Lecture 2B

Cleaner Fossil Energy System

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Outline

- Fossil Energy Eystem
- Cleaner Fossil Energy System

- Fossil energy system

Energy resources

Shale oil

CBM
Shale gas

Fossil

CO_2 ← Coal ← Oil → Natural Gas → H_2O

H/C =1 (s)

H/C=2 (l)

H/C=4 (g)

Renewable: Biomass, Solar, Hydro, Geothermal, Wind, Ocean

Unconventional fossil

Gray, 1977; Masters, 1979; Holditch, 2006

Coal, Oil and Gas – Black Gold!

Politics: fuel source, main producers, supply-demand, peaks, global warming

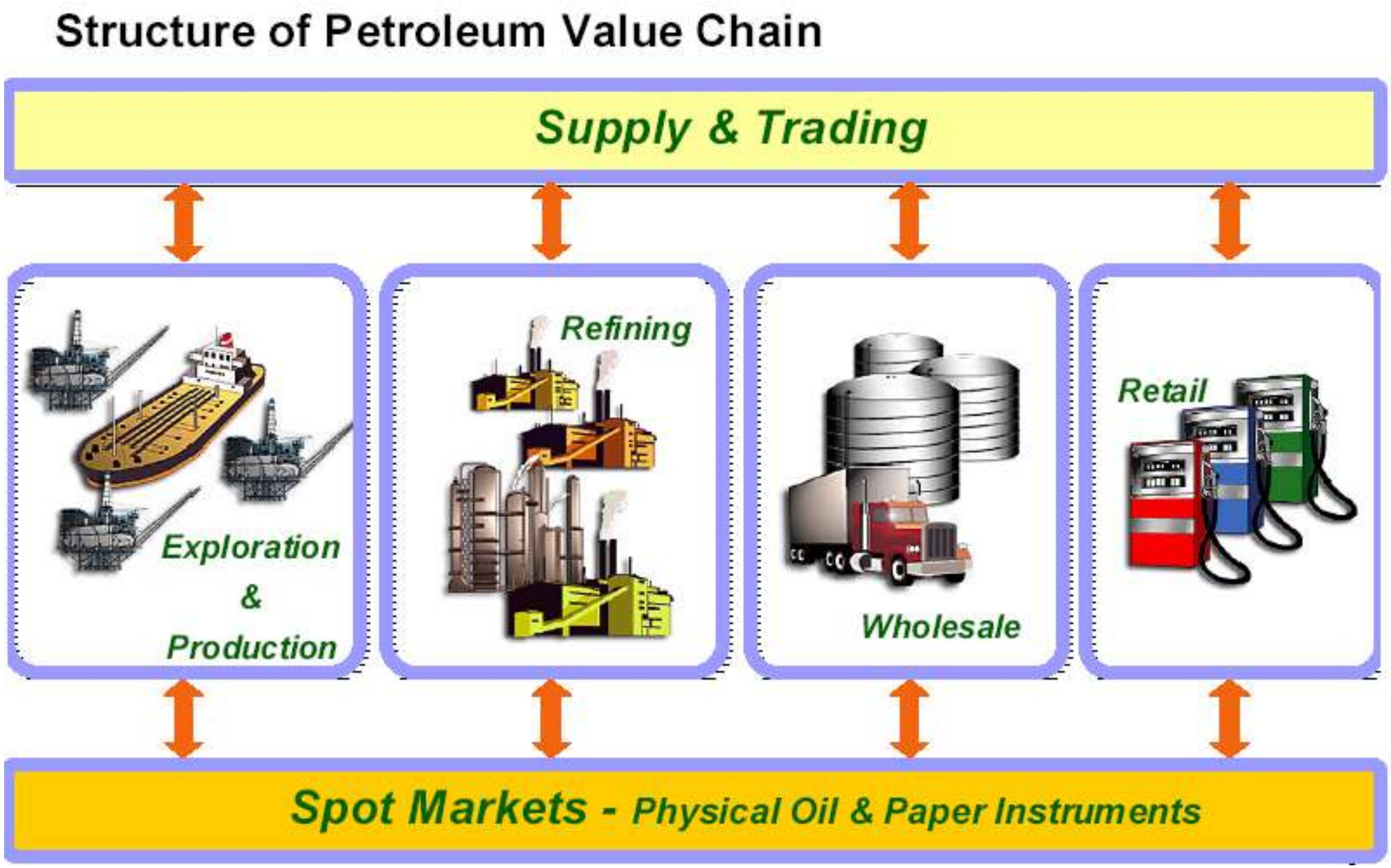
Hydrocarbon

- Within each type of hydrocarbon, there are many types, which have implications for their environmental impact and energy content
- There is an extensive, capital-intensive energy infrastructure that explores, drills, converts and transports fossil fuels from source to consumption
- Three major groups:
  - Coal, oil, and natural gas
- Three major uses
  -Transportation, industry, and electricity

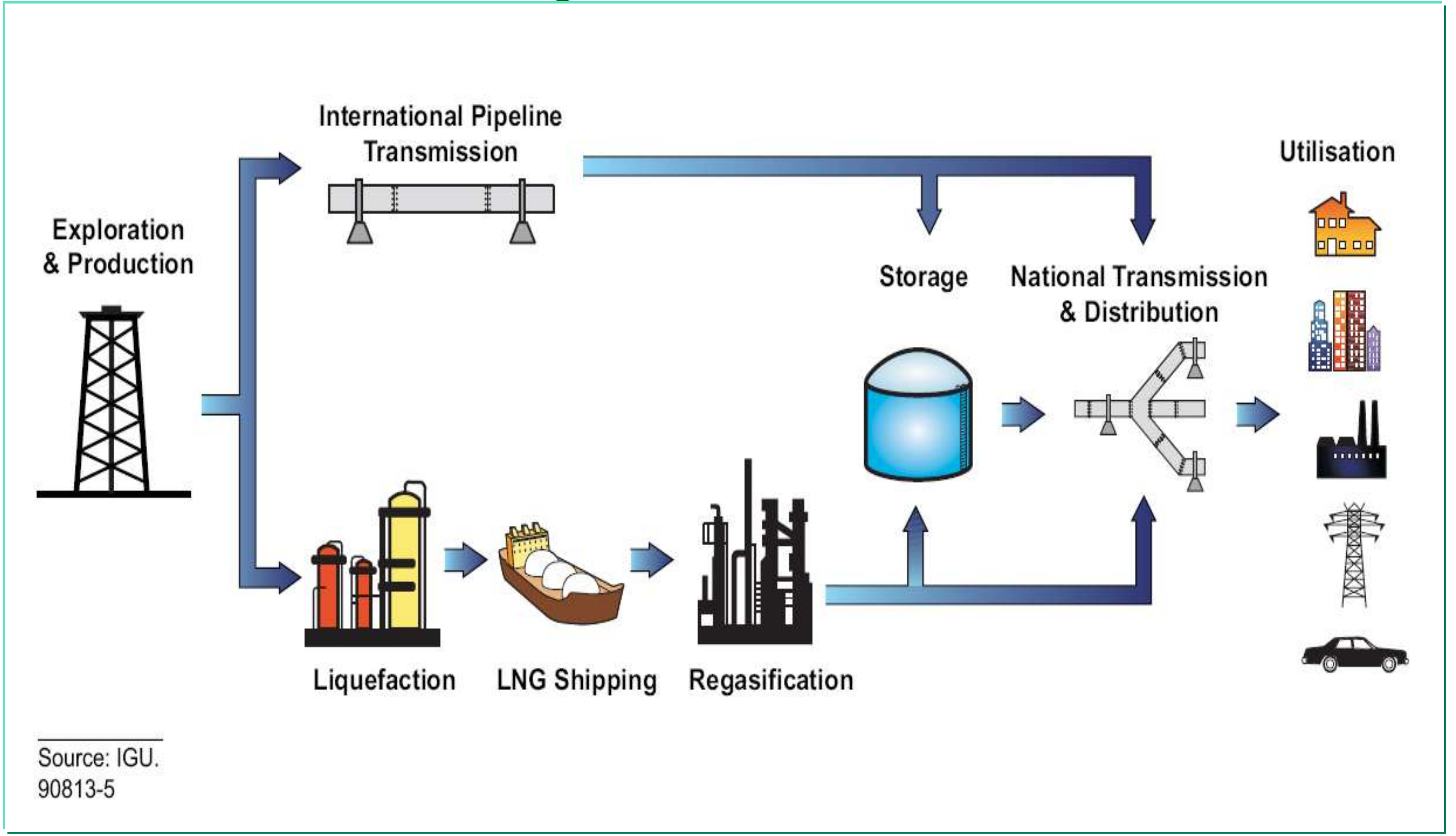
Hydrocarbon value chain

Accenture. 2007

Petroleum value chain

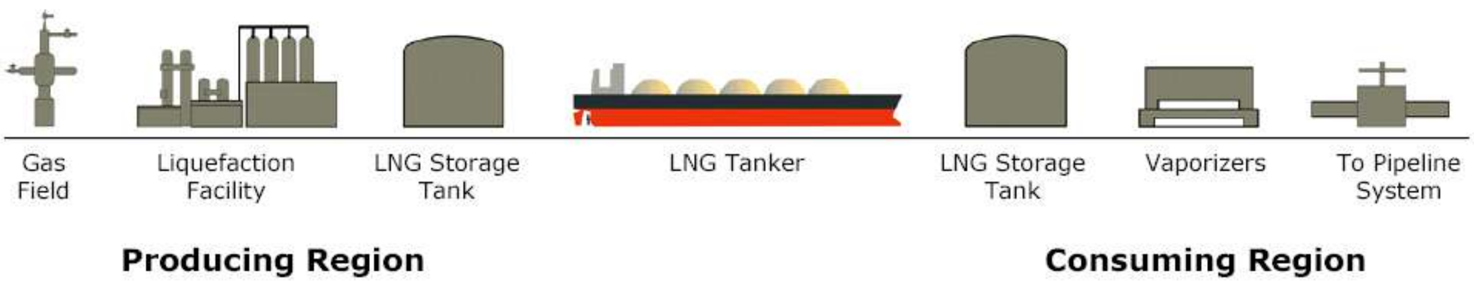


Natural gas value chain



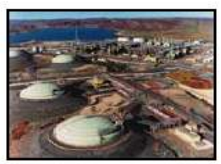
Upstream Midstream Downstream

LNG value chain



Source: CMS Energy

Upstream



Liquefaction

Shipping

Re-gas

Supplies gas to liquefaction plant

~1.1 tcf of gas required per mmtpa for a 20 year project

Plant train size typically ranges from 3 mmtpa to 5 mmtpa, plans to go to 7.8 mmtpa

Trains require approx 150 mmcfd (gross) of gas per mmtpa

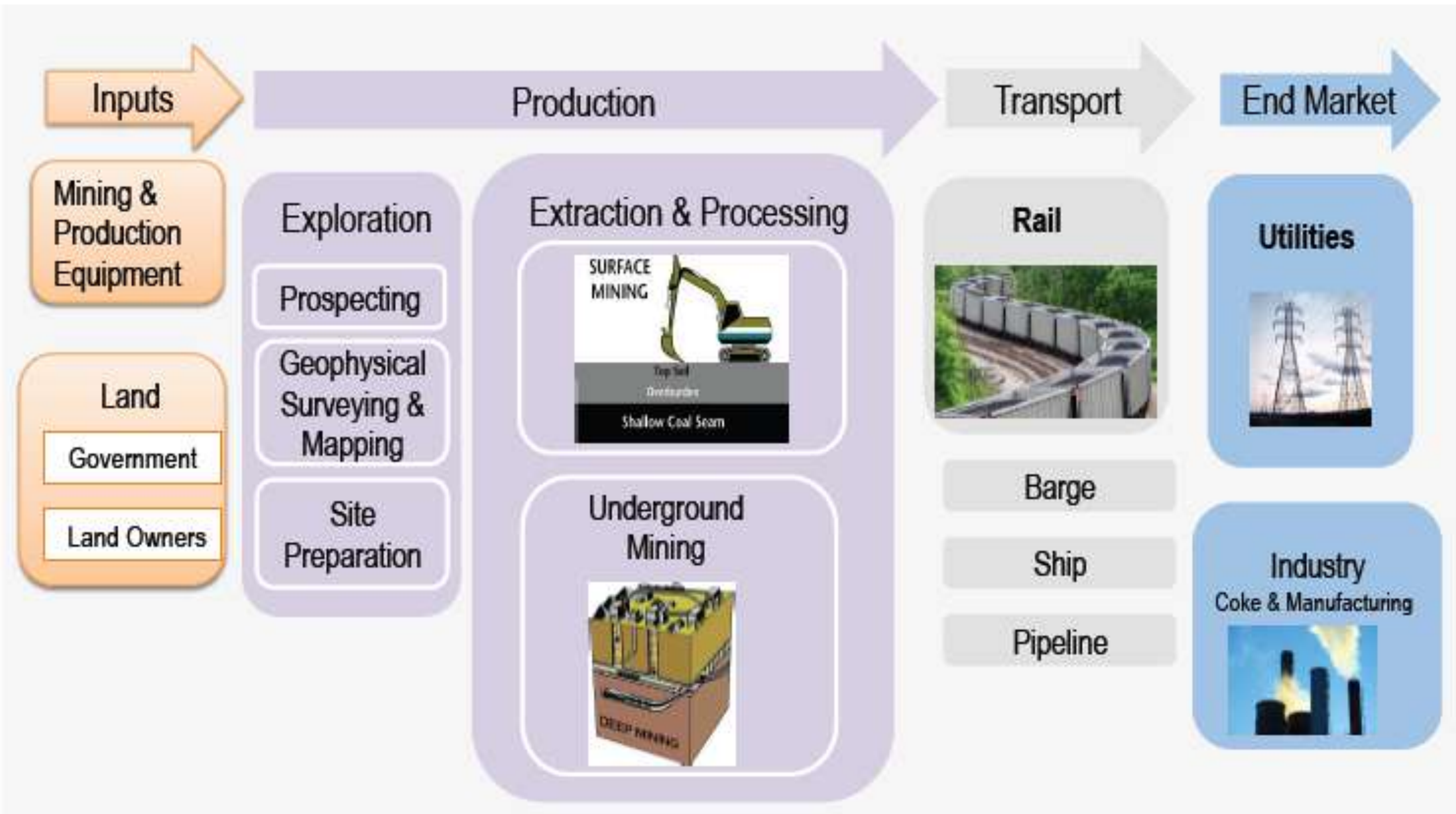
Typical new ship capacity 138,000 m^3 or 145,000m^3 - plans to increase to 200,000 m^3

138,000 m^3 ship delivers ~2.85 bcf of gas (gross)

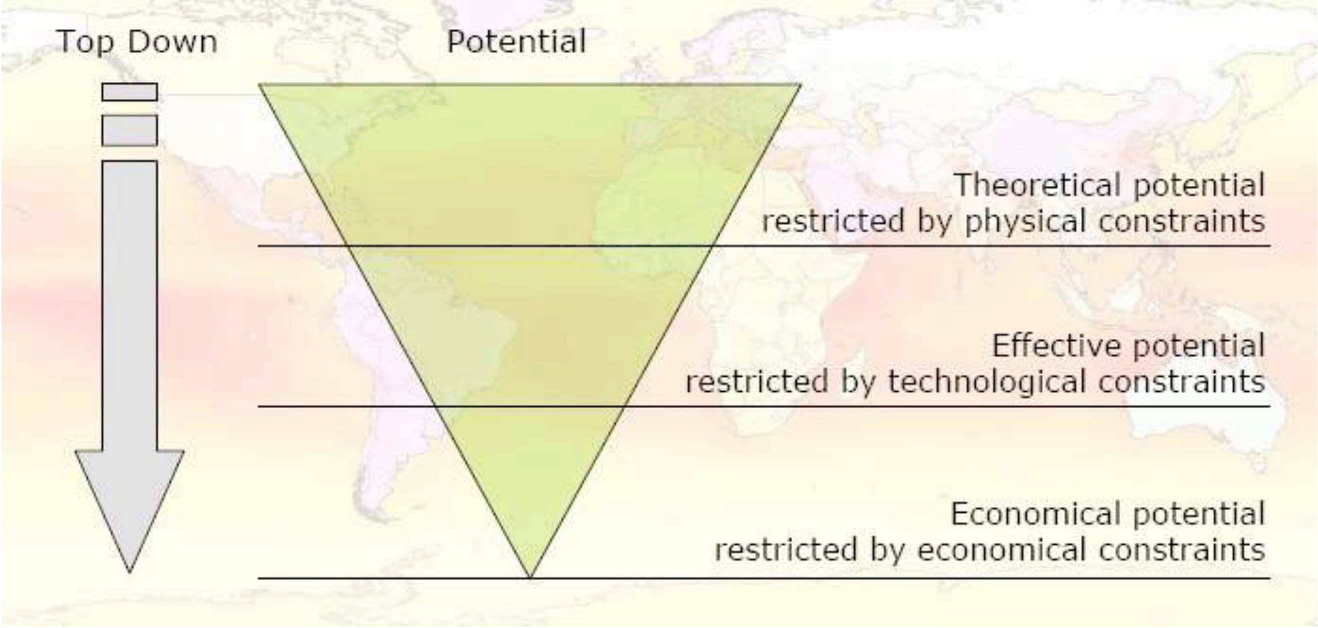
Send-out capacity of new plants ranges from 400 mmcfd to over 1 bcf/d

Storage for at least one ship's worth of LNG

Coal value chain

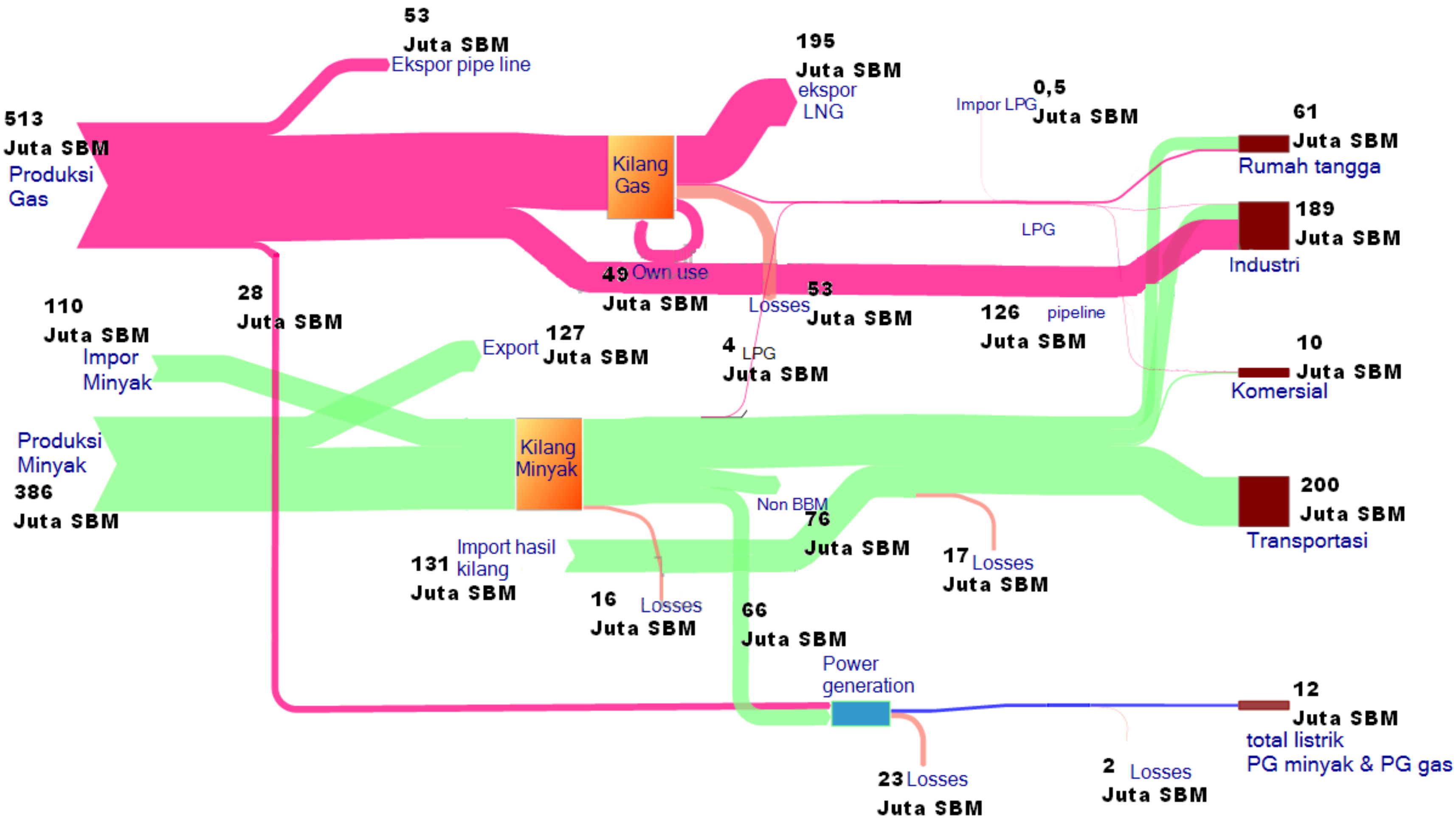


Status of energy resources



Quick estimate of potential supply = 0.9 P1, 0.5 P2, 0.1 P3

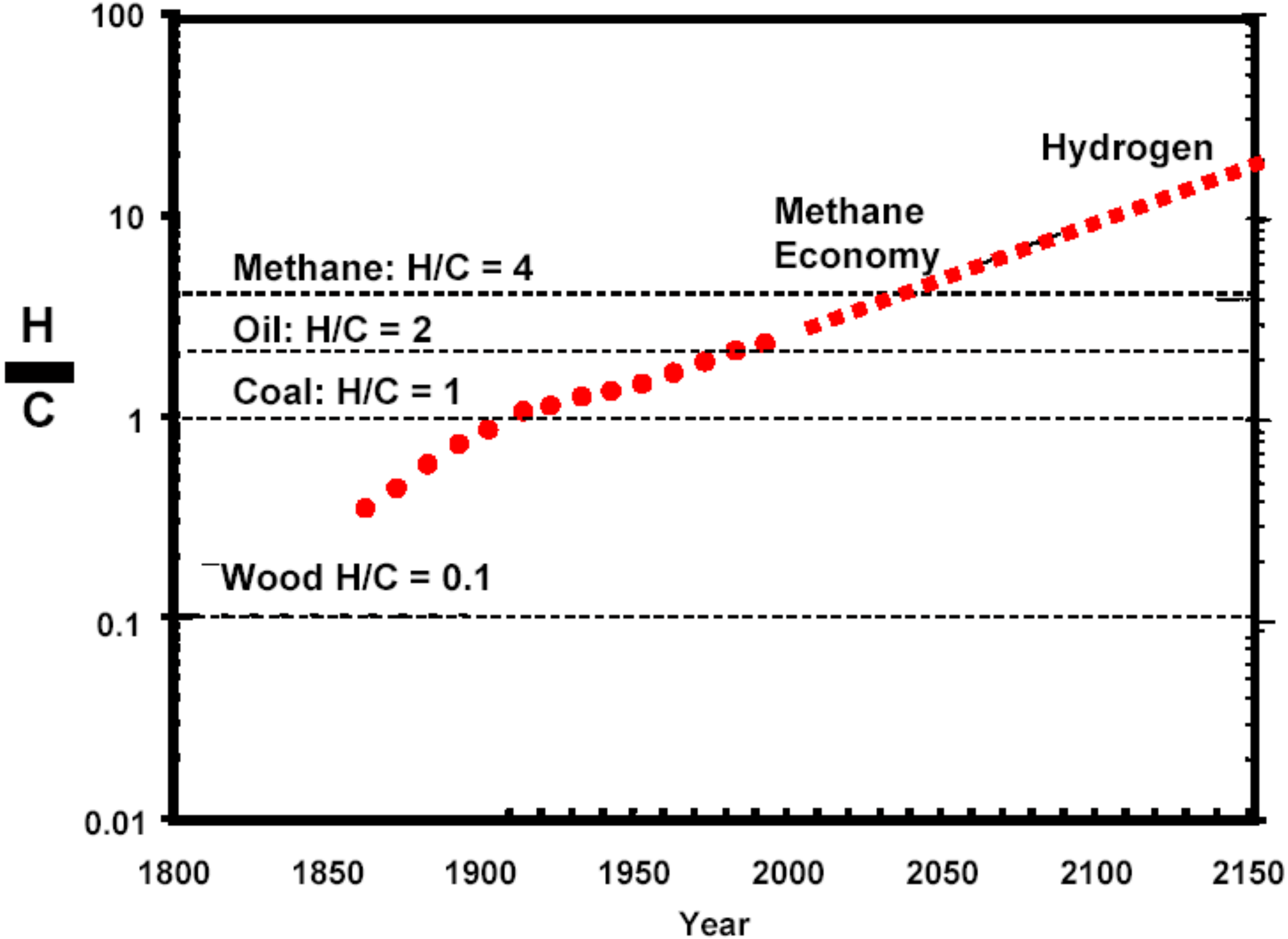
Sankey diagram – Oil & gas Indonesia

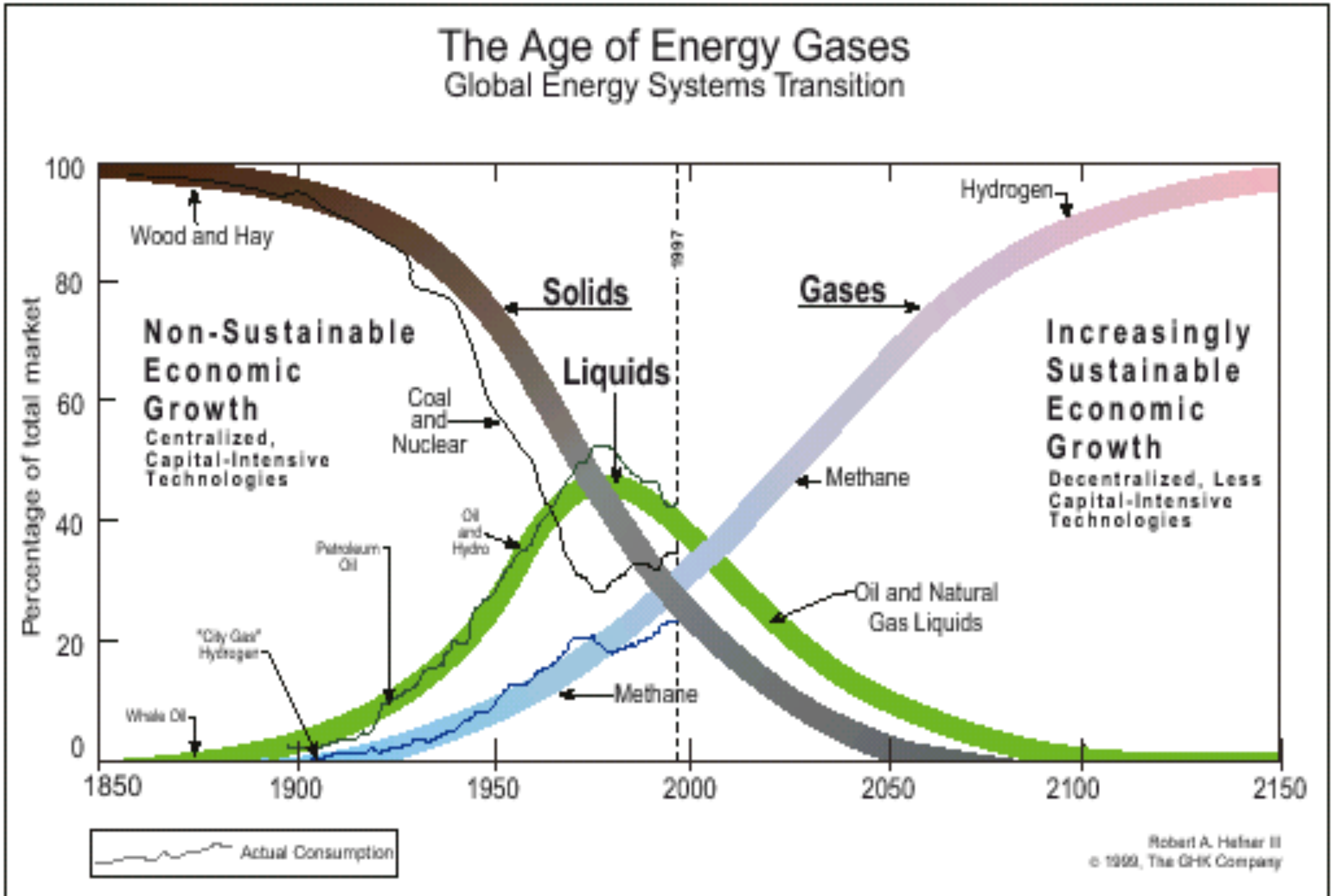


- Cleaner Fossil Energy System

Wood →Coal→Oil→Gas→H2→renewables

Decarbonization




The Age of Energy Gases
Global Energy Systems Transition
Percentage of total market
100
80
60
40
20
0
1850
1900
1950
2000
2050
2100
2150
1997
Wood and Hay
Solids
Liquids
Gases
Hydrogen
Non-Sustainable Economic Growth
Centralized, Capital-Intensive Technologies
Increasingly Sustainable Economic Growth
Decentralized, Less Capital-Intensive Technologies
Coal and Nuclear
Oil and Hydro
Petroleum Oil
"City Gas" Hydrogen
Whale Oil
Methane
Methane
Oil and Natural Gas Liquids
Actual Consumption
Robert A. Hefner III
© 1999, The GHK Company

Clean fossil technologies

- Reforming/Gasiffication
- Oxycombustion
- Chemical looping
- Gas/Coal to liquids
- CCUS

Advanced fossil energy systems

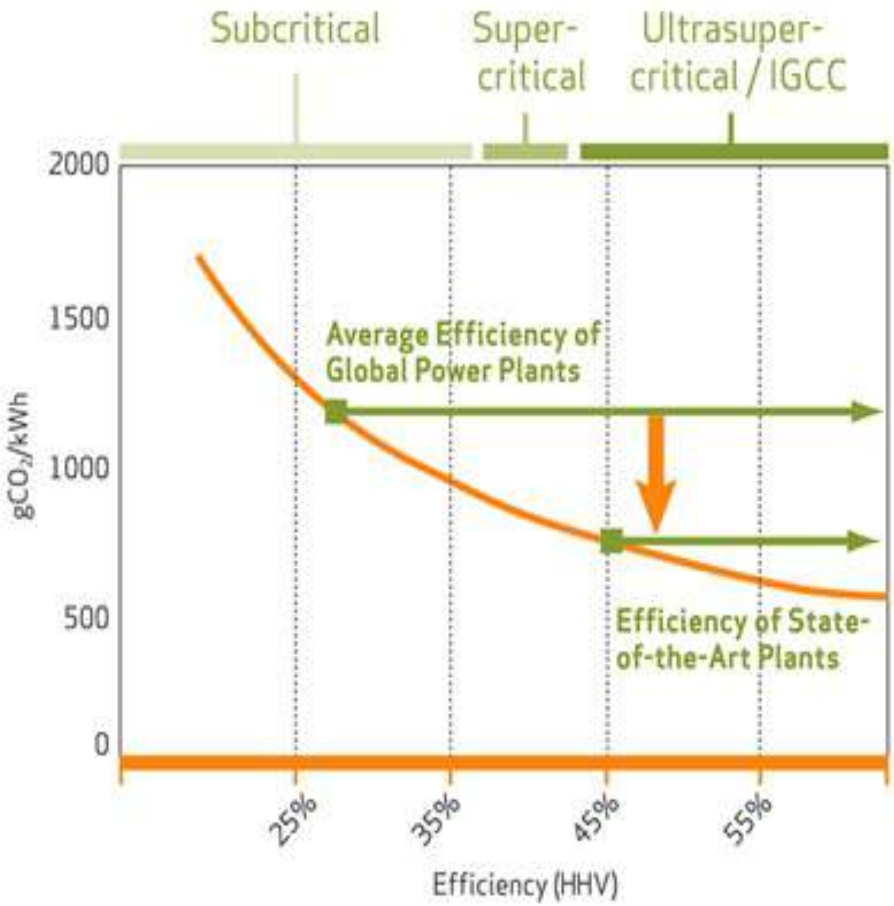
Transformational Advanced Energy Systems		
Technology	**Fuel**	**Description**
Pressurized Oxy-Combustion (P-Oxy)	Coal and Natural Gas	Oxy-combustion power plants remove nitrogen from air cryogenically and perform the combustion of fossil fuels with oxygen and recycled flue gas to produce a stream largely comprised of CO_2 and water, greatly simplifying carbon capture. P-Oxy operates at elevated pressure, improving efficiency and allowing smaller components that combine to potentially reduce costs.
Chemical Looping Combustion (CLC)	Coal and Natural Gas	CLC is a form of oxy-combustion in which oxygen from air is separated using a metal oxide or limestone oxygen carrier, eliminating the need for cryogenic air separation and its significant energy penalty, while maintaining the relatively easy carbon capture provided by oxy-combustion.
Direct-Fired Supercritical CO_2 (sCO_2) Cycles	Coal and Natural Gas	A form of oxy-combustion, direct-fired sCO_2 cycles burn natural gas or syngas (provided by coal gasification) in a high-pressure oxy-combustor, producing very high-temperature CO_2 and water that drive a sCO_2 turbine to make power. Water and CO_2 (at pipeline pressure) are then removed downstream to conserve mass, producing a high efficiency, potentially low-cost carbon capture system.
Indirect-Fired sCO_2 Cycles	Coal and Natural Gas	Replace steam-Rankine cycles with sCO_2 cycles which, due to the superior thermodynamic qualities of CO_2, have higher efficiency and utilize more compact turbomachinery. Can be used on any cycle that currently uses a steam-Rankine one, including solar thermal, geothermal, nuclear, biomass and any type of fossil fuel. The process results in 2–5 percentage point higher efficiencies and can be coupled with a low-cost carbon capture system.
Gasification	Coal	Coal can be gasified in either an air- or oxygen-blown gasifier to produce synthetic gas (syngas) that can be used in an efficient integrated gasification combined cycle (IGCC) system. Pre-combustion carbon capture can also be added. New, highly efficient, compact gasifiers can be used in poly-generation plants that combine electricity generation with co-production of transportation fuels, fertilizer and/or other chemicals to improve the overall economics.
Compact Hydrogen Generator	Natural Gas	New, highly efficient method for producing hydrogen (alternative to steam-methane reforming).

Cross-Cutting Technologies		
Technology	**Fuel**	**Description**
Advanced Ultra-supercritical Materials (A-USC)	Coal and Natural Gas	A-USC materials are needed to allow working fluid temperatures up to 760°C to support highly efficient combustion and heat exchange systems for both steam-Rankine and sCO_2 power systems and other high-temperature technologies. Can be applicable to both new and existing plants.
Turbines	Coal and Natural Gas	RD&D and testing of steam turbines, combustion turbines, sCO_2 turbines and pressure-gain combustion (PGC), all in an effort to improve efficiency, reliability and flexibility and support power systems evaluated in the Roadmap.

Cross-Cutting Technologies		
Technology	**Fuel**	**Description**
CO_2 Capture	Coal and Natural Gas	Advances in solvents, sorbents and membranes for both pre- and post-combustion carbon capture focused on lowering energy requirements and overall cost of capture including capital, operating and maintenance costs. Technologies will need to be adjusted to handle the differences between coal and natural gas flue gas, which include different CO_2 concentrations and trace species. R&D is also focusing on flexibility of operations of carbon capture systems to accommodate ramping cycles.
CO_2 Storage	Coal and Natural gas	Saline reservoirs, enhanced oil and gas recovery and other geologies are being explored for storing CO_2 both onshore and offshore. RD&D as well as large-scale CO_2 storage and regional infrastructure strategies related both to storage and transportation in the U.S. are needed.
Existing Plants	Coal and Natural Gas	RD&D to support flexibility and reliability of operations of existing plants.
Cross-Cutting	Coal and Natural Gas	RD&D on technologies that support all Roadmap areas, including: • Advanced manufacturing • Breakthrough technologies • Sensors and controls • Water management

- Power generation

Combustion Efficiency and Pollutants Emission

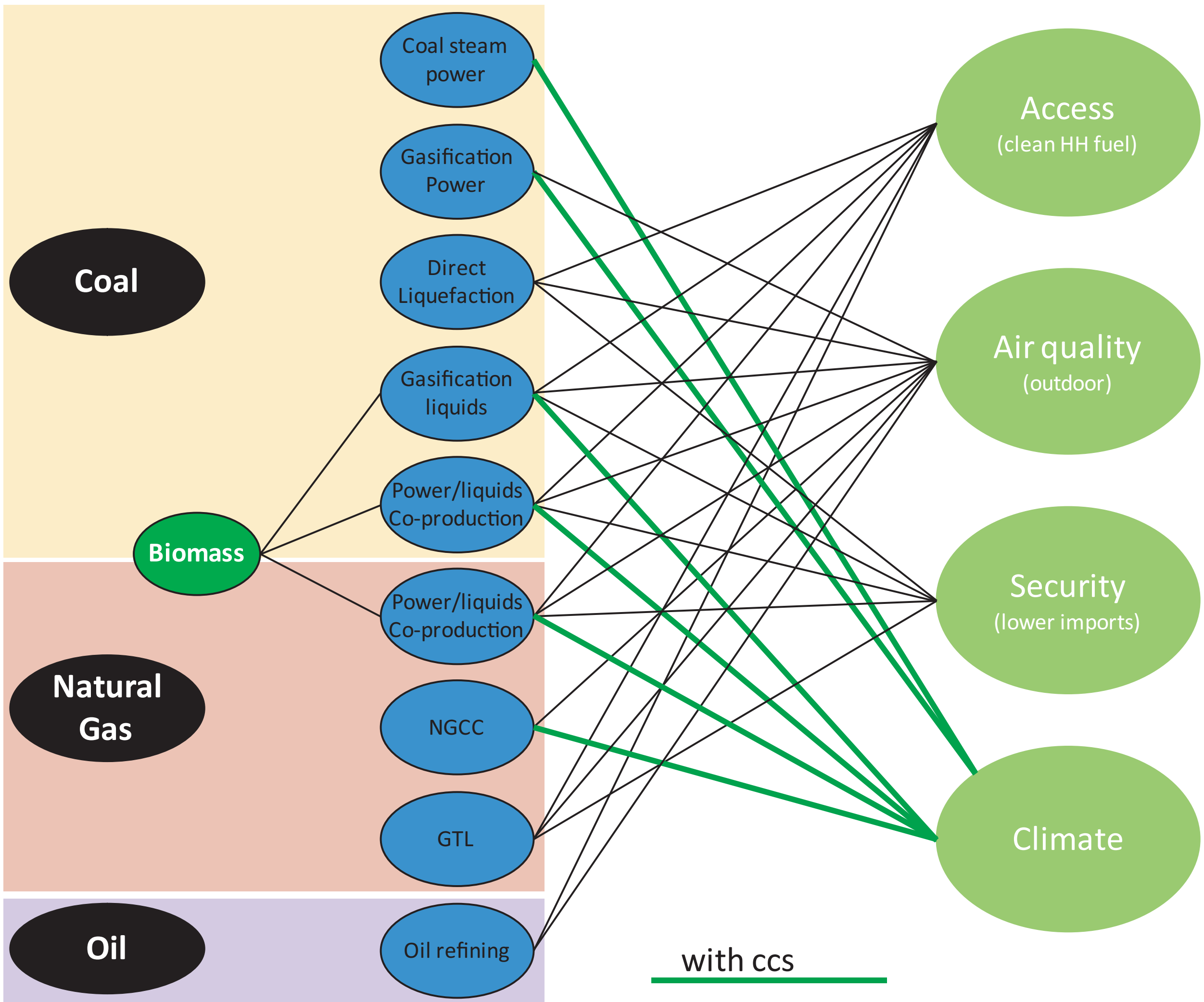


Source: IEA "Focus on Clean Coal" (2006)

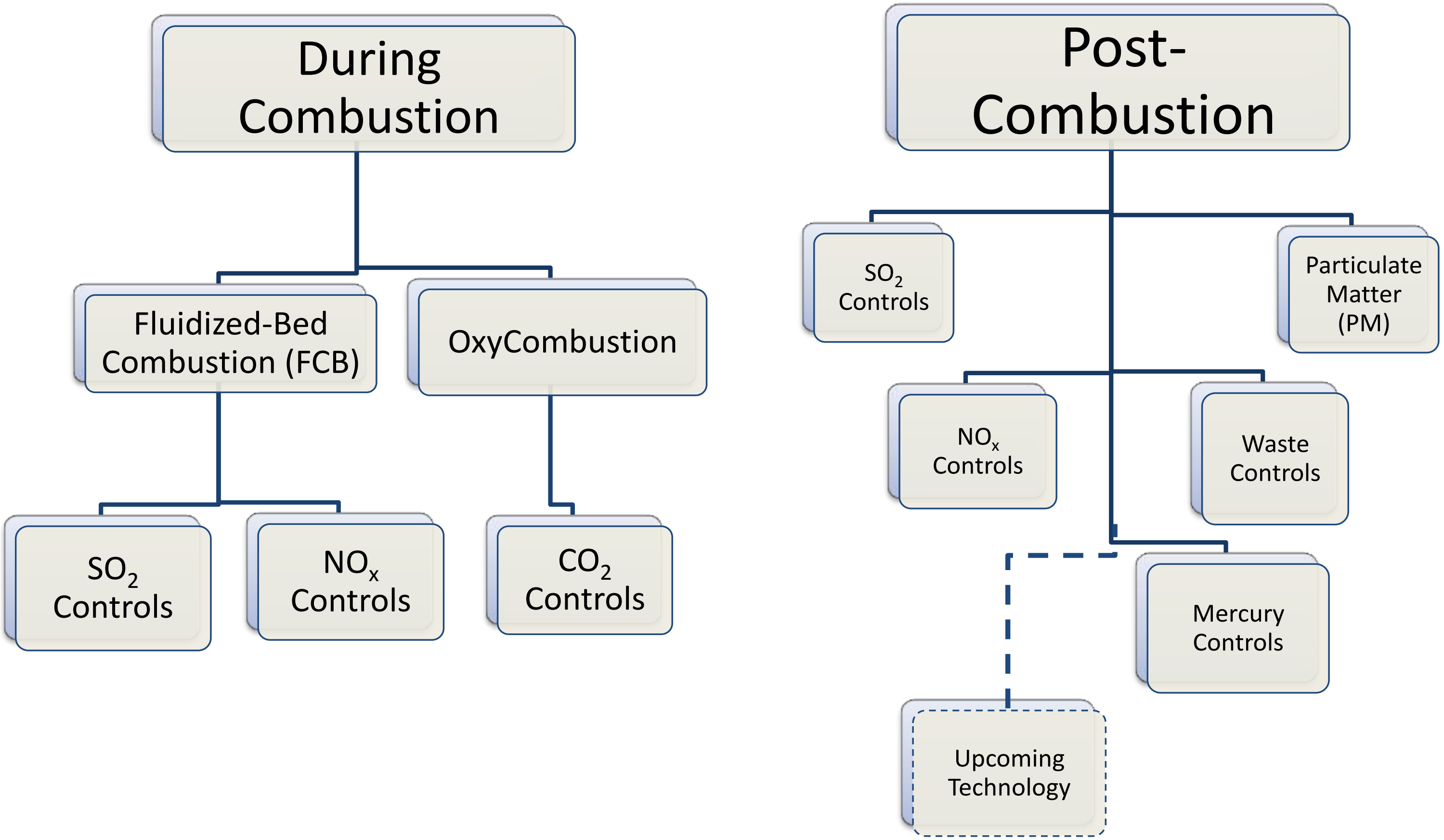
Note: 1% increase in efficiency = 2-3% decrease in emissions

Improving efficiency levels increases the amount of energy that can be extracted from a single unit of coal. Increases in the efficiency of electricity generation are essential in tackling climate change.

Clean fossil strategies



Emission control technologies



Source: Worthington, 2016

Emission Control Technologies

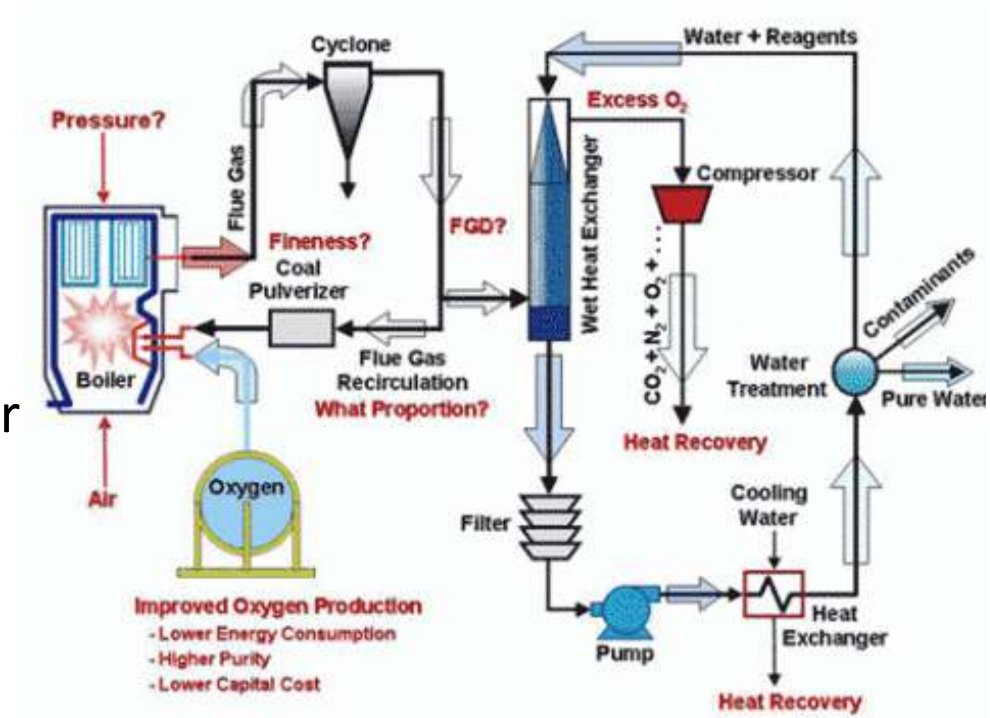
During Combustion: Processes designed to occur inside the furnace while coal is being combusted

- Fluidized-Bed Combustion (FBC)
  - Finely ground coal, mixed with limestone, is injected with hot air into the boiler. As the coal burns, the limestone soaks up the sulfur
  - Can reduce the amount of sulfur release by over 95%
  - Boiler temperatures also drop from 2700°F (1480°C) in conventional boilers to about 1500°F (~820°C), which mitigates the production of nitrogen pollutants

Source: Worthington, 2016

Emission Control Technologies

- OxyCombustion
  - Used with pulverized coal-fired boilers
  - Replaces the combustion air with a mixture of oxygen and recycled flue gas and/or water for temperature control
  - Exiting flue gas, that is not recirculated, is rich in CO_2 and ready for utilization or sequestration



Source: USDOE, Office of Fossil Fuels, Advanced Combustion Technologies http://energy.gov/fe/science-innovation/clean-coal-research/advanced-combustion-technologies

Source: Worthington, 2016

Emission Control Technologies

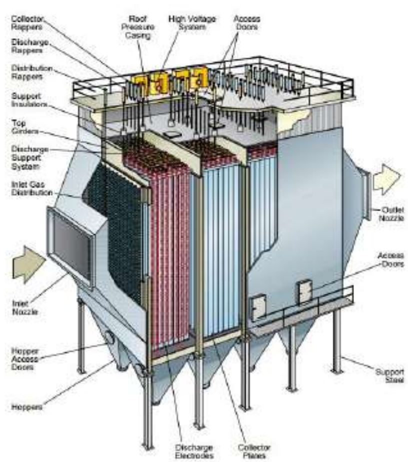
Post-Combustion Processes

- SO_2 controls
  - Wet processes use sorbents to capture SO_2
- NO_x controls
  - Primary Abatement: reduction of NO_x produced in the primary combustion zone
    - Low excess air (LEA) combustion, Low NO_x burners (LNB), Staged Combustion (SC), Flue Gas Recirculation (FGR), NO_x reburning
  - Flue gas treatment: reduction of NO_x in flue gas
    - Selective catalytically reduction (SCR), Selection non-catalytic Reduction (SNCR), Zero Ammonia technology (ZAT)

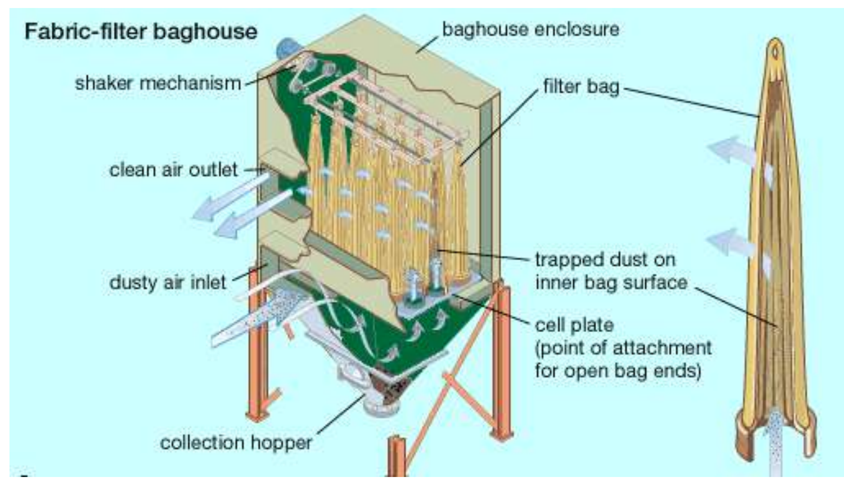
Source: Worthington, 2016

Emission Control Technologies

- Particulate Matter Controls
  - Electrostatic precipitators (ESP), fabric filter or baghouses, wet particulate scrubbers, cyclones and hot gas filtration systems
  - ESP and baghouses are key technologies



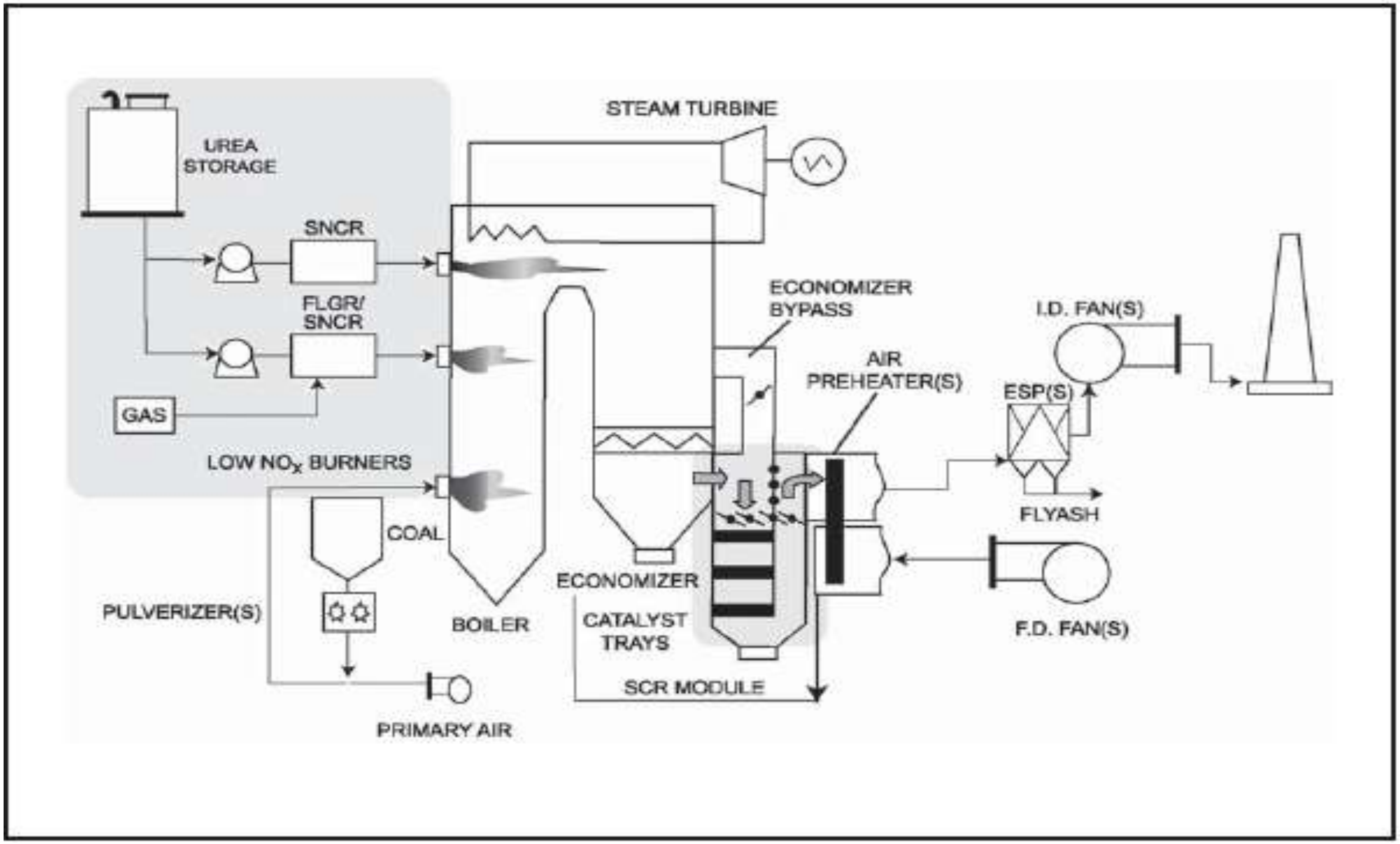
Source:http://www.babcock.com/products/Pages/Dry-Electrostatic-Precipitator.aspx



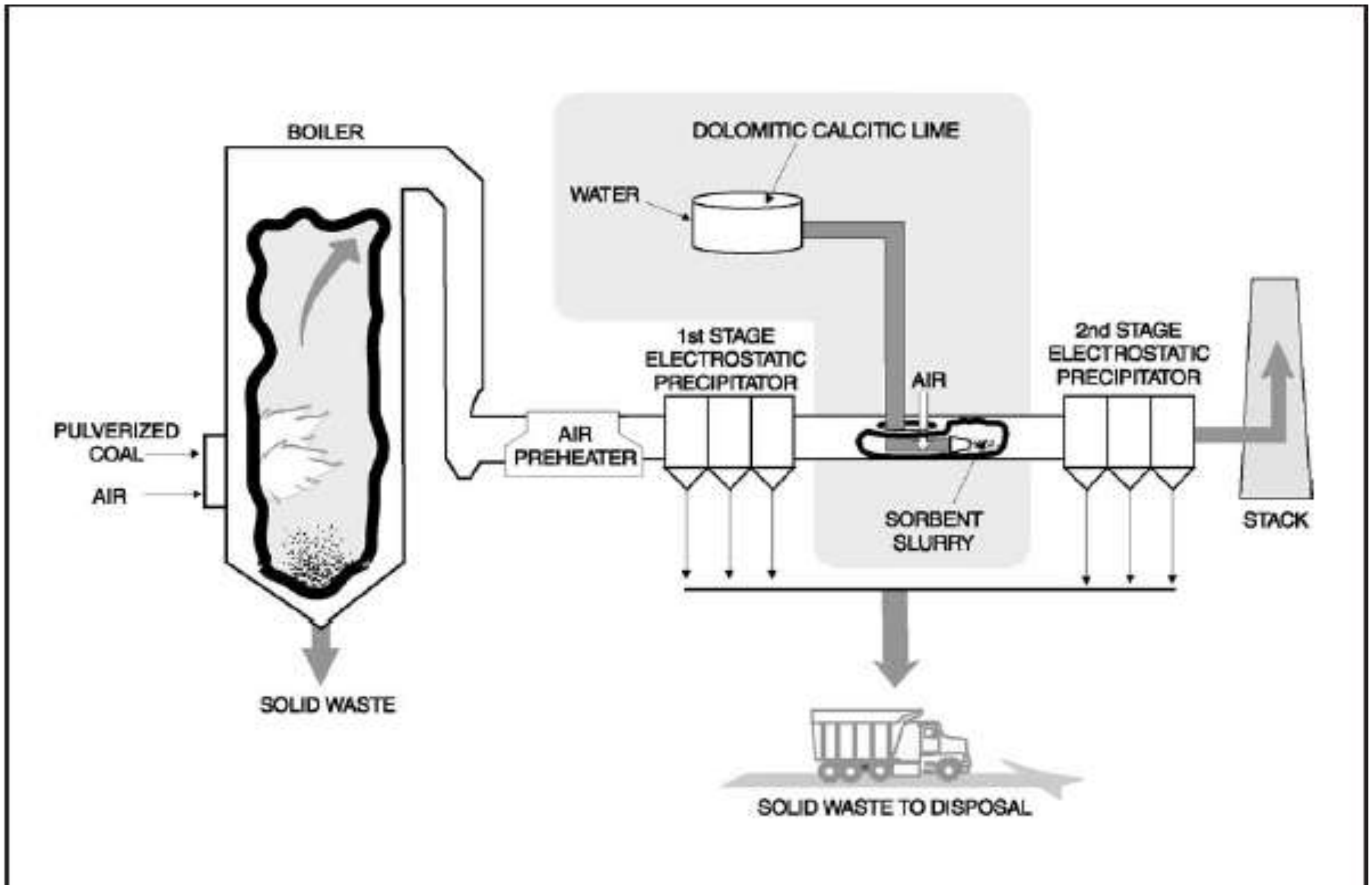
Source:http://www.envirotrain.co.uk/module-a/a3-effects-of-releases/a3-10control-of-releases/a3-10-1physical/a3-10-1-1-bag-house

Source: Worthington, 2016

Low NOx burner



DeSOx

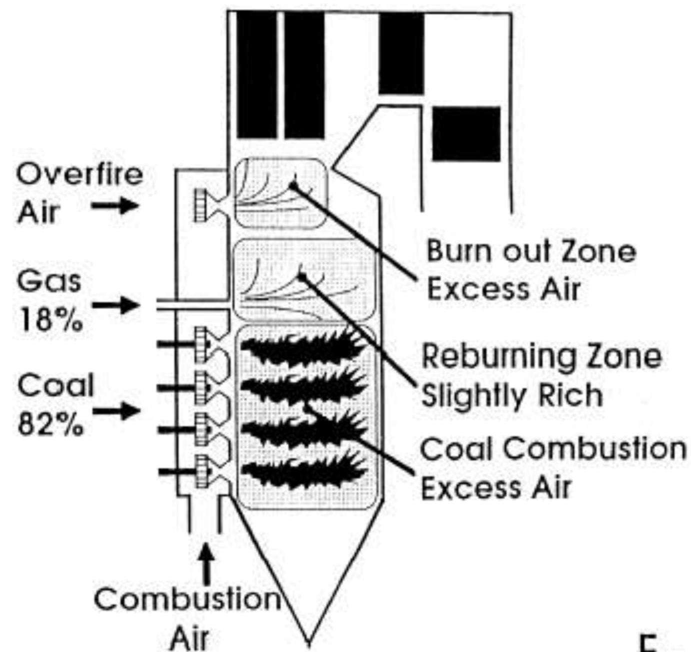


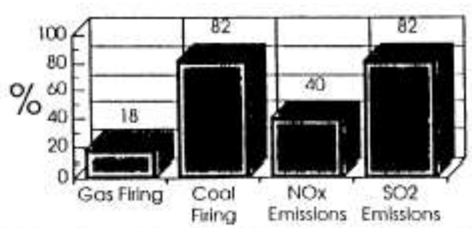
BOILER
DOLOMITIC CALCITIC LIME
WATER
PULVERIZED COAL
AIR
AIR PREHEATER
1st STAGE ELECTROSTATIC PRECIPITATOR
AIR
2nd STAGE ELECTROSTATIC PRECIPITATOR
STACK
SORBENT SLURRY
SOLID WASTE
SOLID WASTE TO DISPOSAL

NO_x Gas Reburning

GAS REBURNING

- Objective: NOx Control
  - Exceeds Low NOx Burners
- Equipment
  - Gas Injectors
  - Overfire Air Ports





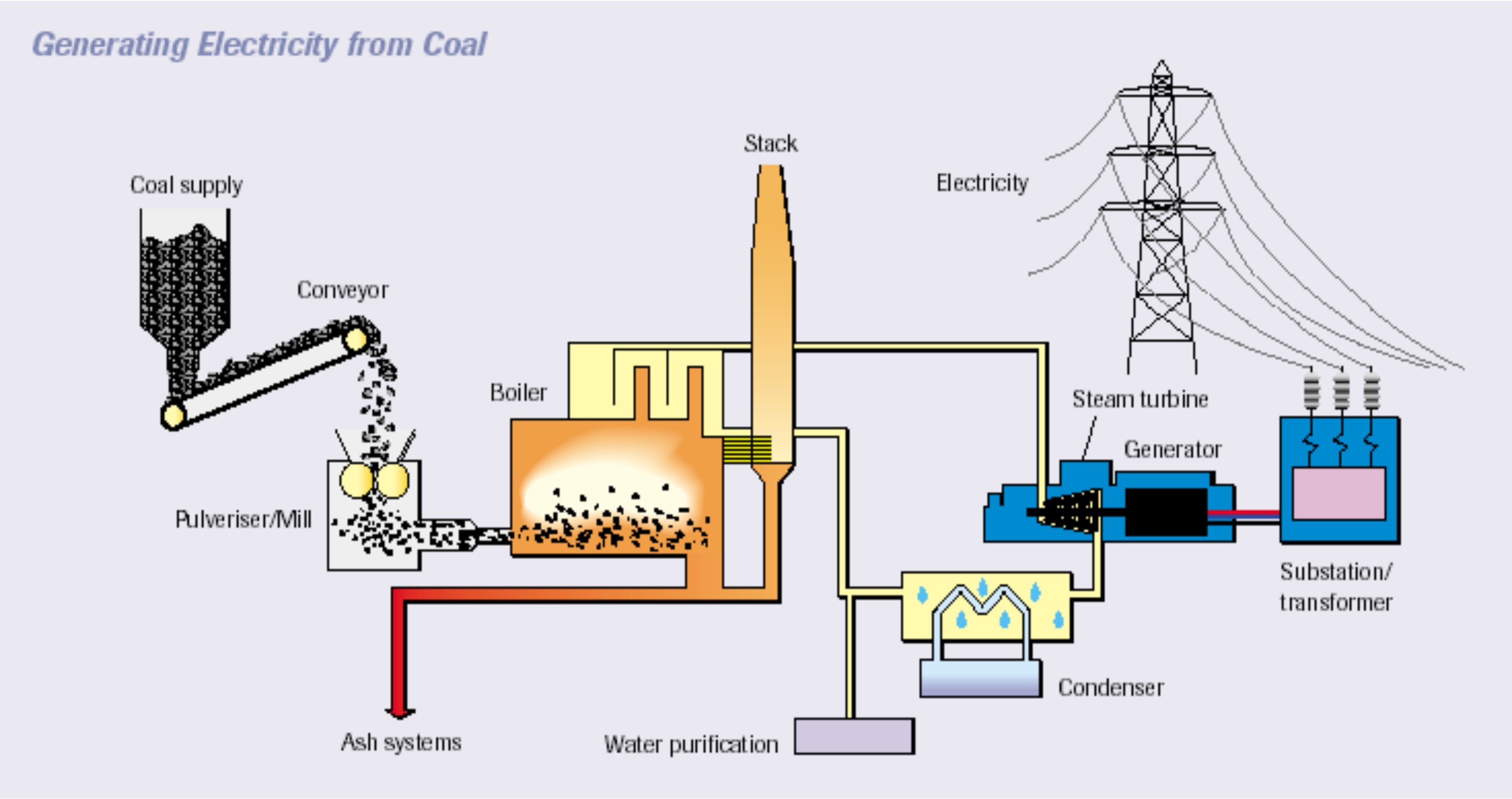
EER

Coal Based Power generation

- Fluidized Bed Combustion (FBC)
- Supercritical/Ultra-supercritical CO_2
  - Operates at higher temperatures and pressures resulting in increased efficiencies over conventional PCC units and significant CO_2 reductions.
  - Supercritical steam cycle technology has existed for decades, but recent R&D efforts are focusing increasing the efficiency levels of ultra-supercritical units to ~50%.
- Gasification
  - Integrated Gasification Combined Cycle (IGCC) plants use a gasifier to convert coal, or other carbon-based materials, to syngas, which drives a combined cycle turbine.

Source: Worthington, 2016

Conventional Coal based Power Generation



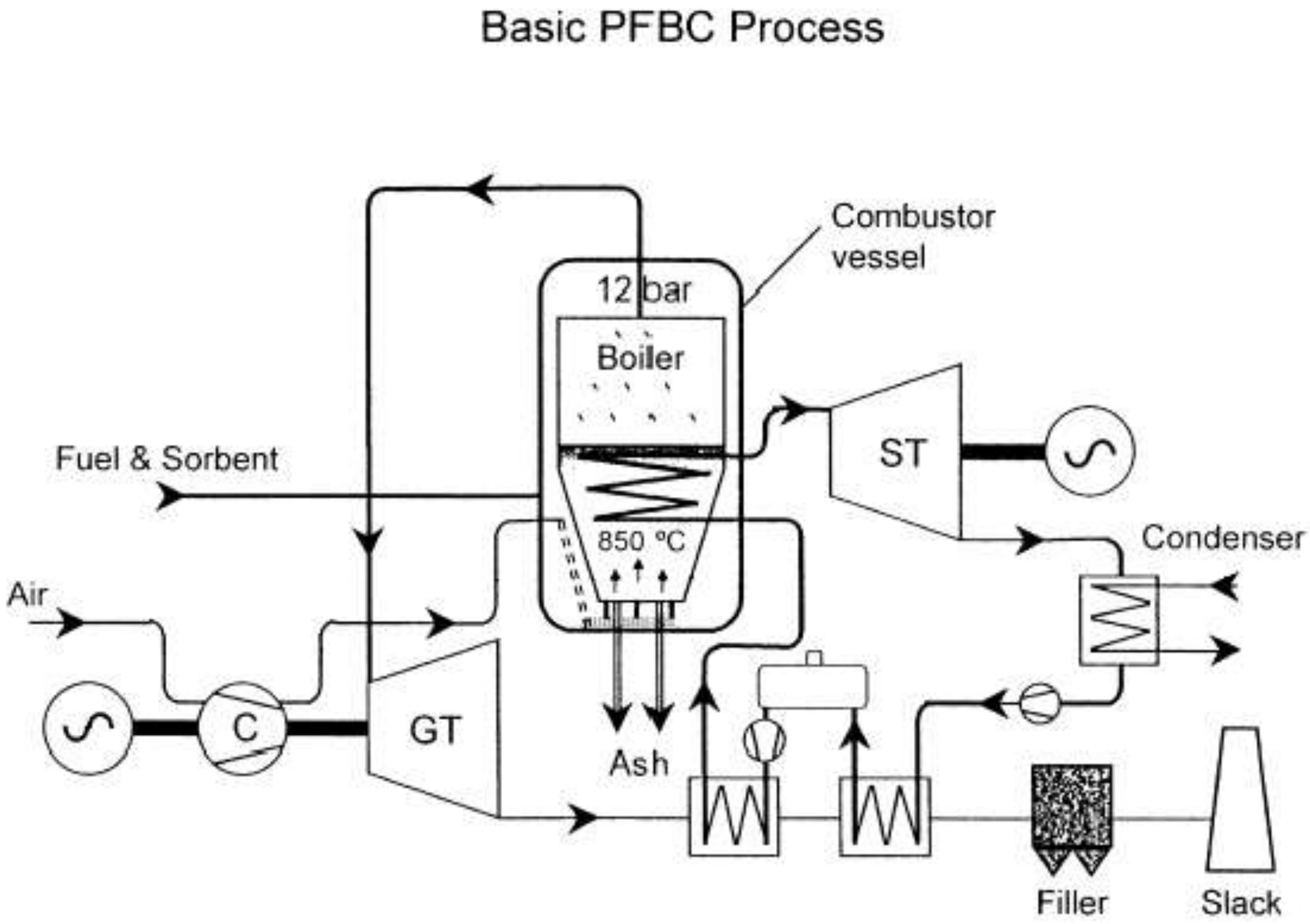
Ultra-supercritical Steam Generation

John W. Turk, Jr. Plant
AEP Southwest Electric Power Co. (SWEPCO)

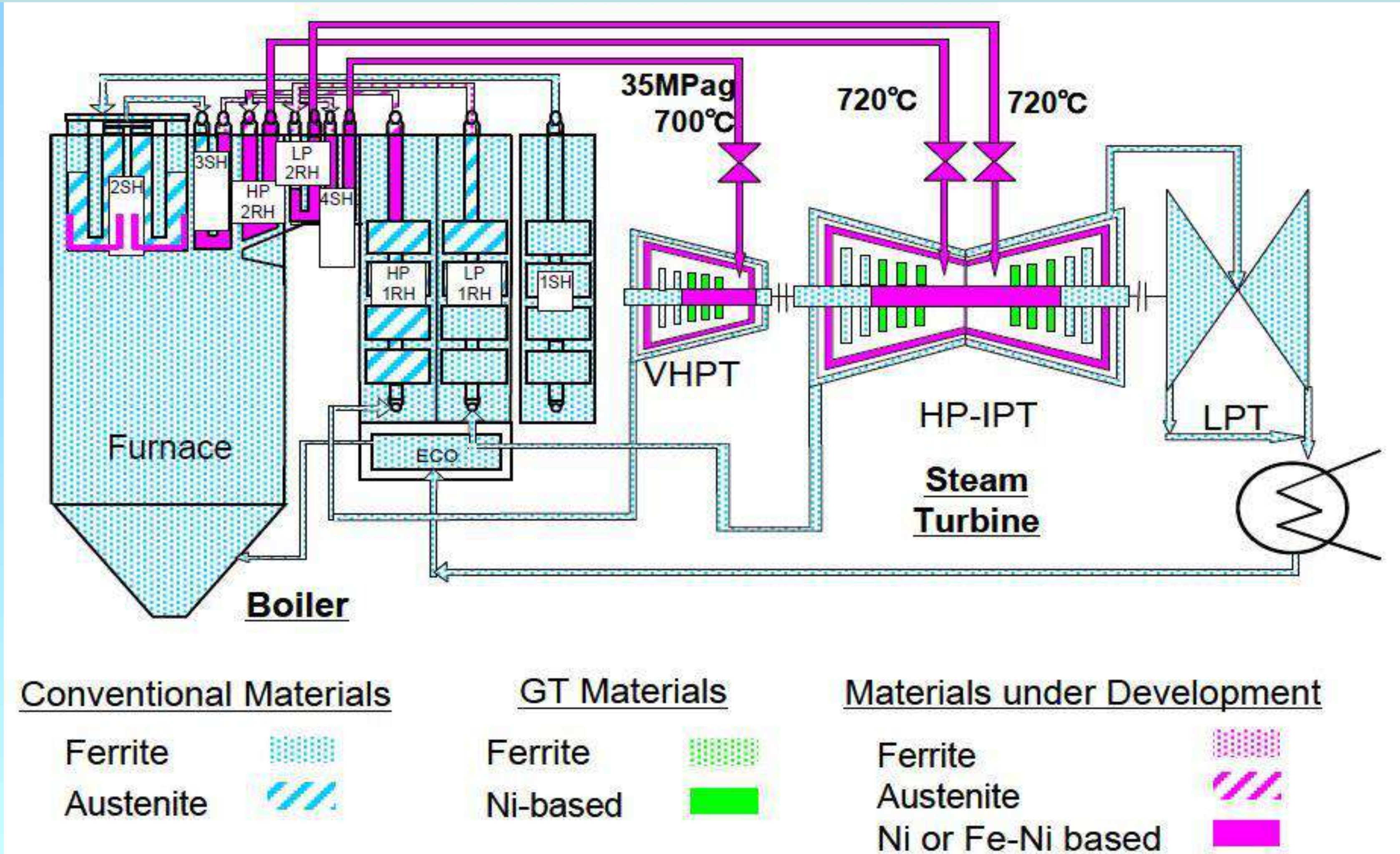
- 600 Megawatts
- Cost= $1.8 billion
- Operating since Dec. 20, 2012
- Emissions controls: SCR , Dry flue gas desulfurization, baghouse, activated carbon injection
- Supercritical steam system works at temperature above 1100°F (593°C) increasing efficiency and reducing fuel consumption, solid waste, water use, and costs.

Source: Worthington, 2016

Pressurized Fluidized Bed Combined Cycle (PFBC)

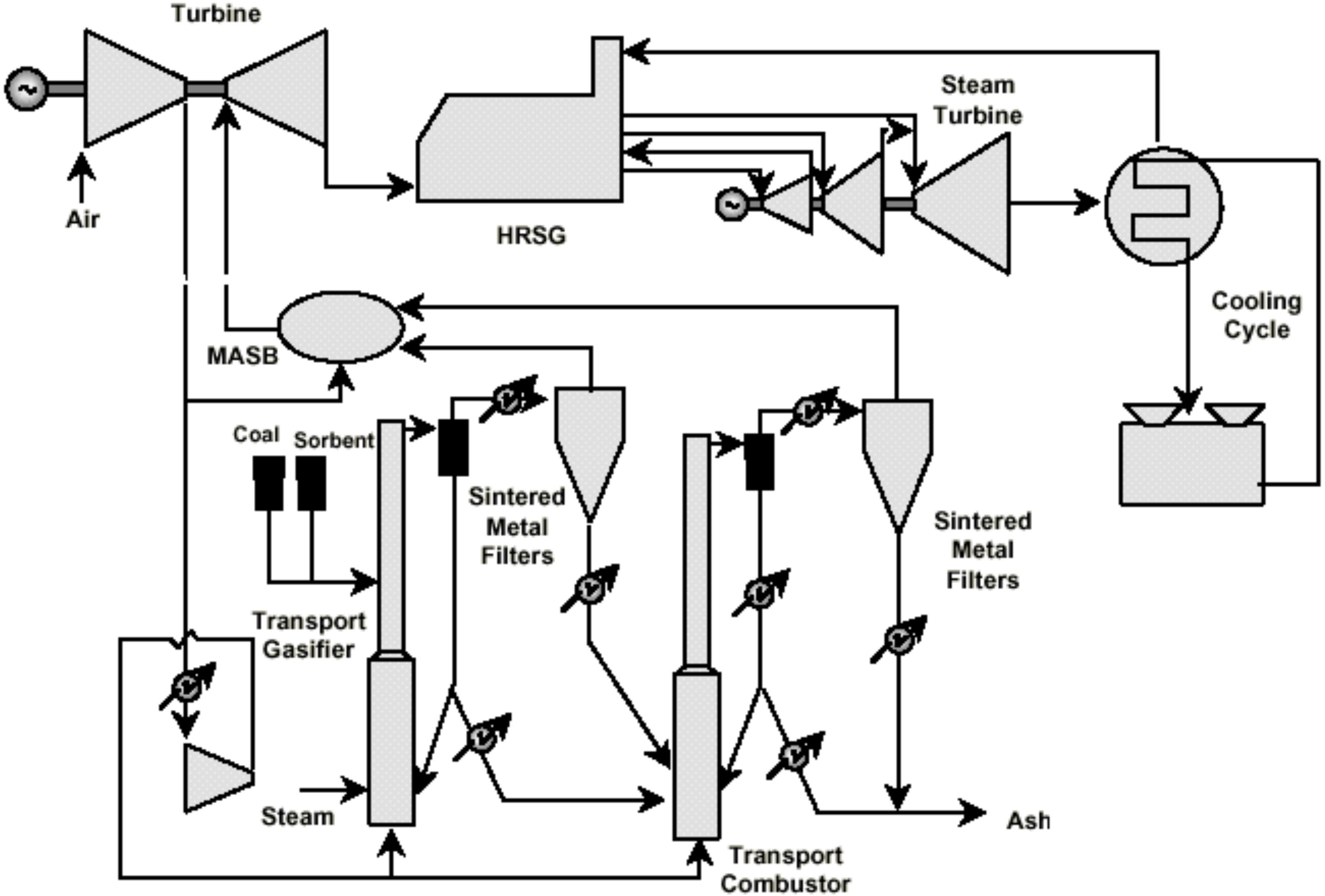


Challenge to A-USC technology: to withstand temperatures of 700+°C Ni-based super alloys wil be needed

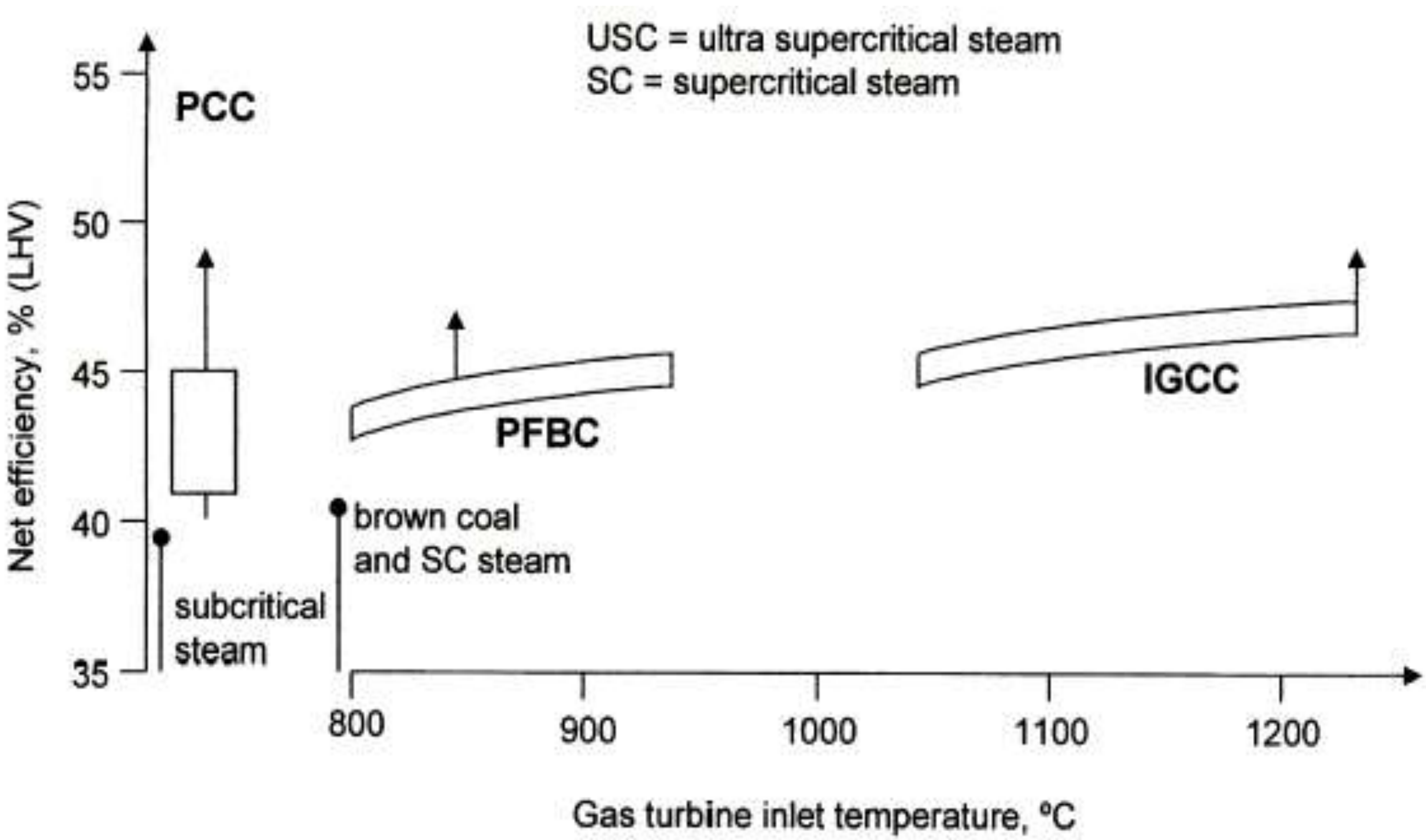


Source: IEA

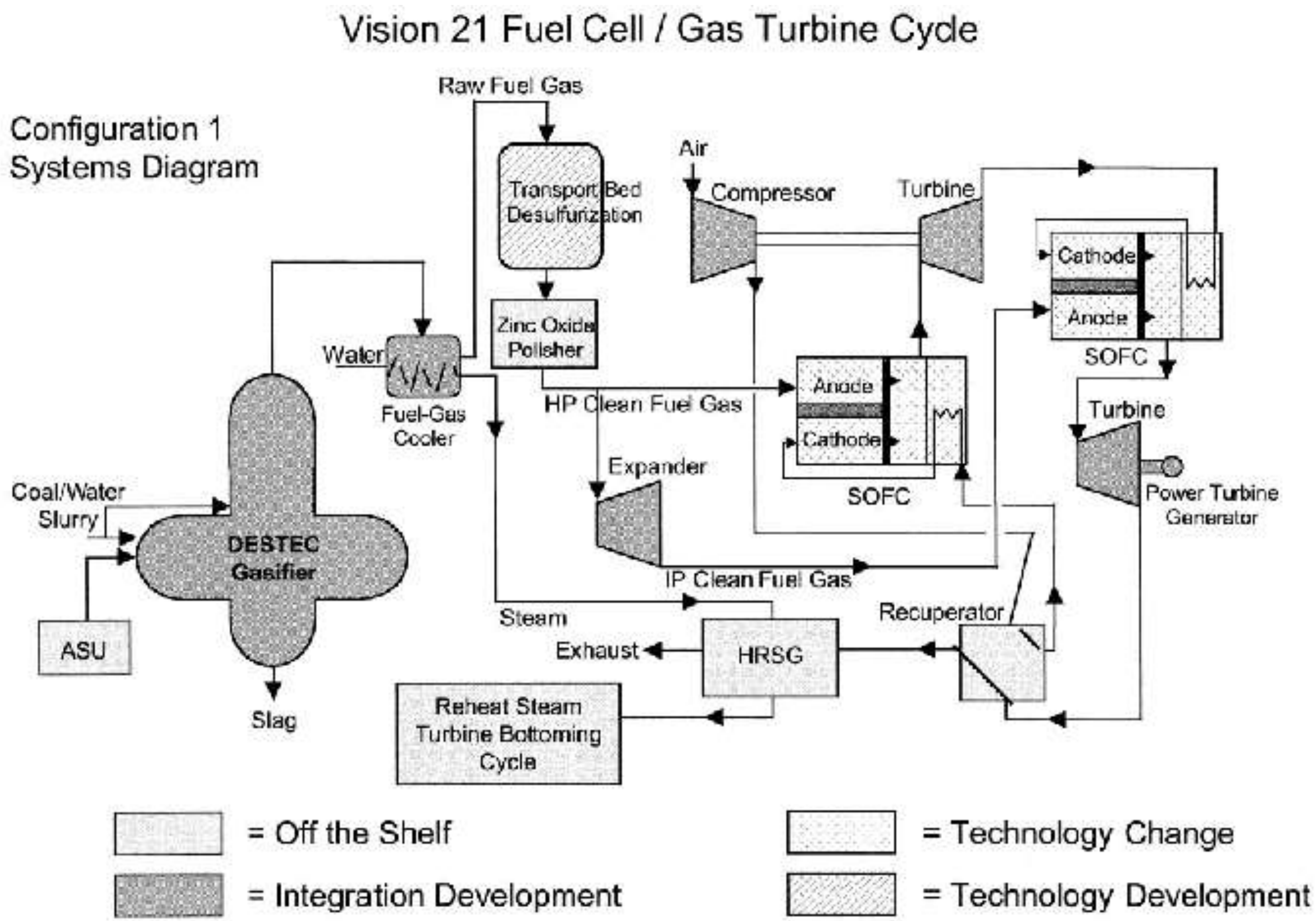
Air-Blown GCC Power Plant



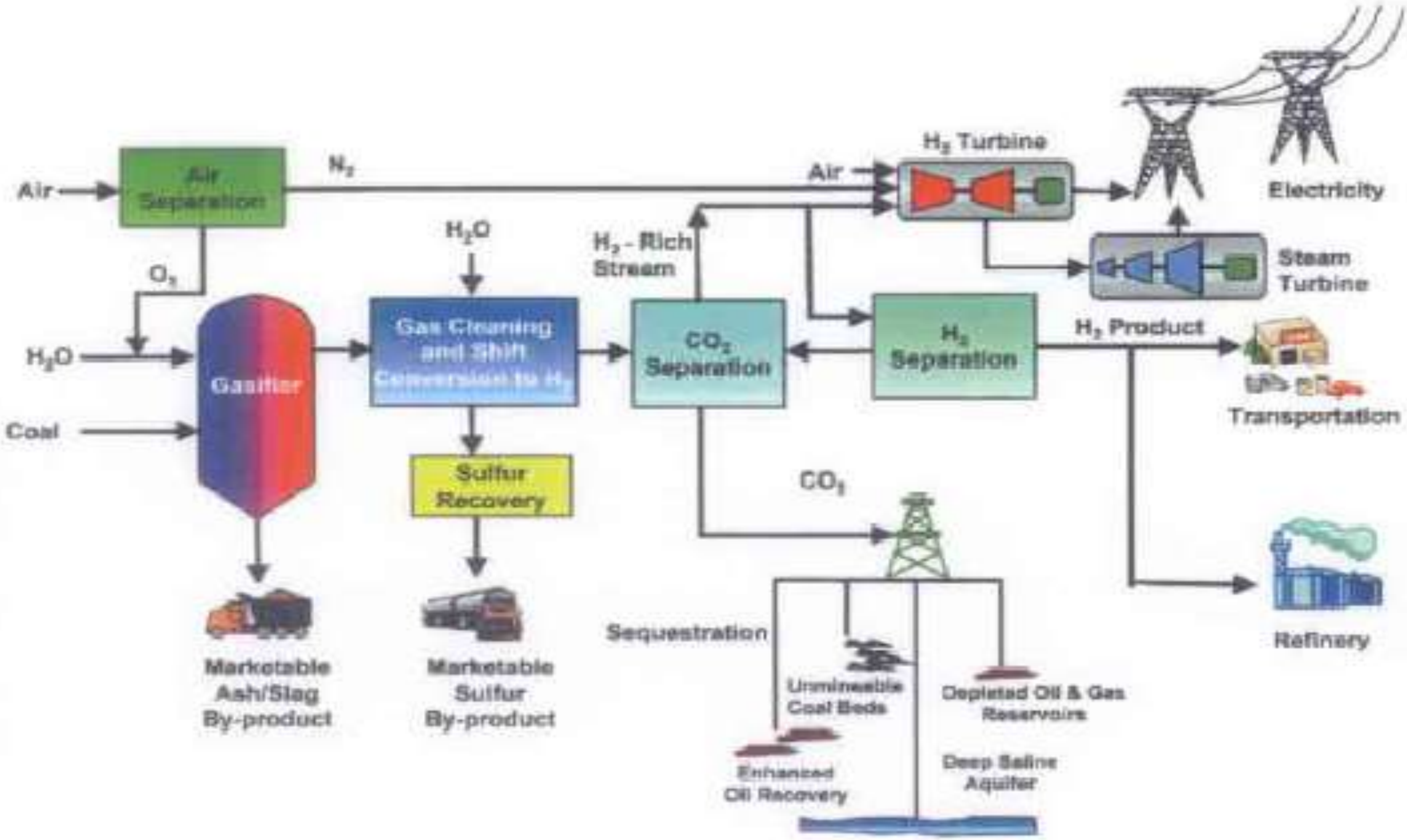
Efficiency cycles. Effect of GT inlet temperature



Fuel cell/GT cycle



IGGC



Air
Air Separation
N₂
O₂
H₂O
Coal
Gasifier
H₂O
Gas Cleaning and Shift Conversion to H₂
Sulfur Recovery
H₂ - Rich Stream
CO₂ Separation
H₂ Separation
H₂ Turbine
Air
Electricity
Steam Turbine
H₂ Product
Transportation
Refinery
CO₂
Sequestration
Marketable Ash/Slag By-product
Marketable Sulfur By-product
Unmineable Coal Beds
Depleted Oil & Gas Reservoirs
Enhanced Oil Recovery
Deep Saline Aquifer

IGCC, H2 production, CO2 capture

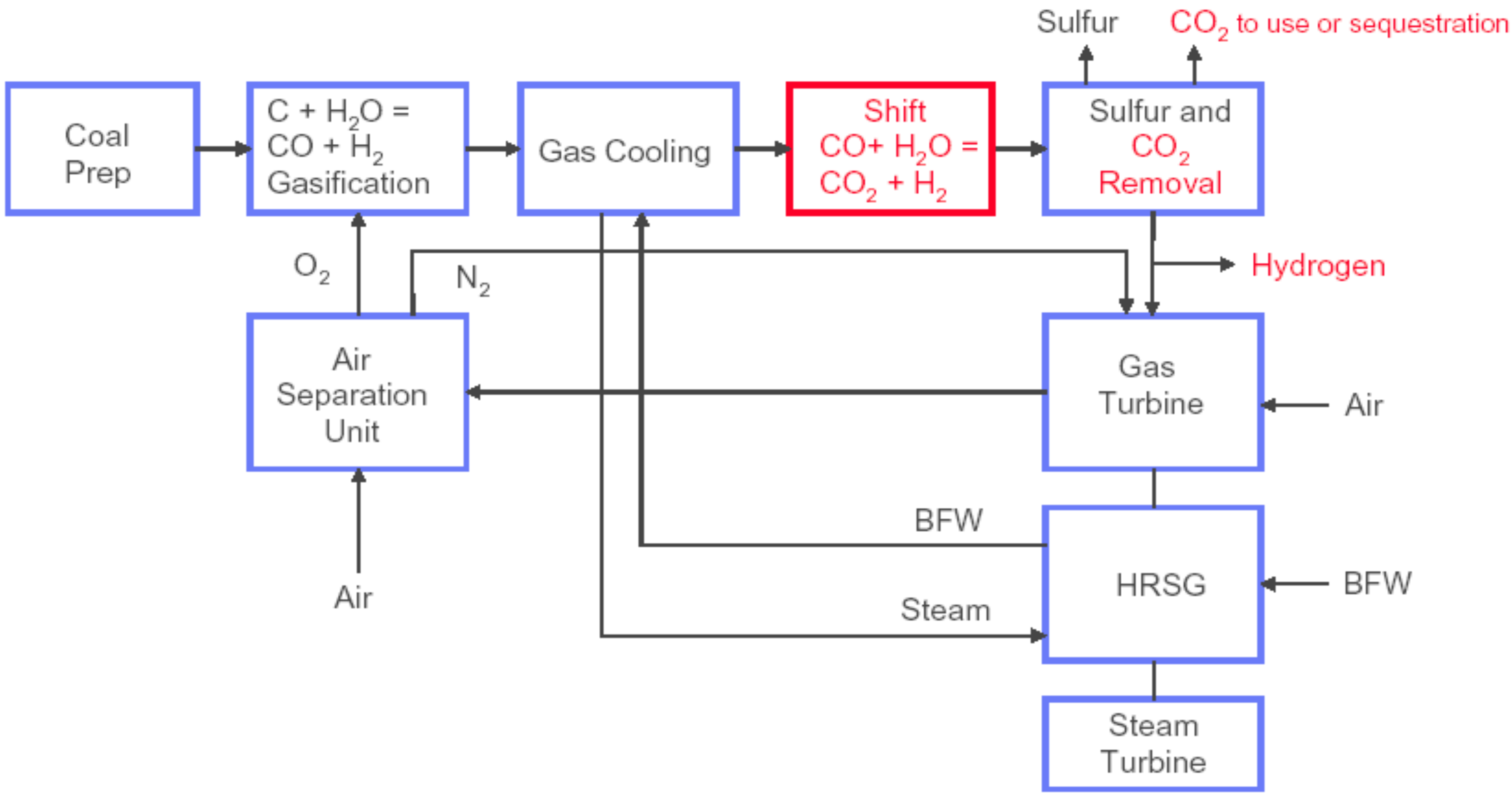
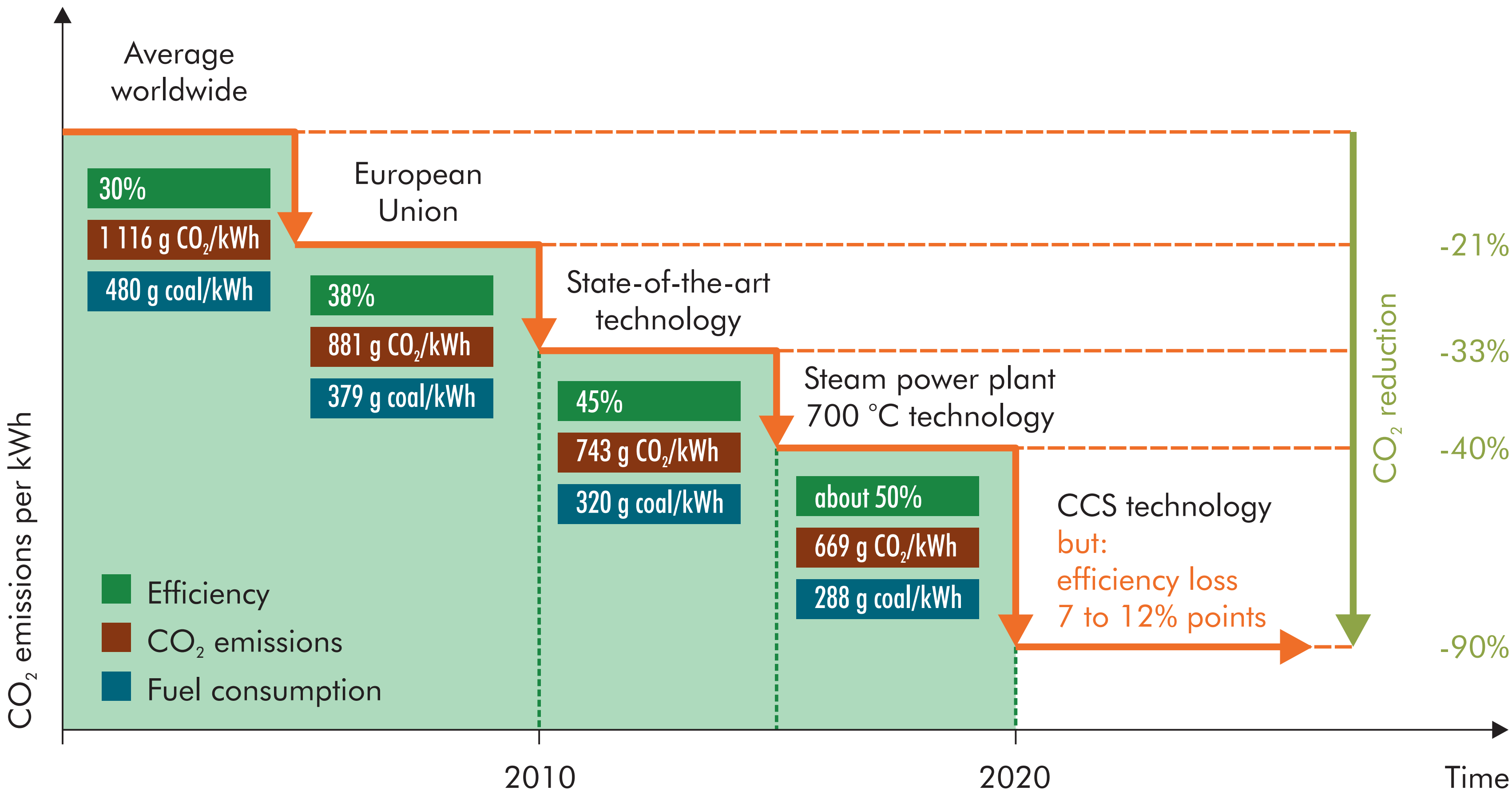
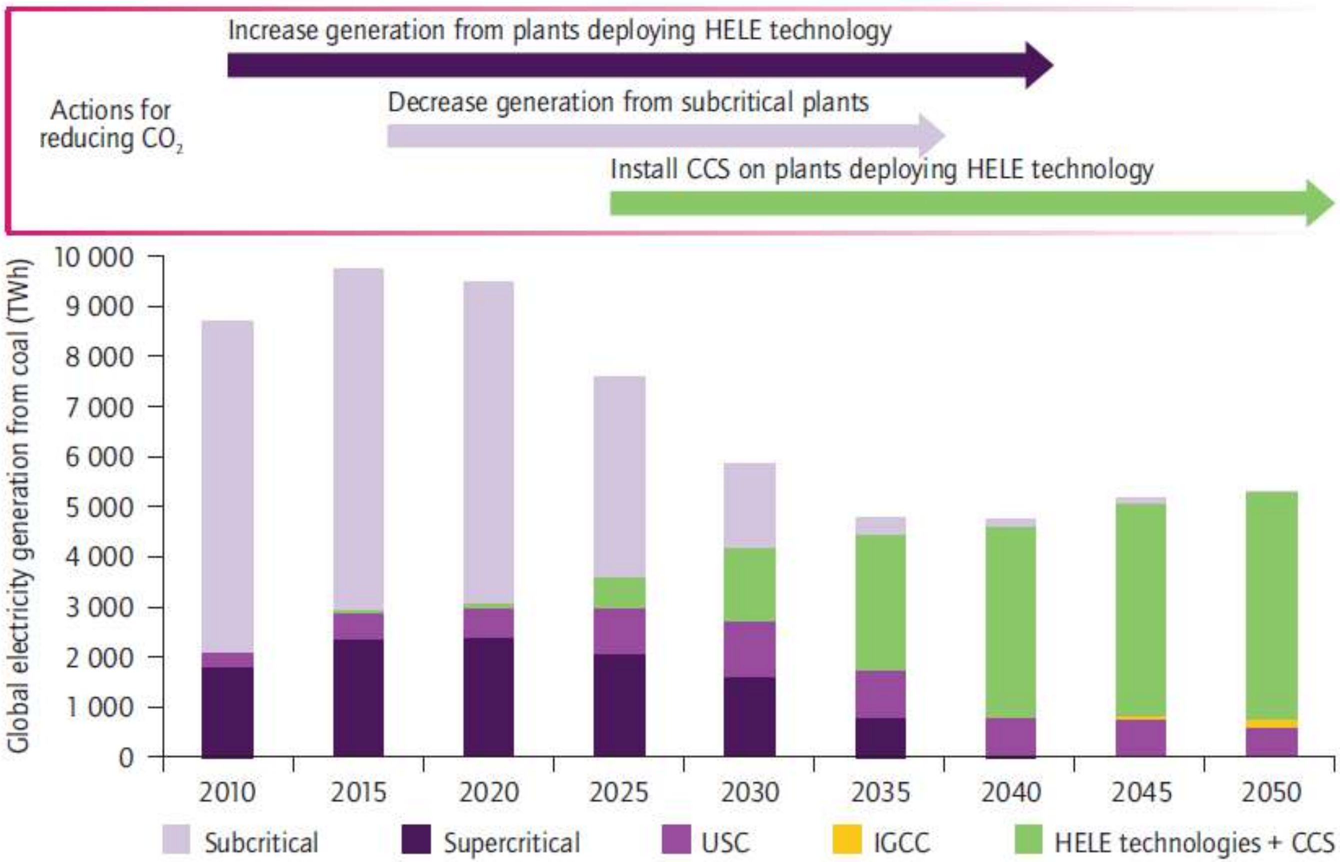


Figure 4.5: Efficiency improvement potential at hard coal-fired power plants



Source: VGB (2009). Reprinted by permission of the publisher. © VGB PowerTech e.V., 2009.

Electricity Generation from Different Coal-fired Power Technologies



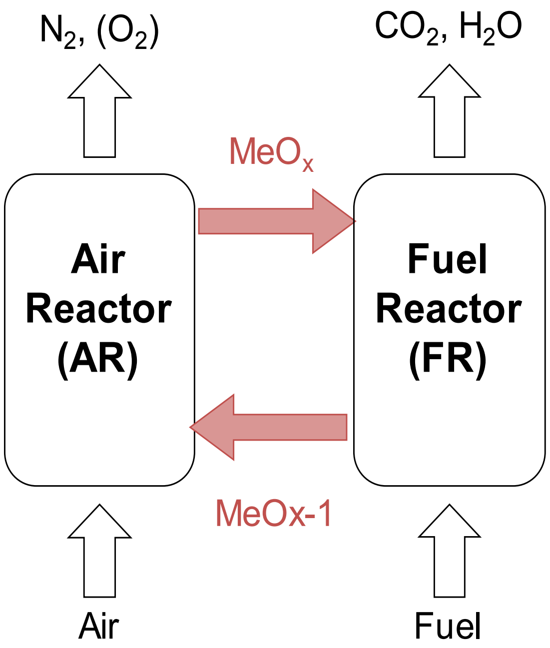
Note: Carbon capture is integrated with HELE coal-fired units to minimise coal consumption and CO_2 abatement cost.

High-Efficiency, Low-Emissions (HELE) coal are important low-carbon technologies

Source: ACE

Chemical looping

Chemical looping combustion (CLC)



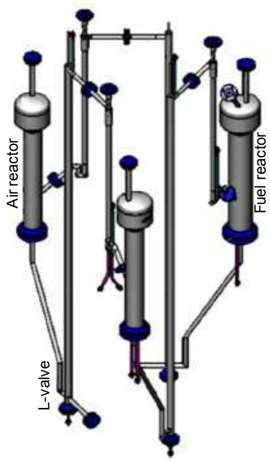
Oxygen Carrier:

- Oxides of Cu, Fe, Mn, Ni
- High reactivity
- Full fuel conversion
- High O_2 transport capacity
- Good economics over the whole life cycle

Pilot plant

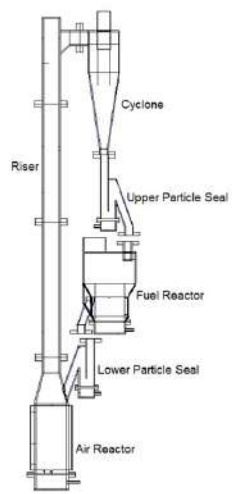
Pilot units up to 1MW

10kW



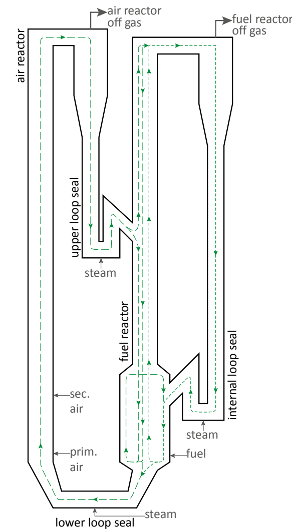
ifp Energies nouvelles

10kW



CHALMERS

120kW



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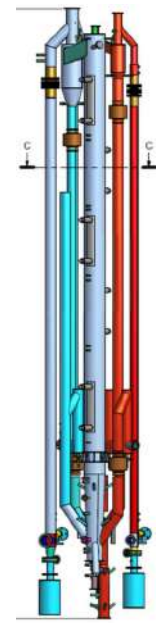
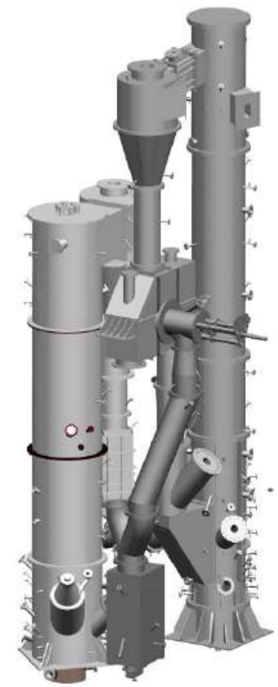
150kW



SINTEF

1MW



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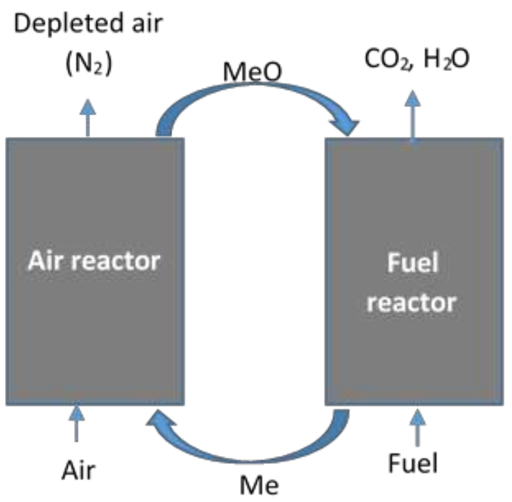
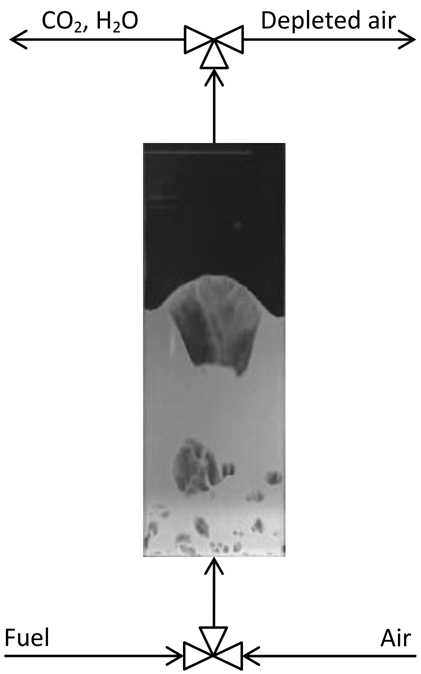
Gas Switching Reactor

Chemical Looping principle



Lack of pressurized CLC in the looping configuration

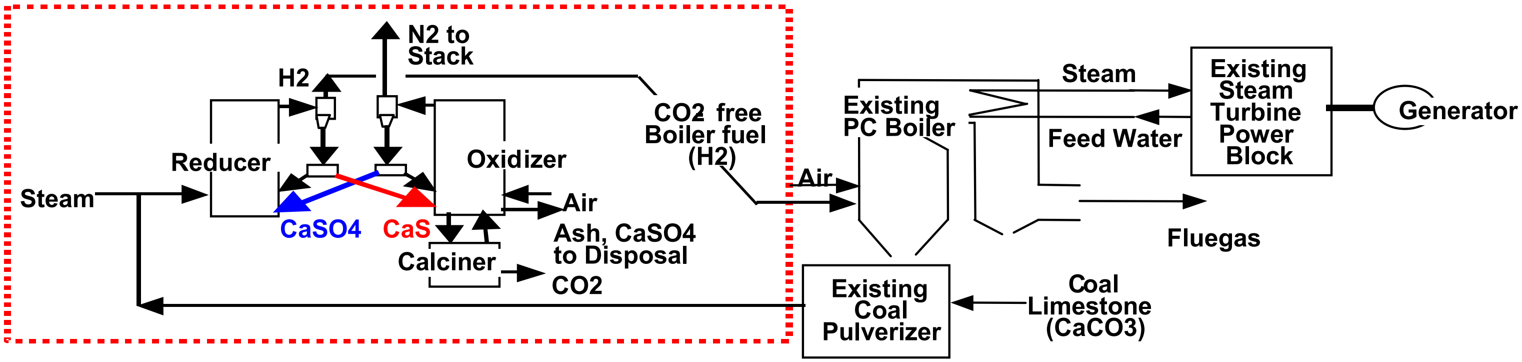
Gas Switching Reactor



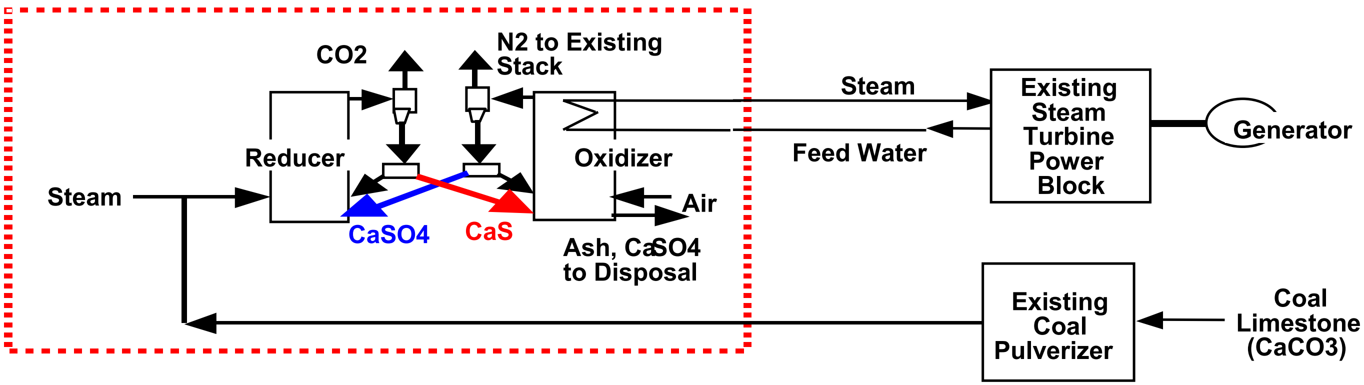
SINTEF

Chemical Looping Technology

Pulverized Coal Power Plant - Retrofit Concepts



Concept 1 – Chemical Looping – CO_2 Free Fuel; Minimum Boiler Modification



Concept 2 – Chemical Looping Oxidizer Replaces / Modifies Boiler

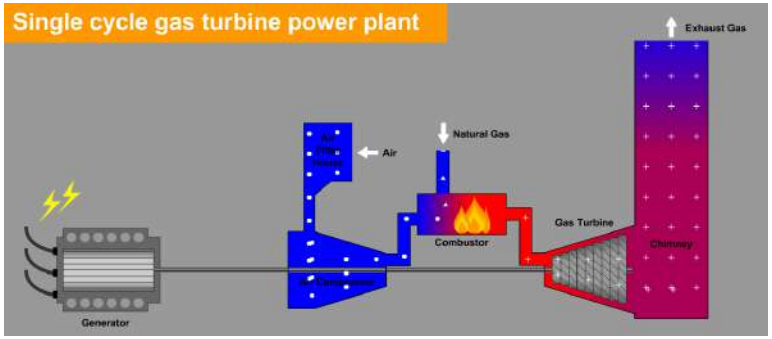
Advance natural gas technologies

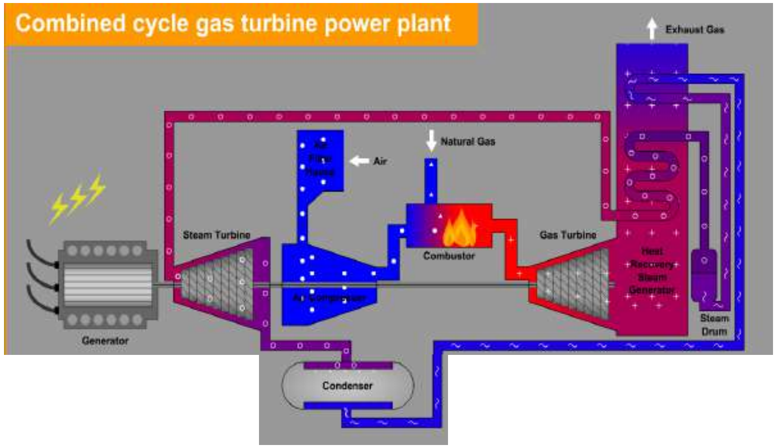
Simple Cycle

- Natural gas is combusted with compressed air to produce a high temperature gas to power a turbine.
- Conventional power plants produce ***33% electricity*** (67% is waste).

Combined Cycle

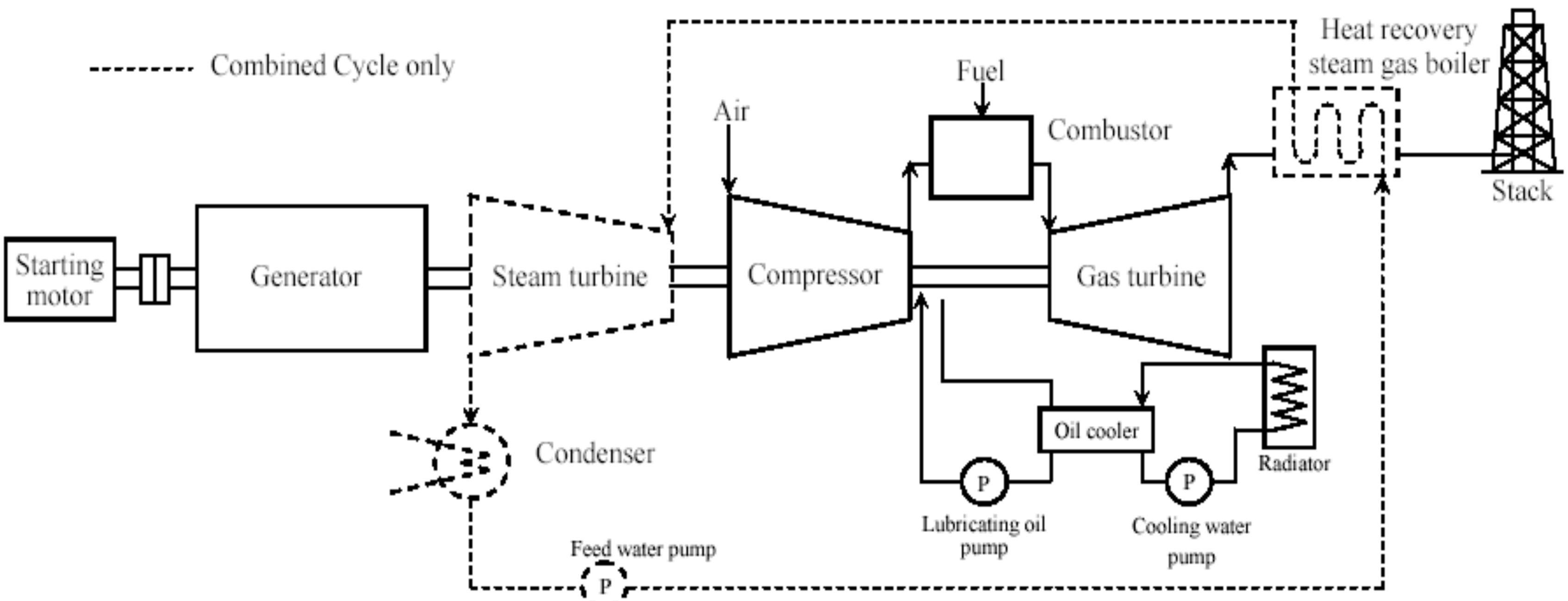
- A gas turbine generator generates electricity; waste heat is used to make steam to generate additional electricity via a steam turbine.
- Combined cycle power plants produce ***68% electricity.***





Source: Worthington, 2016

Combine Cycle Gas Turbine (CCGT)



Key Data and Figures for Natural Gas-based Power Technologies

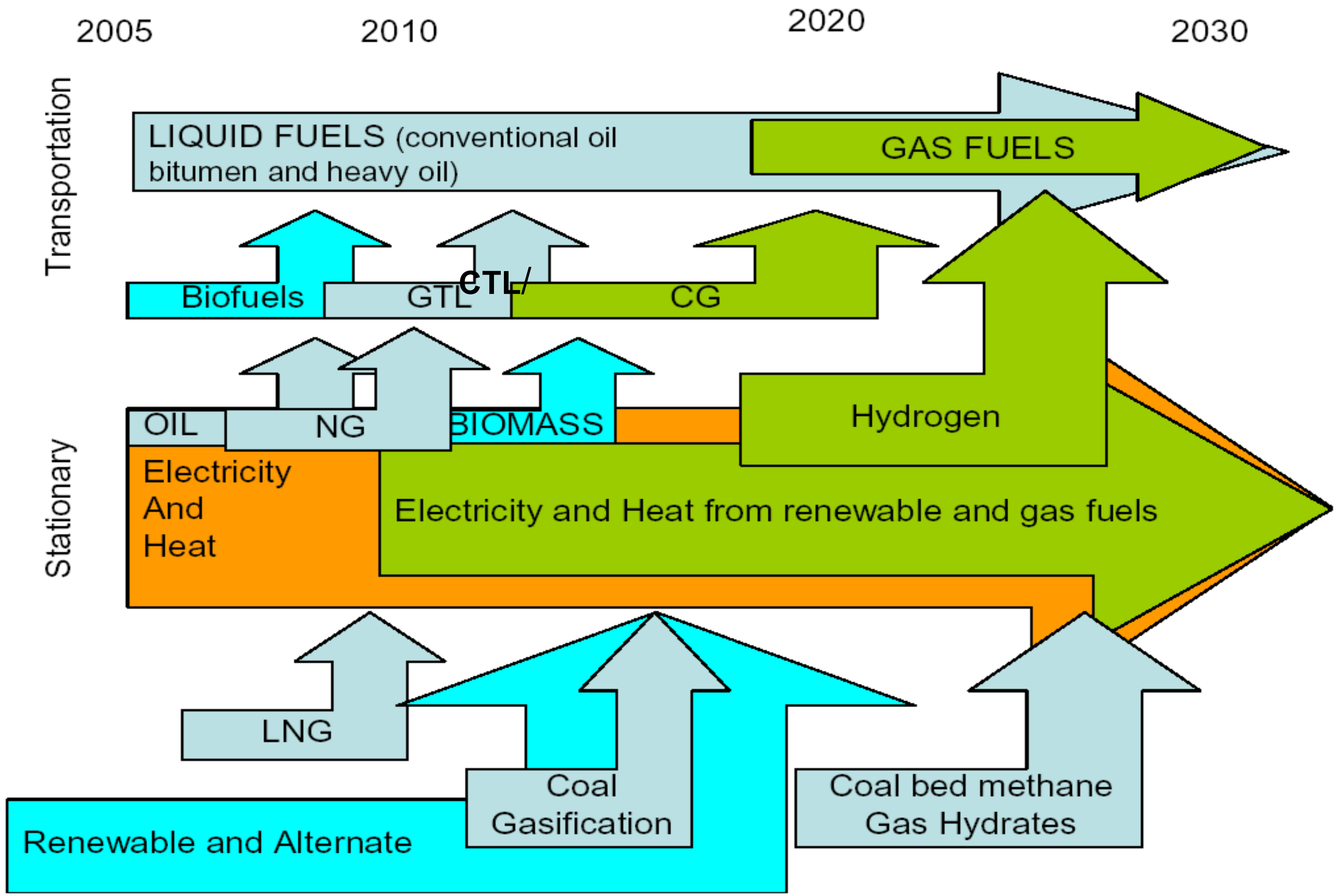
Technical Performance	Typical current international values and ranges	
Energy input	Natural gas	
Output	Electricity	
Technologies	OCGT	CCGT
Efficiency, %	35–42%	52–60%
Construction time, months	Minimum 24; Typical 27; Maximum 30	
Technical lifetime, yr	30	
Load (capacity) factor, %	10–20	20–60
Max. (plant) availability, %	92	
Typical (capacity) size, MW_e	10–300	60–430
Installed (existing) capacity, GW_e	1168 (end of 2007)	
Average capacity aging	Differs from country to country. CCGT construction started end of 1980s.	
Environmental Impact		
CO_2 and other GHG emissions, kg/MWh	480–575	340–400
NO_x, g/MWh	50	30
Costs (US$ 2008)		
Investment cost, incl. IDC, $/kW	800 – 1000; Typical 900 (2010)	1000 – 1250; Typical 1100 (2010)
O&M cost (fixed and variable), $/kW/a	36	44
Fuel cost, $/MWh	45–70	30–45
Economic lifetime, yr	25	
Interest rate, %	10	
Total production cost, $/MWh	200 – 225 / Typical 210	65 – 80 / Typical 72.5
Market share	20	

Data Projections	2010		2020		2030		
Technology	OCGT	CCGT	OCGT	CCGT	OCGT	CCGT	
Net Efficiency (LHV), %	35-42	52-60	≤ 45	≤ 64	≤ 45	≤ 64	
Investment cost, incl. IDC, $/kW	900	1100	850	1000	800	900	
Total production cost, $/MWh	100	72.5	95	70	95	70	
Market share, % global electricity output	20		18		15		

Source: IEA

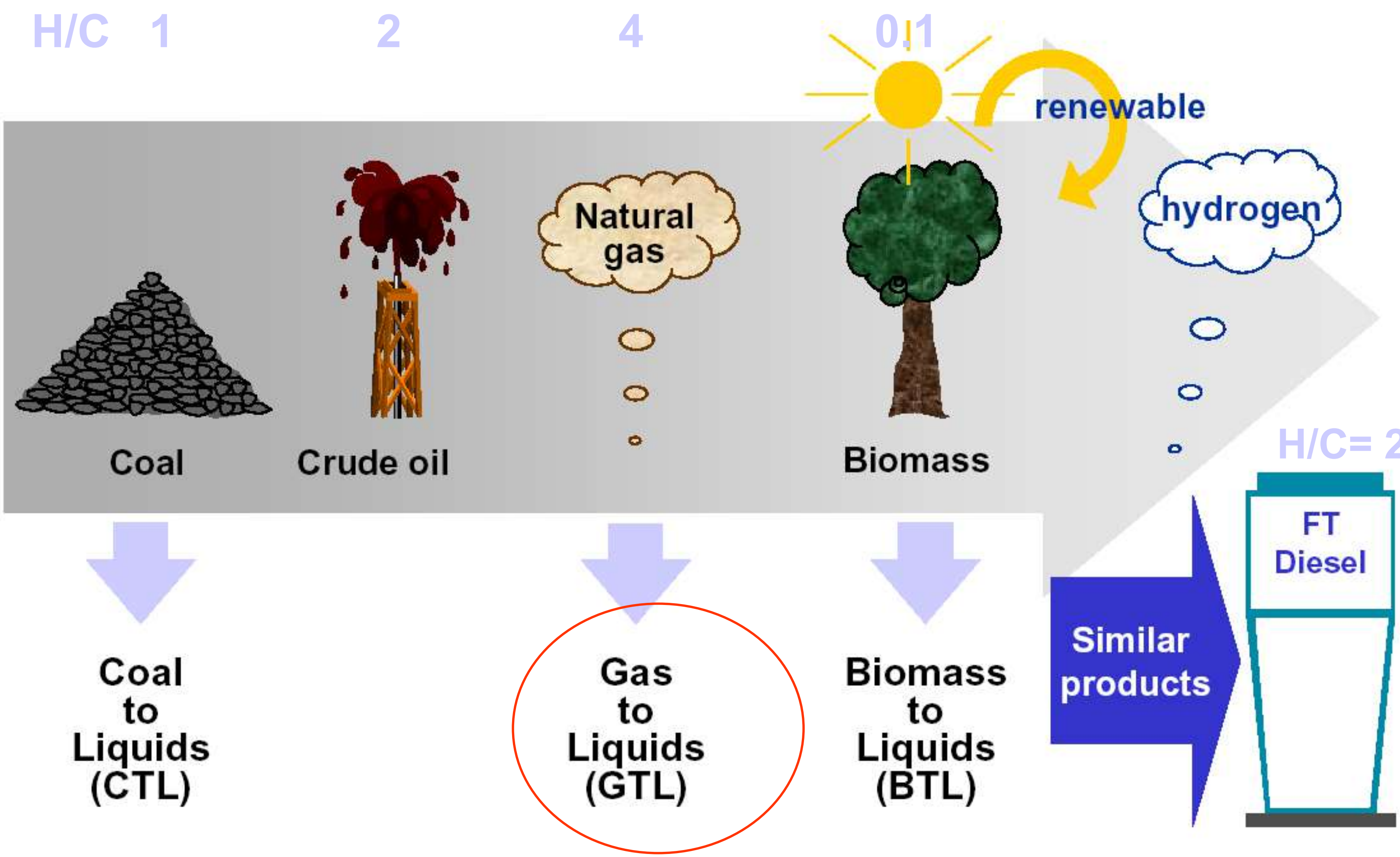
- Coal & Gas to Liquids

Future Fuel Supply



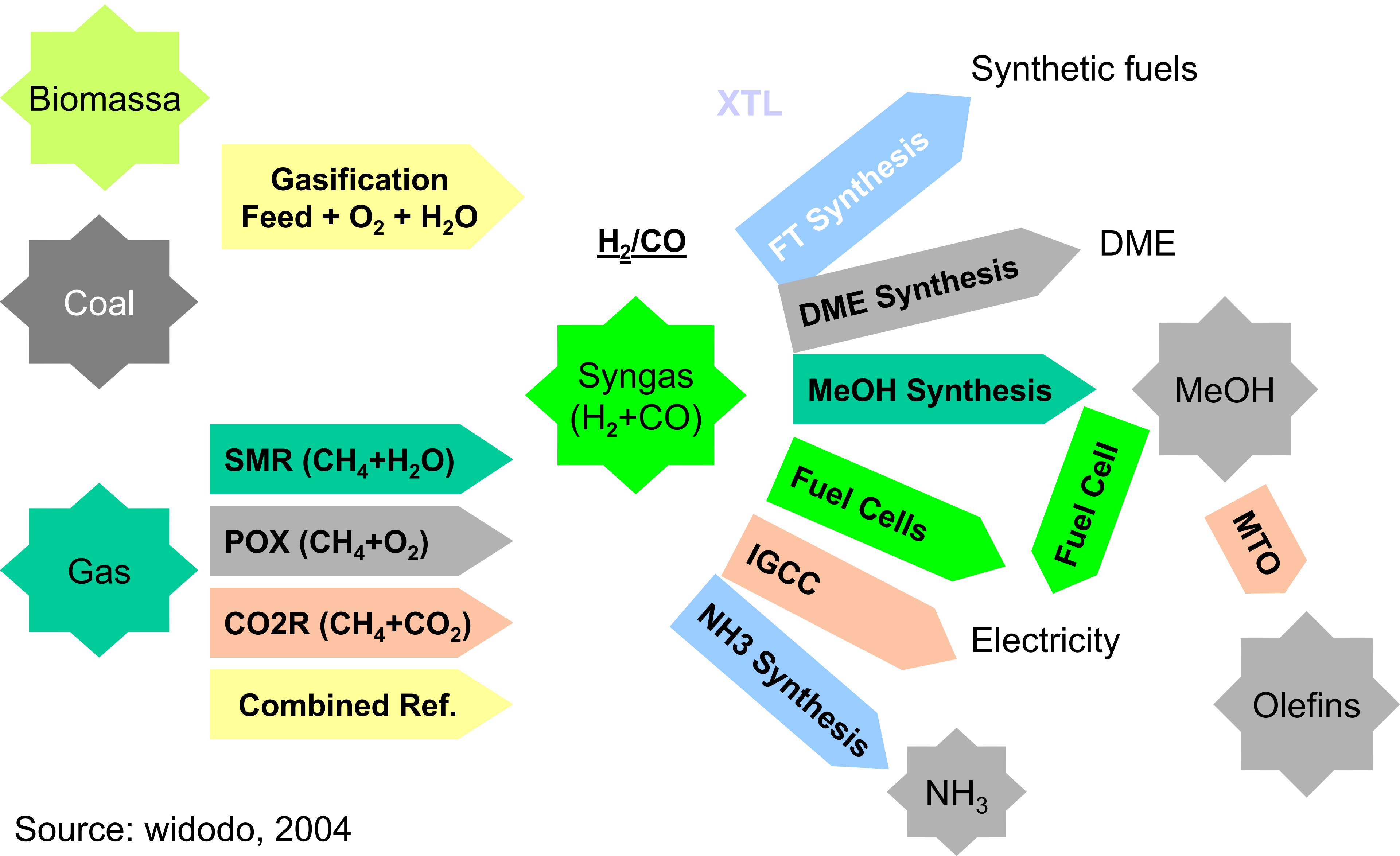
Source:APEC

X to Liquids



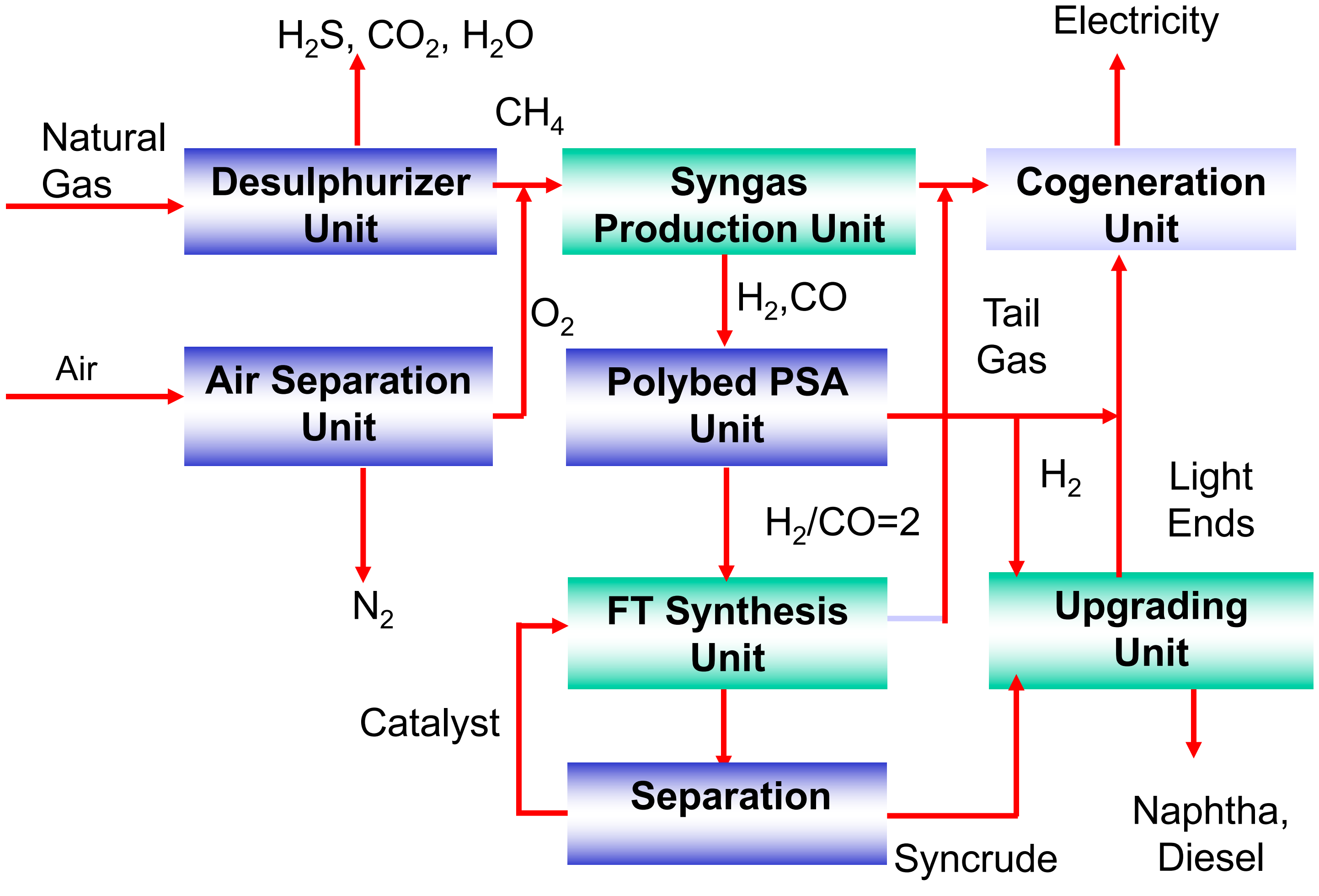
Source: Sasol, modified

Indirect process conversion



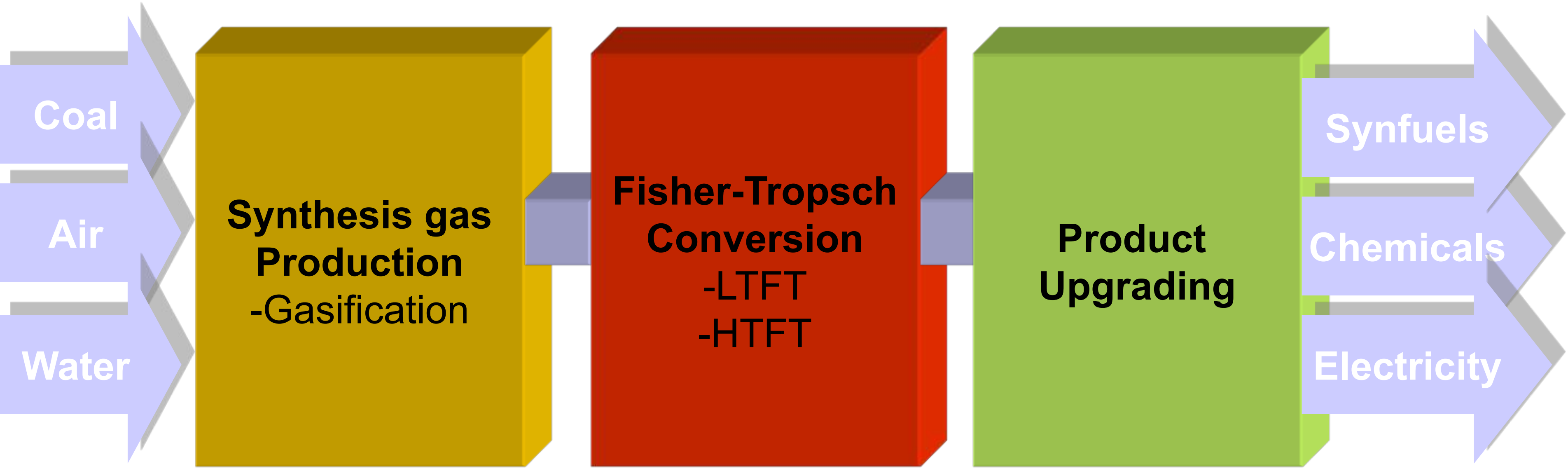
Source: widodo, 2004

GTL Flow Diagram

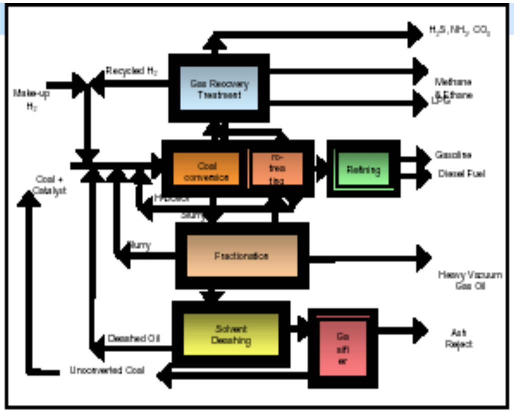


Source: widodo, 2004

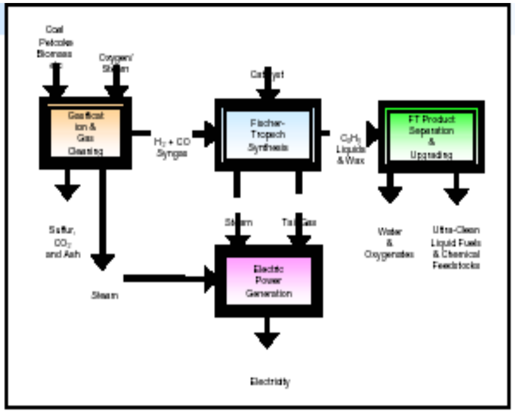
Indirect CTL Processes



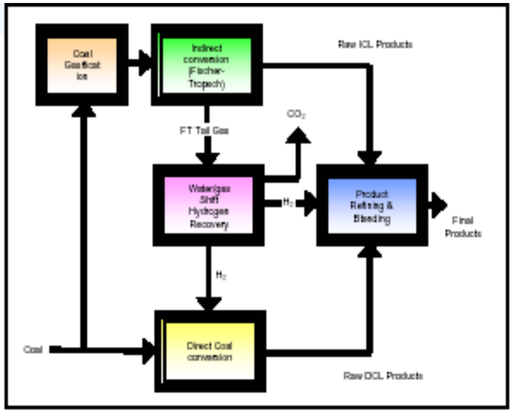
Coal to Liquids Technologies



Direct Liquefaction (Bergius Hydrocracking)



Indirect (Gasification + Fischer-Tropsch)



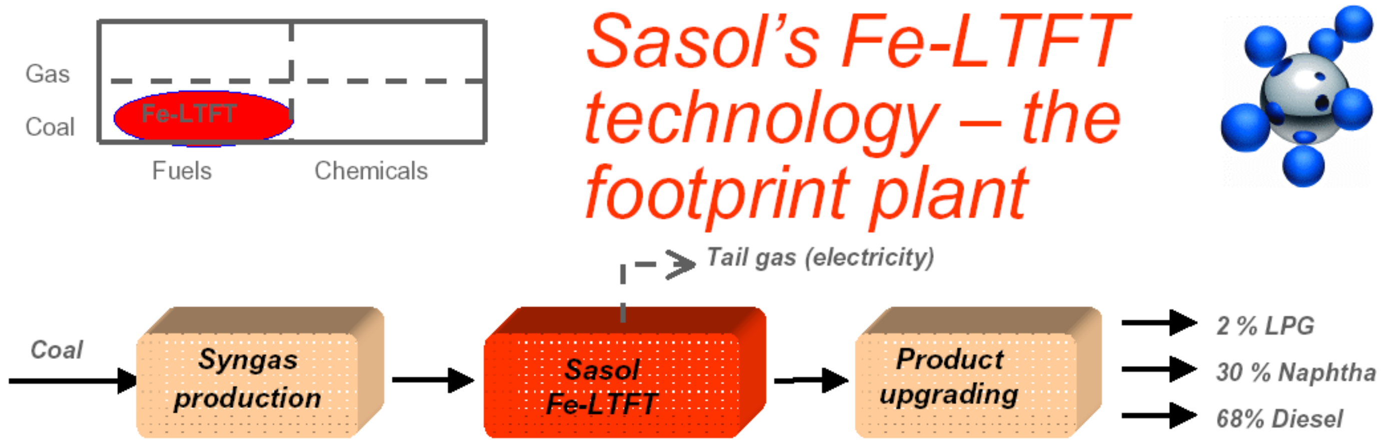
Hybrid Conversion Concept

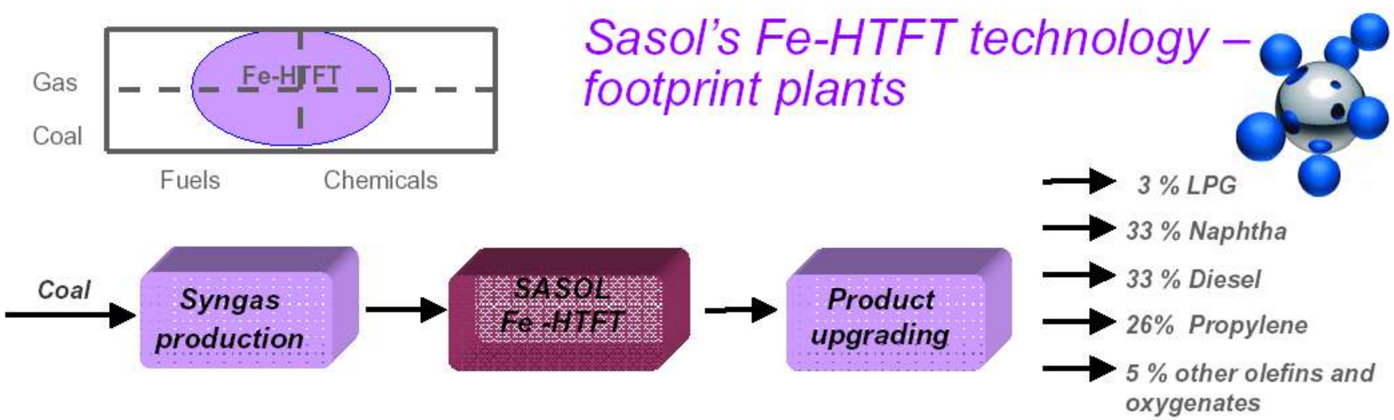
- Produces high-octane gasoline
- More energy efficient
- Products higher energy density
- Low-cetane diesel
- Water & air emissions issues
- Higher operating expenses

- Ultra-clean diesel products
- Well suited for CO_2 capture
- Well suited for electric power co-production
- More complex
- Less efficient fuel production
- Produces low-octane gasoline
- Fewer BTUs per gallon

- Direct and indirect conversion facility built next to one another.
- Products of the direct and indirect conversion trains complement each other
- Can be blended to produce high quality diesel and gasoline.

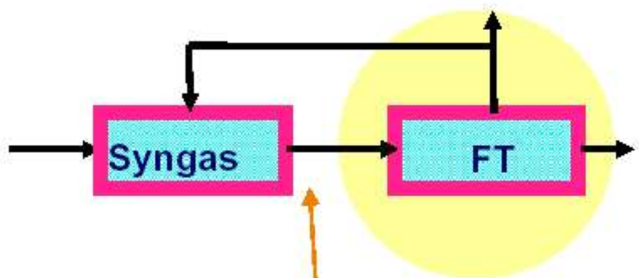
Product split of Fe-LTFT, Fe-HTFT

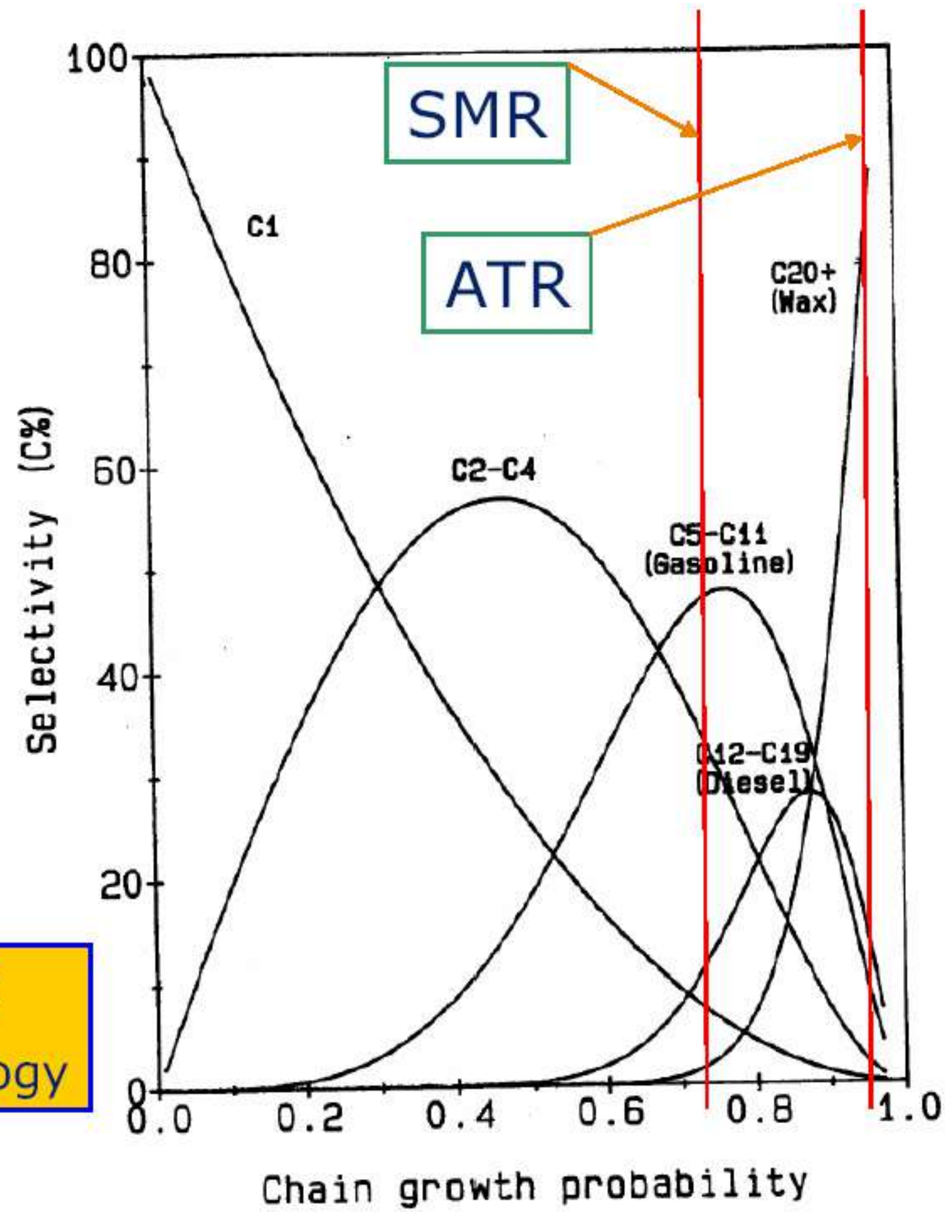




Source: Sasol

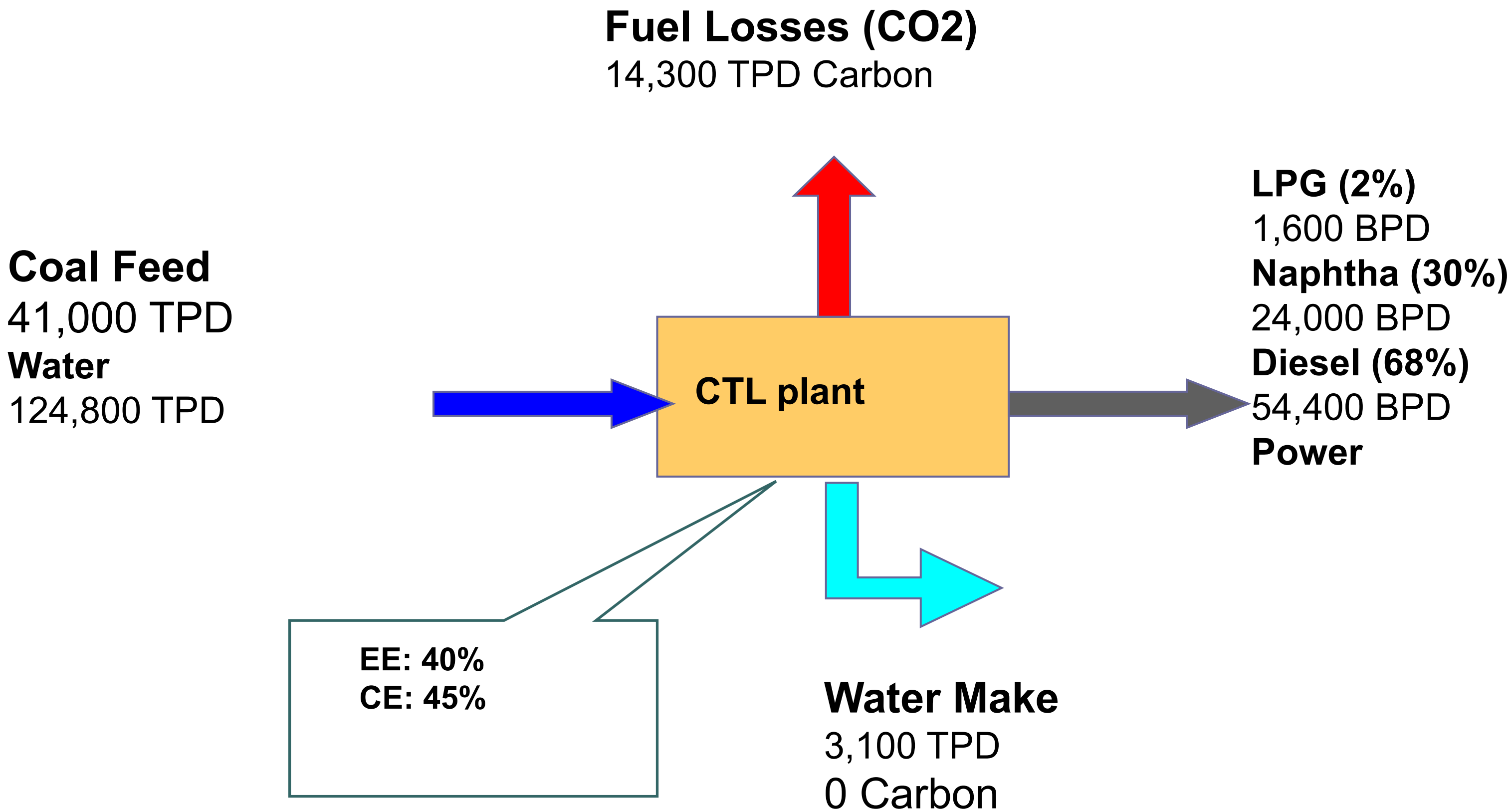
FT- Technology





- ✓H2/CO-ratio a key parameter < 2
- ✓Rules selection of syngas technology

Energy and carbon efficiencies

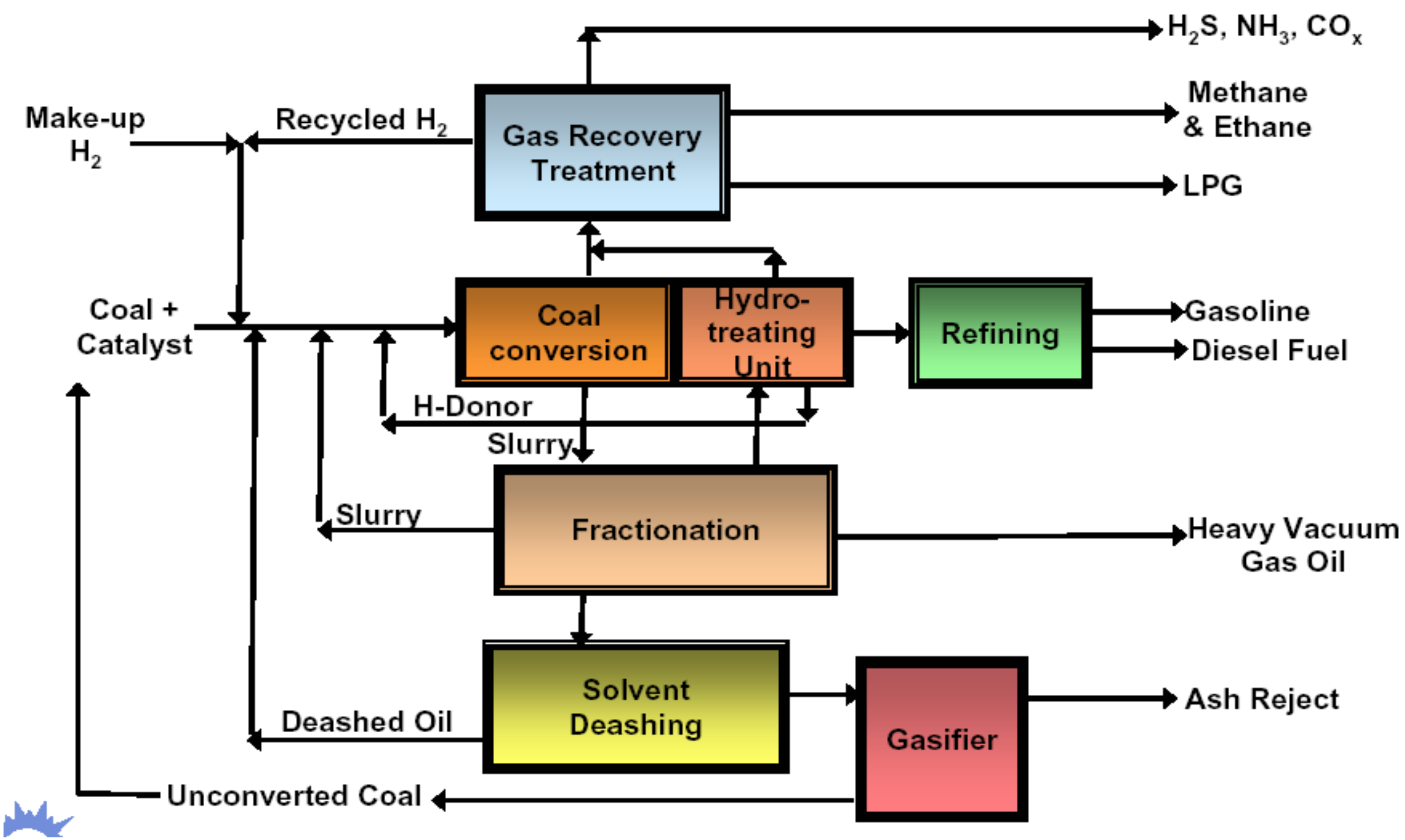


Plant efficiency

Primary energy source	Process	Plant efficiency	
		Current Technology Scenario	Mature Technology Scenario
Oil	Refining	85% to 87%	85% to 87%
Natural gas	GTL	58%	64%
	H_2	72%	77%
	Electricity	50%	55%
Coal	Middle distillates	45%	45%
	H_2	55%	65%
	Electricity	40%	44%
Nuclear energy	H_2	45%	56%
	Electricity	35%	39%
Oil-seed crops	Biodiesel	45%	52%
Grain crops	Alcohol	38%	42%
Sugar crops	Alcohol	36%	40%
Biomass from crops and/or waste products	Biodiesel	46%	53%
	Alcohol	34%	39%
	Methane	62%	69%
	H_2	50%	61%
	Electricity	40%	44%

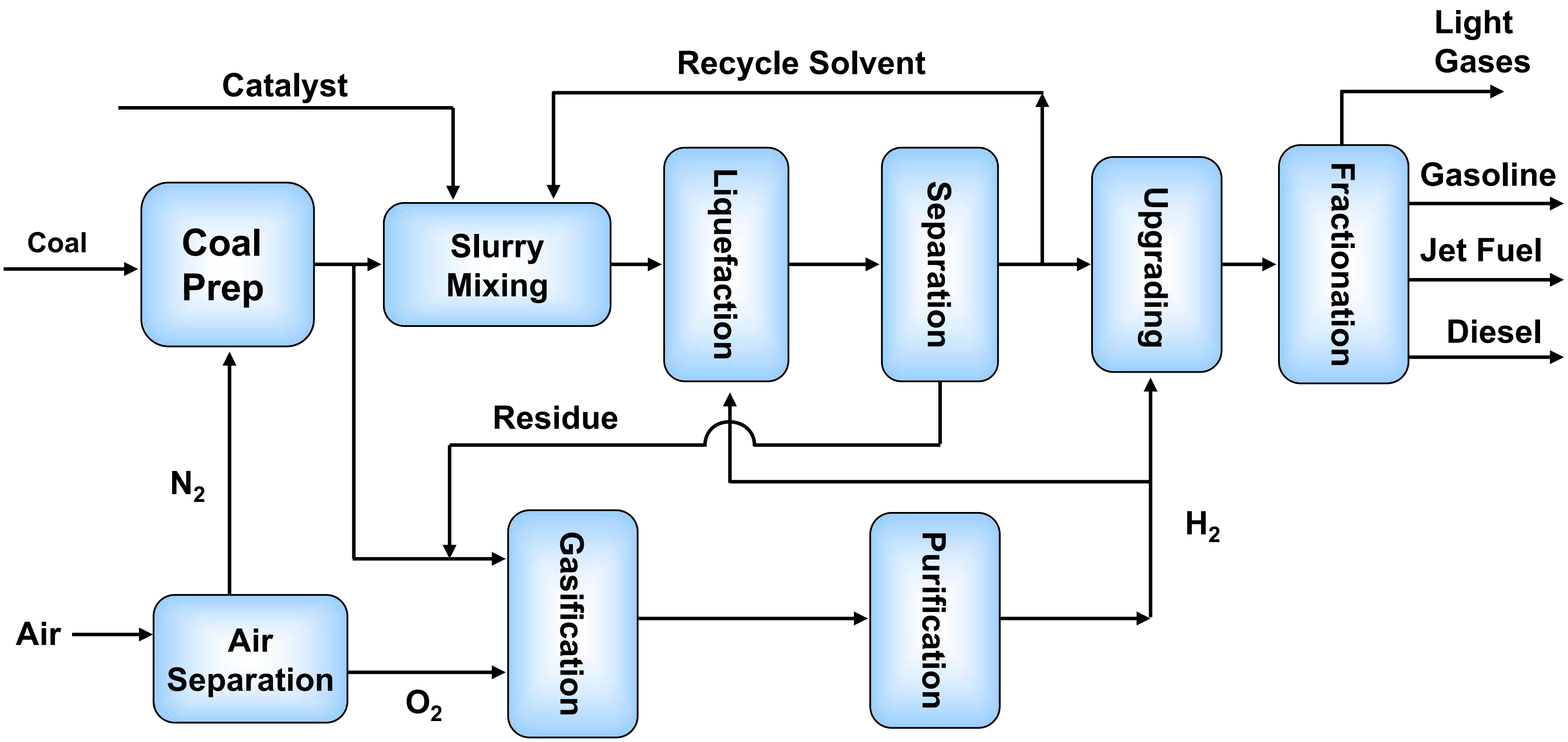
Source: IEA

Direct CTL



H_2S, NH_3, CO_x
Methane & Ethane
LPG
Make-up H_2
Recycled H_2
Gas Recovery Treatment
Coal + Catalyst
Coal conversion
Hydro-treating Unit
Refining
Gasoline
Diesel Fuel
H-Donor
Slurry
Slurry
Fractionation
Heavy Vacuum Gas Oil
Solvent Deashing
Deashed Oil
Gasifier
Ash Reject
Unconverted Coal

Shenhua DCL Process



First Train: 1 MT/a Liquefaction Oil

Comparison of DCL & ICL Final Products

	Direct	**Indirect**
Distillable product mix	65% diesel 35% naphtha	80% diesel 20% naphtha
Diesel cetane	42-47	70-75
Diesel sulfur	<5 ppm	<1 ppm
Diesel aromatics	4.8%	<4%
Diesel specific gravity	0.865	0.780
Naphtha octane (RON)	>100	45-75
Naphtha sulfur	<0.5 ppm	Nil
Naphtha aromatics	5%	2%
Naphtha specific gravity	0.764	0.673

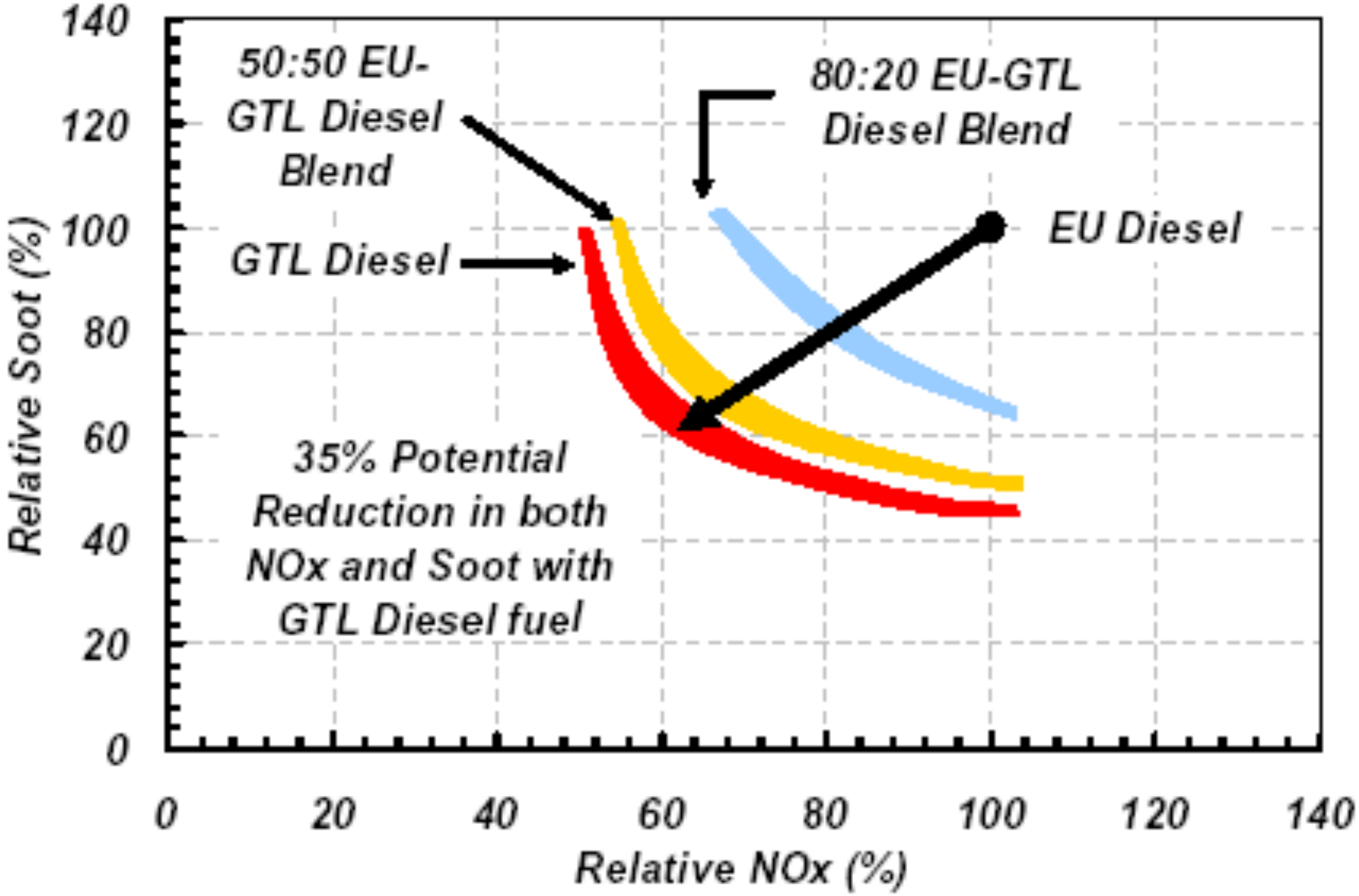
FT diesel properties

			Mossgas Export Diesel	Shell SMDS Diesel	Sasol SSPD Diesel	Diesel Fuel JIS K2204-No.2
Density	15°C	g/cm^3	0.806	0.78	0.7769	0.833
Kinematic Viscosity	40°C	cSt	2.7	2.8	2.43	
	30°C	cSt				3.50
Flash Point			93	88	71	73
Sulfur		ppm	4	<3	10	350
Aromatics		Vol%	8	<0.1	2.68	26.7
Cetane Number			52	80	>73	56
Distillation	IBP	°C		201	189	174
	5%			219	209	
	50%			271	256	277
	90%		340	353	331	333
	EP		362	358	356	360

(Source) Prepared on the basis of the following materials,
Gary Grimes, Proceedings of Gas-To-Liquids Processing 99, May 17-19, 1999
I.T. van Herwijnen, Proceedings of the Gastech 94, Oct. (1994)
P. W. Schaberg et. al., Sasol Oil (Pty) Ltd,
TSUKSAKI, Yukihiro, "*Jidosha Gijutsu*" (Automotive Technology) Vol. 55, No.5, 2001 pp67-72

Source: Morita, 2001

FT Diesel Emission Test



Source: Sasol

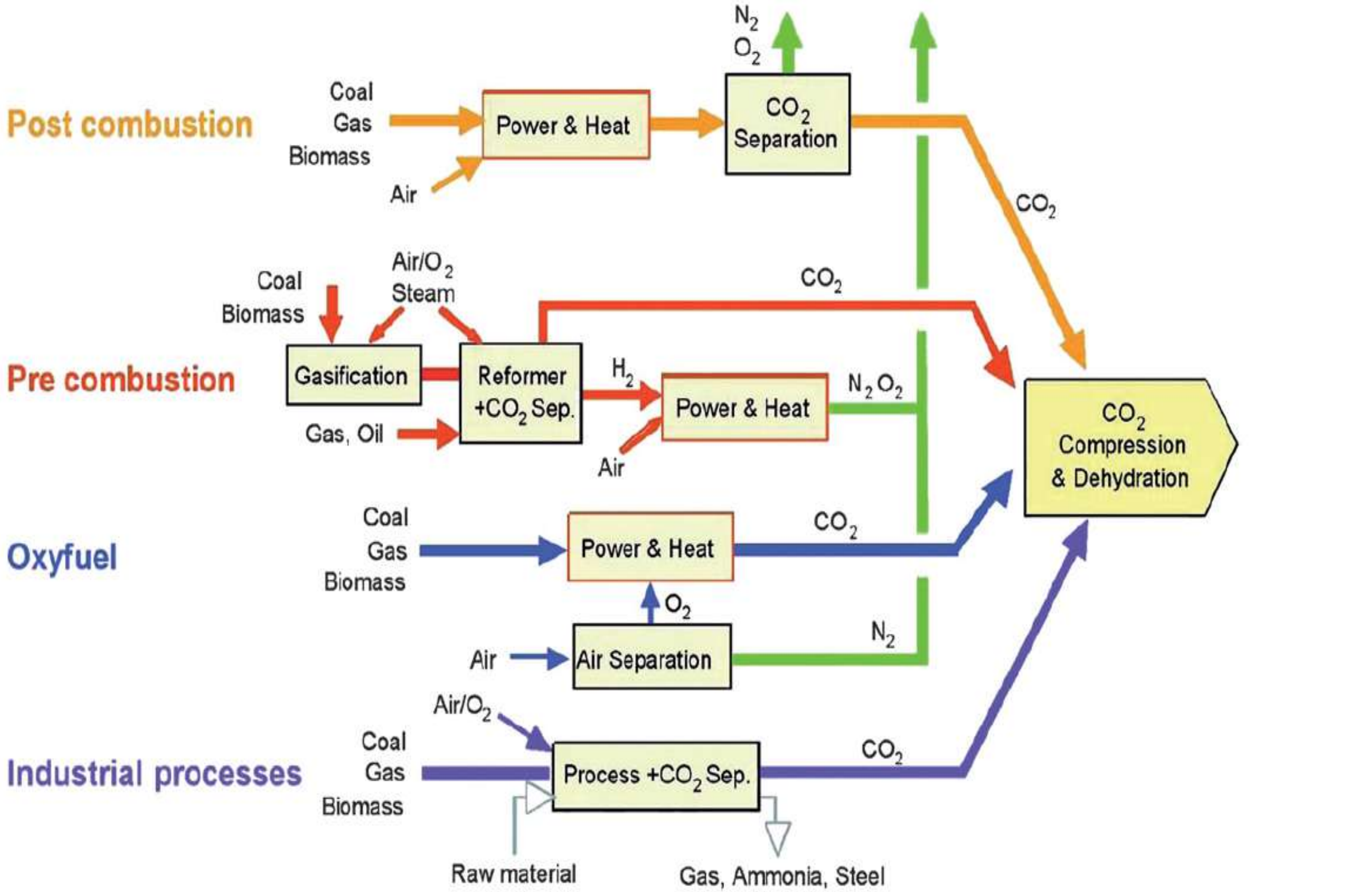
Fuel chain of CO_2 emission

Fuel type	Total CO_2 Emission* (kg CO_2/GJ)
Gasoline from crude oil	78-83
Ethanol (biomass)	10-30
FT GTL	98
FT CTL	233
FT BTL	5

•Process and use emissions, excludes emissions from primary fuels mining and transportation

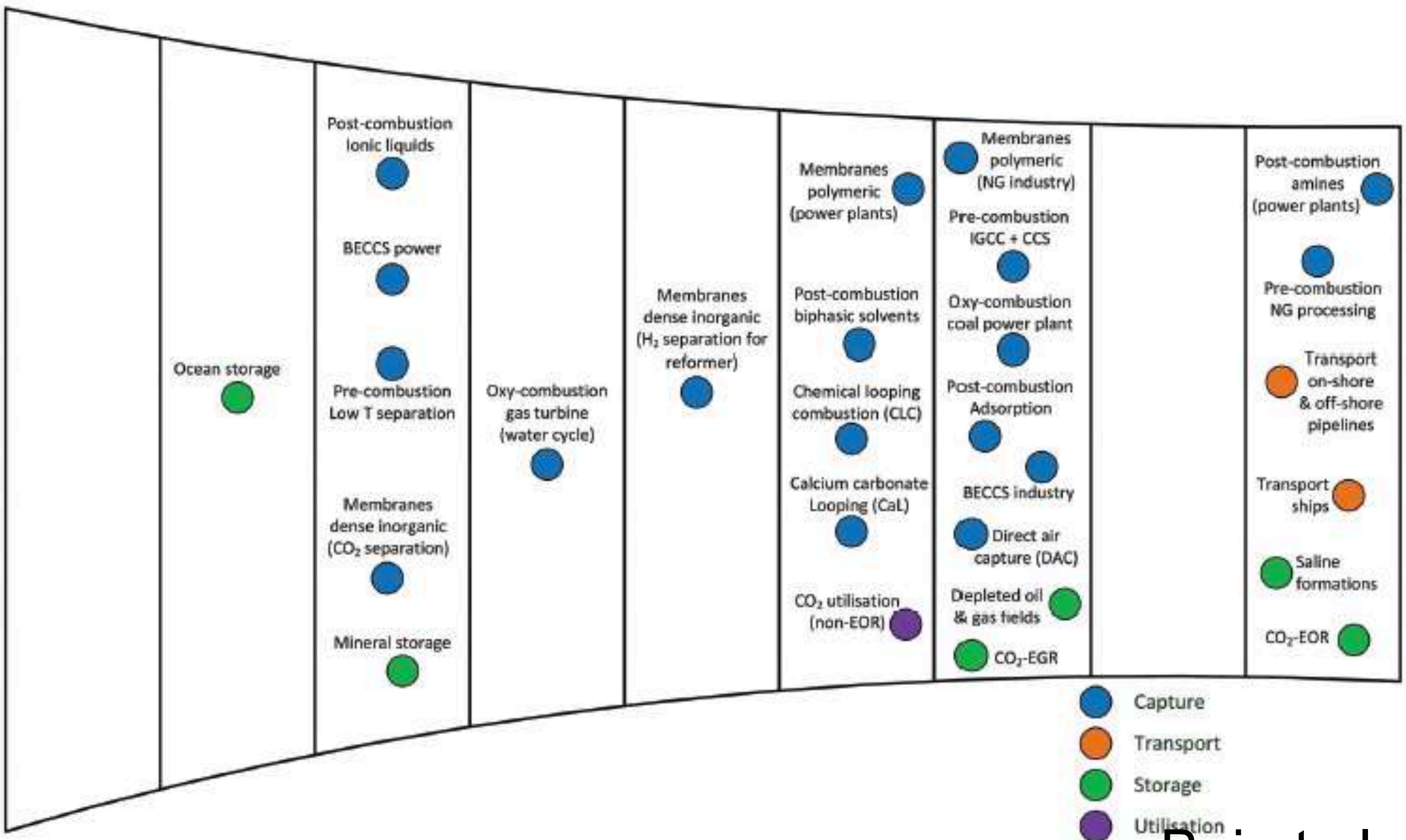
- **CCUS**

Overview of CO_2 capture processes



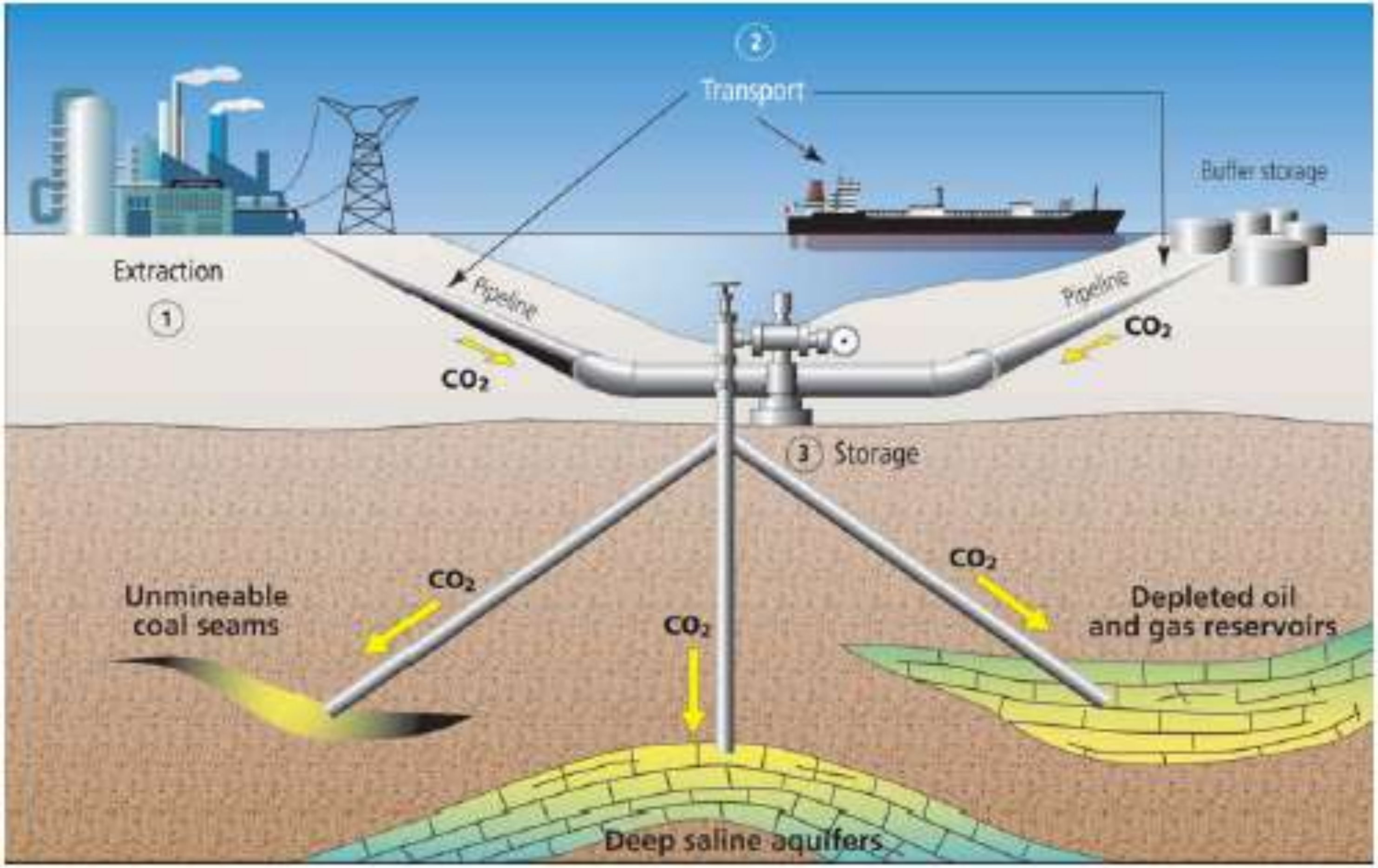
Current development progress of CCUS technologies in terms of TRL

Concept	Formulation	Proof of concept (lab tests)	Lab prototype	Lab-scale plant	Pilot plant	Demonstration	Commercial Refinement required	Commercial
TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9



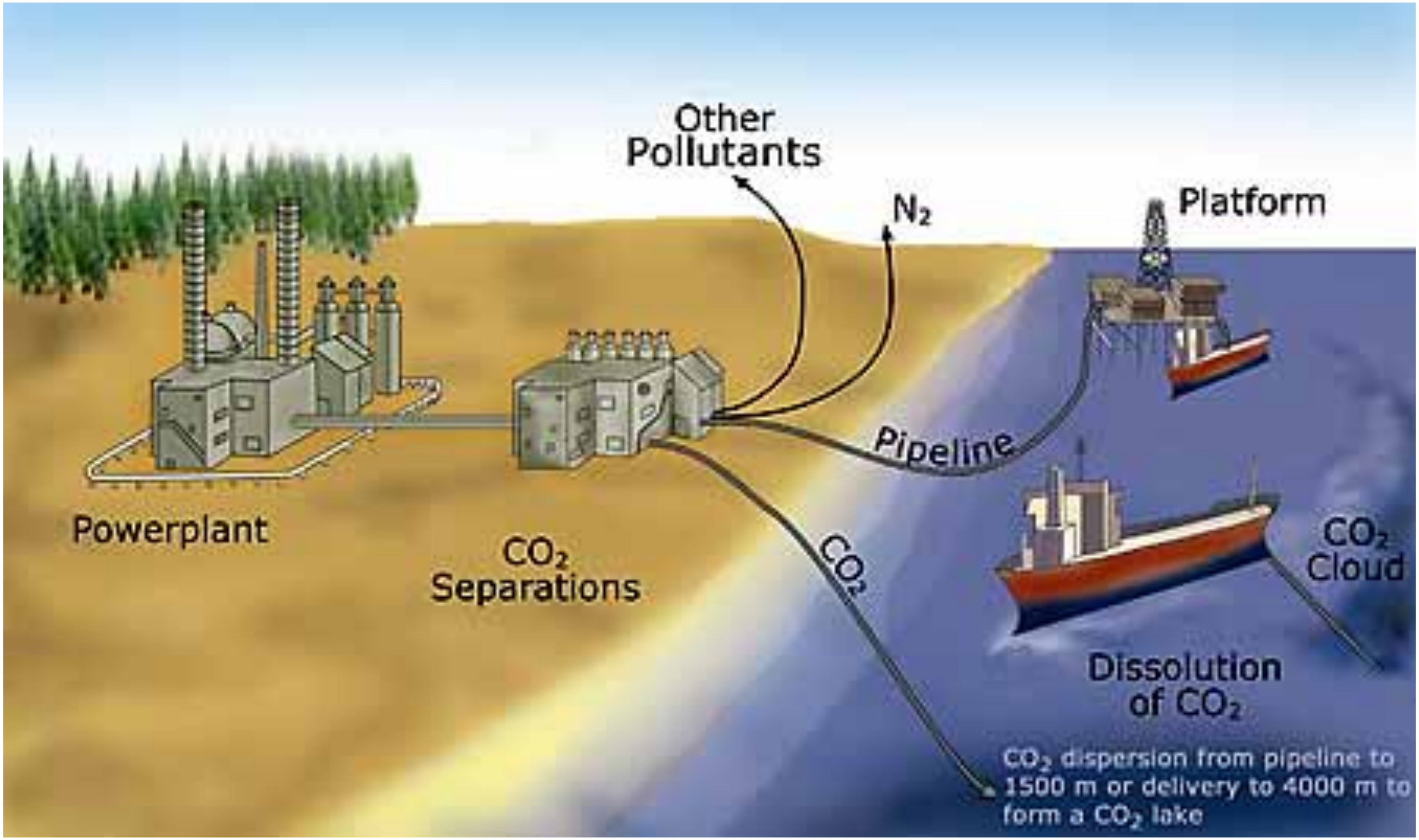
Bui et al, 2018

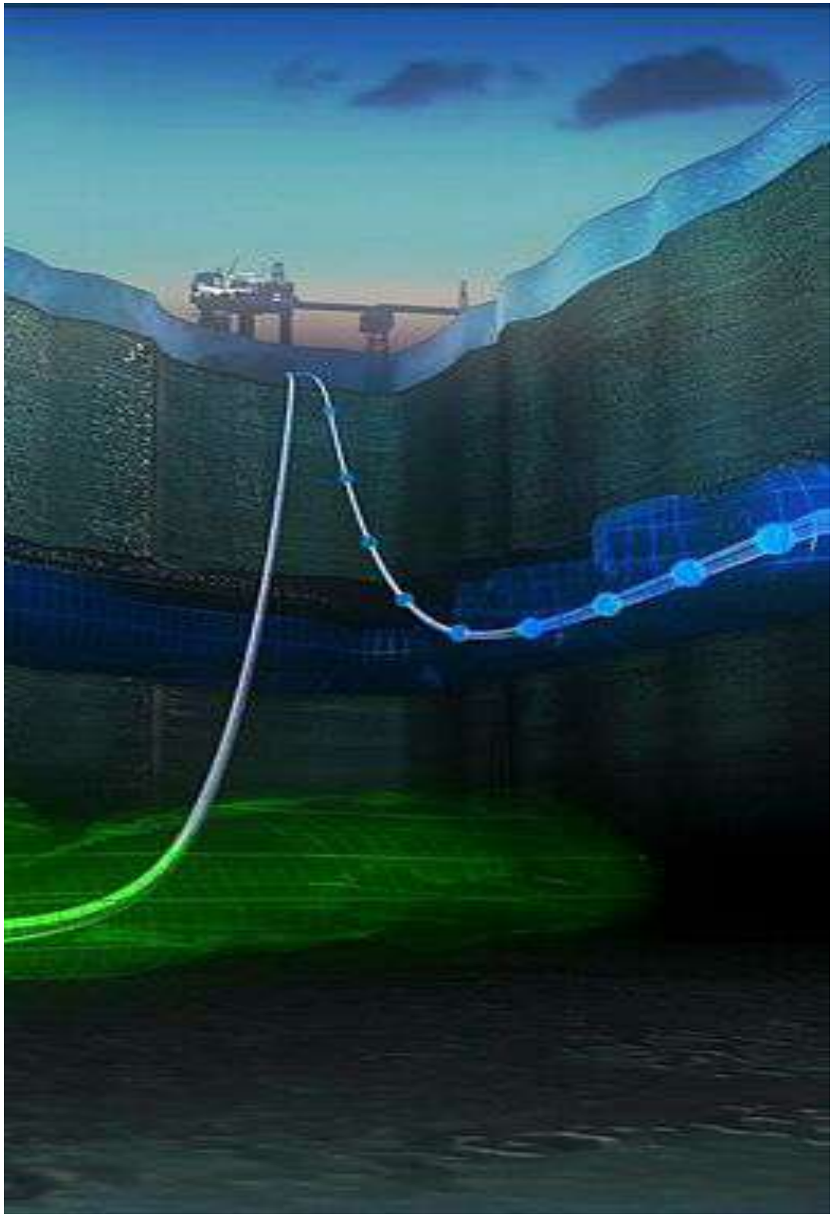
CCS



Three main steps for CCS to avoid CO_2 release into the atmosphere (Courtesy of IFP)

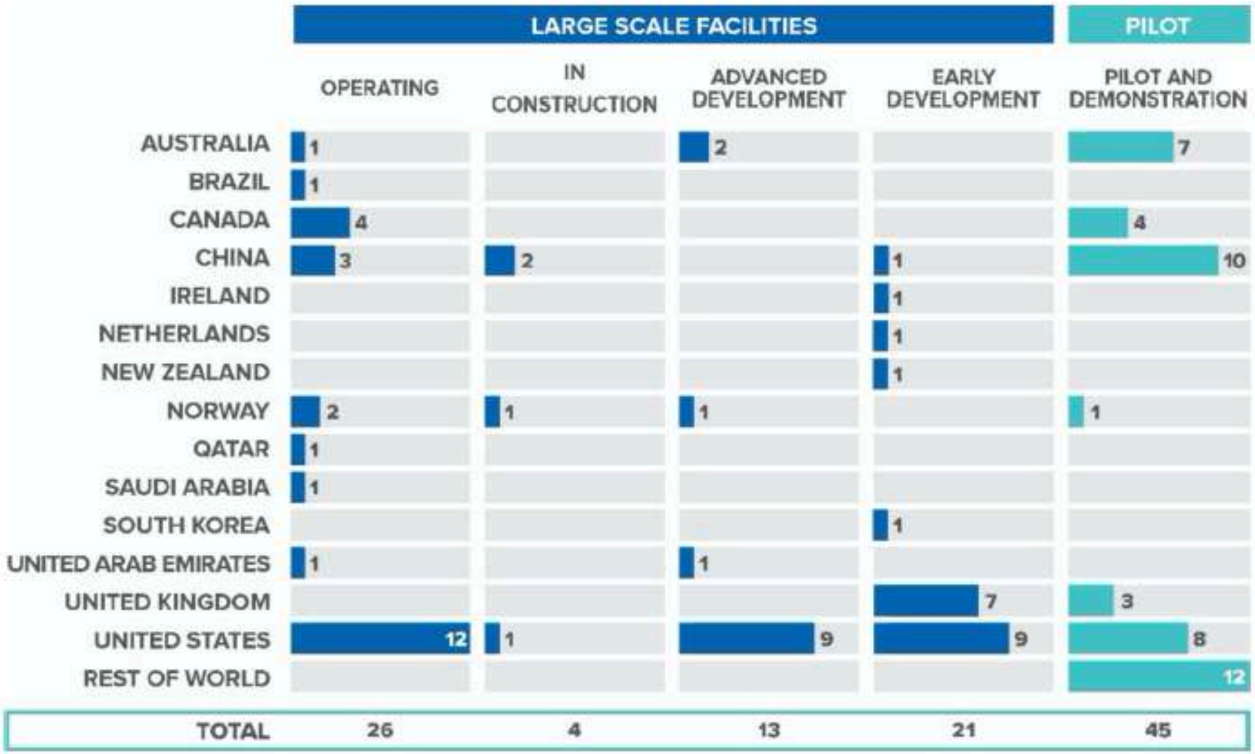
Ocean Sequestration





Sleipner project, offshore Norway

Number of CCS facilities development as of June 2021



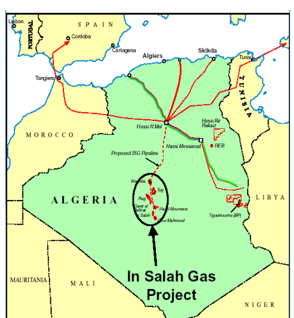
The 38 CCS projects in various stages of development around the world.

CCS Projects in Development		
Yangchang Integrated Carbon Capture and Storage *(China)*	Langskip CCS - Brevik Norcem *(Norway)*	OXY and Carbon Engineering Direct Air Capture and EOR Facility *(US)*
Sinopec Shengli Power Plant CCS *(China)*	Lake Charles Methanol *(US)*	Dry Fork Integrated Commercial Carbon Capture and Storage *(US)*
Acorn Scalable CCS Development *(UK)*	Hydrogen 2 Magnum (H2M) *(The Netherlands)*	Abu Dhabi CCS Phase 2: Natural gas processing plant *(UAE)*
Korea CCS 1 & 2 *(South Korea)*	Northern Gas Network H21 North of England *(UK)*	Net Zero Teesside - CCGT Facility *(UK)*
Sinopec Qilu Petrochemical CCS *(China)*	Ervia Cork CCS *(Ireland)*	Drax BECCS Project *(UK)*
Project Interseqt - Hereford Ethanol Plant *(US)*	HyNet North West *(UK)*	LafargeHolcim Cement Carbon capture *(US)*
Project Interseqt – Plainview Ethanol Plant *(US)*	Wabash CO_2 Sequestration *(US)*	Mustang Station of Golden Spread Electric Cooperative Carbon Capture *(US)*
The ZEROS Project *(US)*	Project Tundra *(US)*	San Juan Generating Station Carbon Capture *(US)*
The Illinois Clean Fuels Project *(US)*	Bridgeport Energy Moonie CCUS project (Australia)	Plant Daniel Carbon Capture *(US)*
Hydrogen to Humber Saltend *(UK)*	Cal Capture *(US)*	Red Trail Energy BECCS Project *(US)*
Clean Energy Systems Carbon Negative Energy Plant - Central Valley *(US)*	Qatar LNG CCS *(Qatar)*	Project Pouakai Hydrogen Production with CCS *(New Zeland)*
Santos Cooper Basin CCS Project *(Australia)*	Prairie State Generating Station Carbon Capture *(US)*	Velocys' Bayou Fuels Negative Emission Project *(US)*
Gerald Gentleman Station Carbon Capture *(US)*	Cal Capture *(US)*	

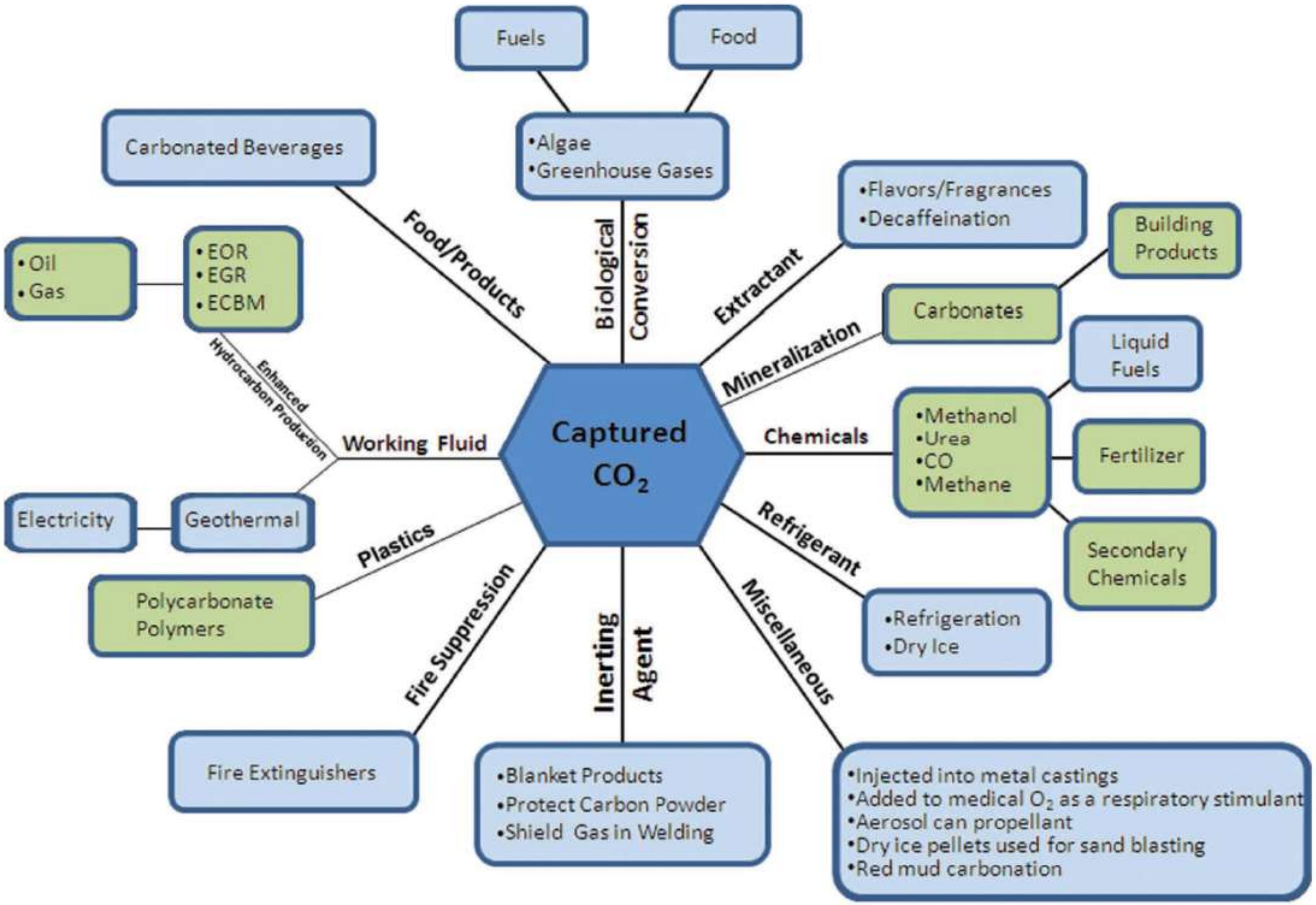
Already, in the middle of the Sahara!

Separation at amine contactor

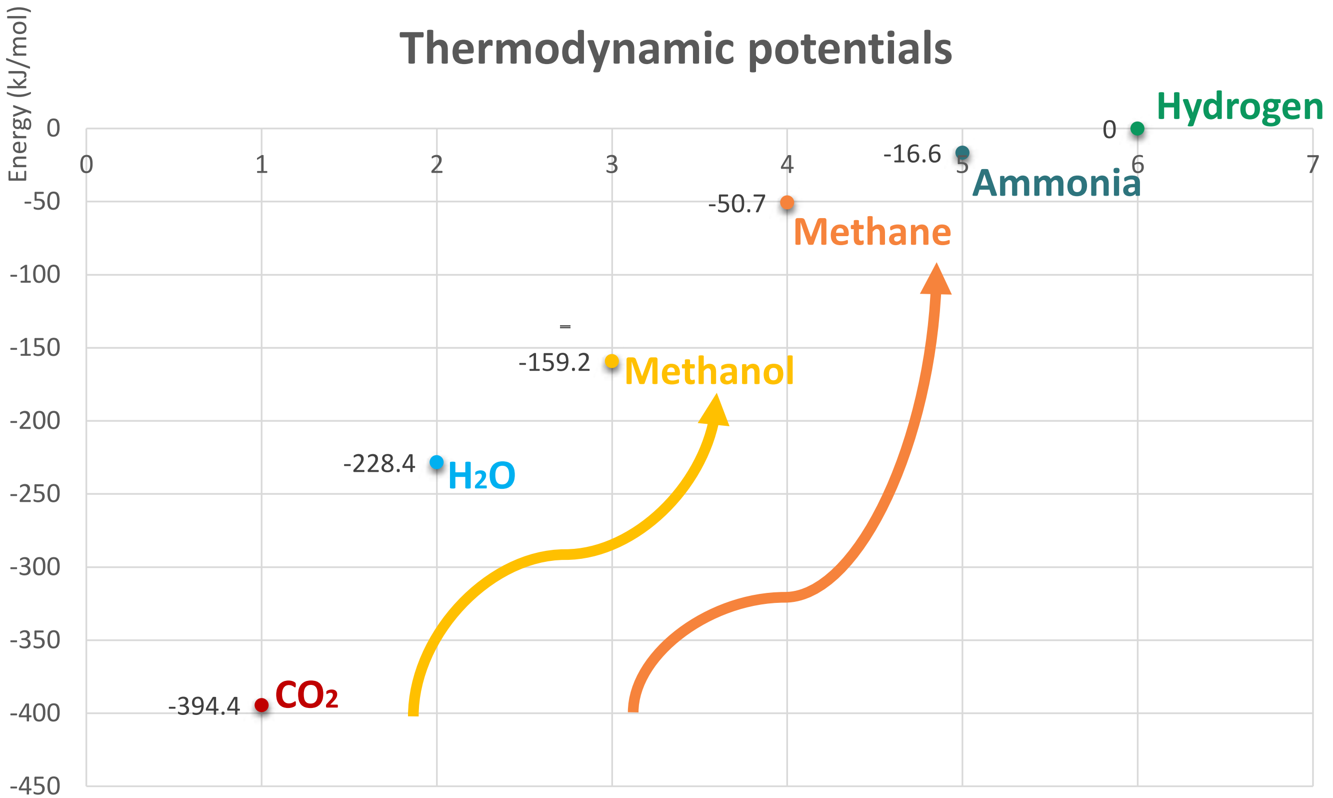
At In Salah, Algeria, natural gas purification by CO_2 removal plus CO_2 pressurization for nearby injection



Beneficial reuse of CO_2

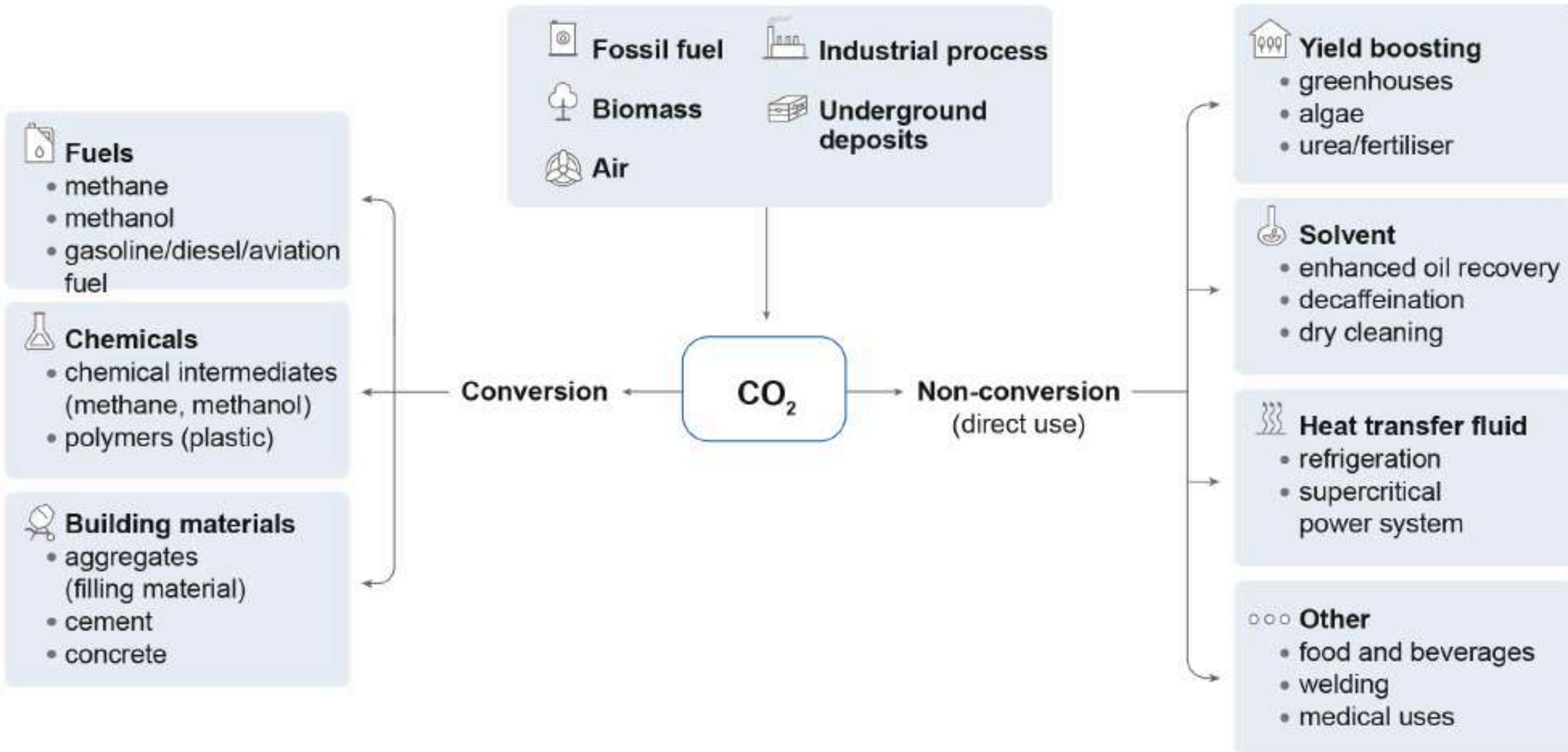


CO_2 is low thermodynamic potential

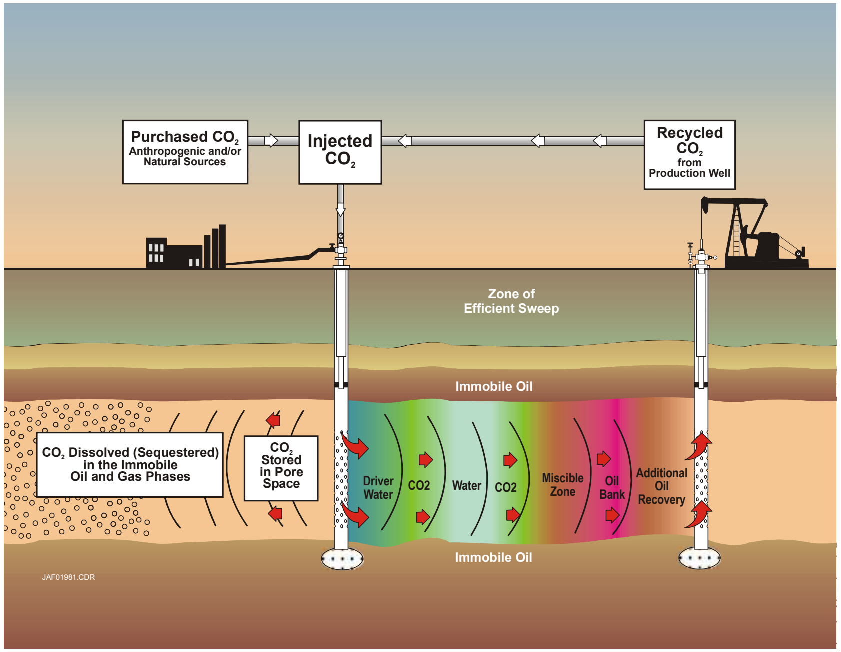


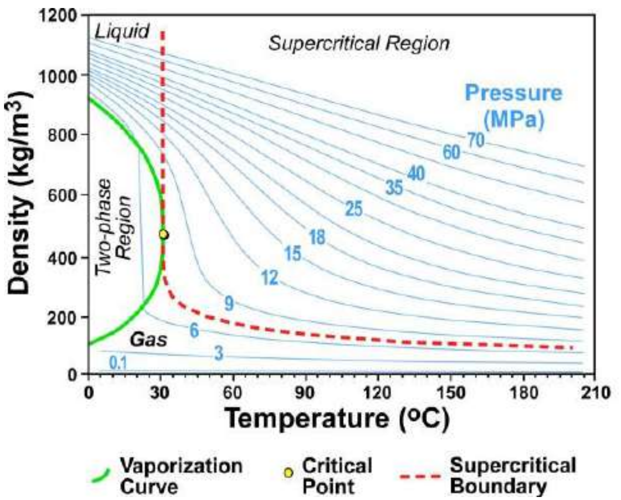
*used to calculate the maximum of reversible work that may be performed by a thermodynamic system at a constant temperature and pressure (isothermal, isobaric).

Technology pathways for CO_2 use

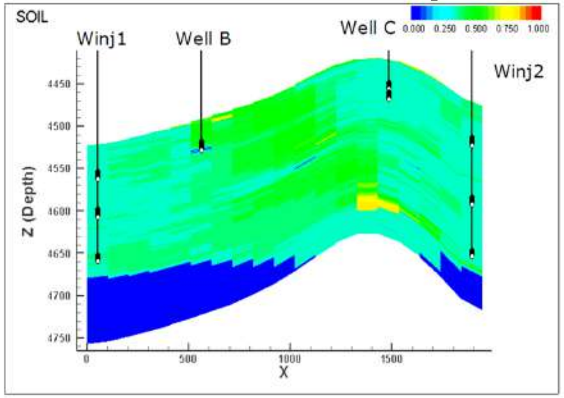


CO_2- EOR

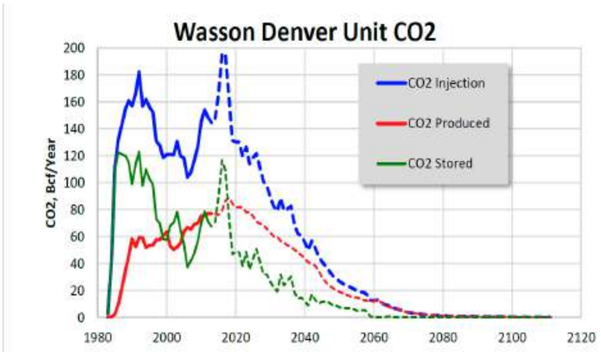




Oil Saturation Distribution Prior to CO_2 Flood

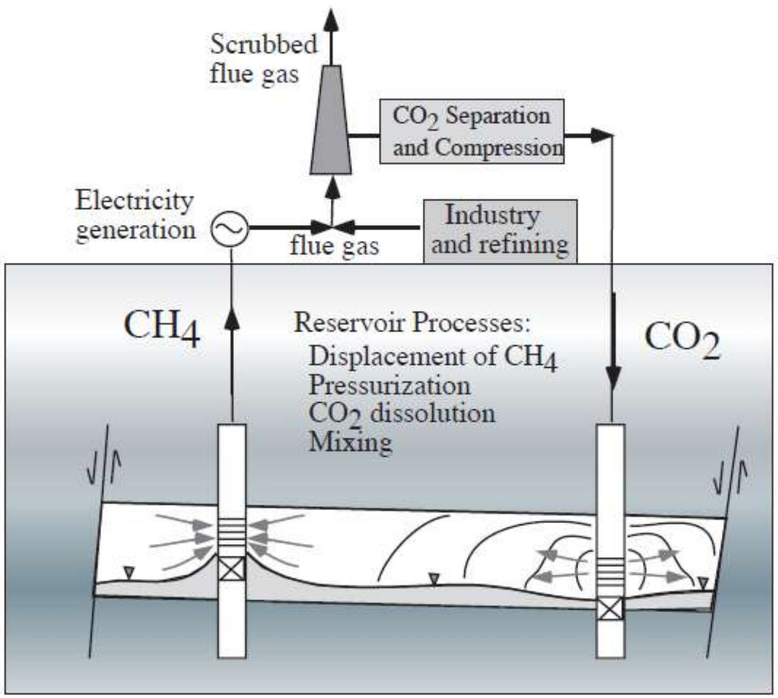


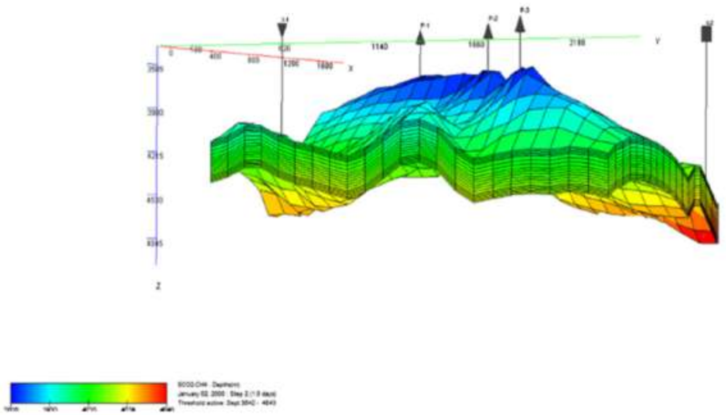
Shows un-swept regions of a carbonate formation with high remaining oil saturations

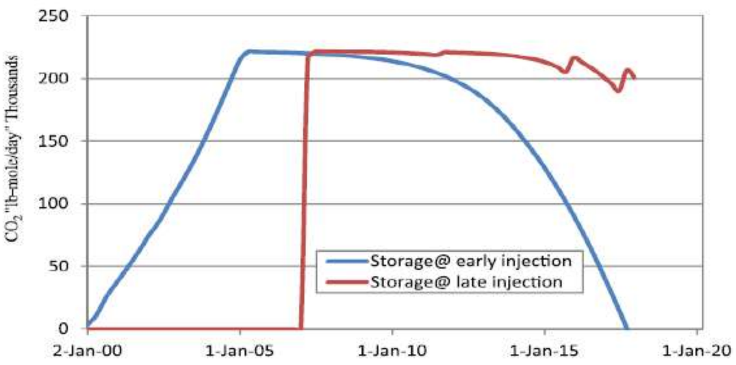


Source: NRETL

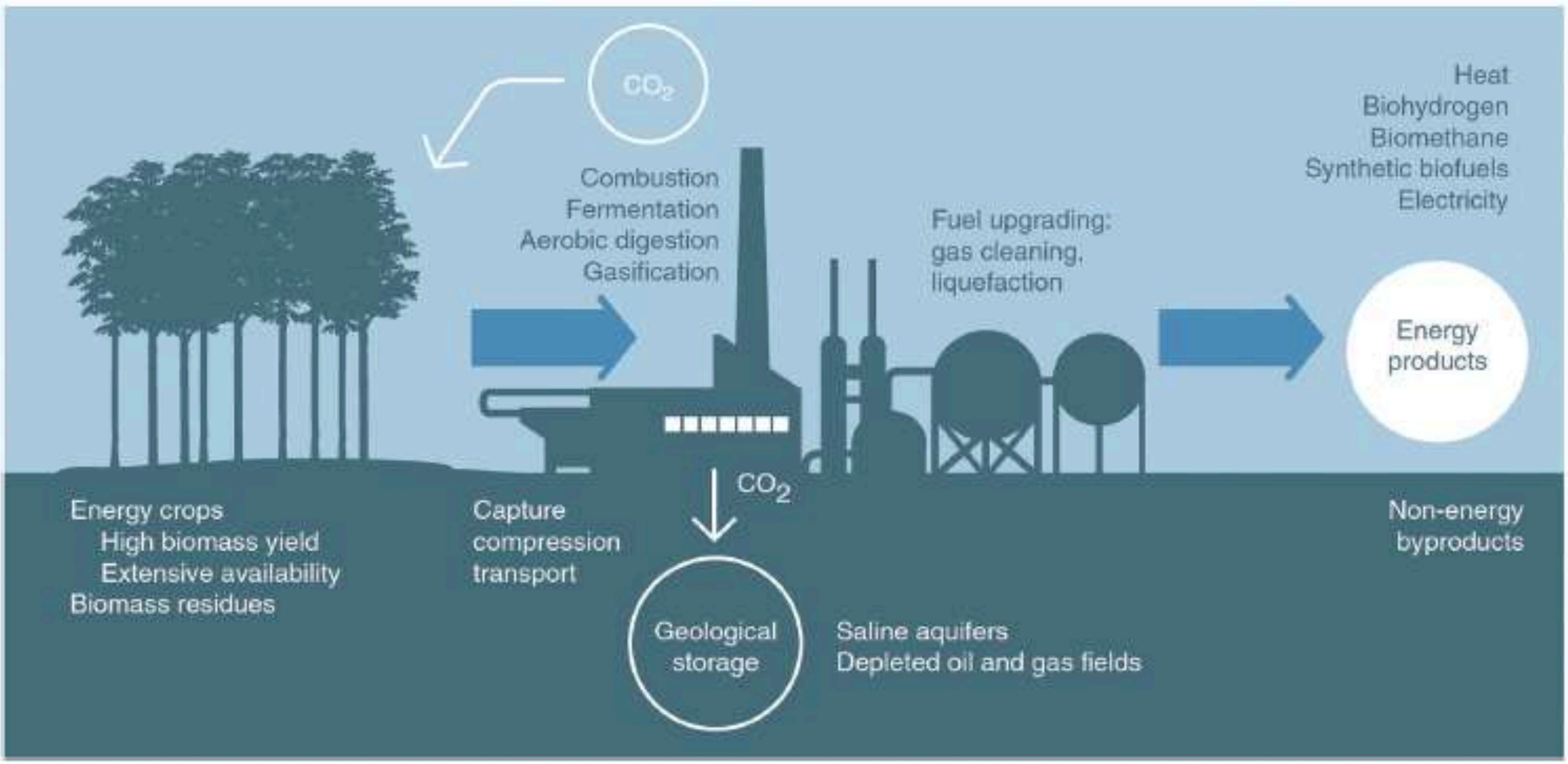
CO_2 enhanced gas recovery (EGR)





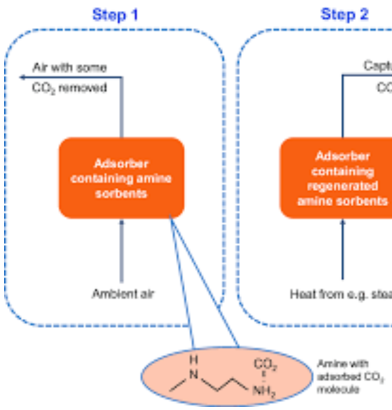


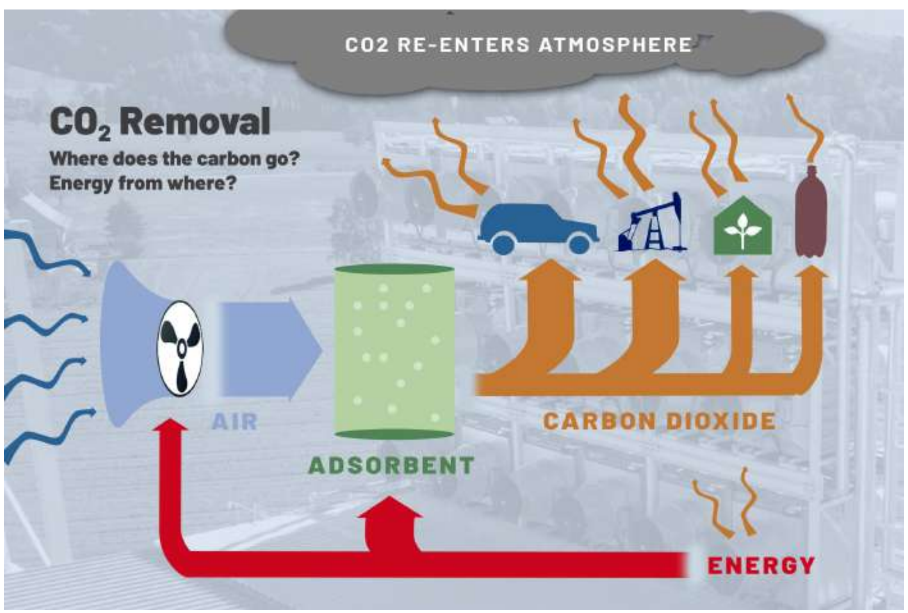
Concept of bioenergy with carbon capture and storage (BECCS)



Bui et al, 2018

Direct air capture (DAC)



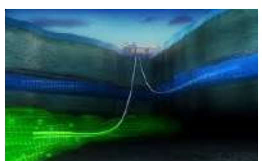


Power Sector CCS




- Boundary Dam 3, Canada
  - 110MWe, coal fired
    - Solvent based technology
    - >1.3Mt CO_2 captured
    - CO2 used for CO2-EOR
- NRG Parish
  - 250 MW slip stream
    - amine based PCC technology
    - 90% capture
    - CO2 sold for EOR
- Kemper County
  - IGCC technology/Lignite
  - Start up awaited
- Osaki CoolGen
  - IGCC Technology/Lignite
    - Co2 capture slip stream 2018/19

Industry CCS



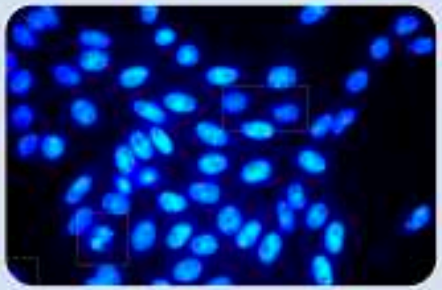

- **Natural Gas Processing**
  - Sleipner, North Sea
    - 20 years operation
    - 16Mt CO_2 stored
  - Snohvit, Barents Sea
    - Operating since April 2008
    - 0.7Mt/y CO2
  - Lula, Brazil
    - Floating Platform offshore
  - Gorgon, Australia
    - 3.5Mt/y CO2
    - Starts operation late 2017

Industry CCS (2)



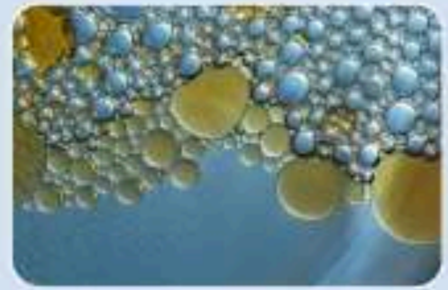

- CCS now deployed in:
  - Hydrogen refining/upgrading
    - Quest – solvent based technology
      - 1Mt injected into deep saline aquifer
    - Air Products, PSA technology
      - Over 3 Mt – used for CO2-EOR
  - Steel sector
    - Emirates Steel – Amine based capture
      - Now operational
      - 800,000 tonnes CO_2 for CO2-EOR
  - Bioethanol production
    - ICCS Project, Illinois USA
    - Start up Q2 2017
    - 1Mt/y - deep saline aquifer

CO_2 utilization strategies



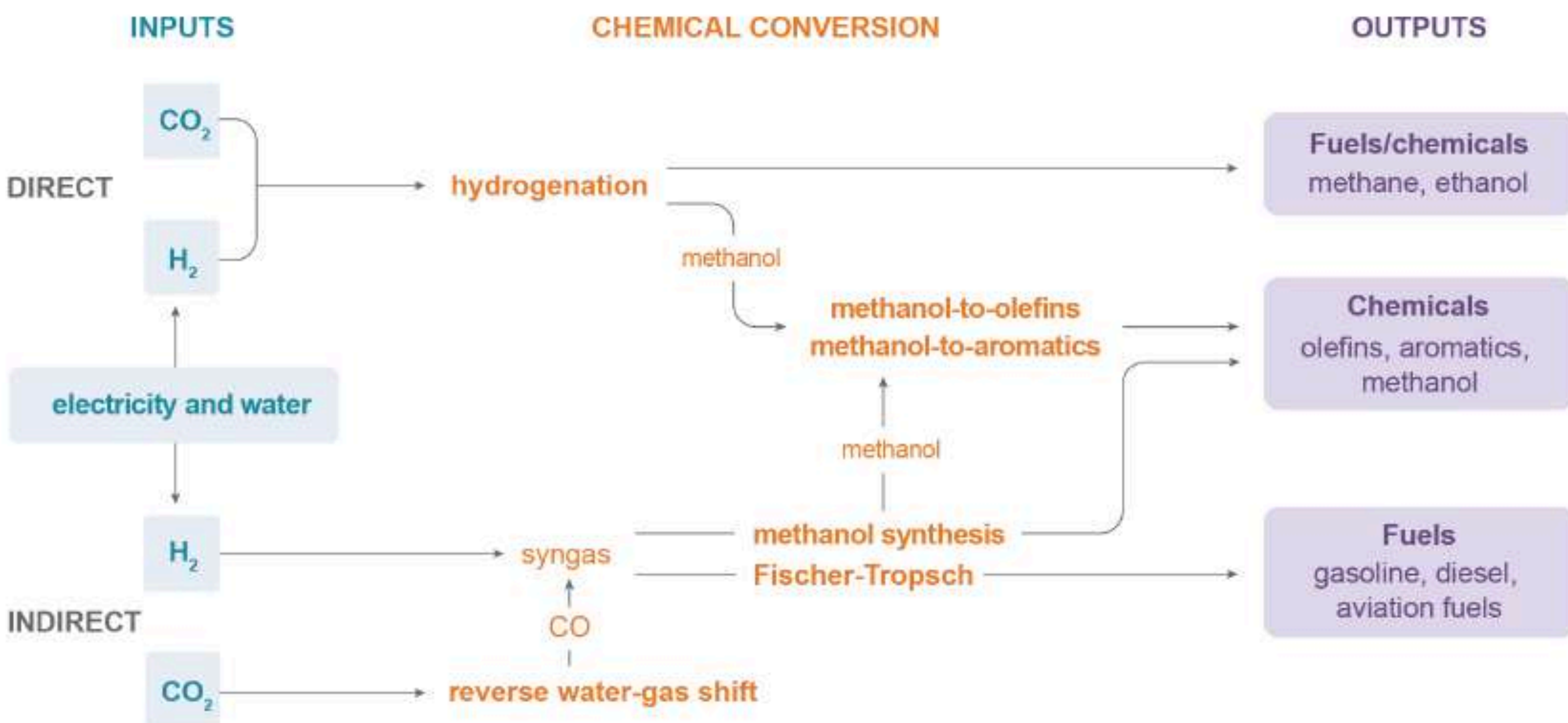
Biological based concepts

Mineralization based concepts

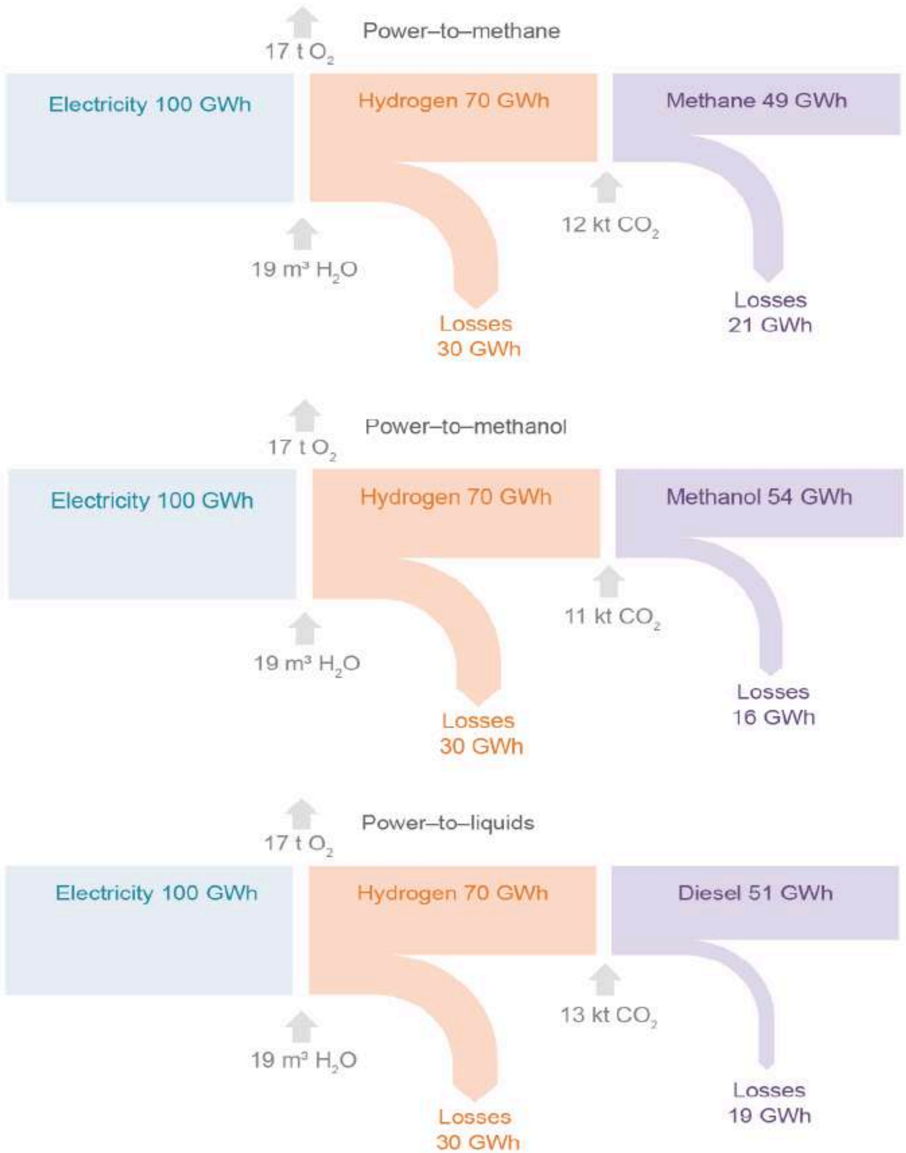


Novel physical and chemical processes

Mature conversion routes for CO_2-derived fuels and chemical intermediates



Power to X



Power–to–methane
17 t O_2
Electricity 100 GWh
Hydrogen 70 GWh
Methane 49 GWh
12 kt CO_2
19 m³ H_2O
Losses 30 GWh
Losses 21 GWh
Power–to–methanol
17 t O_2
Electricity 100 GWh
Hydrogen 70 GWh
Methanol 54 GWh
11 kt CO_2
19 m³ H_2O
Losses 30 GWh
Losses 16 GWh
Power–to–liquids
17 t O_2
Electricity 100 GWh
Hydrogen 70 GWh
Diesel 51 GWh
13 kt CO_2
19 m³ H_2O
Losses 30 GWh
Losses 19 GWh

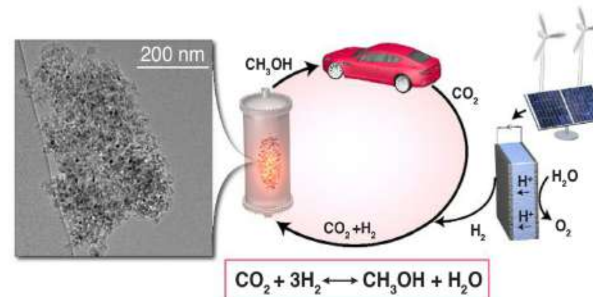
Box 6. Demonstration plants producing fuels from CO_2 and H_2

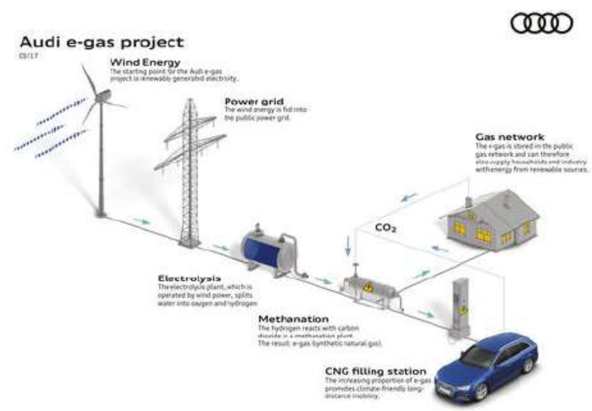
Over the past decade, several firms have built demonstration plants producing methane and methanol from electrolytic H_2 and CO_2. Two well-known examples are plants built by Audi and Carbon Recycling International (CRI). A large number of pilot plants have also been developed by companies such as AFUL Chantrerie, E.ON, RWE, Thüga Group and Korea Gas Corporation.

The Audi e-gas plant in Werlte, Germany, is the largest facility to produce synthetic methane from CO_2 and hydrogen generated from renewable electricity. The facility began operations in 2013 and has a rated output capacity of around 1 kt/yr. It obtains around 2.8 kt of CO_2 per year from the exhaust gas of a biomethane plant in the immediate vicinity. By feeding the synthetic methane into the local gas grid, renewable energy is chemically stored and CO_2 emissions from displaced natural gas are avoided (Audi, 2019).

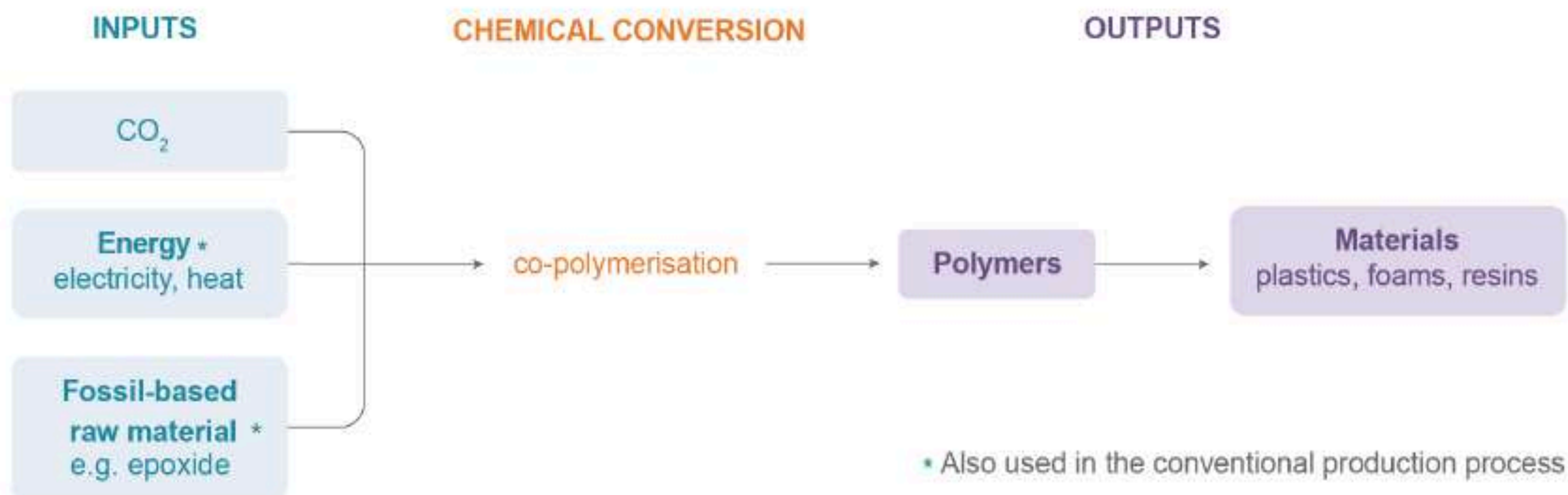
The largest CO_2-based fuel plant in operation today is the George Olah Renewable Methanol facility located in Svartsengi, Iceland. The facility, built by CRI in 2012, converts around 5.6 kt of CO_2 per year into methanol using electrolytic hydrogen. The required energy comes from the Icelandic grid, which provides electricity generated from hydro and geothermal sources. The CO_2 is imported from a geothermal power plant located nearby, where it is a by-product of steam extracted from geothermal reservoirs which would otherwise be vented into the atmosphere. In 2015, CRI expanded its original output capacity of 1 000 tonnes per year to more than 4 000 tonnes per year. The product, called "vulcanol", is sold on the market in Iceland and abroad where it is blended with gasoline and used in the production of biodiesel. CRI claims that vulcanol reduces CO_2 emissions by more than 90% compared to fossil fuels over the complete life cycle of the product (CRI, 2019). The CRI methanol facility is a good example of how lower-emission CO_2-derived fuels or chemicals can be competitive in regions with ample and low-cost renewable energy and CO_2.

CARBON RECYCLING INTERNATIONAL





Mature conversion pathways for CO_2-derived polymeric materials



Box 8. Commercial production of polycarbonates from CO_2

A number of companies developing CO_2-derived polycarbonates announced they have reached the commercialisation phase. Large-scale plants have been built, or are under construction, in various locations around the world.

Chimei Asai, a joint venture of Asahi Kasei Chemicals and Chi Mei Corp, has been operating a polycarbonate plant in Chinese Taipei since 2002. It produces 150 000 tonnes per year and was the first commercial plant to announce that it had succeeded in producing polycarbonates using CO_2 as a starting material. Reported emissions reductions are 0.173 tCO_2 per tonne polycarbonate product compared to the conventional pathway (Fukuoka et al. 2007).

In 2016, Covestro commissioned a commercial plant producing 5 000 tonnes of polycarbonates per year at Dormagen, Germany. Once in operation, the facility will use CO_2 to substitute a portion of the fossil feedstock normally fed into the production process, resulting in a CO_2 content of around 20% by weight in the final product. The product will be used as a feedstock for the production of foams for mattresses and furniture (Covestro, 2018). Savings in life-cycle GHG emissions were estimated to be around 15% relative to the conventional production process (von der Assen, 2015).

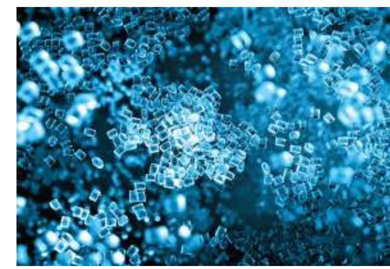
The company Novomer, purchased by Saudi Aramco in 2016, is due to start a commercial production facility with a capacity of 50-100 kt/yr of CO_2-derived polycarbonate in 2019 in Texas, United States. The company produces polymers that contain up to 50% CO_2, which can be used in several industrial applications, such as coatings and foams (Alberici et al., 2017).

Novomer
Catalyzing Green Chemistry

covestro

NOVOMER

Novomer's thermoplastic pellets incorporate waste CO_2 into a variety of consumer products.



Box 9. Commercialisation of CO_2-derived cement and concrete

Two North-American companies are leading the development and marketing of CO_2-derived concrete.

Founded in 2007, Canadian company CarbonCure has developed a commercial CO_2 curing process that can be retrofitted to conventional "ready-mix" concrete plants. The process allows for the use of existing equipment and has little impact on the manufacturing conditions. In mid-2018, the CarbonCure process had already been adopted in 25 masonries and 54 ready-mix installations, with at least 15 more being retrofitted at the time, mainly in North America (CarbonCure, 2018). More recently, CarbonCure's technology is available in nearly 150 concrete plants (Edelstein, 2019). CarbonCure claims that their product has better compressive strength and is more cost-effective than concrete from Portland cement. The CarbonCure process was primarily developed to create a high-value product with improved performance and lower costs rather than because of its low-carbon attributes. The company expects its main revenues to come from product sales and not from a carbon credit scheme or carbon tax, which indicates the difference in value proposition compared to many other CO_2-derived products. Nevertheless, the company claims that for every tonne of CO_2 used in CarbonCure concrete, around 254 tonnes of CO_2 can be avoided, mainly because less cement is needed per m3 of CO_2-cured concrete compared to conventionally produced concrete (CarbonCure, 2018). Furthermore, they estimate that CarbonCure "ready-mix" concrete technologies have the potential to provide a 500-700 $MtCO_2$ per year impact by 2050.

The US-based company Solidia Technologies is developing both specialised cement-making that binds with more CO_2 (Solidia CementTM) and CO_2-based concrete curing (Solidia ConcreteTM, made using Solidia CementTM) for making high-strength, pre-cast concrete materials. In contrast to the CarbonCure process, Solidia CementTM must be cured in a sealed environment. Currently in commercialisation, Solidia reports lower costs, shorter curing times and improved product performance, while reducing the carbon footprint and water use by up to 70% and 80%, respectively. Several pre-cast customers in North America and Europe have been commercially testing the cement and curing process in the production of blocks, roof tiles and pavers. According to Solidia, the company's demand for CO_2 will more than double that of the existing CO_2 market within five years (Solidia, 2019). While the curing process is readily deployable, the commercial adoption of Solidia CementTM could take longer as product standards and building codes need to be updated.

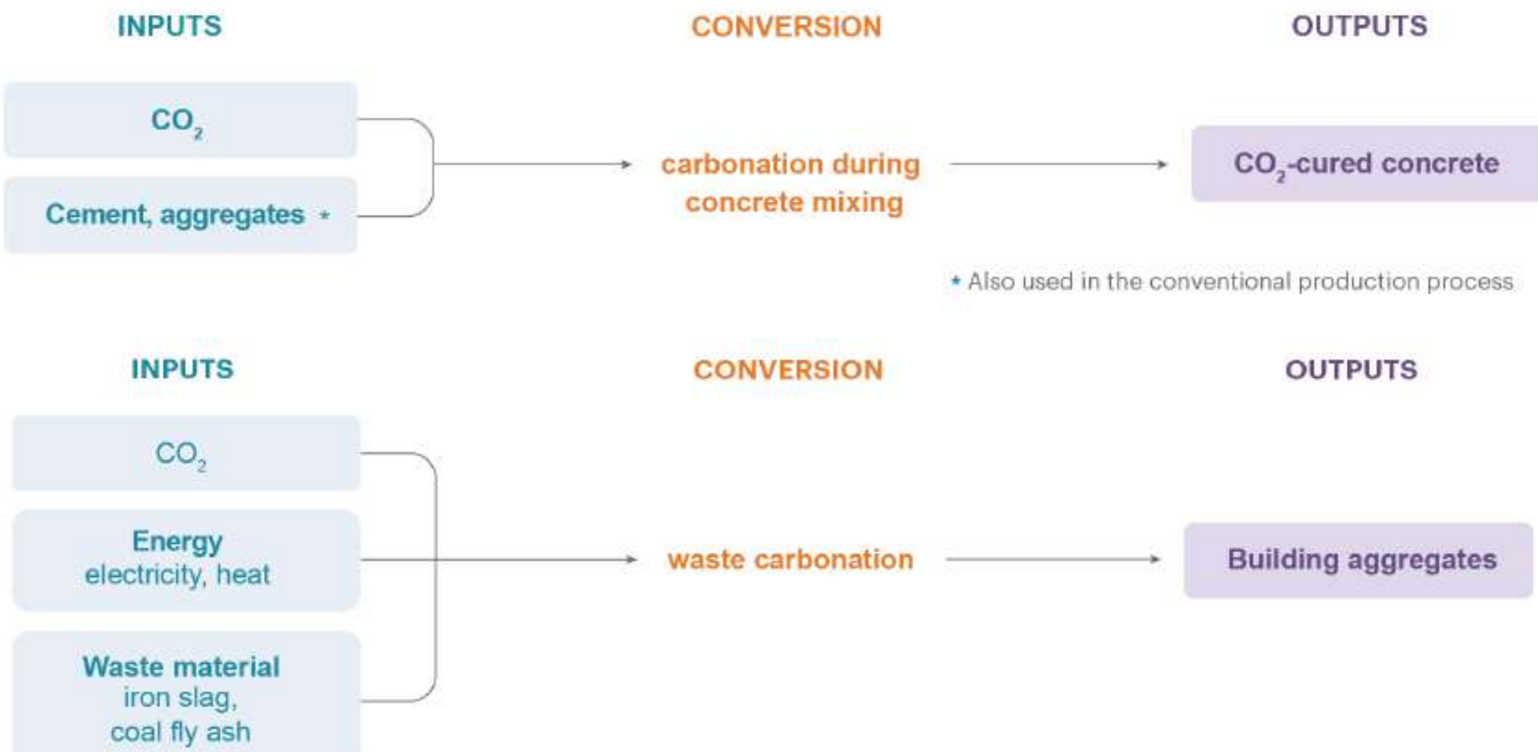
Box 10. Commercial building materials from waste: The case of Carbon8

Formed in 2006, the British company Carbon8 is among the global leaders making build materials out of industrial waste and CO_2. Today, the firm is operating two commer carbonation plants producing lightweight aggregates from municipal air pollution control (Al residues in the United Kingdom. Both plants are located next to a concrete manufacturer that u the Carbon8 product in dense and medium-dense aggregate blocks. The company's busin model is based on two streams of revenue: a fee for waste treatment and the sale of its produ Carbon8's material is reportedly three times less expensive than most other recycled aggrega (Alberici et al., 2017).

On an annual basis, the plants collectively use around 5 kt of high purity CO_2 to convert 60 kt APC residues, which would otherwise be treated and disposed to landfill or stored in salt caverns cheaper CO_2 (with lower purity levels) was available, even more wastes could be process economically with the company's technology, such as cement dust and steel slag. The ener consumed across the value chain is relatively small, due to the short transport distances and li need for pre-treatment. According to Carbon8, the process fixes more CO_2 in the aggregate tha emits over its life cycle, resulting in the first carbon-negative aggregate on the market (Carbo 2019).

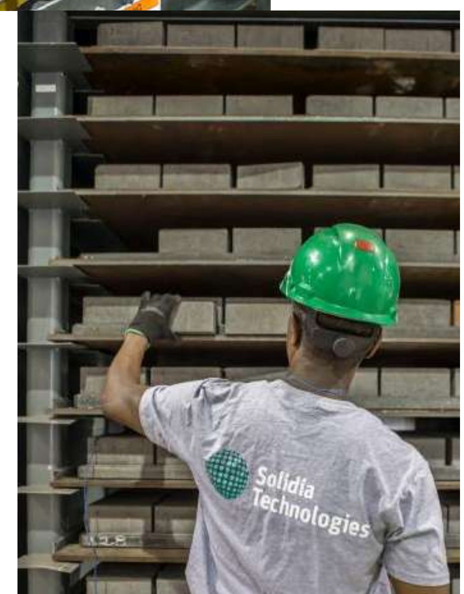
The company aims to have five to six plants in operation by 2021, using around 19 kt/yr of CO_2 may be challenging to find sufficient material to process in the near future as most compan producing these materials are under contract with waste companies. In addition, local polic restrict plant output capacity to 30 kt/yr, while EU waste regulations forbid the use of certain wa streams in commercial products (Alberici et al., 2017). These barriers could seriously delay t company's growth plan.

Mature conversion pathway for CO_2-derived building materials



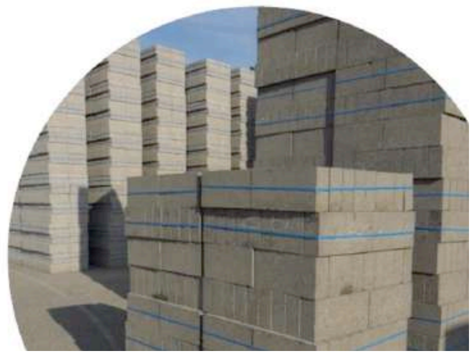
CARBON CURE™

SOLIDIA®



Accelerated Carbonation Technology

- Minerals in thermal/other residues reactive with carbon dioxide
- Mg/Ca silicates/oxides/hydroxides
- Carbonate reduces pH
  - Stabilises metals such as Pb, Zn, Cu
  - Carbonate formation can 'cement' the product
- Reaction takes only a few min. when 'managed'
- Products can be engineered
- Diversion of waste from landfill
- Reduction in disposal costs
- Improves carbon footprint, and corporate responsibility profile and brand



Commercial plants in UK

Brandon commissioned 2012

Avonmouth commissioned 2016

Video of process available on www.c8a.co.uk

CO_2 use to enhance the yield of a biological or chemical process

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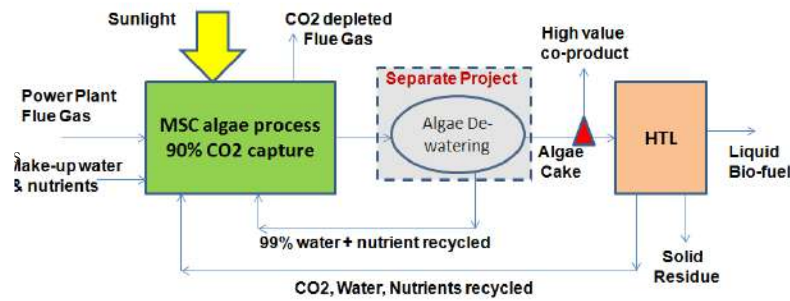
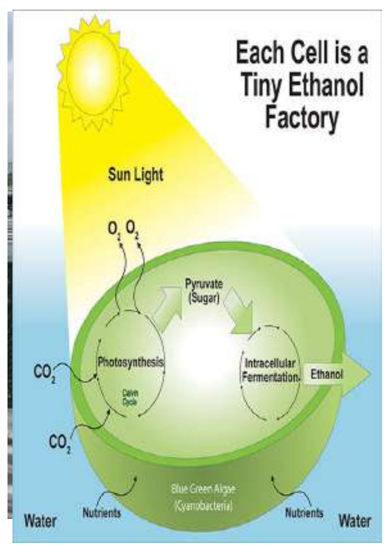
U of Kentucky – Duke Energy's East Bend Station



Algenol biofuels: Algae-to-ethanol

- Algenol Biotech formed in 2006: HQ in Fort Myers, US + R&D in Berlin
- Fort Myers sites has 4.5-acre green-field facility for outdoor cultivation of cyanobacteria in commercial scale photobioreactors (PBRs)
- Uses CO_2 feedstock, salt-water, sunlight, electricity and nutrients to enable growth of proprietary algae in the PBRs for EtOH extraction
- CO_2 use and displacement of gasoline achieves life-cycle GHG benefits



Existing Coal-based IGCCs

Puertollano (Spain)

Wabash (Indiana)

Polk (Florida)

Buggenum (NL)

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Courtesy of Tampa Electric Company

The 250MW Tampa Electric Polk IGCC Power Station

Table 6 Current IGCC plants

Name	Location	Company	Description	Status	Update/Reason for Shutdown
Puertollano IGCC Plant	Puertollano Spain	ELCOGAS	300MW target project through THERMIE program, operational since 1997. Total cost US$ 555 million (1991 US$). [41]	Operational	In 2010, a CO_2 capture and H_2 production pilot plant was added to the system. The IGCC plant has also experimented with running on up to 10 per cent biomass feed, with promising results. [42]
Willem Alexander Powerplant	Buggenum, Netherlands	Nuon	253MWnet demonstration facility, in service since 1994, commercial operation since 1998. [43]	Closed April 2013 [44]	Low energy prices in the region combined with the high-cost basis of the plant made profitable operation "impossible." [44]
Kemper County IGCC Project	Mississippi, US	Southern	582 MW plant, carbon capture used for enhanced oil recovery [40]. Combined cycle operational since August 2014, gasification proving problematic [45]. Total costs have climbed up to US$ 7.1 billion. [46]	Commercial Operation Delayed [47]	Only competitive with natural gas if gas prices go above US$ 5/ MMBTU [46]. A tubing leak has caused an indefinite delay in operation since March 2017 [47].
Polk Power Station	Florida, US	Tampa Electric	260MW (220MWnet) unit began commercial operation in 1996. [48]	Operational	Expansion completed in 2017 to change simple-cycle gas units to combined-cycle units. This is not in the IGCC unit, but the others that make part of the plant. [49]
Wabash River Coal Gasification Repowering Project	Indiana, US	Duke Energy	Retrofit of Unit 1 of a pulverized coal plant, 1995. 192MW gas turbine, 112.5MW steam turbine. Total cost 438 million, half funded by DOE. [50]	Shut down 2016, gasification unit still online [51]	New federal pollution rules push Duke Energy to cut coal power plants or retrofit them to meet stricter emissions standards. Original Wabash power plant is over 50 years old, shut down to avoid expensive pollution control. [51]

Name	Location	Company	Description	Status	Reason for cancellation/ delay in implementation
Nuon Magnum	Netherlands	Nuon	750 MW using coal, biomass, 450 MW using natural gas; partial CO_2 capture. [52]	Postponed	Rise in raw material prices and pending negotiations with environmentalists. [52]
IGCC-CCS Project in Hurth	Germany	RWE	360 MW using lignite feed; storage in depleted gas reservoirs or saline aquifers. [53]	Discontinued	German carbon storage law tightened CCS constraints, CO_2 storage deemed impossible by RWE. [53]
Teesside	UK	Centrica	800 MW using coal feed; 85 per cent CO_2 capture. [54]	On Hold	No government funding for pre-combustion CO_2 capture, not financially viable. [54]
Don Valley Power Project	UK	Powerfuel	650 MW using local coal; 90 per cent CO_2 capture. [55]	Stalled	Financial issues, expected to be in operation by 2020. [55]

Source : UNECE

Mountaineer Project
AEP

- Phase 1: 30MW slip stream from 1,300 MW Mountaineer Station
- Cost= $668 million
- Phase 1 came onto production in October 2009.
  - By December 2010, 21,000 metric tons had been captured at >90% capture rate, ~4,400 hours of operation, and 15,000 metric tons stored.
  - However in July 2011, Phase 2 was halted do to “unknown climate policy”.
- Capture Technology***:*** Post-combustion capture with chilled ammonia, Sequestered in the Mt. Simon deep saline formation

Source: Worthington, 2016

Kemper County
Southern Power Company

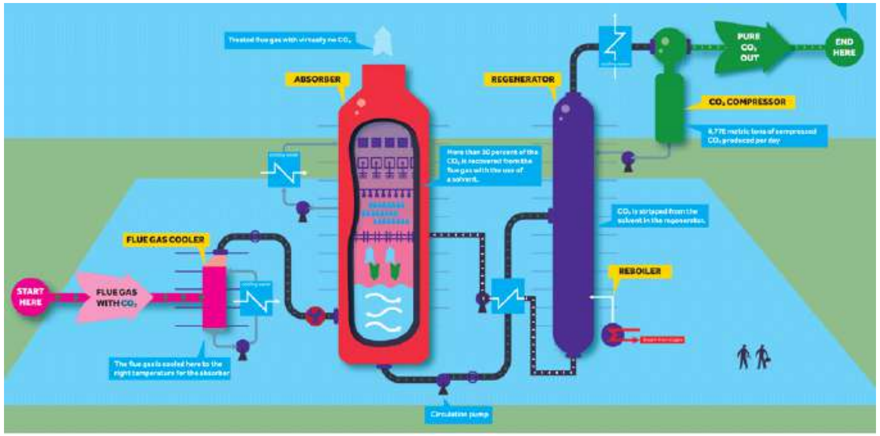
- “Mine to Mouth” project using onsite lignite coal
- Capture Technology : Pre-combustion IGCC plant using Transport Integrated Gasification (TRIG™) with a 65% capture rate
  - Estimated ~ 3.5 Mt/yr of CO_2
  - Captured CO_2 will be piped to onshore EOR field

Source: Worthington, 2016

Petra Nova WA Parish
NRG Energy JX Nippon

- A retrofit on a 240 MW slip stream from 610 MW unit
- Cost= ~$1 billion
- Broke ground Sept 14th, 2014 and projected to begin operating at the end of 2016.
- A 75 MW gas-powered peaking unit will provide power and steam to the carbon capture facility.

- Capture Technology: Post-combustion using KM-CDR amine technology developed by MHI and KEPCO,
  - Expected 90% capture rate = ~1.6 Mt of CO_2 annually
  - Capture CO_2 will be used in a EOR field 82 miles away



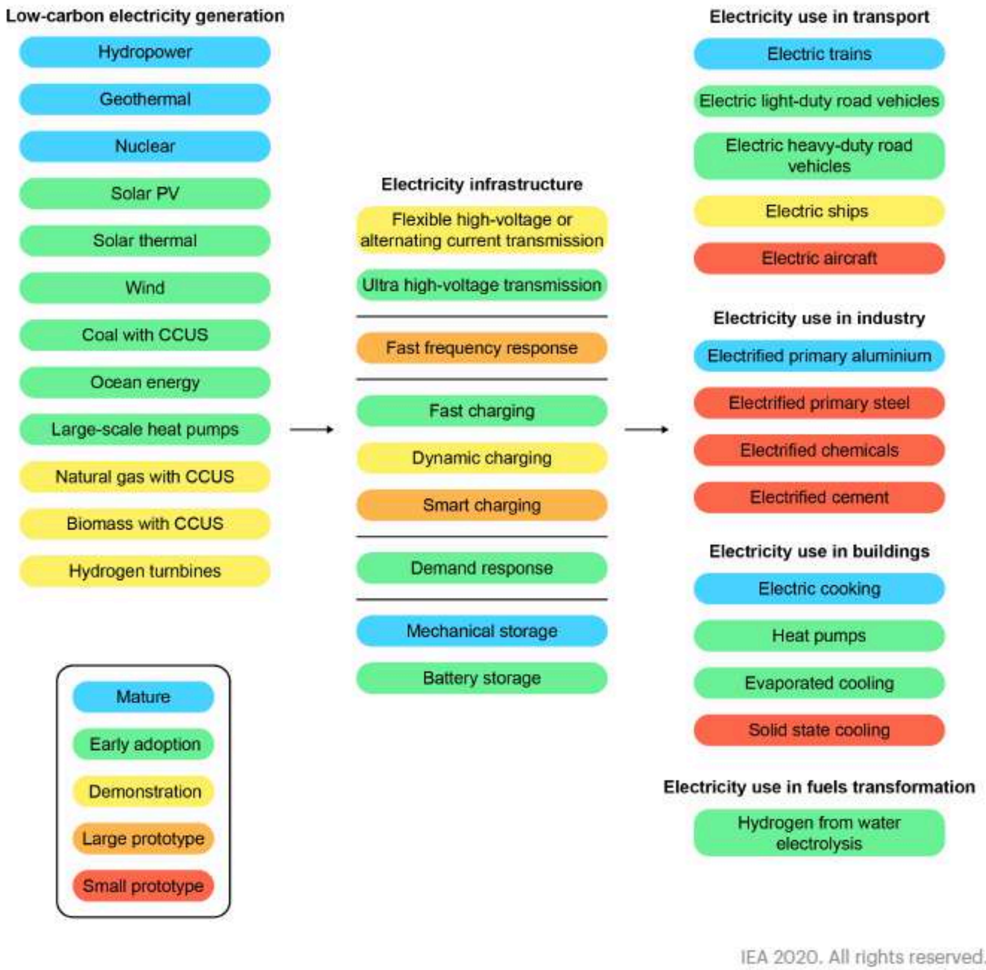
Source: Worthington, 2016

TCEP
Summit Power

- 400 MW capacity
  - Typical baseload is 377 MW -> 105.7 for project equipment, 15.7 MW to compress CO_2, 42.2 MW to produce urea
- Cost= ~$1.727 billion
- Expected to be operational in 2019; in planning stage
- Capture Technology: Coal gasification with Pre-Combustion capture using Siemens IGCC technology and Linde Rectisol acid-gas capture technology with a 90% CO2 capture rate
  - Will also sell 750,000 tons annually of urea byproduct

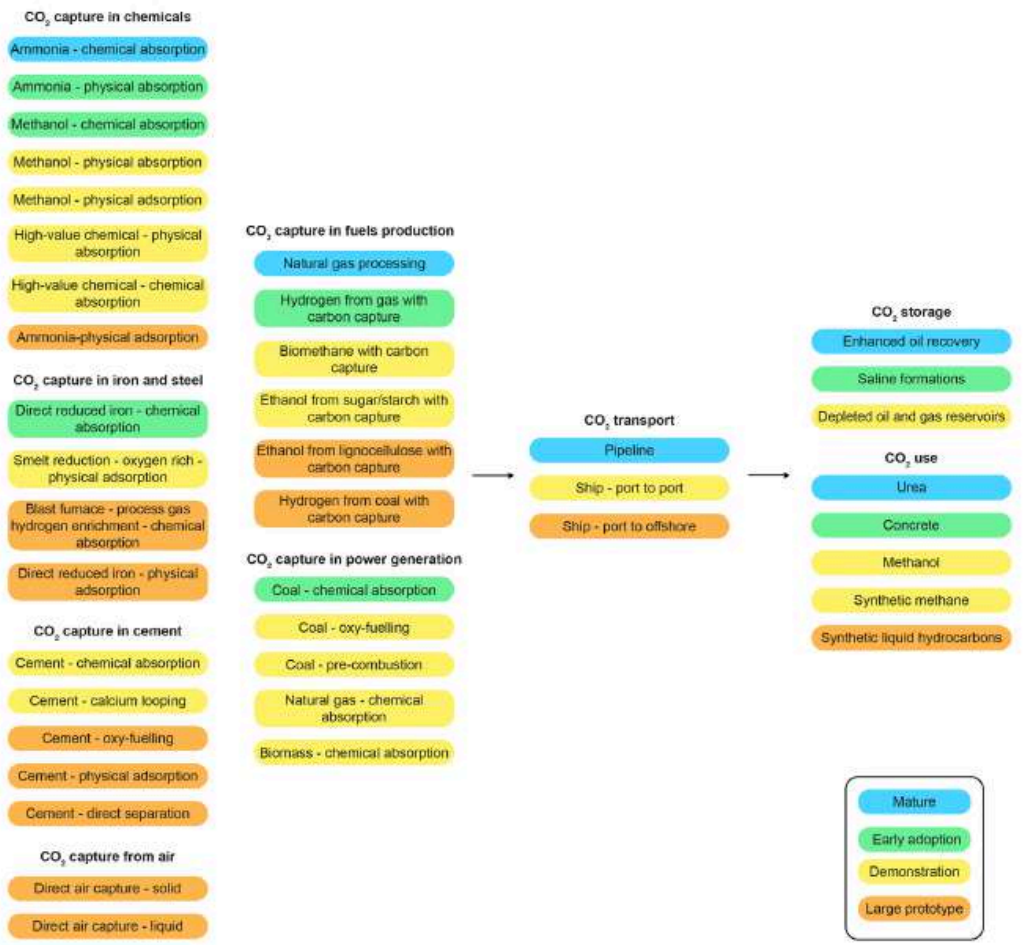
Source: Worthington, 2016

Technology readiness level of technologies along the low-carbon electricity value chain



Source: IEA, 2020

Technology readiness level of technologies along the CO2 value chain



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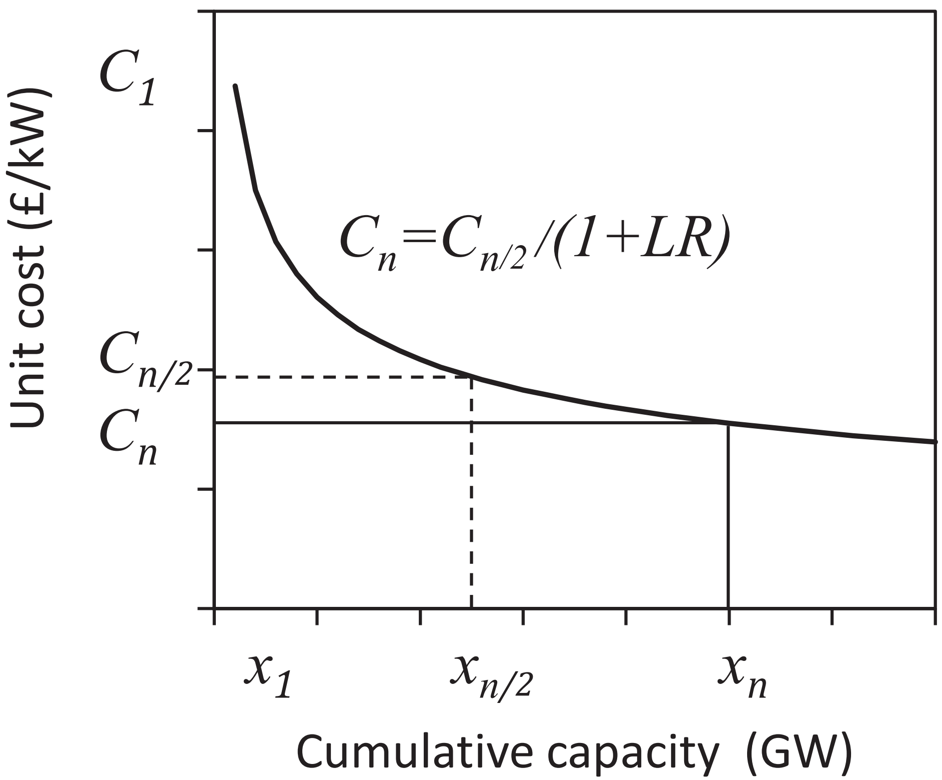
Source: IEA, 2020

- **Cost projection**

Cost learning curve model



$$C_n = C_1 x_n^{-b_{LR}}$$

$$LR = 1 - 2^{b_{LR}}$$

$$PR = 1 - LR$$

Source: Heuberger et al., 2017

Learning Curve Analytics:

- Costs (C) are observed to decline with production volume (V). From an initial cost ($C(V_0)$) and volume (V_0), we find that:

$$C(V)/C(V_0) = (V/V_0)^b$$

Increase production by a factor of two, then the cost declines by:

Progress ratio, R =

$$= C(2V_0)/C(V_0) = (2V_0/V_0)^b = 2^b$$

R is typically 70% to 90% across a wide range of technologies

R= Progress ratio = PR

Table 5 Cost estimations conducted based on different power plants*

Base Power Plant studied	Location	Conclusions
300 MW pulverized coal-fired [9]	Australia	If the carbon price is zero, this integration will be feasible when the solar field price goes below US$ 100/m^2.
520 MW coal-fired [8]	Australia China US	In order to achieve lower cost of electricity and lower cost of CO_2 avoidance, the price of solar collector should be lower than US$ 150/m^2 (solar trough) and US$ 90/m^2 (vacuum tube).
600 MW coal-fired [37]	China	The COAs are 25.8 US$/ton-$CO_2$ for a simple SAPG plant and 10.8 US$/ton-$CO_2$ for a Solar-Aided-CCS plant.
300 MW coal-fired [12]	China	Solar aided post combustion CO_2 capture yields higher generation than ordinary post combustion CO_2 capture (2126 GWh and 1996 GWh), solving about 200 GWh energy penalty.

These results come from simulations, not from real projects.

Table 8 Cost and CO_2 modelling results from IECM

Plant Type	MW Gross	MW Net	LCOE (US$/MWh)	CCS	CCS Energy Use (MW)	Cost of CO_2 Control (US$/MWh)	CO_2 emissions intensity (kg/MWh)
PC	758	690	130.33	None	0	0	952.7
IGCC	1,153	690	211.03	None	0	0	1,371.6
PC	675	515	223.05	Amine	228.78	45.06	140.6
IGCC	1,121	515	327.38	Sour Shift and Selexol	83.88	75.82	114.6

Source : UNECE

Table 4
Technology parameters related to the capacity expansion and cost learning curve model. Learning rate data can be found in [17,27,32], global capacity levels in [87–89].

Technology	2015 Capacity (GW)	Build rate (GW/year)		Learning rate (%)			Global capacity 2015 (GW)
Symbol[a]	$DIni_i$	BR_i		LR_i			–
		Low	High	Low	Nom.	High	
Nuclear	9.6	0.6	3	−6	−1	6	385
Coal	21	0	0	6	8.3	12	1647
IGCC	0	0.25	0.5	3	9.25	16	7.6
CCGT	31.5	0.9	4.5	−1	14	34	1296
OCGT	4	0.5	0.5		15		
Coal-CCS	0	0.25	0.5	1	5.5	10	0.11
CCGT-CCS	0	0.375	0.75	2	4.5	7	0
BECCS	0	0.25	0.5	0	1.1	24	0
Wind-Onshore	10	1	2	−1	12	32	421
Wind-Offshore	5	1	2	5	12	19	12
Solar	9.5	1	3	10	23	47	200
InterImp	3	1	2		38		195[b]
InterSto	1	1	2		38		
PHSto	3	0.6	1.5		1.4		1055
GenSto	0	0.5	0.5		19		0.7
Totals	97.6	9.225	23.25		–		5219.4

[a] Referring to the nomenclature in the model formulation in Section 3.
[b] Global capacity installed of HVDC interconnectors (InterImp and InterSto) amounteed to 195 GW in 2012 [88].

Source: Heuberger et al., 2017

LCOE Fomula

- LCOE stands for "Levelized Cost of Electricity"
- LCOE is represents the cost per unit of energy (e.g., in USD/MWh)
- LCOE divide the discounted cost over the life cycle of a plant by the discounted energy output over the lifetime

$$LCOE = \frac{\sum_{t=1}^{n} \frac{Expenditures_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Electricity\ generated_t}{(1+i)^t}}$$

n: lifetime

t: year

i: Discount rate

- Thereby the LCOE represents the constant unit cost over the entire life cycle of a plant (i.e., lifecycle costs)
- If a plant owner is remunerated the LCOE, the plant operates exactly at the profitability threshold (NPV=0)

⇒ LCOE is a good concept to calculate Feed-in tariffs (a FIT should provide the LCOE and potentially a premium)

⇒ LCOE is a good indicator to compare technologies (even with different life times)

⇒ Commonly used by policy makers, planners, researchers and investors

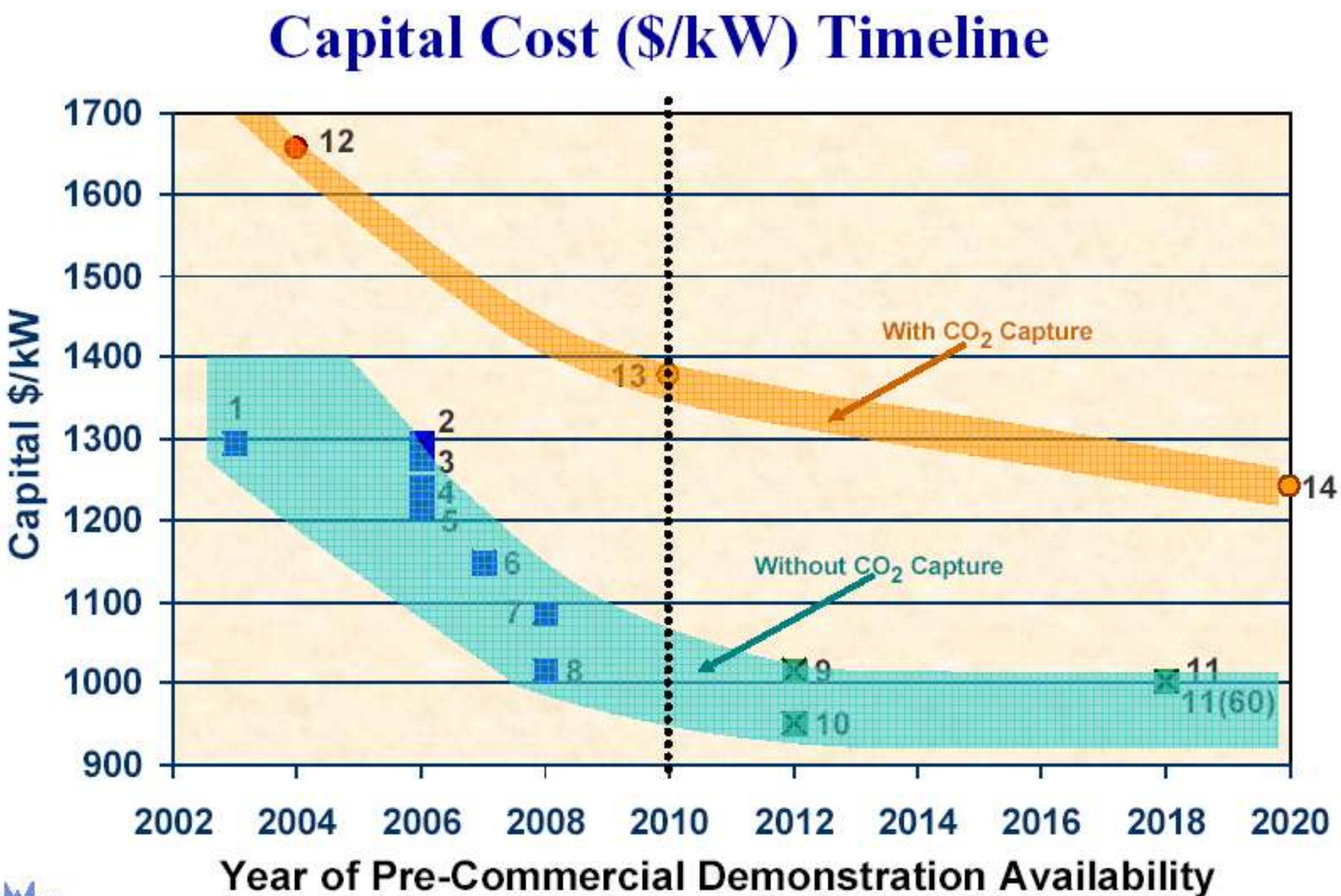
- The discount rate in LCOE represents the financing costs
- In the model we use an equity perspective, hence the formula is more complicated

$$\frac{\%\ \text{Equity Capital} * \text{Total Investment} + \sum_{\tau=1}^{T} \frac{(O\&M\ Expense)_\tau + (Debt\ Financing\ Costs)_\tau - Tax\ Rate * (Interest\ Expense_\tau + \text{Depreciation}_\tau + O\&M\ Expense_\tau)}{(1 + Cost\ of\ \text{Equity})^\tau}}{\sum_{\tau=1}^{T} \frac{Electricity\ Production_\tau * (1 - Tax\ Rate)}{(1 + Cost\ of\ \text{Equity})^\tau}}$$

Where,
% Equity Capital = portion of the investment funded by equity investors
O&M Expense = operations and maintenance expenses
Debt Financing Costs = interest & principal payments on debt
Depreciation = depreciation on fixed assets
Cost of Equity = after-tax target equity IRR

Source: UNDP 2013

IGCC – Learning curve



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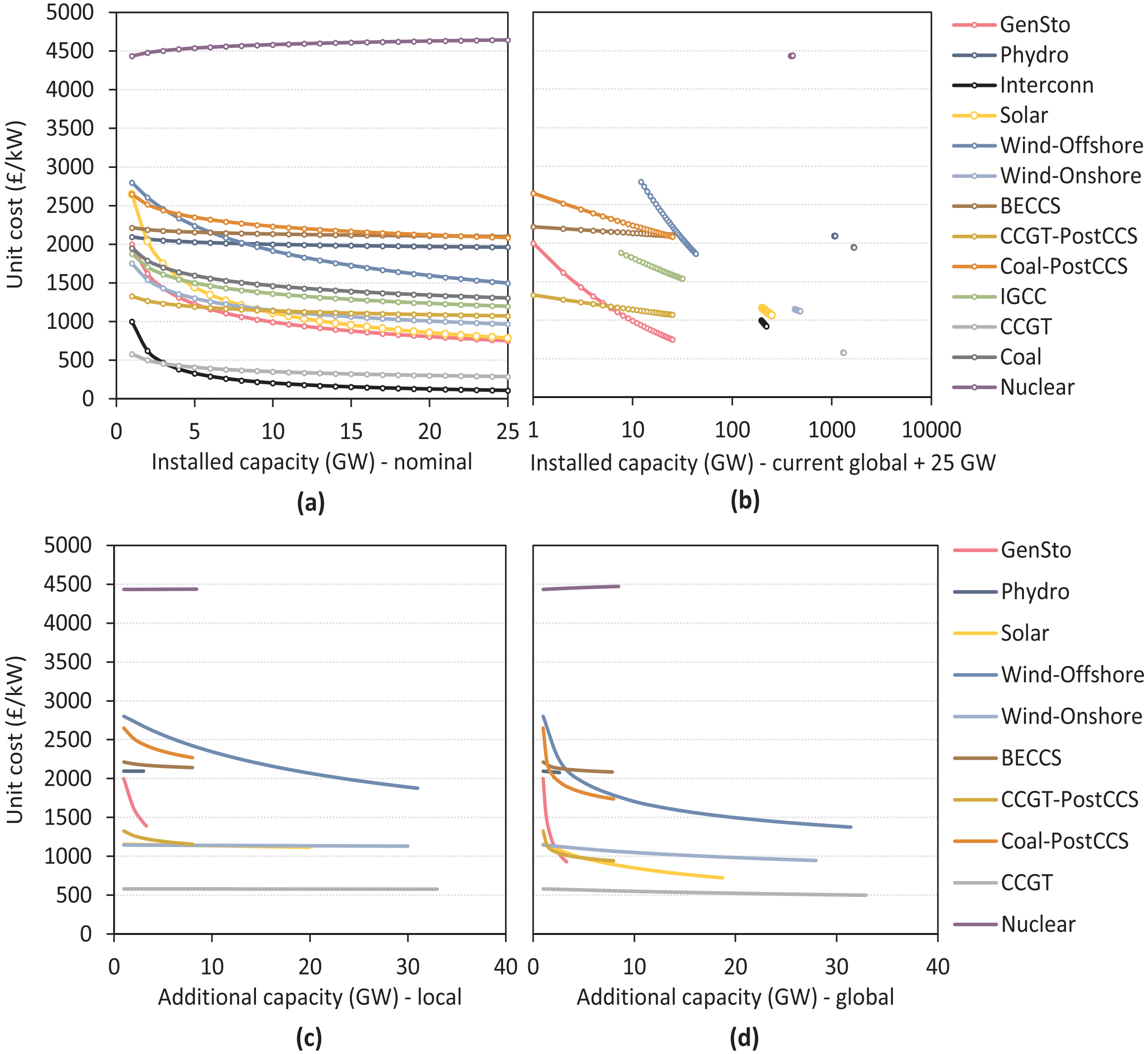

Fig. 6. Learning curves for the capital cost (CAPEX) of various power technologies; (a) illustrative curve starting at today's CAPEX and applying respective learning rates over the addition of 25 GW; (b) as (a) but starting at the global level of installed capacity in 2015; (c) as (b) but shown for capacity additions up to 2050 on a UK-level [90]; (d) as (c) but accounting for global learning effects up to 2050 by considering expected global capacity additions [87,92] converted to UK-equivalent capacity additions.

Source: Heuberger et al., 2017

Power generation technologies

Table 2.4 *continued*

	Investment cost [$/kW$_e$]	FIXOM [$/kW$_e$]	VAROM [$/kWh]	Efficiency [%]	Capacity factor	Life	Start year	Peak contribution
Gas engine	700	25	0.001	0.36	0.65	15	2000	1
Micro gas turbine	800			0.30	0.9	10	2005	1
Gas turbine, large	390	12	0.0025	0.33	0.9	25	2000	1
Gas-fired conventional	810	21	0.002	0.47	0.85	30	2000	1
Gas Combined Cycle (CC)	510	10	0.002	0.55	0.8	25	2000	1
Gas Combined Cycle (CC) 2010	510	8	0.002	0.57	0.8	25	2010	1
Gas Combined Cycle (CC) 2020	510	8	0.002	0.59	0.8	25	2020	1
Gas Combined Cycle (CC) 2030	510	7	0.002	0.61	0.8	25	2030	1
Gas engine CHP	900	30	0.0025	0.36 electric 0.885 total	0.45	15	2000	1
Gas turbine CHP	590	20	0.0025	0.36 electric 0.80 total	0.8	25	2000	1
Gas CC SOFC CHP	1300	55	0.005	0.55 electric 0.80 total	0.8	25	2020	0.8
Gas CC CHP	540	11	0.003	0.43 electric 0.80 total	0.8	25	2000	1
Diesel engine	362	2.4	0.001	0.38	0.68	15	2000	0.9
Oil-fired conventional	825	20	0.001	0.45	0.75	30	2000	1
Oil IGCC	1220	30	0.002	0.47	0.75	25	2005	1
Coal-fired conventional	1125	35	0.002	0.38	0.75	30	2000	1
Coal supercritical	1250	37	0.002	0.42	0.75	30	2005	1
Coal ultra supercritical	1260	37	0.002	0.44	0.75	30	2005	1
Fluidised Bed Combustion (FBC)	900	27	0.002	0.37	0.80	30	2000	1
Pressurised FBC	1025	35	0.002	0.42	0.80	30	2000	1
Integrated Gasification Combined Cycle (IGCC)	1315	28	0.008	0.43	0.80	30	2000	1

Source: IEA, 2003

Power generation technologies

Table 2.4 *continued*

	Investment cost [$/kW$_e$]	FIXOM [$/kW$_e$]	VAROM [$/kWh]	Efficiency [%]	Capacity factor	Life	Start year	Peak contribution
Integrated Gasification Combined Cycle (IGCC) 2010	1315	25	0.007	0.45	0.80	30	2000	1
Integrated Gasification Combined Cycle (IGCC) 2020	1315	22	0.006	0.49	0.80	30	2000	1
Integrated Gasification Combined Cycle (IGCC) 2030	1315	20	0.005	0.52	0.80	30	2000	1
IGCC Solid Oxide Fuel Cell (SOFC)	1790	50	0.01	0.55	0.75	25	2020	1
Steam turbine Coal CHP	1100	50	0.001	0.35 electric 0.80 total	0.85	25	2000	1
FBC CHP	1850	110	0.0025	0.25 electric 0.80 total	0.80	30	2000	1
IGCC CHP	1710	36	0.01	0.40 electric 0.75 total	0.75	25	2010	1
IGCC SOFC CHP	2250	54	0.015	0.45 electric 0.75 total	0.75	25	2020	1
Solid waste incineration	7000	67	0.01	0.25	0.75	30	2000	1
Biomass fired conventional	1600	43	0.002	0.38	0.75	30	2000	1
Stirling engine with gasifier	2700		0.004	0.20	0.6	15	2005	1
Biomass IGCC	1900		0.015	0.35	0.75	25	2010	1
Bio oil (HTU) CC	640	30	0.015	0.52	0.75	25	2005	1
Biomass gasification CHP	2050	200	0.02	0.40 electric 0.70 total	0.75	25	2010	1
Tomlinson +Bark boiler	2960	62	0.006	0.08 electric 0.48 total	0.75	25	2000	0.8
Indirect Black Liquor GCC + bark boiler	1300	25	0.003	0.18 electric 0.53 total	0.75	25	2000	0.8
Ind Bl Liq GCC + bark GCC	1430	52	0.003	0.17 electric 0.37 total	0.75	25	2000	0.8

nd – data is missing

Source: IEA, 2003

Power generation technologies

Table 2.7 *Technical and economical data for electricity production technologies with CO_2 capture*

	Investment [cost $/kW$_e$]	FIXOM [$/kW$_e$]	VAROM [$/kWh]	Efficiency [%]	Capacity factor	Life	Start year	Peak contribution	CO_2 removed [%]
IGCC with flue gas capture	2700		0.012	0.39	0.80	30	2010	1	85
IGCC with input fuel capture (Selexol)	1730	28	0.011	0.36 (2010) 0.48 (2040)	0.80	30	2010	1	88
Conventional advanced coal with flue gas capture	2040		0.007	0.35 (2000) 0.40 (2020)	0.80	30	2010	1	90
Retrofit of existing conventional coal with flue gas capture	817		0.002	-9% (2000) -4% (2020)	0.80	30	2010	1	90
IGCC SOFC with capture	2500	100	0.02	0.51	0.75	25	2020	1	95
NGCC with flue gas capture	1120	10	0.005	0.47 (2010) 0.52 (2030)	0.75	25	2010	1	89
Nat gas Fuel cell with capture	1500	75	0.015	0.60	0.75	25	2010	1	95
Industrial HT gas turbine CHP with CO_2 capture	1185	22	0.08	0.35 electric 0.80 total	0.85	25	2010	0.3	90

Source: IEA, 2003

Thank you