ROYAL SOCIETY OF CHEMISTRY

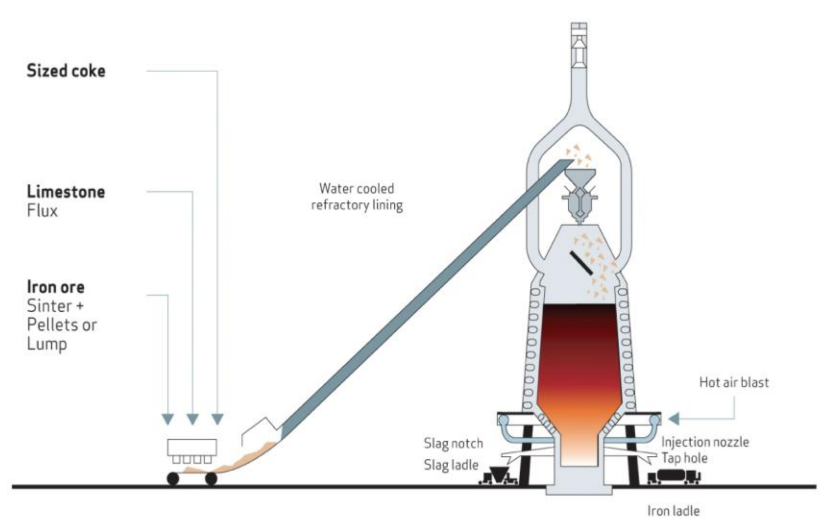
TECHNOLOGY IN THE USE OF COAL

Professor James Harrison FRSC FEng

National Coal Board
1947

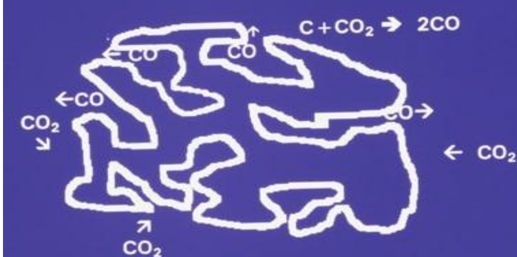
Mines	958
Manpower	718000
Use –electricity	28
-domestic	37
-steel	43
-other	80
Total Use Mt	188

Coal Use in Steel Production

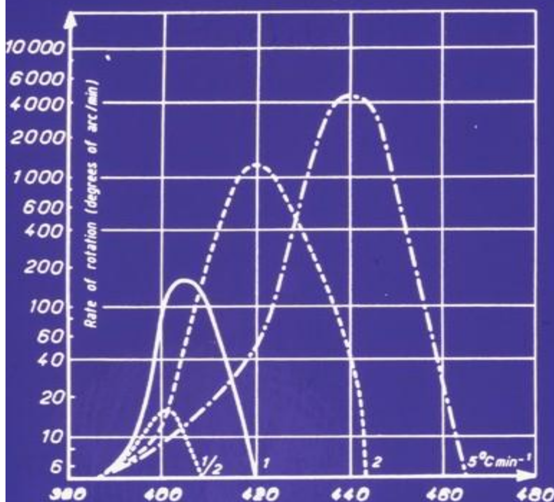


BLAST FURNACE REACTIONS

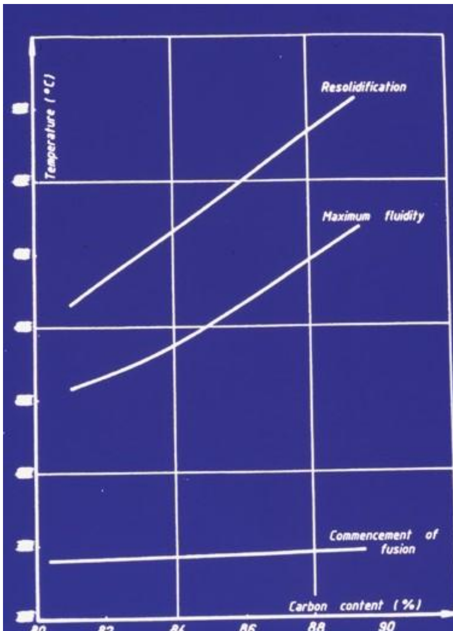
TEMPERATURE RANGE °C	REACTIONS	COKE CONSUMED %
<900	DRYING VOLATILE LOSS	negligible
900 to 1000 Thermal reserve zone Smelting zone "direct" reduction	$C_{(Coke)} + (CO_2, H_2O) \rightarrow CO + H_2$ $FeO + (CO, H_2) \rightarrow Fe + (CO_2, H_2O)$	30
1000 to 1200 Fusion zone	Fe melting, SiO_2, P_2O_5, MnO reduction Slag formation, potassium cycle	15
> 1200 Tuyère zone	$C + (O_2, CO_2, H_2O) \rightarrow CO + H_2$	50-60



TEMPERATURE °C	REACTION REGIME	RATE DETERMINED BY
900 - 1100	chemical	chemical reaction rate
1200 - 1400	internal diffusion	pores blocked by CO
>1400	external diffusion	CO_2 arrival at surface



Plasticity of a *gras* coal as a function of heating rate



Characteristic temperatures of a coal as a function of rank

TAR REACTIONS
CRACKING EQUATIONS

Hydromethanation $R\text{-}CH_3 + H_2 \rightarrow RH + CH_4$

Condensation $R\text{-}OH + R'\text{-}H \rightarrow R\text{-}R' + H_2O$

$R\text{-}H + R'\text{-}H \rightarrow R\text{-}R' + H_2$

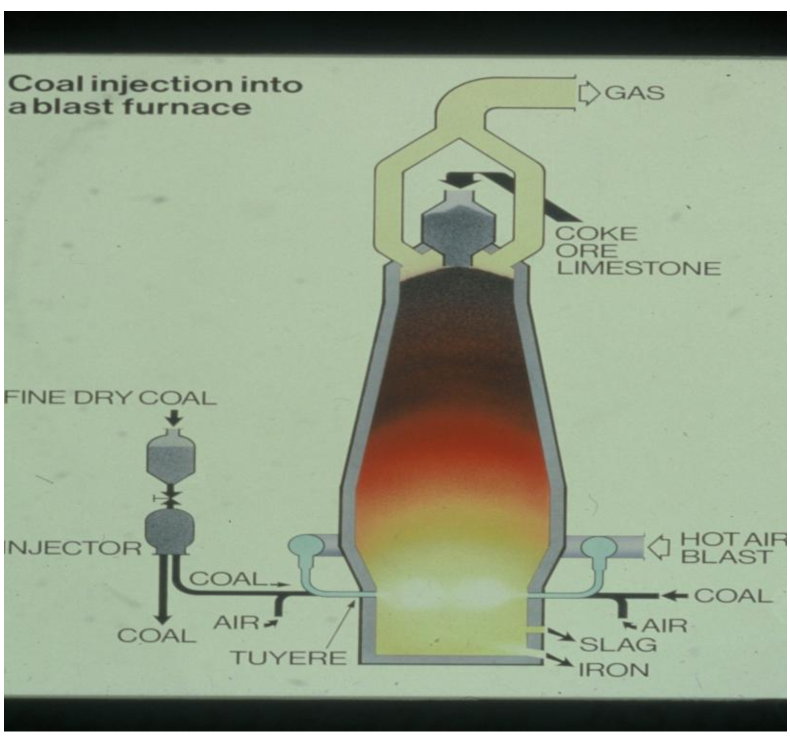
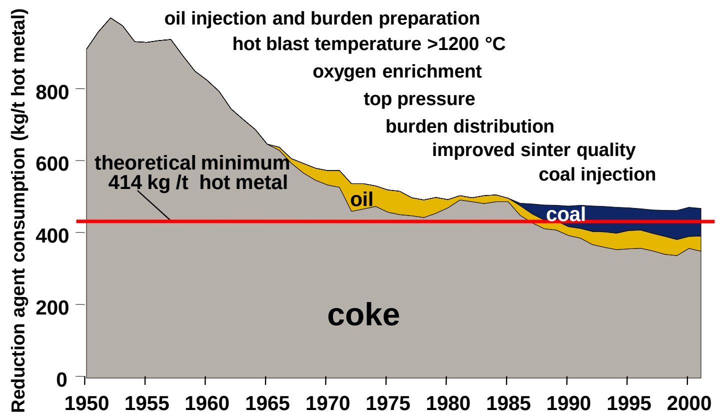


Figure 1: Carbon usage in blast furnace ironmaking and associated technology developments over the last 50 years



Source: Thyssen-Krupp, Germany

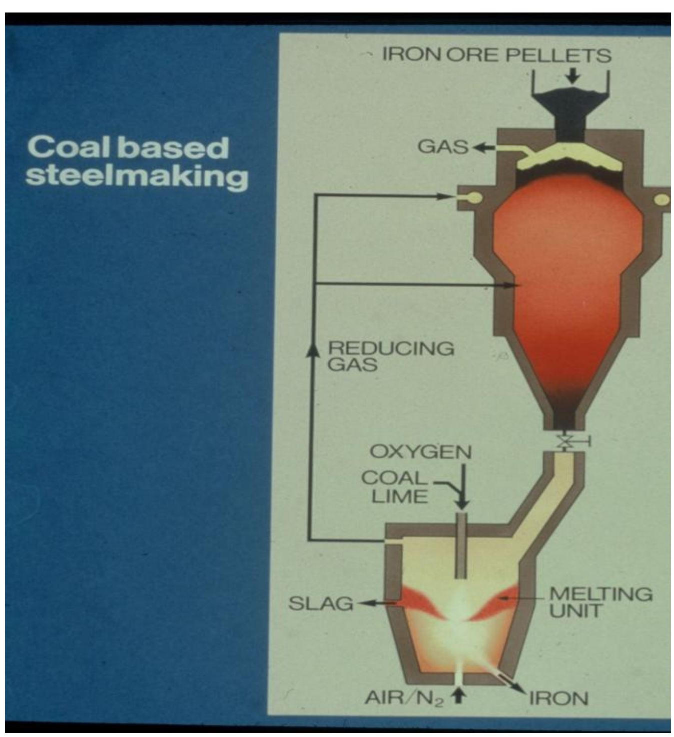
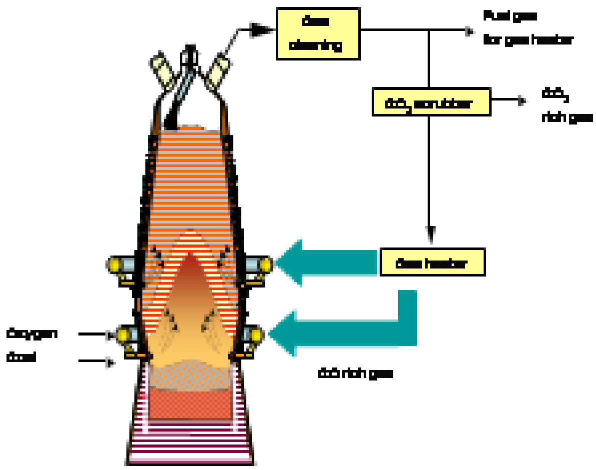
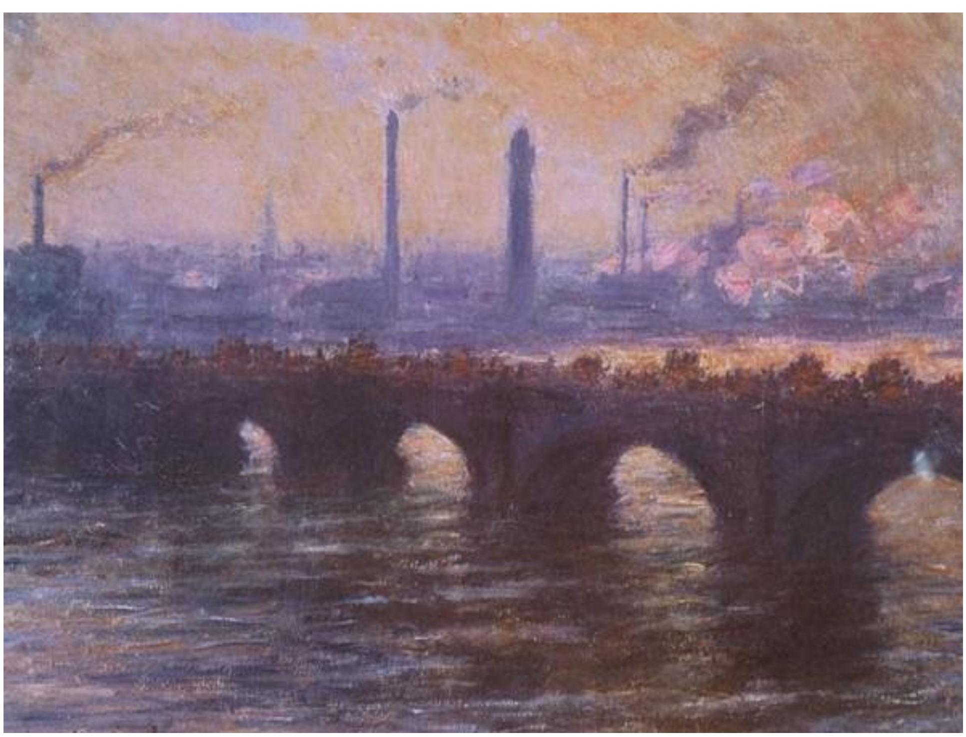
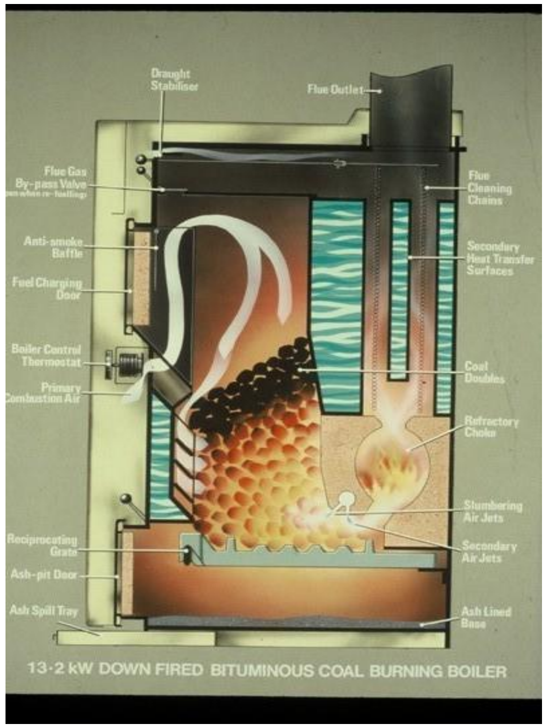
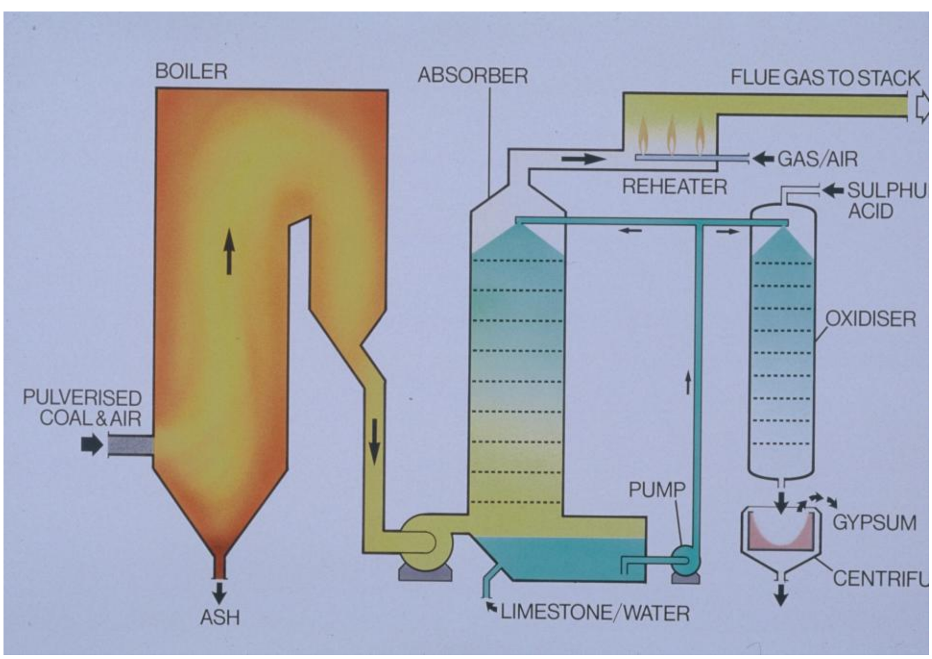


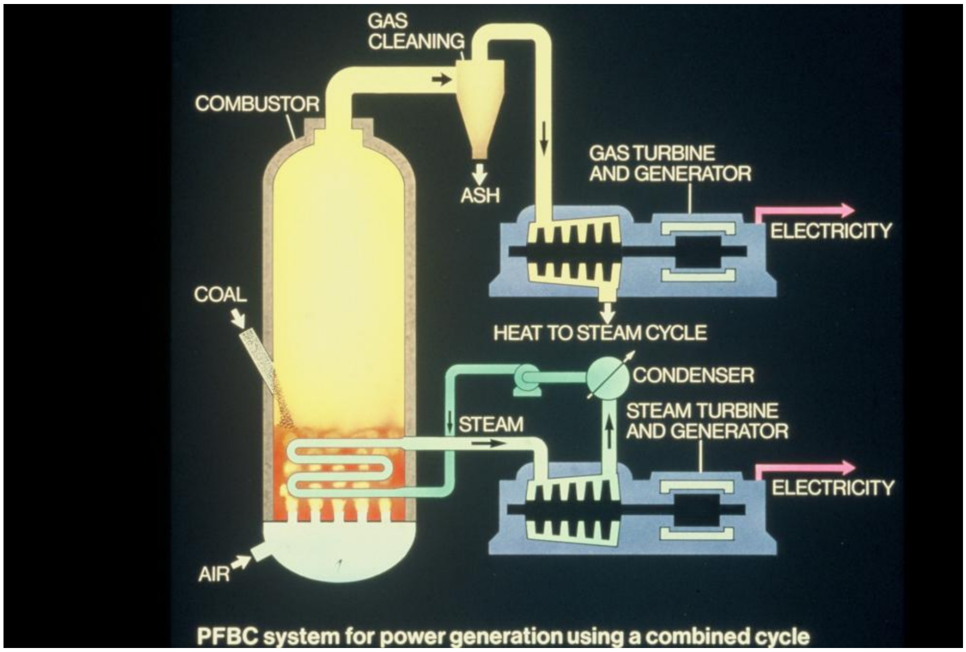
Figure 3: The Top Gas Recycling Blast Furnace Concept

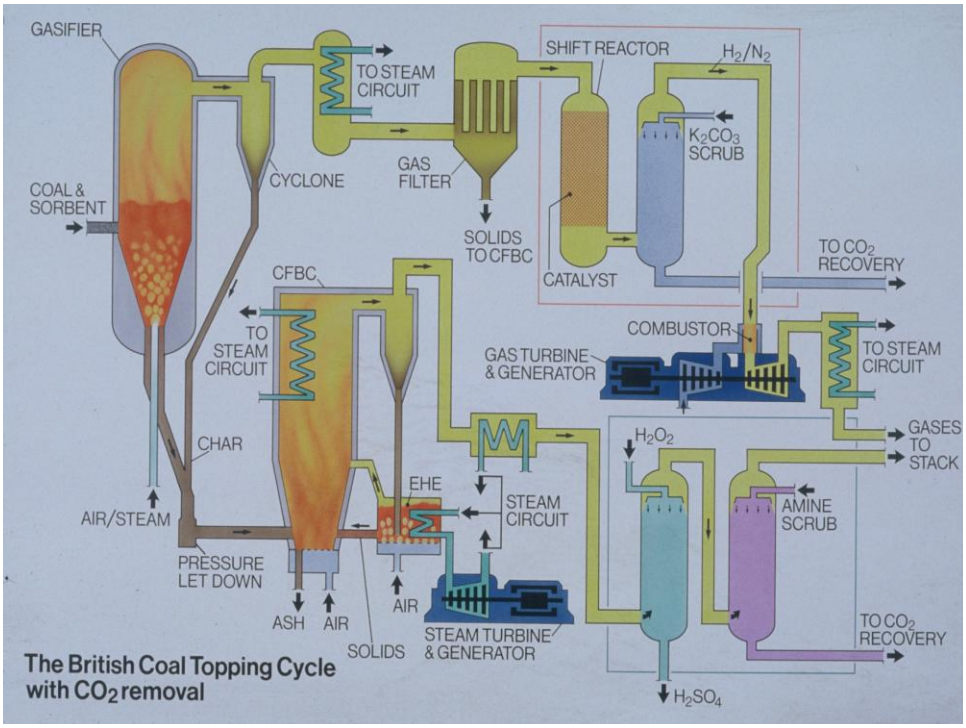





Draught Stabiliser
Flue Outlet
Flue Gas By-pass Valve
Flue Cleaning Chains
Anti-smoke Baffle
Fuel Charging Door
Secondary Heat Transfer Surfaces
Boiler Control Thermostat
Primary Combustion Air
Coal Doubles
Refractory Choke
Slumbering Air Jets
Reciprocating Grate
Secondary Air Jets
Ash-pit Door
Ash Spill Tray
Ash Lined Base
13·2 kW DOWN FIRED BITUMINOUS COAL BURNING BOILER


BOILER
ABSORBER
FLUE GAS TO STACK
GAS/AIR
REHEATER
SULPHU
ACID
OXIDISER
PULVERISED
COAL & AIR
PUMP
GYPSUM
CENTRIFU
ASH
LIMESTONE/WATER


GAS
CLEANING
COMBUSTOR
ASH
GAS TURBINE
AND GENERATOR
ELECTRICITY
COAL
HEAT TO STEAM CYCLE
CONDENSER
STEAM
STEAM TURBINE
AND GENERATOR
ELECTRICITY
AIR
PFBC system for power generation using a combined cycle



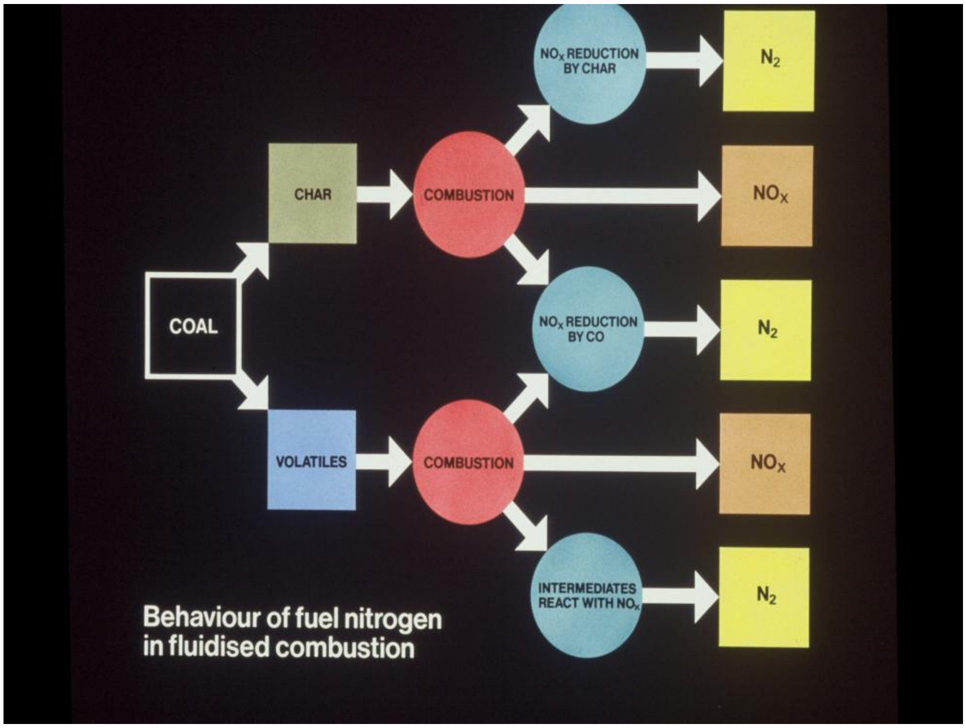
The British Coal Topping Cycle with CO_2 removal

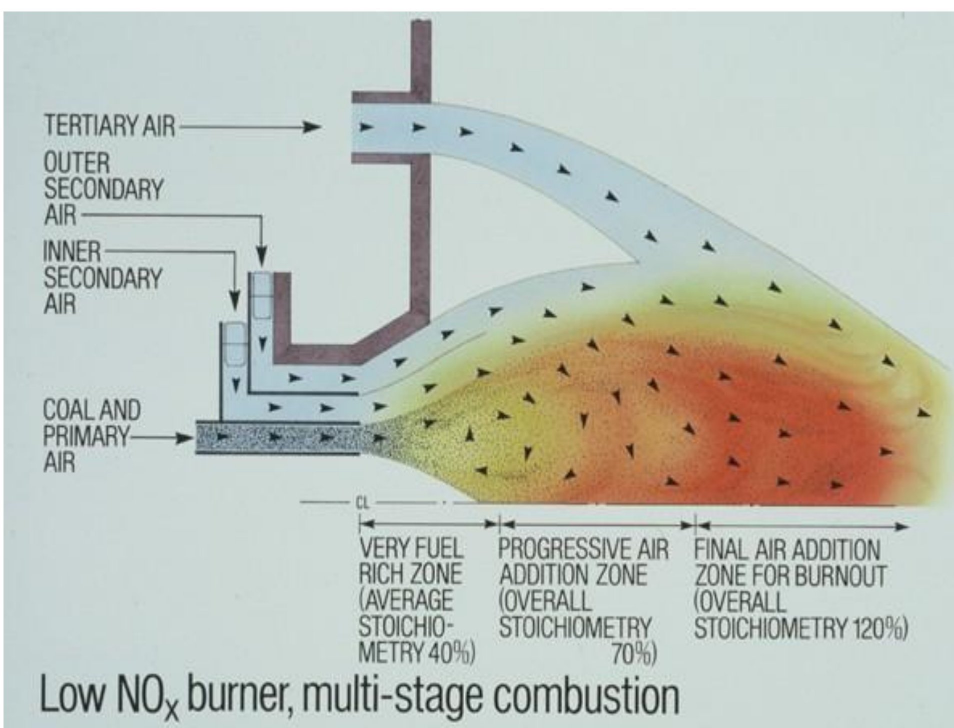
NO_x formation in coal combustion

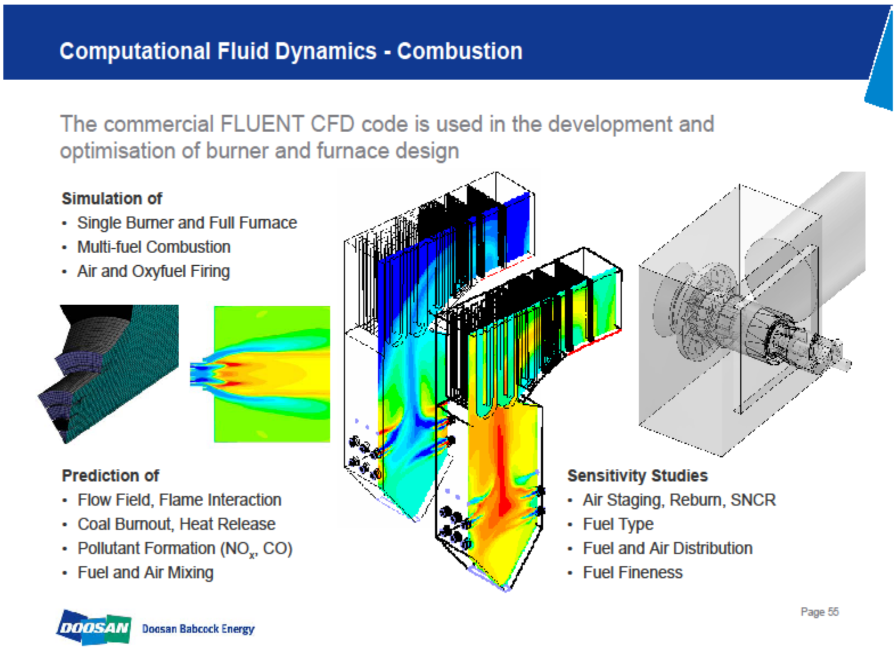
About 50% of the NO_x comes from nitrogen in volatiles from coal

30% from nitrogen in char

20% from atmospheric nitrogen


COAL
CHAR
VOLATILES
COMBUSTION
COMBUSTION
NO$_X$ REDUCTION BY CHAR
NO$_X$ REDUCTION BY CO
INTERMEDIATES REACT WITH NO$_X$
N$_2$
NO$_X$
N$_2$
NO$_X$
N$_2$
Behaviour of fuel nitrogen in fluidised combustion


TERTIARY AIR
OUTER SECONDARY AIR
INNER SECONDARY AIR
COAL AND PRIMARY AIR
CL
VERY FUEL RICH ZONE (AVERAGE STOICHIO-METRY 40%)
PROGRESSIVE AIR ADDITION ZONE (OVERALL STOICHIOMETRY 70%)
FINAL AIR ADDITION ZONE FOR BURNOUT (OVERALL STOICHIOMETRY 120%)
Low NO$_X$ burner, multi-stage combustion


Computational Fluid Dynamics - Combustion
The commercial FLUENT CFD code is used in the development and optimisation of burner and furnace design
Simulation of
• Single Burner and Full Furnace
• Multi-fuel Combustion
• Air and Oxyfuel Firing
Prediction of
• Flow Field, Flame Interaction
• Coal Burnout, Heat Release
• Pollutant Formation (NOx, CO)
• Fuel and Air Mixing
Sensitivity Studies
• Air Staging, Reburn, SNCR
• Fuel Type
• Fuel and Air Distribution
• Fuel Fineness
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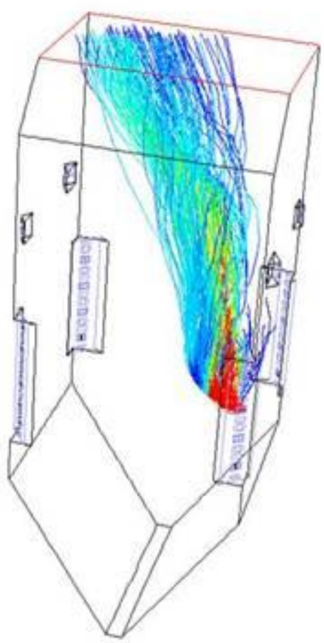
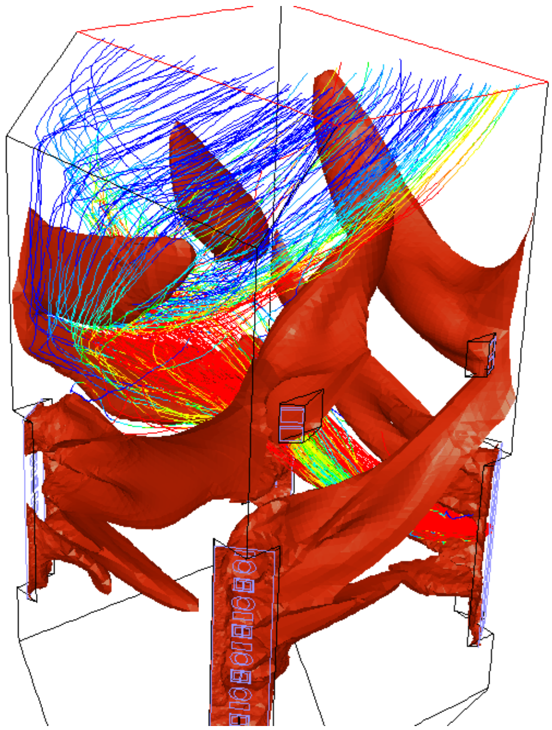
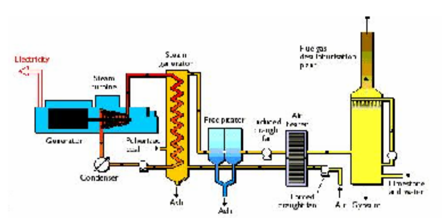
DOOSAN
Doosan Babcock Energy





Clean Coal Power Plant

Advanced Supercritical Pulverised Coal Boiler /Steam Turbine 350-1000MW



- Best Available Technology *now 46/47% efficient (290 bar/600C/610C), cf 35%*
- Advantages are proven Availability (>95%), Load Flexibility (20-100%) and wide fuel range (inc Biomass cofiring up to 20%)
- Matches any other coal technology for emissions, easily meets LCPD limits
- Can be built now, designed to be "capture ready" and fitted with economical CO_2 capture when CCS is possible
- Technology of choice for vast majority of new build orders

DOOSAN Doosan Babcock Energy

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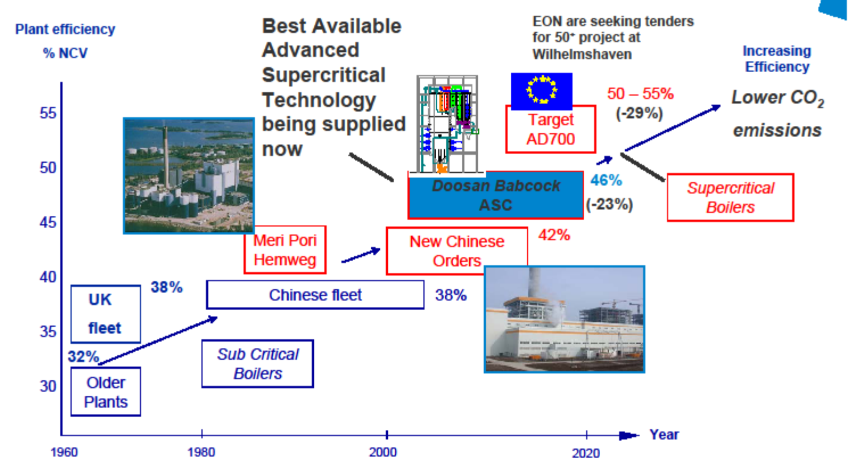
Abatement of CO_2 by efficiency improvement of Pulverised Coal Plant



Doosan Babcock Energy

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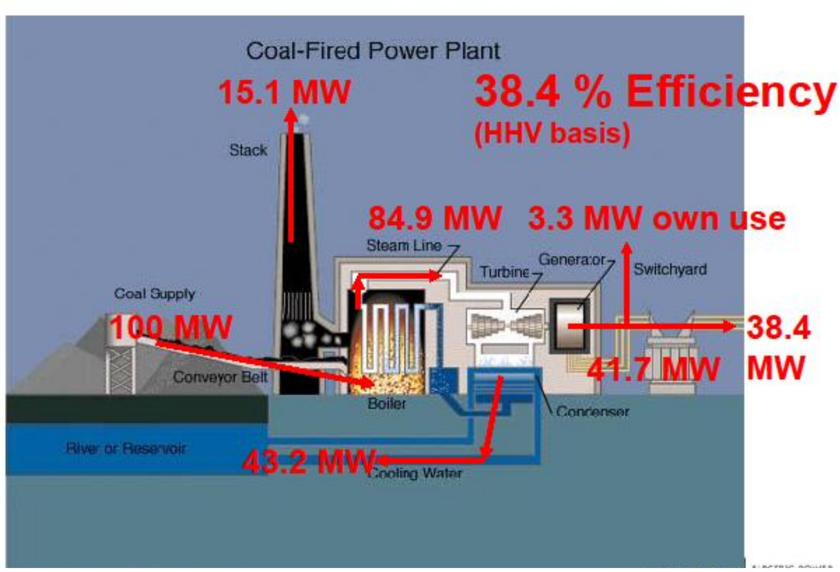
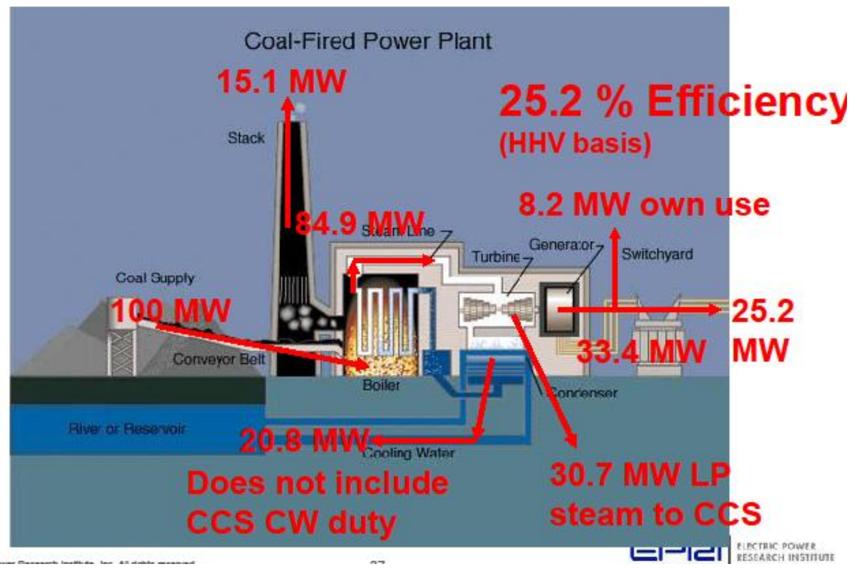
SCPC Plant – PRB Coal
(basis EPRI Report 1014924)



SCPC Plant – PRB Coal with 90% CCS using Generic MEA Capture Process
(basis EPRI Report 1014924)



The water-gas reaction :-

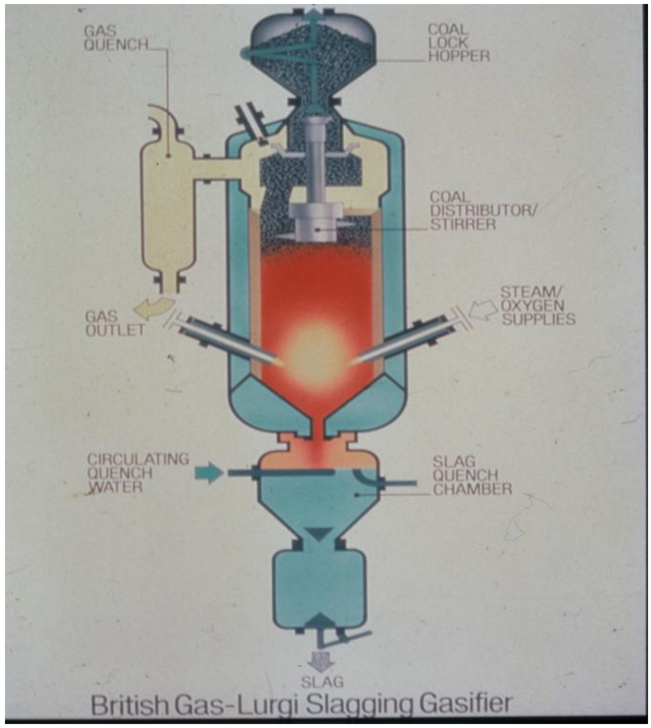
$C + H_2O \leftrightarrow H_2 + CO$ - heat + 131.6kJ/mol

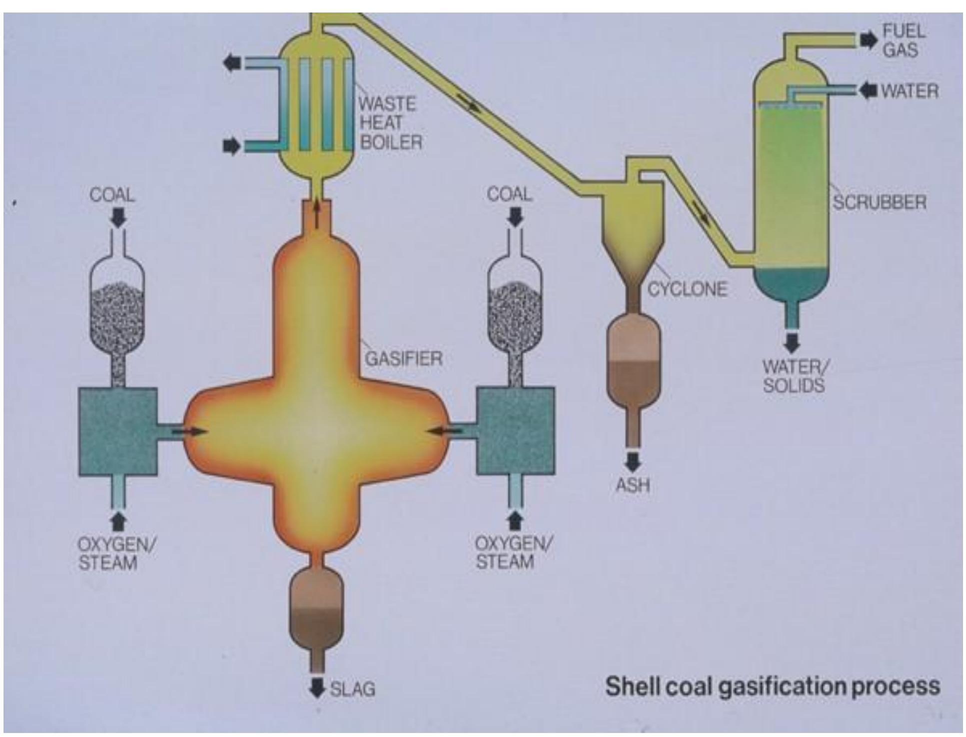
heat for the reaction can be provided externally or by combining the reaction with combustion reactions:-

$C + O_2 \leftrightarrow CO_2$ + heat - 94.1k/mol

The water- shift reaction,

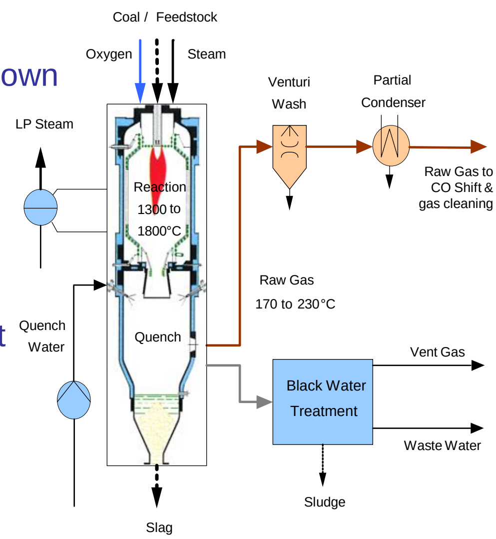
$CO + H_2O \leftrightarrow H_2 + CO_2$ + heat - 41.7kJ/mol

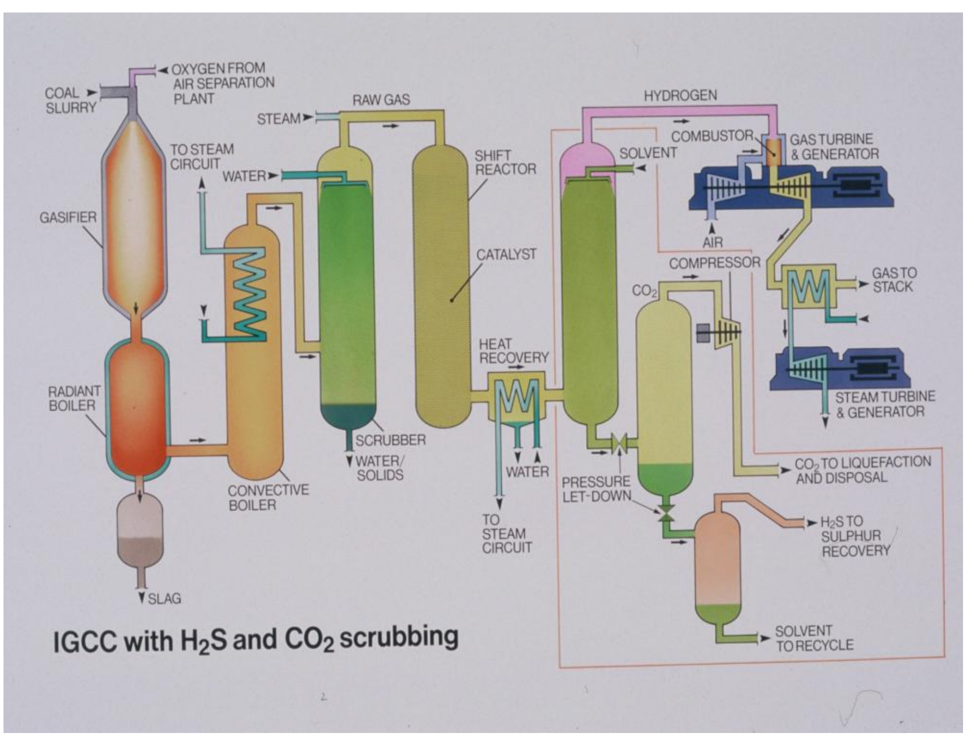

GAS QUENCH
COAL LOCK HOPPER
COAL DISTRIBUTOR/ STIRRER
STEAM/ OXYGEN SUPPLIES
GAS OUTLET
CIRCULATING QUENCH WATER
SLAG QUENCH CHAMBER
SLAG
British Gas-Lurgi Slagging Gasifier

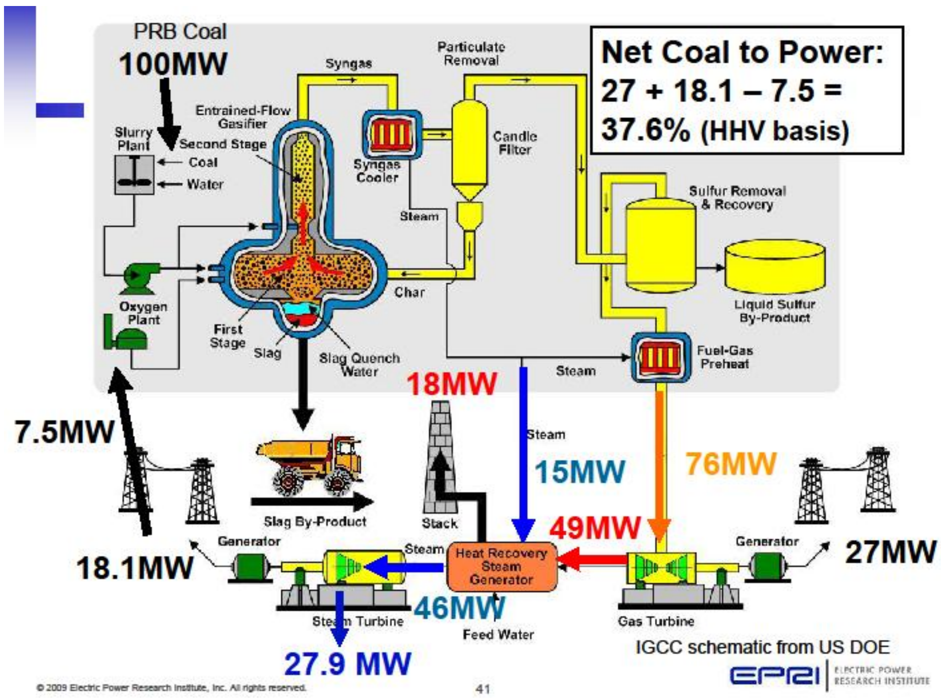

FUEL GAS
WATER
WASTE HEAT BOILER
SCRUBBER
COAL
COAL
CYCLONE
GASIFIER
WATER/ SOLIDS
ASH
OXYGEN/ STEAM
OXYGEN/ STEAM
SLAG
Shell coal gasification process

Siemens Fuel Gasifier (SFG) Standard Design

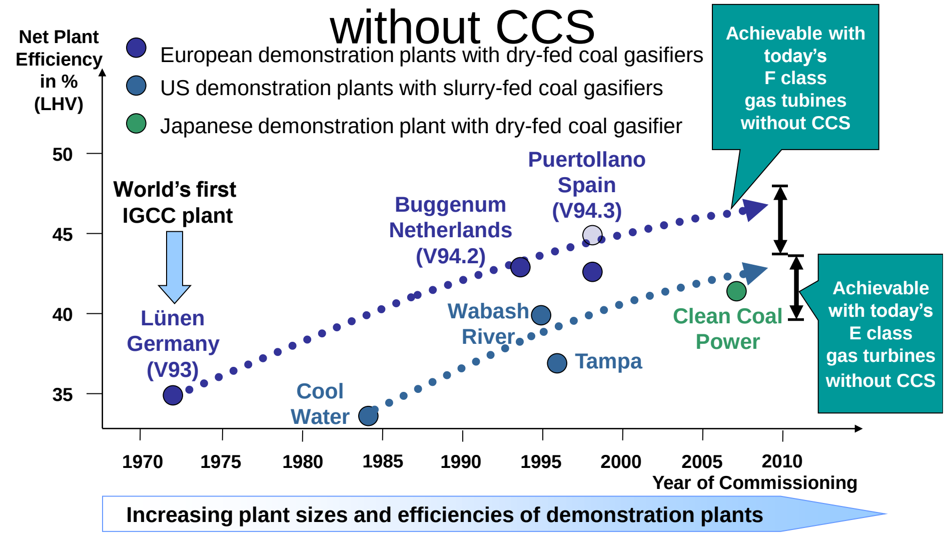
- **Cooling screen**
  - short start-up / shut-down
  - low maintenance
  - high availability
  - high conversion rate
- **Full quench**
  - simple and reliable
  - ideal for CO sour shift
- **Dry feeding**
  - high efficiency





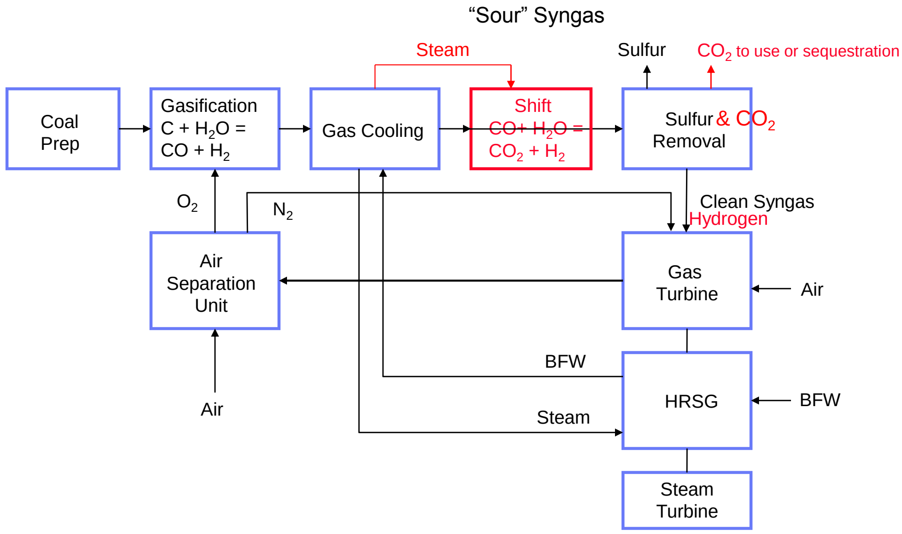


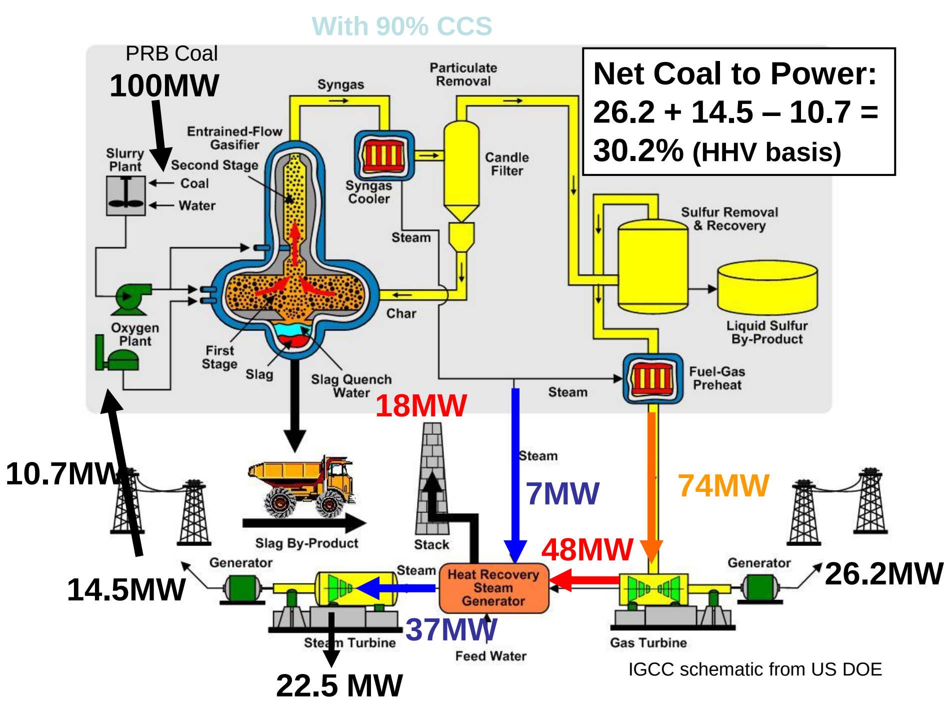
Development of IGCC net plant efficiencies for coal-based IGCC plants without CCS



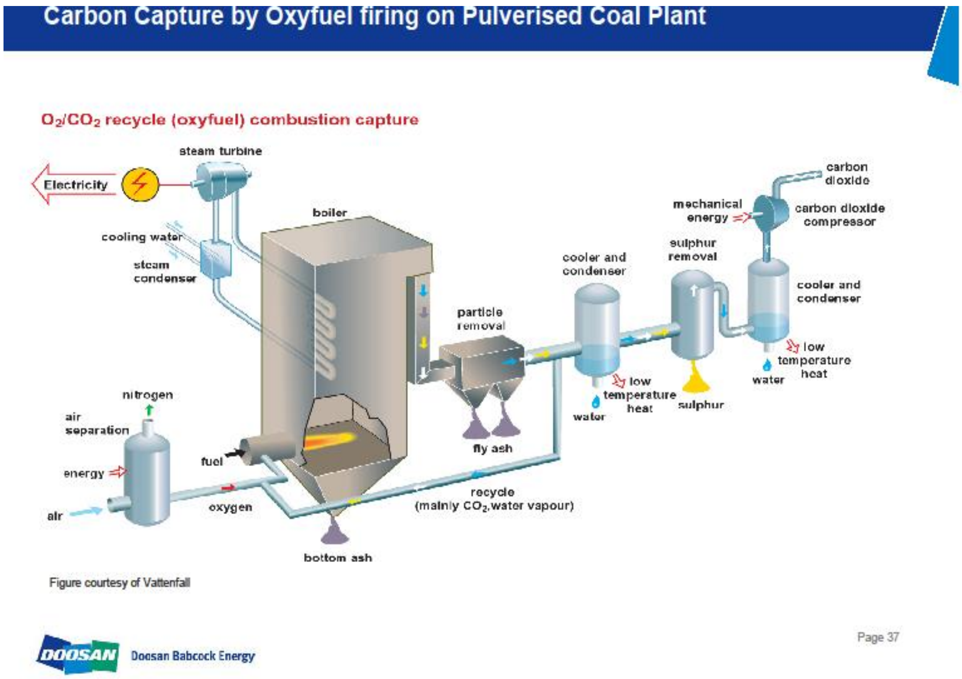
Puertollano plant efficiency for ISO conditions and high quality coal

IGCC with CO_2 Removal

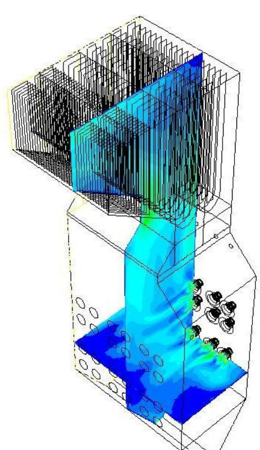


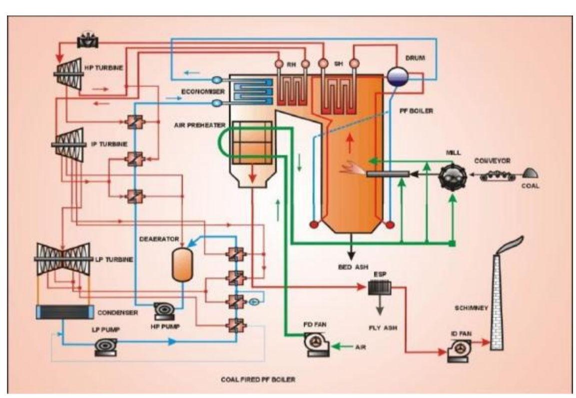


IGCC schematic from US DOE



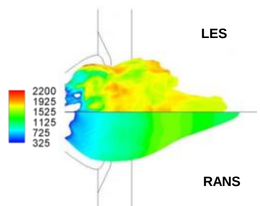
Full scale modelling 500MWe boiler



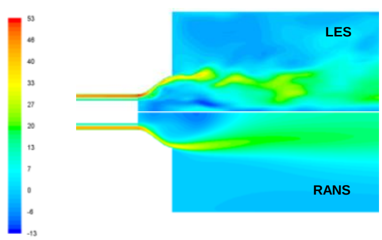


Looking at oxygen enhancement and oxyfuel combustion

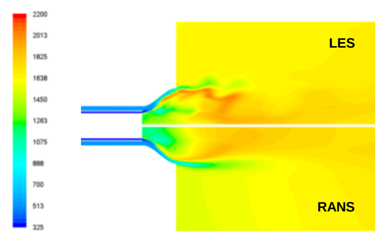
Test facility scale modelling Large Eddy Simulations



Temperature on flame surface

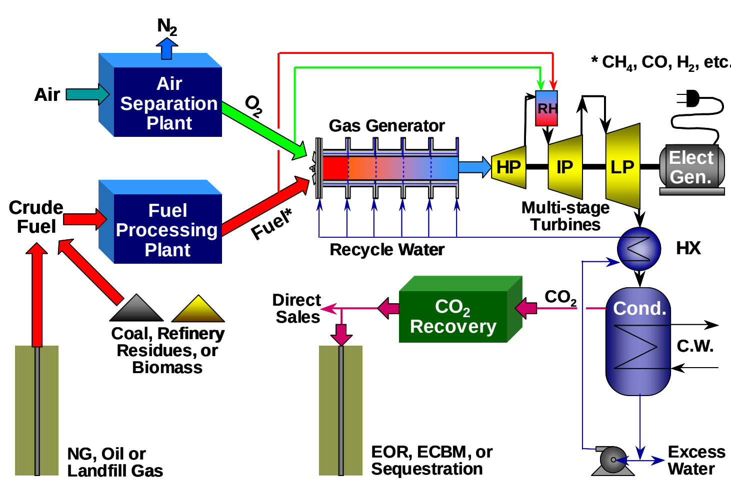


Axial velocity contours

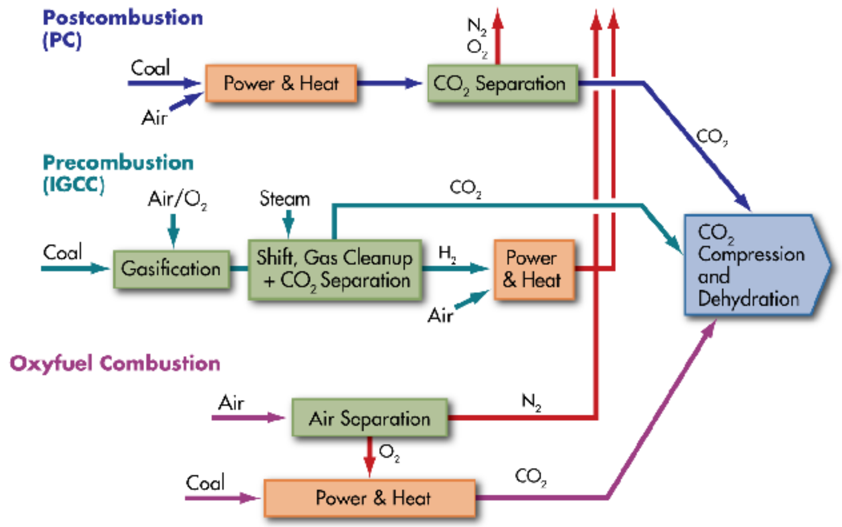


Temperature contours

Clean Energy Systems Process



CO_2 Capture in Coal Power Systems



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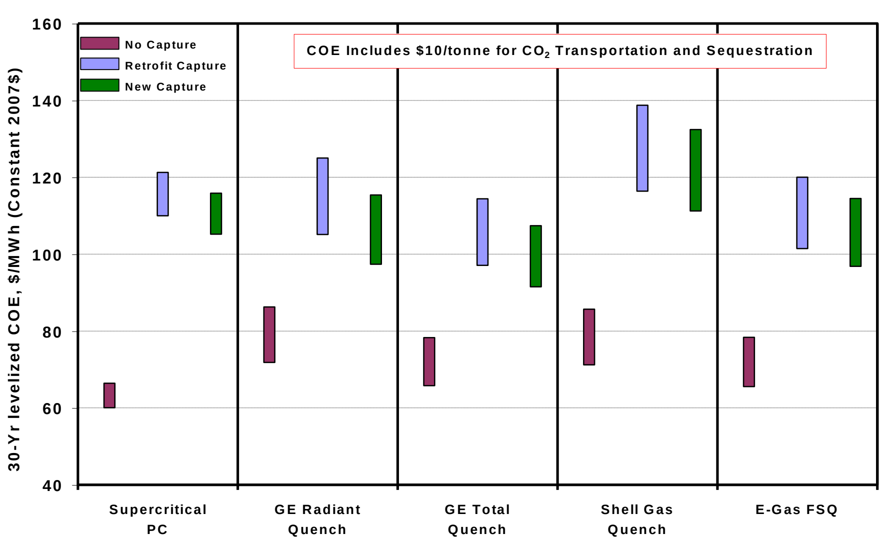
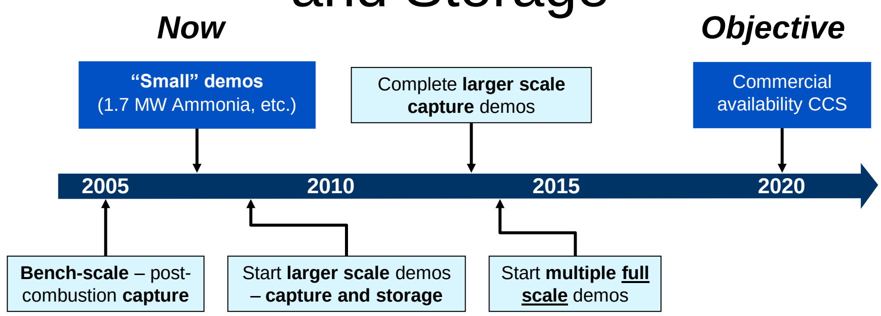
ELECTRIC POWER RESEARCH INSTITUTE

No Clear Winners in Current Designs



A Roadmap for CO_2 Capture and Storage



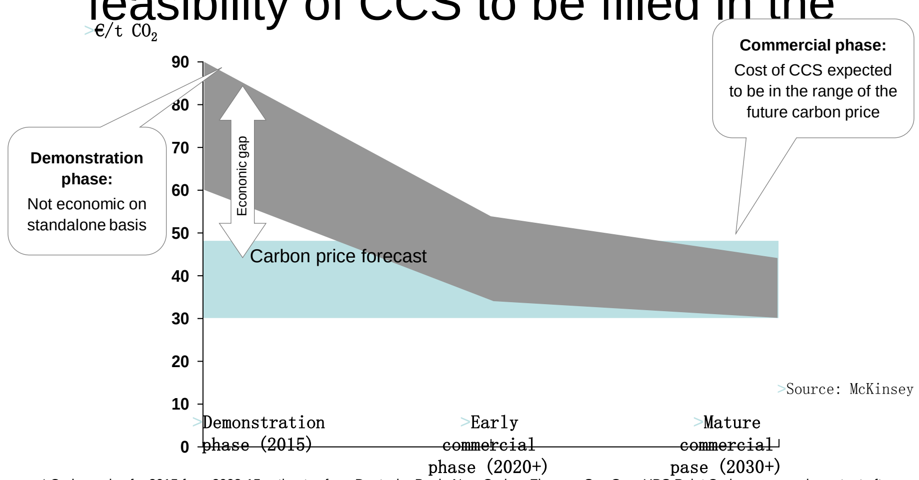
Needs: Multiple large-scale CAPTURE and STORAGE demos

Timing: 2020 objective ➔ start today, parallel paths

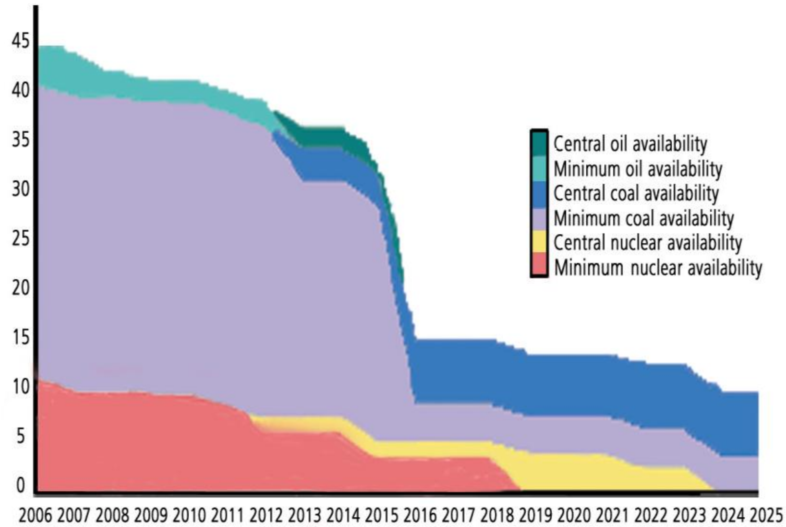
Realistic? A challenge – need technical, policy, funding alignment

Source: DOE-NETL Carbon Sequestration R&D Roadmap
Modified to add Chilled Ammonia example

McKinsey: Gap for economic feasibility of CCS to be filled in the

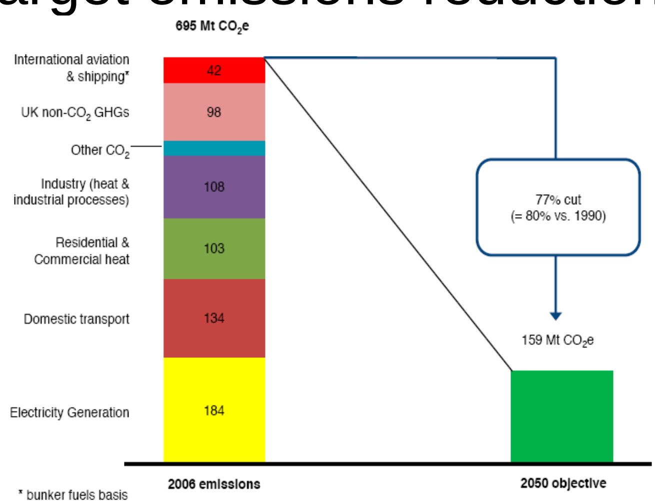


* Carbon price for 2015 from 2008-15 estimates from Deutsche Bank, New Carbon Finance, Soc Gen, UBS,Point Carbon,assumed constant afterwards
Source: Reuters; Team analysis



Estimates of available UK generating capacity (in GW)
Note: This figure is based on a graph contained in EdF's submission to the UK government's
Energy Review in 2006. The statistics were based on views and plausible future scenarios at
the time of submission

The scale of the challenge for target emissions reductions



Source: UK National Atmospheric Emissions Inventory (2008).

UK CCC Page 38, Figure 2.1

Worldwide Market Scenario in 2015

- **Transit Buses***
  - **130,000-150,000 buses in service**
- **Light Duty Vehicles***
  - **17- 80 million vehicles in service**
- **Hydrogen Required†**
  - **2.5 - 9 million tonnes per year**
- **Current Largest Merchant H_2 Plant**
  - **100,000 tonne/year**
- **Sources:**
- ***UBS Warburg Global Equity Research, Ballard June 2000**
- **†OGDEN et al, Princeton University**

Hydrogen for Transport

- Biomass
- Renewable electricity
- Electricity - nuclear or coal
- Nuclear - chemical cycles
- Coal gasification

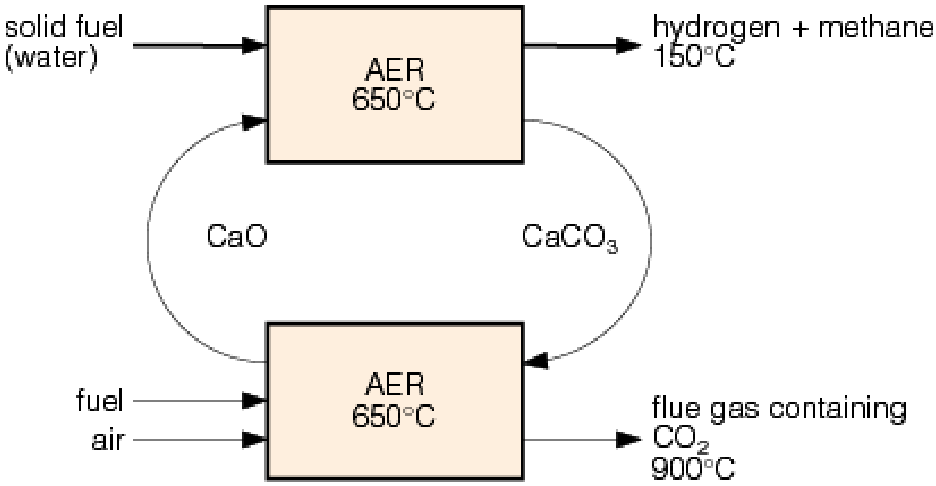
The water-gas reaction :-

$C + H_2O \leftrightarrow H_2 + CO$ - heat + 131.6kJ/mol

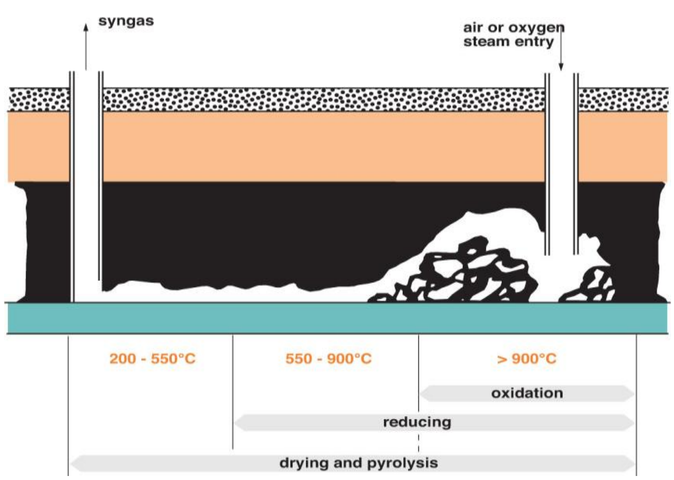
The water- shift reaction,

$CO + H_2O \leftrightarrow H_2 + CO_2$ + heat - 41.7kJ/mol

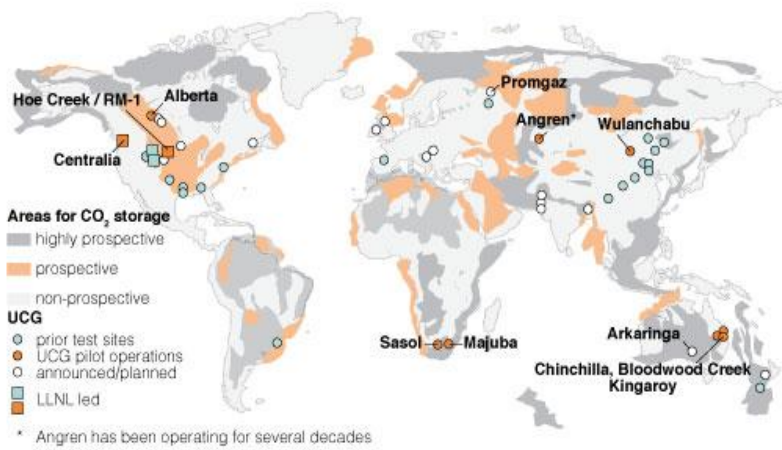
$CaO + CO_2 \leftrightarrow CaCO_3$ +heat -178kJ/mol



What UCG involves



Worldwide activities



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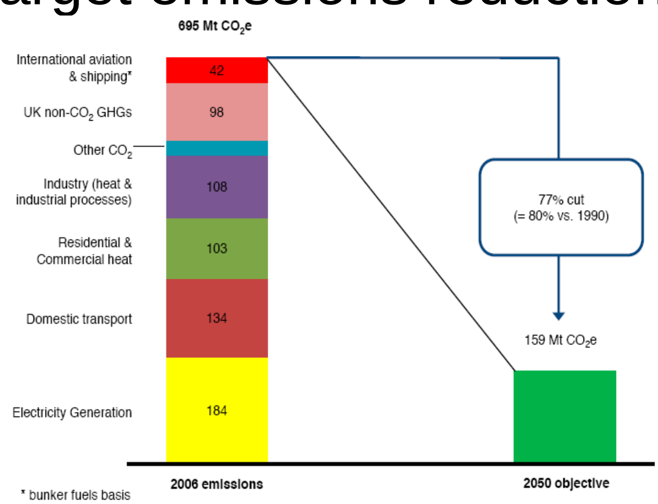
The scale of the challenge for target emissions reductions



Source: UK National Atmospheric Emissions Inventory (2008).

UK CCC Page 38, Figure 2.1