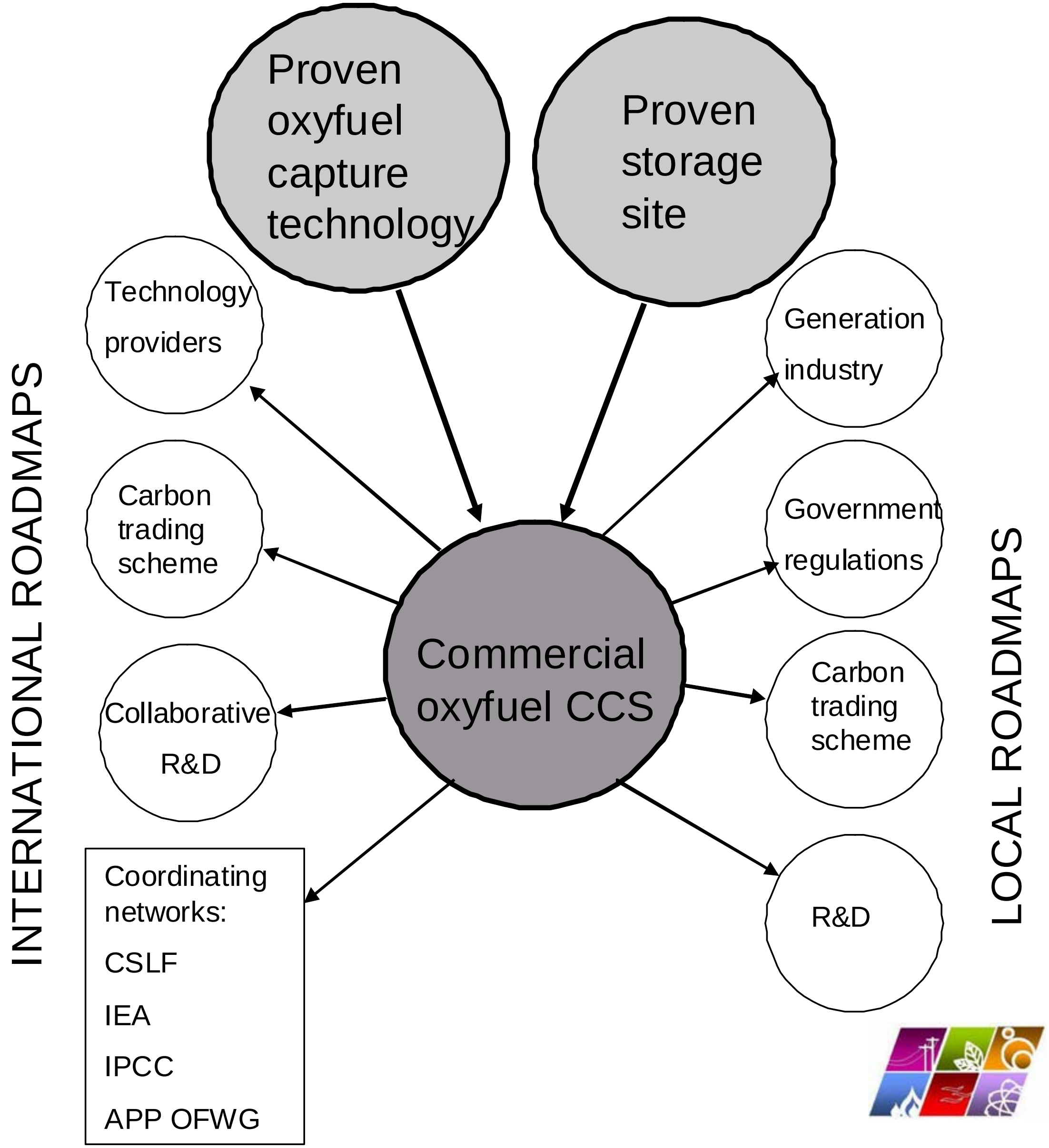
Roadmaps involved which lead to a commercial oxyfuel CCS plant



Proven oxyfuel capture technology

Proven storage site

Commercial oxyfuel CCS

INTERNATIONAL ROADMAPS

Technology providers

Carbon trading scheme

Collaborative R&D

Coordinating networks:

CSLF

IEA

IPCC

APP OFWG

LOCAL ROADMAPS

Generation industry

Government regulations

Carbon trading scheme

R&D

Roadmaps in the literature

Canada’s CO2 Capture and Storage Technology Roadmap

(www.co2trm.gc.ca)

CURC/EPRI Roadmap

(http://www.coal.org/UserFiles/File/Roadmap.pdf)

“Clean Coal Technology Roadmap”, CURC/EPRI/DOE Consensus Roadmap

(http://www.netl.doe.gov/technologies/coalpower/cctc/ccpi/pubs/CCT-Roadmap.pdf)

UK Energy Research Centre, CO2 Capture and Storage Roadmap

(http://ukerc.rl.ac.uk/Roadmaps/CarbonCapture/CCS_road_map_workshop_Aug08.pdf)

Cleaner power in India: Towards a Clean-Coal Technology Roadmap, pp173-193

(http://belfercenter.ksg.harvard.edu/files/Chikkatur_Sagar_India_Coal_Roadmap.pdf)

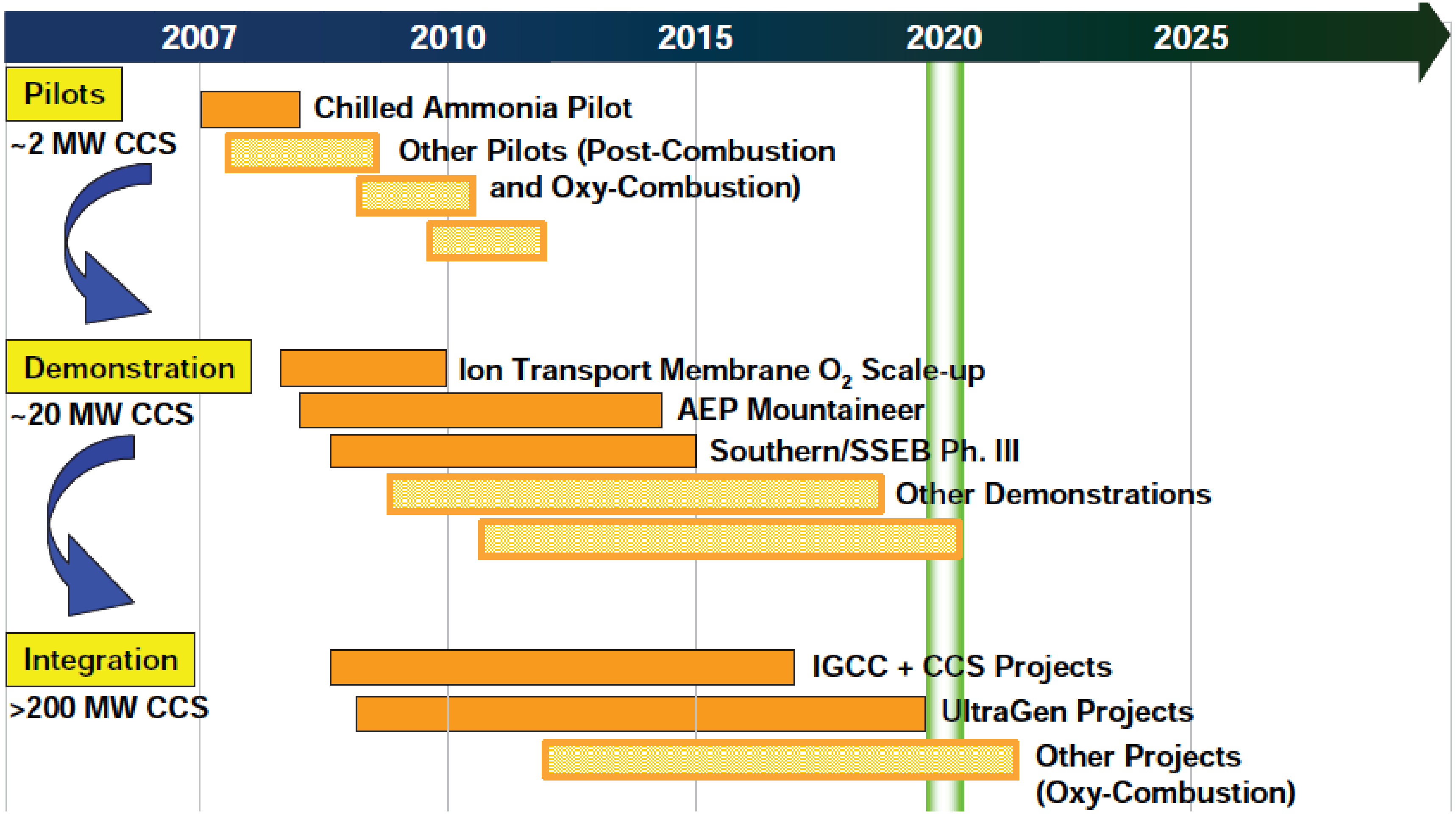
IEA Greenhouse Gas R&D Programme: Review of CO2 capture technology roadmap for power Generation industry

(http://www.ieagreen.org.uk/presentations/SSRoadmap.pdf)

Australia’s CCS Technology Roadmap

(http://www.cslforum.org/documents/SaudiArabia/T2_3_CSLF_PJC_DVP_Australia_Jan08.pdf

CCS roadmap for US (Parkes, Maxson et al. 2008) (Novak 2007)



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Times of targets and milestones

Related deployment targets

By 2020 - Improved efficiency of PF plants by more severe steam conditions, such that efficiencies for oxyfuel with capture reaches 42-44% HHV, similar to PCC and IGCC

By 2022 – Commercial availability of CO2 storage, with new coal plants capture and storing 90% of CO2

By 2030 – Further improvement in efficiencies with CCS, > 45% HHV

Related regulatory milestones

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

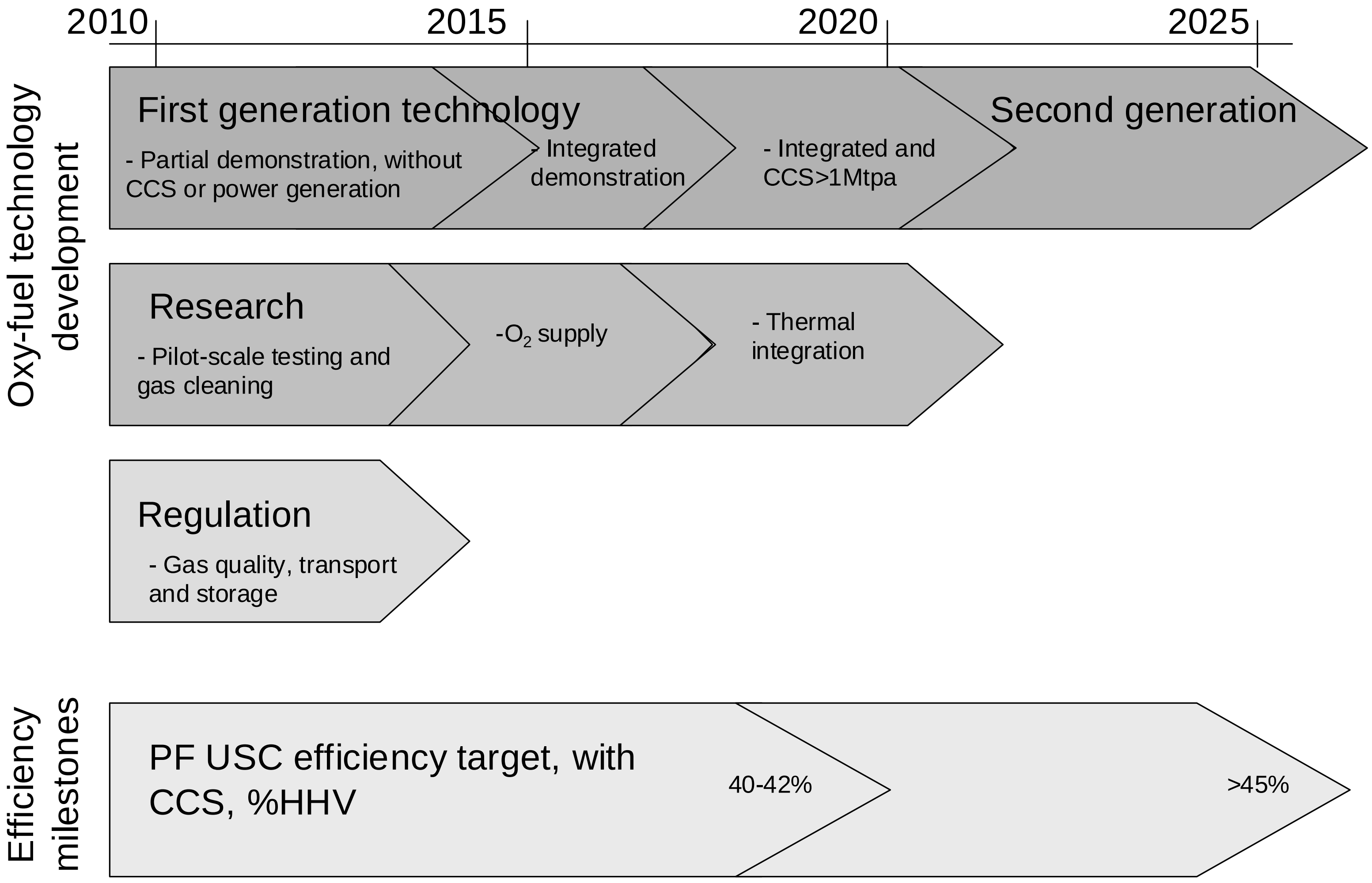
Related research milestones

By 2014 – Gas cleaning technology to meet regulatory requirements for CO2 transport and storage

After 2016 – Alternative oxygen supply technology to ASU such as membranes and chemical looping demonstrated at scale

After 2020 – Second generation oxyfuel plant applied using learnings from first generation demonstrations

Simplified roadmap to deployment of first-generation oxyfuel technology – to be developed further



2010 2015 2020 2025

Oxy-fuel technology development

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

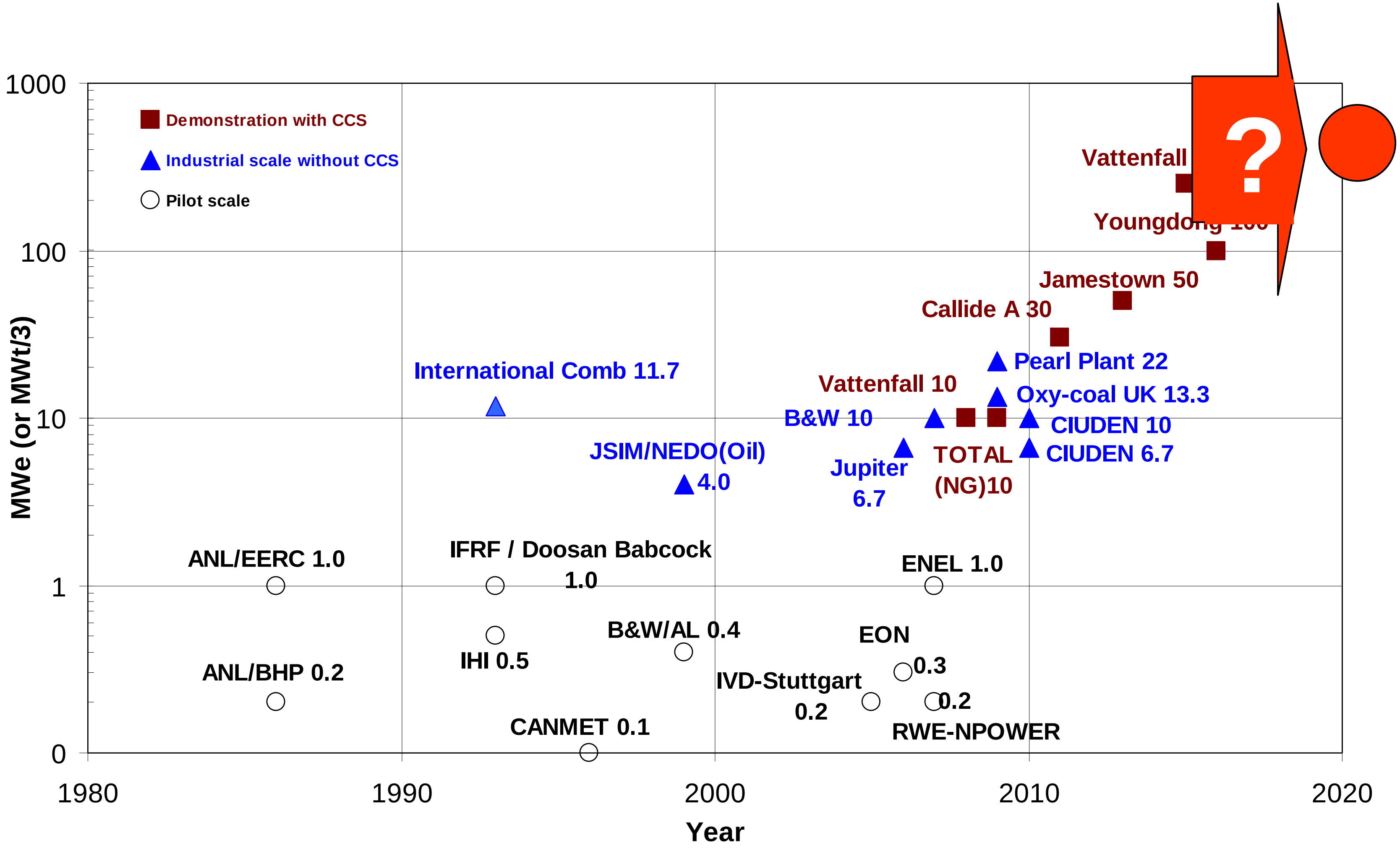
Efficiency milestones

PF USC efficiency target, with CCS, %HHV

40-42%

>45%

Fully integrated industrial-scale demonstration projects by 2020?



Final comments

Oxy-fuel technology is on the path through a development and demonstration phase

….. With 2020 the target for early commercialisation

….. Requiring earlier fully integrated industrial-scale demonstration projects

Current and emerging first generation demonstrations – for retrofits and new plant - will drive future research and technology developments

Second generation technologies – for new plant – will have lower energy penalties and capital costs

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