Post-combustion Carbon Capture with liquid solvents

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CCS – Basics, practical examples and deployment: an immersive workshop

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Presentation Outline

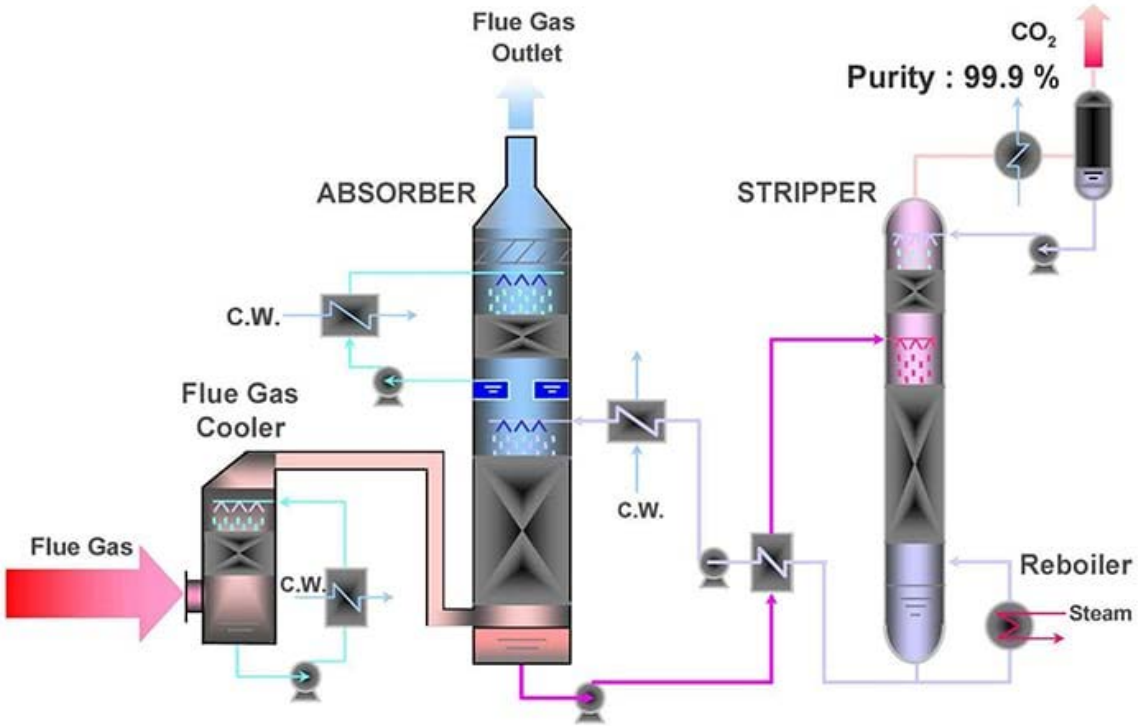
- Post-combustion CO_2 Capture **technologies**
- Considerations for PCC **integration**
- **Steam cycle design options** for steam extraction
- **CCS retrofits** on existing power / industrial plants
- **Carbon Capture Readiness**
- **Future-proofing** plants with PCC against technology developments
- **Flexible operation** with PCC
- **Challenges for implementation** of PCC with solvents
- Recommendations for **Pilot Plant Test Program**
- Operation options for **cost reduction**

Post-combustion CO_2 Capture technologies

- Post-combustion Carbon Capture (PCC) can be implemented in new-build power plants and industrial facilities (e.g. cement, steel and iron, refineries, hydrogen plants via steam methane reforming, etc.)
- PCC technologies are also suitable for retrofitting existing plants, as they are located at the tail end
- The original plant/core process remains unchanged
- Highly-developed alternative – commercial experience at large scale operation
- The presence of impurities in the flue gas can however affect the subsequent CO_2 capture process (depending on the technology)

Post-combustion CO_2 Capture technologies

- **Chemical absorption with aqueous solvents**
  - ✓ Amine-based solvents (MEA, amine-based blended solvents, proprietary solvents, etc)
  - ✓ Other solvents
- Adsorption on solid sorbents
  - ✓ Zeolites, carbon-based materials, metal-organic frameworks, functionalised adsorbents
- Calcium looping and Chemical looping
- Membrane-based separation
- Cryogenic capture



Source: National Energy Technology Laboratory

Post-combustion Carbon Capture

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- Adsorption on solid sorbents
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- Cryogenic capture

Source: Membrane Technology & Research (MTR)

Post-combustion Carbon Capture technologies

Post-combustion carbon capture technologies: TRLs and LCOE reduction prospects (IEAGHG, 2014/TR-4)

Technology	TRL	Prospects to reduce the LCOE increase for capture
Benchmark proprietary mono-ethanolamine (MEA) process	9	LCOE increase expected to be about 100% of baseline
Improved conventional solvents	6-8	Incremental reductions possible
Encapsulated solvents	1	Potential still to be proven
Precipitating solvents	4-5	5-10%
Biphasic solvents	4	16%
Ionic liquids	1	No viable process yet
Polymeric membranes	6 (fast development possible)	30%
Polymeric membrane/cryogenic separation hybrid	6 (fast development possible)	Similar or better than polymeric membrane alone
Room temperature ionic liquid (RTIL) membranes	2	Could be similar or better than polymeric membranes

Technology	TRL	Prospects to reduce the LCOE increase for capture
Enzyme catalysed adsorption	1	7% Incremental reduction due to reduced absorber size
Algae based capture	1	Unlikely in mid-term future
Electrochemically mediated absorption	1	High electrical energy consumption makes reduction unlikely
Cryogenic capture	3 (fast development possible)	Moderate reduction possible if favourable assumptions are valid
Supersonic inertial capture	1	Too early to validate
Vacuum pressure swing adsorption (VPSA)	3	Relatively high energy requirement makes significant reduction unlikely
Temperature swing adsorption (TSA) with thermal regeneration	1	Uncertain
TSA with electric regeneration	1	Likely much higher

Post-combustion Carbon Capture technologies

TRLs for emerging CO_2 capture systems

Separation process	Application	TRL* 2005	TRL* 2015	Comments
Absorption				
Physical	Industry	9	9	Commercial technology for the separation of H_2/CO_2 mixtures from syngas (<3 Mt CO_2/y).
	Pre-combustion	8	8	Most components are TRL 9, but hydrogen-based power generation is less mature.
Chemical	Industry	9	9	Commercial technology in refineries and for the natural gas sweetening.
	Post-combustion	7	8	Demonstrated at a capture rate of 1 Mt CO_2/y in the Boundary Dam CCS project.
Cryogenics				
Air separation	Industry	9	9	Commercial technology for oxygen production (<4000t O2/d).
	Oxy-combustion	5	7	Combustion island has been demonstrated up to 30 MW_{th}.
CO_2 anti-sublimation	Post-combustion	3	3	
High temperature solid looping				
Chemical looping	**Oxy-combustion**	**3**	**6**	Demonstrated at 1 MW_{th} pilot plant using hard coal and ilmenite as oxygen carrier
	Pre-combustion	2	3	
Calcium looping	**Post-combustion**	**2**	**6**	Demonstrated at a scale of > 1 MW_{th} using oxyfuel combustion-calcination
	Pre-combustion	2	2	Challenging sorbent regeneration at high pressure and temperature

Separation process	Application	TRL* 2005	TRL* 2015	Comments
Solid sorbents				
Adsorption	Industry	9	9	Commercial technology for natural gas sweetening and H_2 production (i.e. Port Arthur CCS project)
	Pre-combustion	8	8	Most components are TRL 9, but hydrogen based power generation is less mature.
	Post-combustion	**2**	**5**	CO_2 capture from flue gases by VPSA <2 t CO_2/d.
	Oxy-combustion	6	6	VPSA is commercial for oxygen production, but at low capacity (<500t O_2/d)
Low T G/S reactions	**Post-combustion**	**4**	**6**	Initial results from a 10 MW_e fluidized bed pilot
	Pre-combustion	3	5	Sorption enhanced water gas shift (SWEGS)
Membranes				
Polymeric membranes	Industrial	9	9	Commercial technology for natural gas sweetening (i.e. Sleipner CCS project)
	Post-combustion	**3**	**5**	Demonstrated at a capture rate of 1t CO_2/d using polymeric membranes.
Other membranes	Pre-combustion	3	3	
	Oxy-combustion	4	5	Oxygen production using Ion transport membranes (5 t O_2/d)

(Abanades et al. 2015, Int. Journal of GHG control)

Post-combustion Carbon Capture technologies

Traffic light table of improvement potential for emerging separation processes for CO_2 capture (process with TRL>4 only) compared to benchmark, today's 1st-generation.

Process	Solvent based processes	Solid sorbent processes	High temperature solid looping systems		Membrane systems		
Separation Technology / Assessment criteria			Chemical looping	Calcium looping	Polymeric (post)	Ceramic (Oxy)	Metallic (pre)
Cost CAPEX							
Cost OPEX							
Efficiency penalty (thermodynamics, T- and P- level)							
Degradation solvent, sorbent, membrane							
Operational flexibility (on/off)							
HSE (waste, toxicity)							
Retrofitability[3)]							
Materials availability (abundance, manufacturing chain)							
FOAK cost							
Applicability, most suitable to	Power, NG processing, Steel, Refineries, other	Power (pre combustion), Steel, Refineries	Power (solid fuels), Refineries	Power (post combustion, solid fuels), Cement	Power, NG processing, Cement, Steel	Power (oxy and pre combustion)	Power (pre combustion), Refineries

Source: ZEP. Future CCS Technologies, 2017.

Considerations for PCC integration

Retrofit an existing power plant	• Access for steam extraction where available. • Integration aims to minimise loss of power output and efficiency.
New-build power plant with CCS	• Dedicated steam cycle. • Integration aims to minimise loss of power output and maximise efficiency.
New-build power plant as Carbon Capture Ready (CCR)	• Access for steam extraction planned on the design stage. • Steam cycle designed so that before retrofit the plant achieves identical performance to a standard “non-CCR” plant, and • Retrofitted plant should be as efficient as a new plant built with CCS with the same steam conditions.

Considerations for PCC integration

Retrofit an existing power plant

New-build power plant with CCS

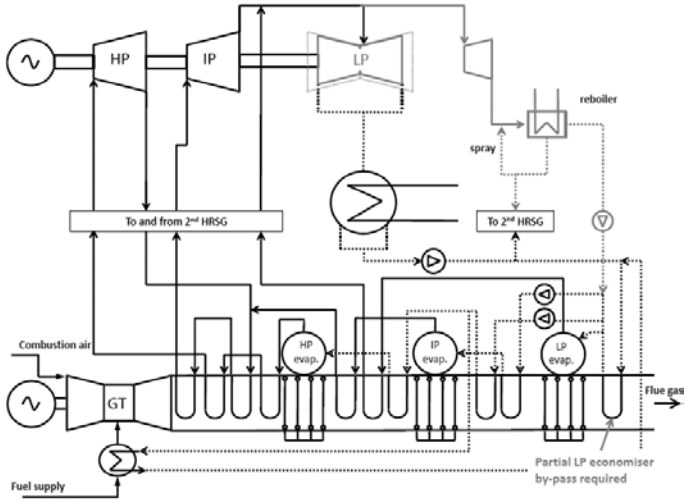
New-build power plant as Carbon Capture Ready (CCR)

- **Minimise loss of power output** and maximise efficiency.
- **Flexible operation** at partial CO_2 capture rates and by-passed CO_2 capture plant.
- **Availability to be retrofitted/upgraded with unknown improved future solvents** (wide rate of steam temperature and pressure) to avoid locking-in plants to a specific solvent (technology lock-in).

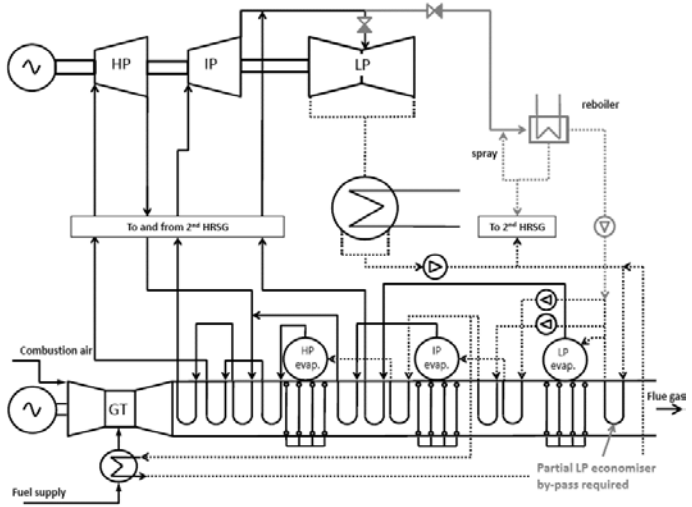
Steam cycle design options for steam extraction

Examples for possible integration with the steam cycle and steam extraction options for Combine Cycle Gas Turbine power plants equipped with PCC Lucquiaud and Gibbins (2011)

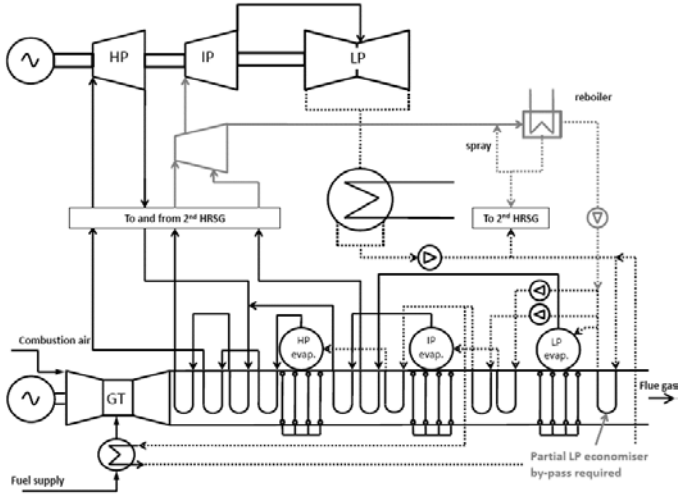
a) Replacement of the LP Turbine Cylinder and Let-Down Turbine



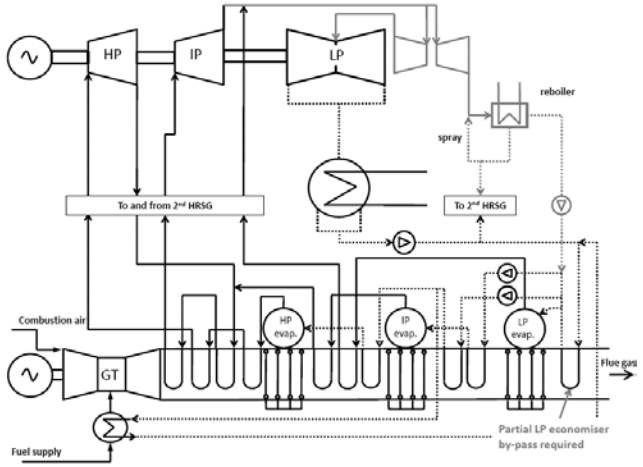
b) Retrofit with two Throttle Valves



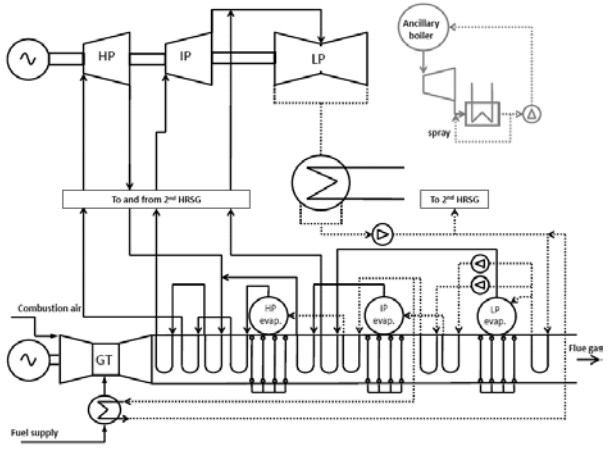
c) Pass-out Back-Pressure Turbine from reheated outlet



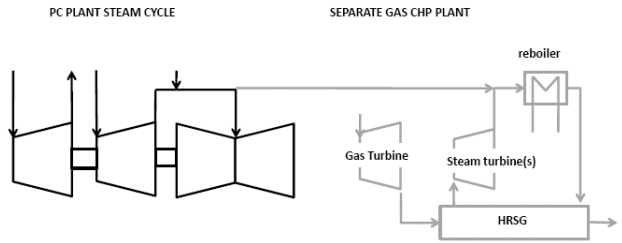
d) Retrofit with Two Back-Pressure Turbines



e) Retrofit with Ancillary Boiler and Optional Back-Pressure Turbine



f) Retrofit with Gas CHP plant for Power or Heat matched retrofit



Lucquiaud and Gibbins (2011)

	LP turbine replacement	Two back-pressure Turbine	Pass-out back-pressure turbine	Ancillary boiler
Main specific Capture Ready design actions	Provision for cylinder replacement	Space and foundations for reinforcements for new turbines	Space and foundations for reinforcements for new turbines	Space for boiler (and back pressure turbine)
Penalty before capture	None	None	None	None
Efficiency before capture	55.4%	55.4%	55.4%	55.4%
Efficiency with capture	48.1%	48.2%	48.1%	42.5% (44.2%)
Performance with capture	Reference	+ 1.9 KWh/t_{CO2}	+ 3.3 kWh/t_{CO2}	+ 487.6 kWh/t_{CO2} (*418.9 kWh/t_{CO2})
CO_2 emission with Capture	58.8	58.5	58.8	65.8 (63.8)
Extra CAPEX (compared to new-build CCS unit)	New LP turbine cylinder	Back pressure turbines	Pass-out back-pressure turbine	Ancillary boiler (and back-pressure turbine)
Retrofit with higher/lower temperature solvents	NO/YES	YES/YES	YES/YES	YES/YES
Capacity to export additional power with improved solvents	NO	YES	YES	YES (NO)

If steam extraction requirements decrease, additional steam generates power in the LP turbine

- Lucquiaud, M. and Gibbins, J. (2011). *Managing capture technology uncertainty in capture-ready gas power plants*. Energy, vol. 165, issue EN2.

CCS retrofits on existing power / industrial plants

Influential factors that affect the feasibility for CCS retrofit:

Suitability criteria (determine whether a plant is likely to be a candidate for retrofitting)

- ✓ Location of the plant and its **access to potential CO_2 storage** sites,
- ✓ **Onsite space** availability (e.g. 0.03 to 0.08 hectares per MW retrofitted for units 300 – 600 MW)
- ✓ **Plant Age** (exclude plants that are likely to reach the end of the economic lifetime before a CCS retrofit decision)
- ✓ **Plant Size** (e.g. in China units > 600 MW(net) are candidates for retrofitting)
- ✓ **Load factors** (exclude plants are that used just to provide peaking power or are not regularly dispatched for cost or technical reasons).
- ✓ Other **technical consideration** (e.g. efficiency, steam cycle design)
- ✓ **Local policy and strategic factors** (proximity to coal mines, access to cooling water, pollution controls)

CCS retrofits on existing power / industrial plants

Influential factors that affect the feasibility for CCS retrofit:

Cost factors (would influence the relative attractiveness of the retrofit through their impact on the cost of generating electricity with CCS)

- ✓ Costs of transporting CO_2 and storing it at a storage site
- ✓ Costs relating to age, size and load factor
- ✓ Efficiency and stream cycle design (ease of extracting steam from the turbines at suitable T and P)
- ✓ Cooling type (e.g. air cooling does not significantly increase water needs but it is more expensive)
- ✓ Pollution control (plant equipped with FGD?)

Additional factors: availability of alternatives to CCS, regulatory framework, incentives, market structure and policy risk, etc.

Source: IEA, 2016. Ready for CCS Retrofit: The potential for equipping China's existing coal fleet with carbon capture and storage

CCS retrofits on existing power / industrial plants

Influential factors that affect the feasibility for CCS retrofit:

Suitability assessment factors for retrofit of CCS to existing coal-fired units in China (IEA, 2016)

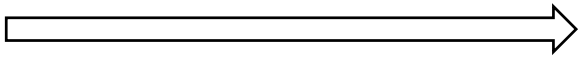
Factor	Suitability criteria
Age	≤ 40 years old in 2035
Size	≥ 600 MW, or ≥ 300 MW and at a plant that could in total potentially capture ≥ 10 $MtCO_2$/yr
Load factor	≥ 50%
Location	Not in a province with a polity to phase out coal completely
Access to CO_2 storage	≤ 800 km

Carbon Capture Readiness

A **plant** seeking to demonstrate the capture ready status should carry out an **engineering feasibility study** for the retrofit with CCS to demonstrate that **no predictable site-specific or technology-specific barriers to CCS** (IEAGHG 2007)

New-build plant as CCR

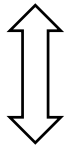
When technology and economic drivers are in place:



✓ *Technology developments*

✓ *Improved future solvents*

Retrofitted CCR plant with PCC



Performance?

New-build plant with CCS

Ideal principles for Carbon Capture Ready

Plant efficiency before capture?	The **efficiency** of a **CCR plant before capture** should be the **same as** the efficiency of a **state-of-the-art standard plant** (without CCR considerations)
Plant efficiency with capture?	The **efficiency** of a **retrofitted CCR plant** should be the same as a **new-build plant with CCS** (for the same steam conditions)
Additional costs?	There should be **no up-front additional costs** for a CCR plant compared to a state-of-the-art standard plant
Operation without capture?	The retrofitted CCR power plant should be able to **operate without capture** (by-passed) and at **partial CO_2 capture rate**s (flexible operation).
Upgraded with new solvents?	The CCR plant should **allow for future technology development**, i.e. advanced solvents that required lower steam flow rates at different pressures and temperatures.

Future-proofing plants with PCC against technology developments

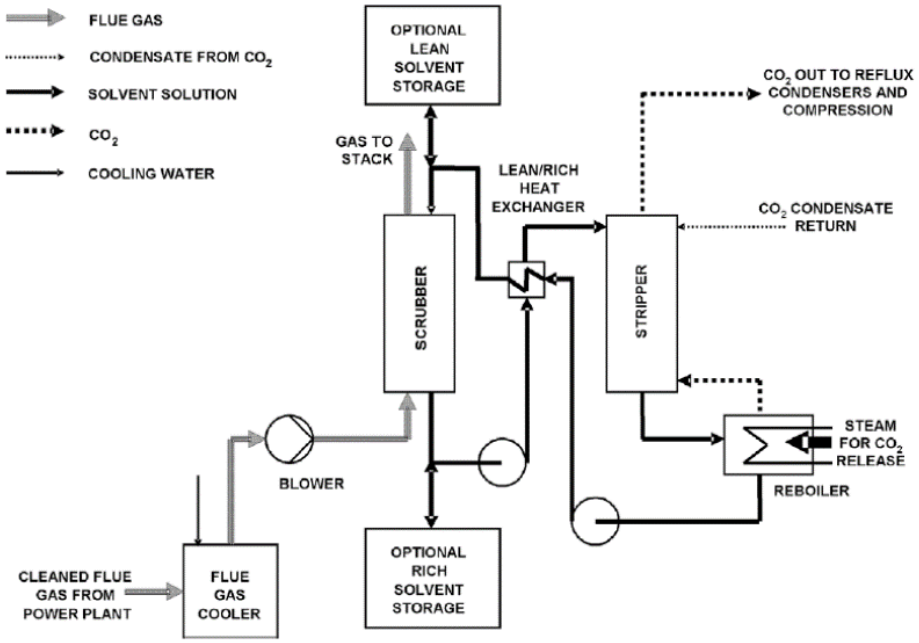
- If investments are made to **future-proof the first (and future) CCS plants**, this could reduce the number of power generation assets that need to be built, contribute to minimising the cost of electricity decarbonisation through CCS, and also stimulate an open market where power plant owners are not tied in to using the same solvent supplier throughout the plant's lifetime
- Possible reasons can justify a solvent upgrade
  - ✓ Keep the plant license to operate by securing compliance with stricter environmental legislation
  - ✓ Improve power plant economic

Lucquiaud et al (2011) Energy Procedia

Flexible operation with PCC

- Post-combustion CO_2 capture with solvents offers the option of designing and operating the capture plant with **solvent storage**

  - ✓ Flexible operation of a power plant to dispatch electricity (i.e. allows achieving higher profits by boosting electrical output of the power plant when electricity prices are high by storing rich solvent, and delaying the energy intensive step of solvent regeneration to a later point in time)
  - ✓ Allows to **balance CO_2 flow variability**, within the boundaries of CCS power/industrial plant, reducing the need for injection wells to operate flexibly (Spitz, 2019)



Schematic diagram of post-combustion capture plant with optional solvent storage tanks (Chalmers and Gibbins 2007).

Challenges for implementation of PCC with solvents

- Long-term operation at large-scale PCC facilities has underscore the importance of solvent management (e.g. Boundary Dam, TCM, etc)
- Importance of “matching the fuel with the solvent” - testing solvents with actual flue gas composition
- Importance of designing pilot-scale / large-scale testing programs and developing solvent management strategies

Recommendations for Pilot Plant Test Program

- **DCC Performance – 1 to 2 months**
  - ✓ DCC should be tested in isolation to very acceptable SO_x capture levels
- **Initial Assessment of Optimised PCC Operation Conditions – 1 month**
  - ✓ With fresh solvent, capture plant operating parameters, capture level and energy input measurement should be optimised
  - ✓ Assess possible variations in configuration
- **Extended PCC operating trials – 5 to 9 months**
  - ✓ Long term performance, operating 24/7 and using actual plant flue gas
  - ✓ Air emissions
  - ✓ Proposed solvent management measures implemented throughout this period and adjusted if necessary

Source: Bechtel 2018, Retrofitting an Australian brown coal power station with post-combustion capture: A conceptual study

Recommendations for Pilot Plant Test Program

- **Investigation of Transient Performance –**
  - ✓ Varying flue gas flow to mimic full scale operations at part load, ambient conditions changing, interrupting capture as for maximum power output, varying capture level/energy penalty with changing market conditions,
  - ✓ Performance of instrumentation and automated control systems
- **Final assessment of optimised PCC operating conditions and detailed heat and mass balances on aged solvent** – up to 1 month
  - ✓ Using additional test instrumentation, sample collection and analyses to allow evaluation of heat and material balances
  - ✓ Results should be compared with modelling to verify consistency in the measurement and for model calibration for subsequent full scale design work

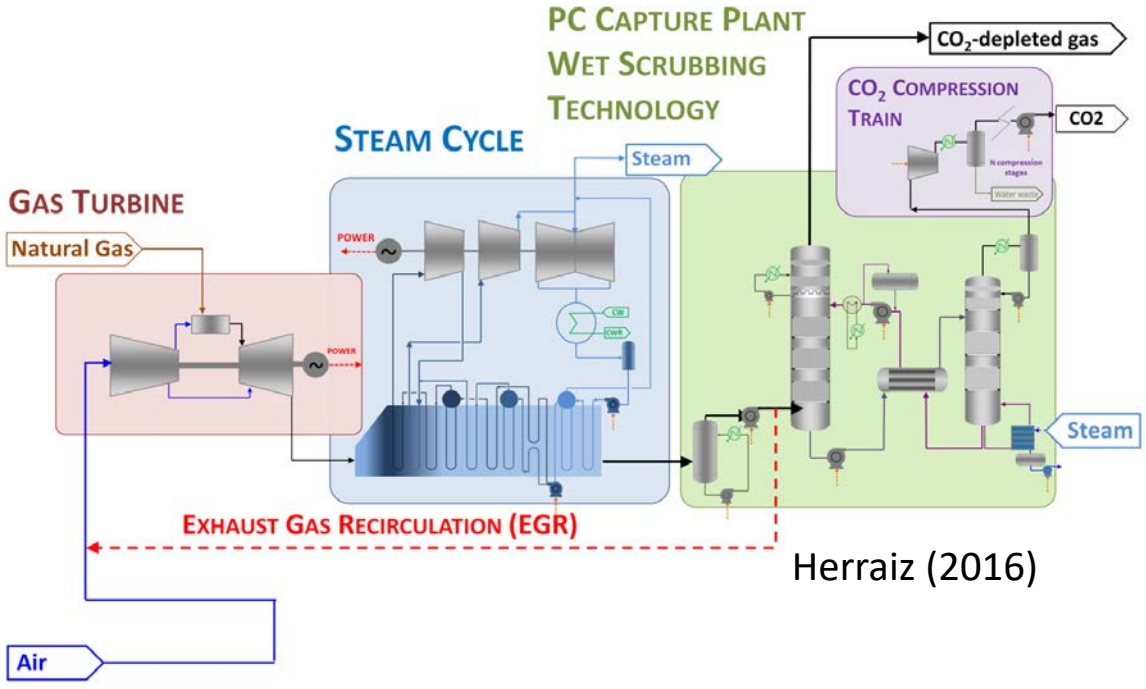
Source: Bechtel 2018, Retrofitting an Australian brown coal power station with post-combustion capture: A conceptual study

Operation options for cost reduction

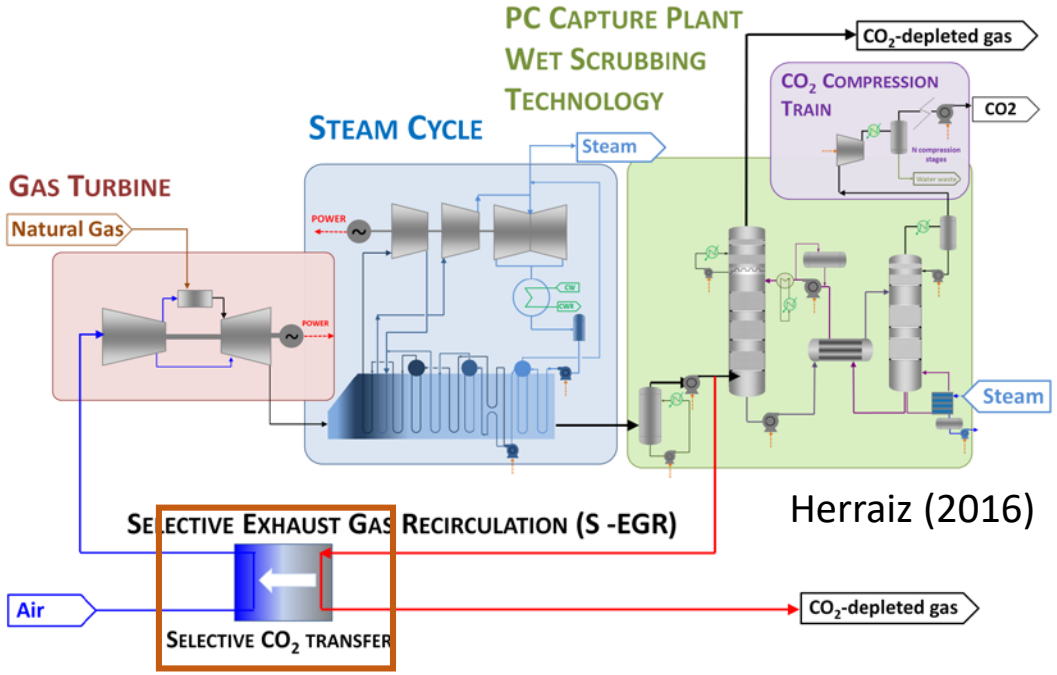
- **CAPEX reduction** of the capture plant is possible via **process intensification,** i.e. implementing operating and design options that reduce the capture plant size by reducing the flue gas flow rates and/or increasing the CO_2 concentration
  - Exhaust Gas Recirculation
  - Selective Exhaust Gas Recirculation
  - Supplementary firing
  - Sequential supplementary firing
  - Synergistic design options
  - Etc …

Operation options for cost reduction

- **Exhaust Gas Recirculation (EGR) and Selective Exhaust Gas Recirculation (SEGR)**



Herraiz (2016)



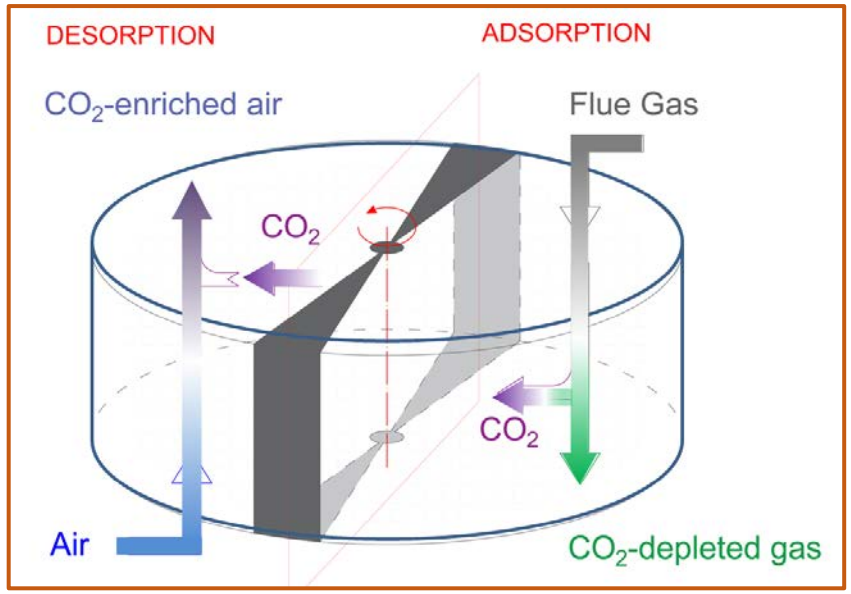
Herraiz (2016)

Operation options for cost reduction

Rotary Adsorption

Physical adsorption with structured materials in a rotary wheel.

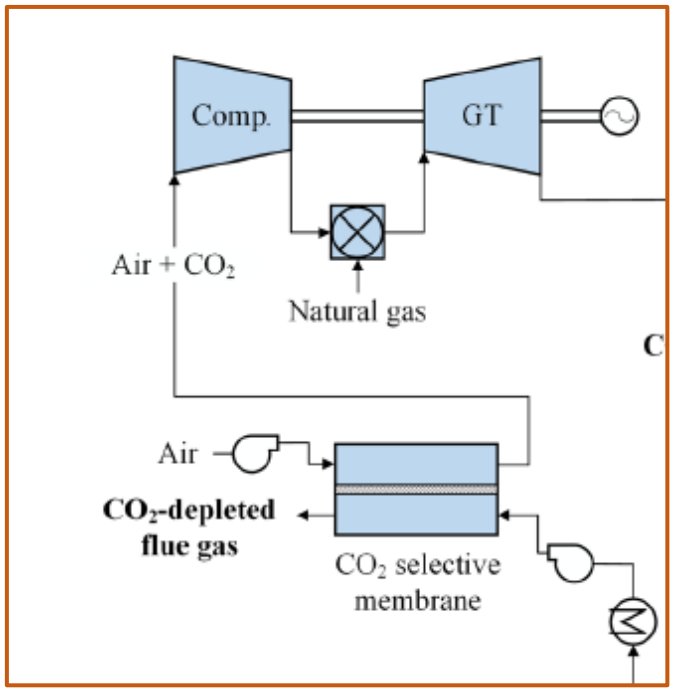
Low pressure drop.



Herraiz (2016)

Selective CO_2 membrane system

Low energy input, operating with a moderate ratio of feed pressure to permeate pressure.



(Diego et al. 2017a)

Operation options for cost reduction

Selective Exhaust Gas Recirculation (SEGR)

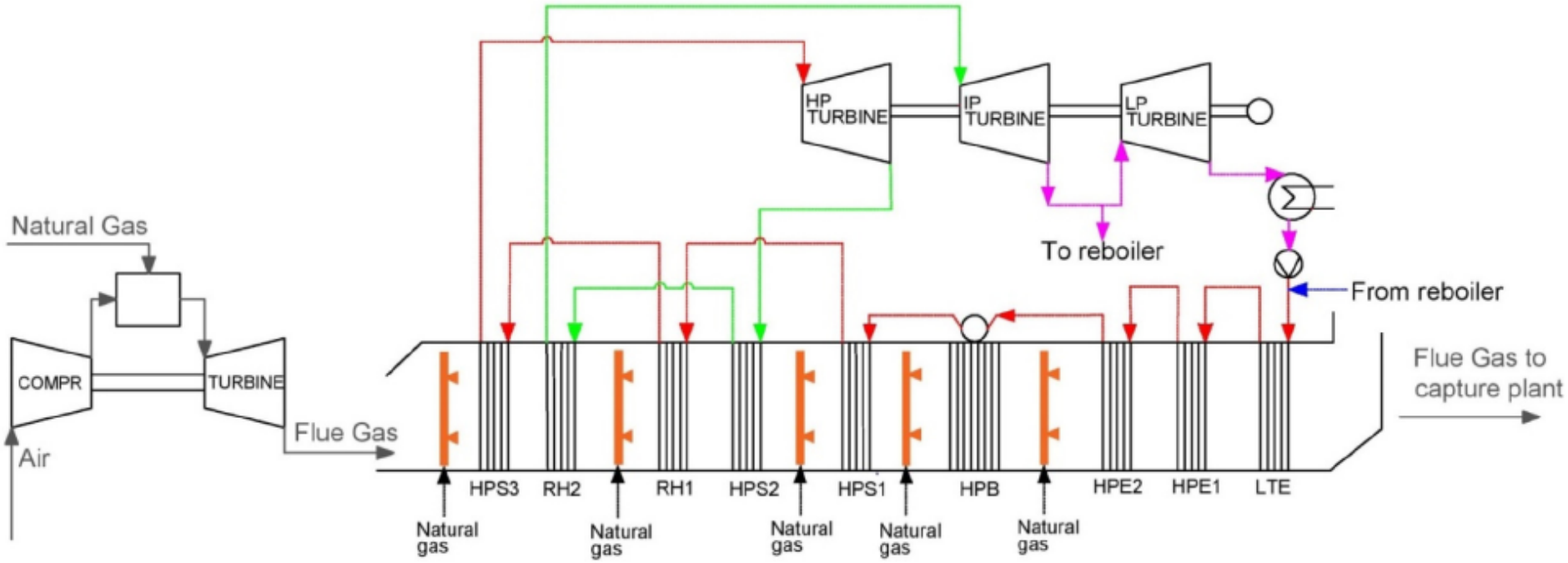
Key aspects for selective CO_2 transfer technologies:

- High selectivity for CO_2 transfer over other components in the flue gas (e.g. N_2)
  - Rotary adsorption: trade-off between CO_2 affinity and possibility to regenerate the solid with ambient air.
  - Membranes: trade-off between permeability and selectivity.
- Low Oxygen transfer from ambient air to flue gases
- Low heat transfer rate from flue gases into the air entering the compressor
- Low pressure drop (typically overcome by an air fan)

Minimise Gas Turbine derating

Operation options for cost reduction

- Supplementary Firing (SF) and Sequential Supplementary Firing (SSF) in CCGT power plants and refineries with PCC

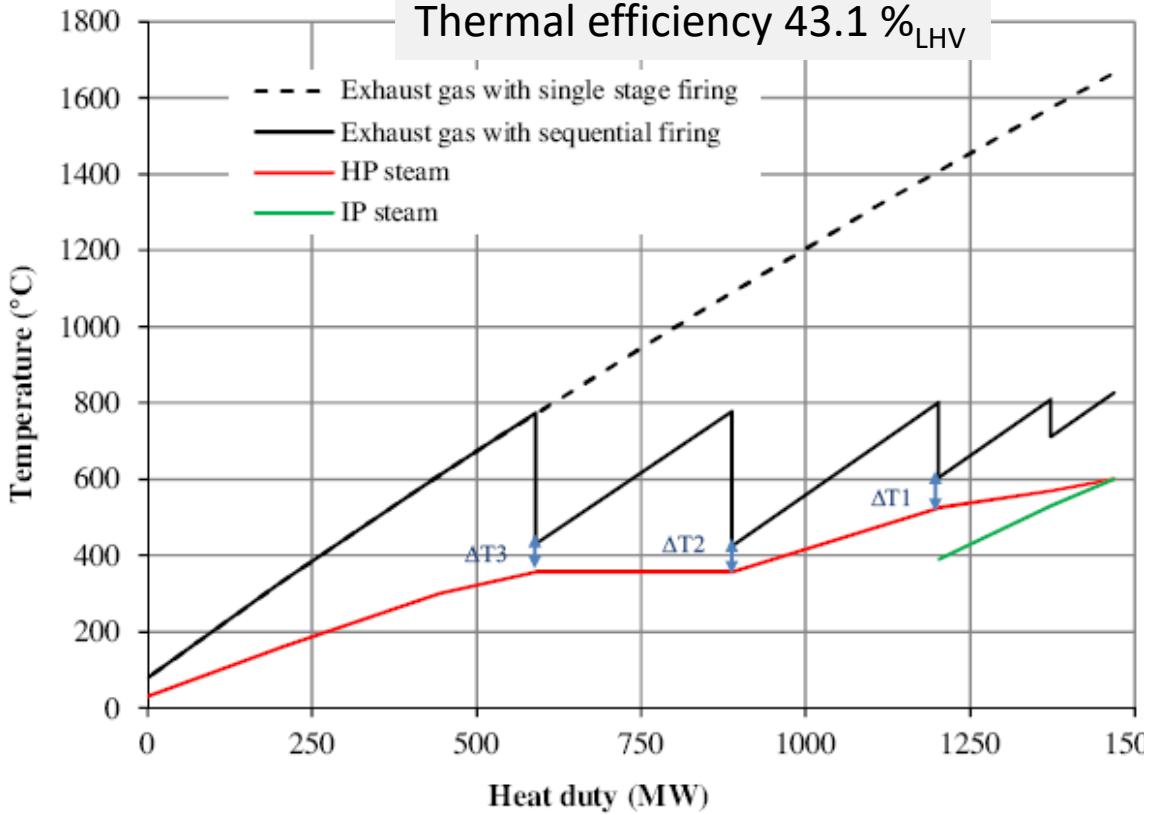


Schematic process flow diagram of a SSFCC with a subcritical steam cycle(González et al. 2016)

Operation options for cost reduction

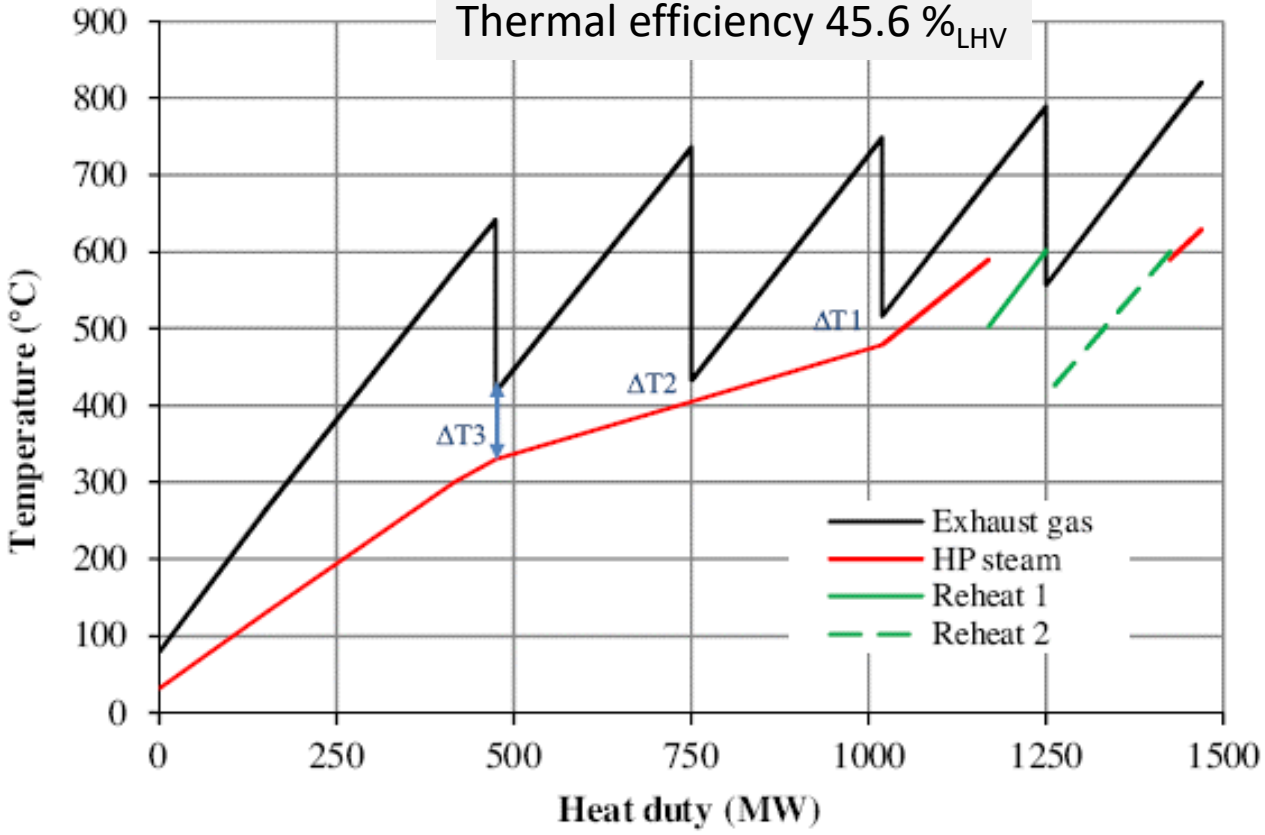
Temperature/heat diagram of a SSFCC with a subcritical SC (González et al. 2016)

Power output 781 MW
Thermal efficiency 43.1 $\%_{LHV}$



Temperature/heat diagram of a SSFCC with a supercritical SC (González et al. 2016)

Power output 824 MW
Thermal efficiency 45.6 $\%_{LHV}$



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Thank you!

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