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CO₂ CAPTURE TECHNOLOGIES

TECHNOLOGY OPTIONS FOR CO₂ CAPTURE
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TECHNOLOGY OPTIONS FOR CO₂ CAPTURE

Brief description of major technologies for CO₂ capture

The main competing technologies for CO₂ capture from fossil fuel usage are:

- Post Combustion Capture (PCC) from the flue gas of Combustion-based plants;
- Pre Combustion Capture from the Syngas in Gasification based plants; and
- Oxy Combustion – the direct combustion of fuel with Oxygen.

These three approaches are shown diagrammatically for coal based power systems in Figure 1-1.

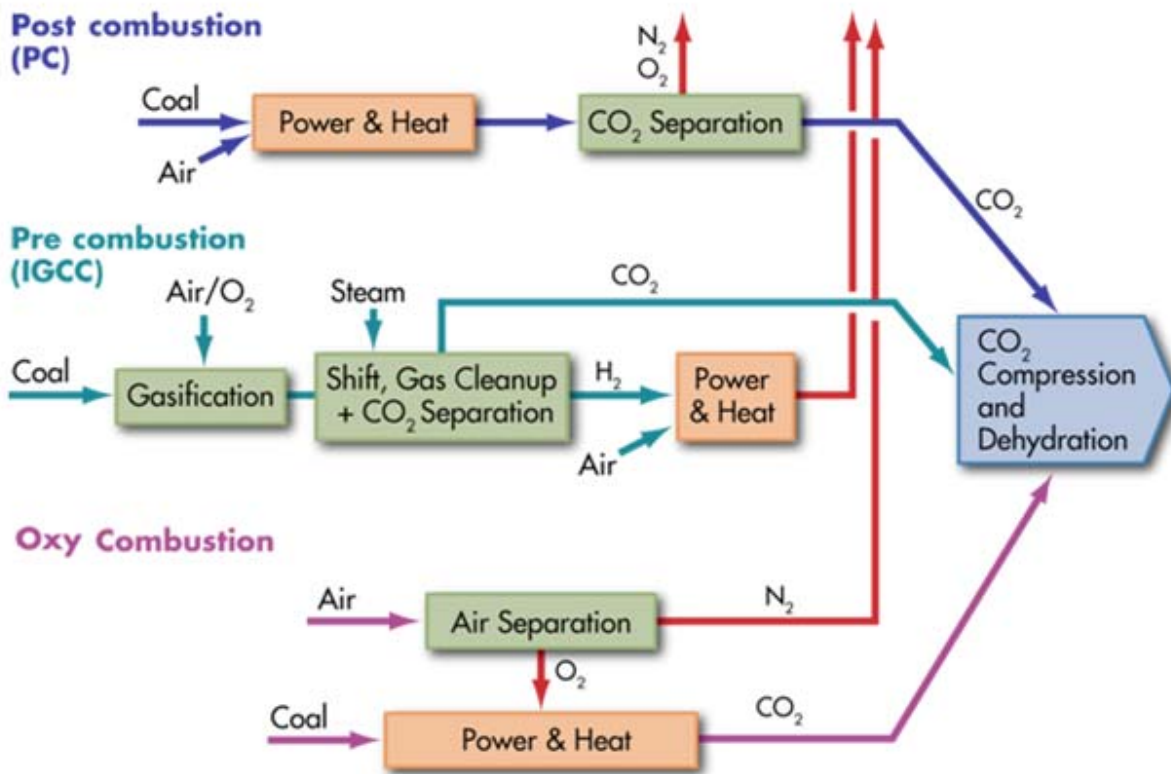


Figure 1-1 Technical Options for CO₂ Capture from Coal Power Plants

Post combustion capture (PCC) at near atmospheric pressure can be applied to newly designed plants or retrofitted to existing coal plants after suitable flue gas clean up. Absorption processes are currently the most advanced of the PCC technologies. The PCC technologies can also be used in other industries besides power e.g. cement, oil refining, and petrochemicals.

Pre-combustion capture in the IGCC power application comprises gasification of the fuel with oxygen or air under high pressure, the use of the shift reaction followed by CO₂ removal using Acid Gas Removal (AGR) processes with hydrogen rich syngas supplied to the gas turbine based power block. Pre combustion capture can be added to existing IGCC plants but in the future IGCC plants will almost certainly be designed with capture from the start. The pre-combustion capture of CO₂ using AGR processes is also practiced commercially in natural gas processing, natural gas reforming and coal gasification plants.

Oxy combustion is the combustion of fuel with oxygen. In an Oxy coal power plant, flue gas is recycled to the oxygen fired boiler to keep the boiler temperature at the level acceptable for boiler tube material integrity. The



flue gas containing mostly CO₂ is purified, dried and compressed. The Oxy technology may also be applied to existing plants but in most cases a new boiler and steam turbine would probably be justified.

Within each of the three major capture categories there are multiple pathways using different technologies which may find particular application more favourably in certain climate conditions, locations, elevations and coal types.

The importance of improved efficiency

The addition of CO₂ capture incurs a very significant loss of efficiency and power output that has a large effect on the LCOE economics since the capital cost has to be spread over less MWh and the fuel cost per MWh is increased. This document is focused on the CO₂ capture technologies and potential improvements to reduce the energy losses and capital costs associated with capture. However, a major contribution to the reduction of CO₂ from fossil based plants will be achieved through increases in the efficiency of the basic technologies of pulverized coal combustion and combustion (gas) turbines.

For example, considerable work is underway to develop and qualify advanced materials that will enable the use of ultra supercritical steam conditions with higher temperatures (up to 700-750°C) and pressures (up to 350 bar). This, in turn, will lead to higher plant efficiencies and lower CO₂ emissions per MWh. As illustrated in Figure 1-2 a 20% reduction in CO₂ emissions can be achieved through efficiency improvement. EPRI studies indicate that this CO₂ emissions reduction from efficiency improvement can be accomplished at lower cost per tonne of CO₂ removed than from CO₂ capture.

For PCC, the major energy losses are incurred in sorbent regeneration and CO₂ compression. Current PCC R&D is focused on improved sorbents that require less energy for regeneration and/or could be regenerated at pressure, thereby reducing the CO₂ compression energy required.

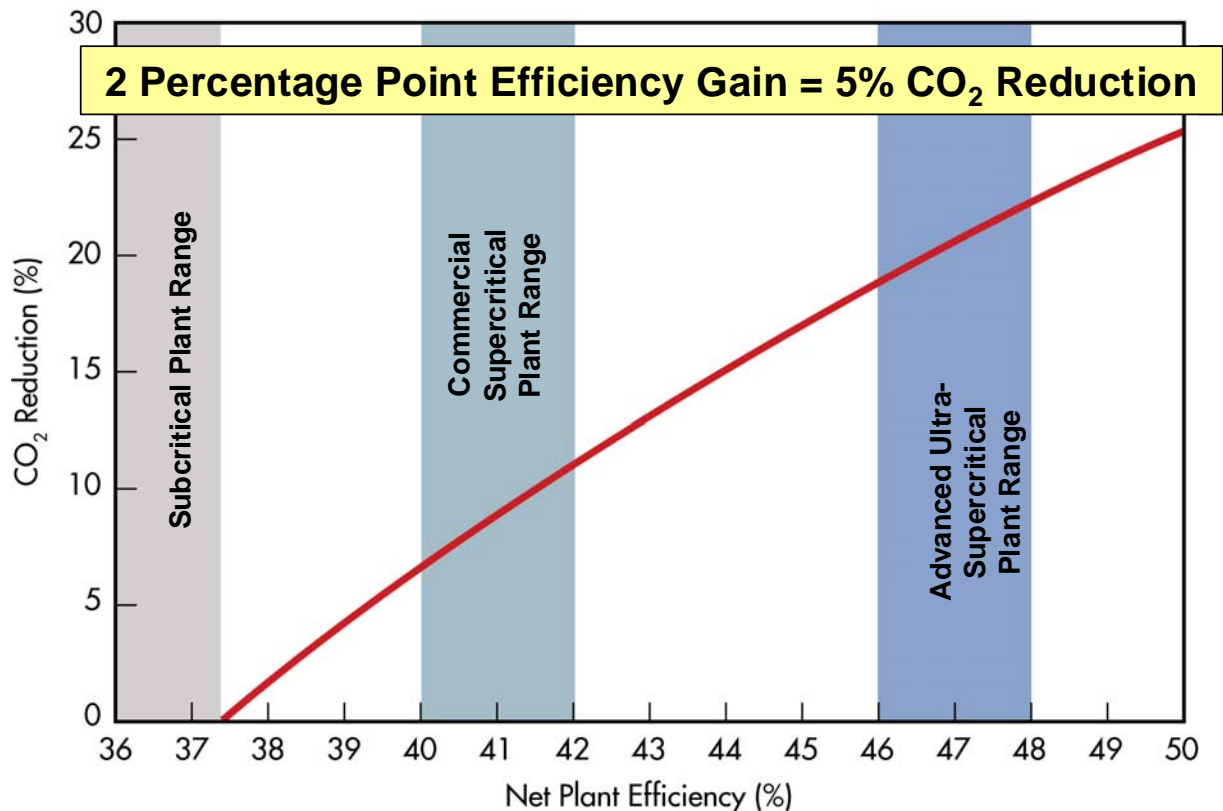


Figure 1-2 PC Plant Efficiency and CO₂ Reduction



There are also major developments underway to increase the firing temperatures (up to 1600°C) and efficiencies of gas turbines. These developments will in turn reduce the CO₂ emissions from natural gas combined cycle (NGCC) and Integrated Gasification Combined Cycle (IGCC) plants.

For IGCC pre combustion capture, the major energy losses are incurred in the air separation unit (ASU), water-gas shift, gas cooling and CO₂ separation areas. The IGCC R&D is focused on improvements to the ASU, gasification, shift catalysts, and in the processes and equipment that reduce the energy loss of the separation of hydrogen from CO₂ and of CO₂ compression. The use of higher firing temperature higher efficiency gas turbines will further increase plant efficiency and reduce the CO₂ emitted per MWh. These gas turbines will also be of larger sizes that will provide further economies of scale and improve economics.

For oxy combustion the major energy penalty is in the ASU area. Current oxy combustion R&D is focused on energy improvements to the ASU, potential reduction of recycle gas and CO₂ purification energy losses. . The use of higher temperature materials in the boiler and steam turbine will further increase efficiency and reduce the CO₂ emitted per MWh.

Technology readiness level (TRL)

Throughout this chapter the term Technology Readiness Level (TRL) will be used to indicate the development level of the technologies described. The following outline of the TRL concept has been mostly taken from the Global CCS Institute Report #4 of the Strategic Analysis Series.

This TRL approach can be particularly useful in tracking the status of individual technologies throughout the stages of the R&D timeline. The nine TRLs are listed in Table 1-1.

The achievement of a given TRL will inform process developers and organizations of the resources required to achieve the next level of readiness. An achievement of TRL-9 indicates that the first successful operation at normal commercial scale has been achieved and that the technology can be deployed with risks that are comparable to those undertaken on other commercial technologies. Progressively higher technical and financial risks are required to achieve the TRLs up to and including TRL-9.

Table 1-1 The nine technical readiness levels

TRL-9	Full-Scale Commercial Deployment
TRL-8	Sub-Scale Commercial Demonstration Plant (>25% commercial scale)
TRL-7	Pilot Plant (>5% commercial scale)
TRL-6	Component Prototype Demonstration (0.1-5% of full scale)
TRL-5	Component Prototype Development
TRL-4	Laboratory Component Testing
TRL-3	Analytical, 'Proof of Concept'
TRL-2	Application Formulated
TRL-1	Basic Principles Observed

More detailed information on the background justification for the TRL rankings in this document are included and discussed in the separate sections of this document that cover each of the three major capture pathways.

While the actual TRL levels of technologies and sectors have not changed since 2009 there has been significant progress towards higher TRL in most areas.



Commercial demonstration of advanced coal technologies

The development of emission controls on coal fired power plants can be used as an example of technology progression through the required TRLs. In the mid-20th century, coal-fired power plants had limited controls for sulphur dioxide (SO₂), nitrogen oxides (NO_x) or mercury emissions. Throughout the past 50 years, various technologies to control these pollutants have progressed from about TRL-4 to full commercial availability. This experience has shown that the achievement of TRL-9 can take approximately 20 or more years. This long development period is largely dictated by costs, design, construction and operational testing activities associated with the pilot plants (to achieve TRL-7), sub-scale commercial demonstration plants (to achieve TRL-8) and the first full-scale, commercial deployment (TRL-9).

EPRI comments

The use of TRL in the context of advanced coal technologies has some drawbacks. The TRL classification system was devised by NASA to assess technology readiness only. It was not designed to address 'economic' readiness. Thus, a technology may reach TRL-9 and be technically mature and still not meet project economic requirements. The TRL system does not address the economic feasibility of deploying the technology.

In the past few years, 'full scale' coal-fired power plants purchased by utilities have a net capacity exceeding 400 MWe and largely greater than 600 MWe. For the purposes of a TRL assessment of advanced coal technology, it is suggested that TRL-9 would be achieved by a power plant in the capacity range 400-800 MWe (net). By this metric, successful operation of the Kemper County (524 MWe) would achieve TRL-9, albeit at a CO₂ capture rate less than the 90% commonly imagined. Successful operation of Boundary Dam (110 MWe) and FutureGen (200 MWe) would achieve TRL-8: sub-scale commercial demonstration plant. Technology suppliers to Boundary Dam and FutureGen may claim 'commercial' operation, but it would be operation at a scale significantly less than that commonly purchased by utilities.

Integrated CCS demonstration is crucially needed

Although current technology needs further improvements, it is extremely important to demonstrate CCS on a commercial scale as soon as possible. This is needed for the demonstration of capture technology operating in an integrated mode in a real power plant and in a real power grid environment. It is also necessary to demonstrate sequestration/storage at sufficient scale that has credibility for further deployment. Unless progress is made at the commercial CCS demonstration scale to answer these two basic issues it will become increasingly difficult to justify continued R&D funding on potential improvements to capture and storage technologies.

If multiple CCS demonstrations with improved technologies are to be achieved at large-scale (i.e., TRL-9) by 2020 to proceed with commercial deployment, then many technologies need to be approaching the pilot plant stage (TRL-7) today. However, currently there are very few organizations funding demonstrations at one-tenth to full commercial-scale. Some pilot plant scale capture projects have been funded but advancing to sub-commercial scale demonstrations and larger will require an order of magnitude greater level of funding.

The total capital cost of investment for PCC demonstration would be significantly lower if PCC was retrofitted to an existing coal plant than if a new SCPC with PCC was constructed. However, the technical risk is probably not very different from that associated with a newly built SCPC with PCC. PCC retrofit to an existing plant will also incur a loss of power output of perhaps 30% so that replacement power may be needed.

Commercial deployment of CCS technology

Sub-scale commercial demonstration projects are being developed in the US and Europe and the Boundary Dam PCC plant is under construction. The initial integrated full scale commercial sized CCS coal based demonstration projects will only proceed with significant government support. The Kemper County IGCC plant is currently the only full scale CCS plant that is fully funded and in construction. While integrated commercial CCS demonstration projects are clearly a pre-requisite, full scale commercial deployment will only proceed is



there is a value attributable to the reduction of CO₂ emissions (or possible sale) and that CCS is found to be a competitive abatement choice.

It can be noted that some pre combustion and post combustion capture industrial projects have been able to proceed because of the value attributable to the sale of the CO₂ for EOR.

Advantages and disadvantages of major CO₂ capture technologies

Post combustion capture advantages

- Can be retrofitted to existing plants allowing the continued operation of valuable resources
- In either new build or retrofit application it enables the continued deployment of the well established Pulverized Coal (PC) technology familiar to power industries worldwide
- The continued development of improved materials for Ultra Supercritical (USC) plants will increase the efficiency and reduce the CO₂ emissions of future PC plants
- The widespread R&D on improved sorbents and capture equipment should reduce the energy penalty of PCC capture
- Sub-scale demonstration of PCC is proceeding. The 110 MW Boundary Dam project of Saskatchewan Power with PCC using the Cansolv process is under construction with planned operation in 2014.

Post combustion capture challenges

- Amine processes are commercially available at relatively small scale and considerable re-engineering and scale-up is needed
- The addition of capture with current amine technologies results in a loss of net power output of about 30% and a reduction of about 11 percentage points in efficiency. In the case of retrofit this would imply the need for replacement power to make up for the loss.
- Most sorbents need very pure flue gas to minimize sorbent usage and cost. Typically < 10 ppmv or as low as 1 ppmv of SO₂ plus NO₂ is required depending on the particular sorbent
- Steam extraction for solvent regeneration reduces flow to low-pressure turbine with significant operational impact on its efficiency and turn down capability.
- Water use is increased significantly with the addition of PCC particularly for water cooled plants where the water consumption with capture is nearly doubled per net MWh. For air cooling the water consumption is also increased with capture by about 35% per net MWh.
- Plot space requirements are significant. The back-end at existing plants is often already crowded by other emission control equipment. Extra costs may be required to accommodate PCC at some more remote location.

Pre combustion capture advantages

- Pre combustion capture using the water-gas shift reaction and removal of the CO₂ with AGR processes is commercially practiced worldwide.
- Pre combustion capture of the CO₂ under pressure incurs less of an energy penalty (~20%) than current PCC technology (~30%) at 90% CO₂ capture.
- Ongoing R&D on improved CO shift catalysts, higher temperature gas clean up and membrane separation technology for hydrogen and CO₂ has the potential to produce a step-change reduction in the energy penalty of capture
- Water use, while still substantial, is lower than with PCC
- The ongoing continued development of larger more efficient gas turbines can markedly improve the efficiency of future IGCC plants
- The Kemper County plant in Mississippi, an IGCC plant with pre combustion capture, is under construction with planned operation in 2014.



Pre combustion capture challenges

- While the energy loss with addition of pre-combustion capture is lower than with the addition of PCC the energy loss is still significant
- The commercial demonstration of large F or G gas turbines firing hydrogen has yet to be demonstrated in an IGCC plant with capture
- In the event of a need to vent the CO₂ additional purification may be needed
- IGCC is not yet very widely used in the power industry
- The capital costs of IGCC without capture are much higher than SCPC without capture. The IGCC costs need to be reduced to compete more effectively.

Oxy combustion advantages

- Oxy-combustion power plants should be able to deploy conventional, well-developed, high efficiency steam cycles without the need to remove significant quantities of steam from the cycle for CO₂ capture.
- The added process equipment consists largely of rotating equipment and heat exchangers; equipment familiar to power plant owners and operators. (No chemical operations or significant on-site chemical inventory).
- Ultra-low emissions of conventional pollutants can be achieved largely as a fortuitous result of the CO₂ purification processes selected, and at little or no additional cost.
- On a cost per tonne CO₂ captured basis, it should be possible to achieve 98+% CO₂ capture at an incrementally lower cost than achieving a baseline 90% CO₂ capture.
- Development of chemical looping combustion with advanced ultra-supercritical steam cycles could result in an oxy-combustion power plant (with CO₂ capture) that is higher efficiency than air-fired power plants being built today (without CO₂ capture).
- The best information available today (with the technology available today) is that oxy-combustion with CO₂ capture should be at least competitive with pre- and post-combustion CO₂ capture and may have a slight cost advantage.

Oxy combustion challenges

- It is not possible to develop sub-scale oxy-combustion technology at existing power plants. An oxy-combustion power plant is an integrated plant and oxy-combustion technology development will require commitment of the whole power plant to the technology. Thus, the technology development path for oxy-combustion may be more costly than that for either pre-combustion or post-combustion capture which can be developed on slip streams of existing plants.
- The auxiliary power associated with air compression in a cryogenic air separation unit and CO₂ compression in the CO₂ purification unit will reduce net plant output by up to 25% compared to an air fired power plant with the same gross capacity (without CO₂ capture).
- There is no geological or regulatory consensus on what purity levels will be required for CO₂ compression, transportation and storage. For this reason, most oxy-combustion plant designs include a partial condensation CO₂ purification system to produce CO₂ with purity comparable to that achieved by amine post combustion capture. Oxy-combustion costs may be reduced if the purity requirements could be relaxed.
- Air-fired combustion is commonly anticipated for start-up of oxy-combustion power plants. The very low emissions achieved by oxy-combustion with CO₂ purification cannot be achieved during air-fired start-up operations without specific flue gas quality controls for air-fired operations that are redundant during steady state oxy-fired operations. If a significant number of annual restarts are specified, either these added flue gas quality controls will be required (at additional capital cost) or provisions must be made to start up and shut down the unit only with oxy-firing and without venting significant amounts of flue gas.
- Plot space requirements are significant for the air separation unit and CO₂ purification units.



ACRONYMS AND SYMBOLS

AFBC	Atmospheric Fluidized Bed Combustion
AGR	Acid gas removal
AQCS	Air Quality Control System
ASU	Air Separation Unit
B&W	Babcock & Wilcox
Bara	Bars absolute
Barg	Bars gauge
BFW	Boiler feedwater
BP	British Petroleum
Btu	British thermal unit
CC	Combined Cycle
CCGT	Combined Cycle Gas Turbine
CCPI	Clean Coal Power Initiative
CCS	CO ₂ capture and Storage (or Sequestration)
CCT	Clean Coal Technology
CF	Capacity Factor
CFB	Circulating fluidized bed
CHP	Combined Heat and Power
CO ₂	Carbon dioxide
COE	Cost of electricity
COP	ConocoPhillips
CT	Combustion Turbine
DOE	U. S. Department of Energy
DOE NETL	Department of Energy National Energy Technology Laboratory
ECUST	East China University of Science and Technology
EEPR	European Energy Programme for Recovery
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
FBC	Fluidized-bed combustion/combustor
FEED	Front End Engineering Design
FGD	Flue gas desulphurization
FOAK	First of a kind
F-T	Fischer Tropsch
ft ³	Cubic feet
FW	Foster Wheeler
FWI	Foster Wheeler Italiana
GHG	Greenhouse Gas
GI	Gasification Island
GJ	Gigajoule
gpm	Gallons per minute (US)
GT	Gas Turbine
H ₂ S	Hydrogen sulfide
HgA	Mercury absolute
HHV	Higher heating value
HRSG	Heat recovery steam generator
HP	High pressure
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IP	Intermediate pressure
IPP	Independent power producer
kJ	Kilojoules
KBR	Kellogg, Brown & Root



LCA	Life Cycle Analysis
LCOE	Levelized Cost of Electricity
LHV	Lower heating value
LP	Low pressure
LSTK	Lump Sum Turnkey
mt	Metric ton
MDEA	MethylDiethanolamine
MMBtu	Million Btu
MPa	Mega Pascal
MTG	Methanol to Gasoline
MTO	Methanol to Olefins
NCCC	National Carbon Capture Center
NDRC	National Development and Reform Commission (China)
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle
NH ₃	Ammonia
Nm ³	Normal cubic meters
NO _x	Nitrogen oxides
NSPS	New Source Performance Standards
OCGT	Open Cycle Gas turbine
O&M	Operation and maintenance
PC	Pulverized Coal
PCC	Post Combustion Capture
ppmv	parts per million by volume
PRB	Powder River Basin (Coal)
PSDF	Power System Development Facility
psia	Pounds per square inch absolute
psig	Pounds per square inch gage
R&D	Research & Development
RD&D	Research, Development and Demonstration
RQ	Radiant Quench (GE)
RTI	Research Triangle Institute
RWE	Rheinische Westphalien Electricidadeswerke
SCFD	Standard Cubic Feet per day
SNG	Substitute Natural Gas
SCPC	Supercritical Pulverized Coal
SCR	Selective catalytic reduction
SO ₂	Sulphur dioxide
SRU	Sulphur Recovery Unit
st	Short ton (2000 pounds)
stpd	Short tons per day
TCR	Total Capital Requirement
TFC	Total Field Cost
TPC	Total Plant Cost
USC	Ultra Supercritical
US EPA	US Environmental Protection Agency
WGCU	Warm gas clean up