Toward US/China Collaboration to Get the Faltering Global CO_2 Capture and Storage Enterprise Back on Track

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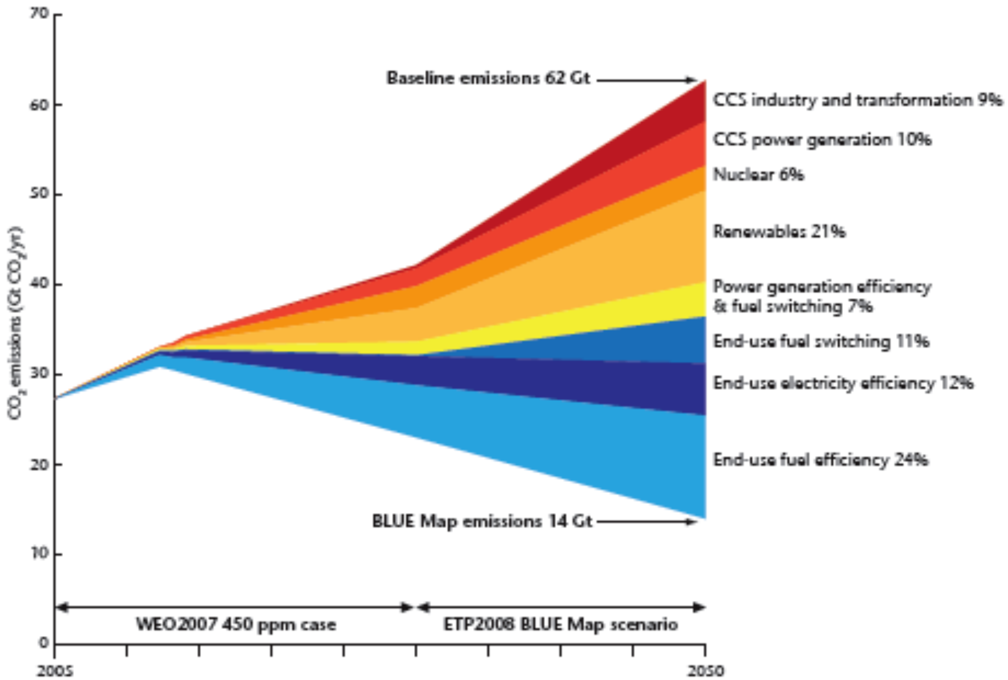
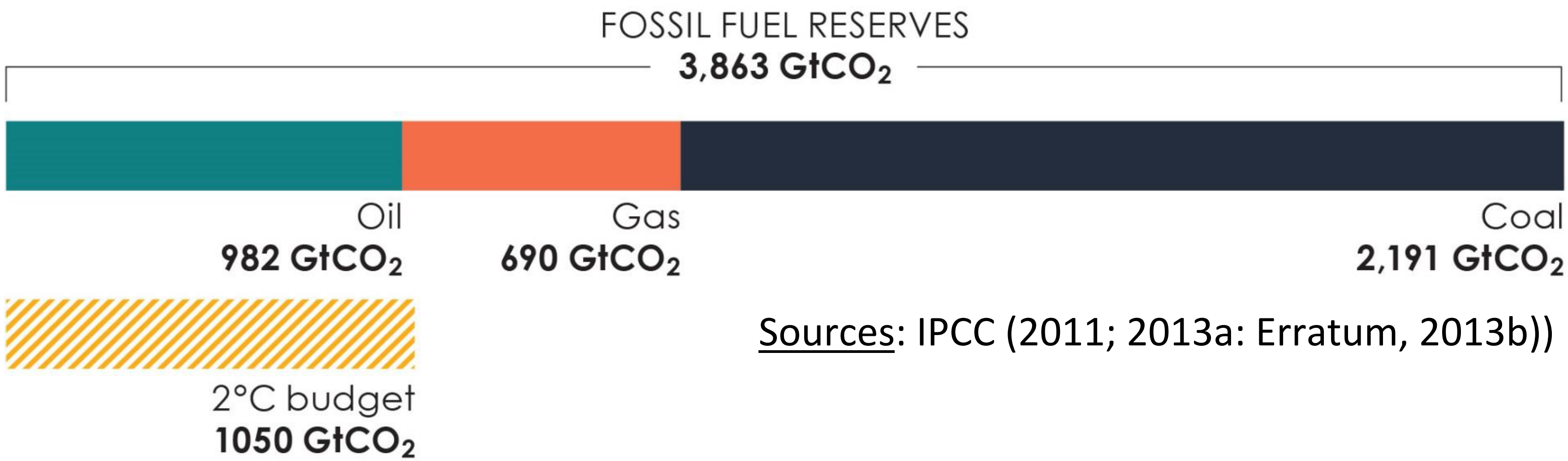
CCS Role in Global C Mitigation



In its *Energy Technology Perspectives 2008* report (IEA, 2008) the IEA showed how a 50% reduction in CO_2 emissions by 2050 might be realized in enable a 2DS future for global energy

- Distribution of effort:
  - 54% energy efficiency improvement/fuel switching
  - 21% renewables
  - 19% CCS
  - 6% nuclear
- CCS in 2050: 10 Gt CO_2 stored/y (⅓ of 2010 emissions)

2DS CO_2 Budget = 1 Trillion Tonnes ➔ CCS Urgently Needed



<u>Sources</u>: IPCC (2011; 2013a: Erratum, 2013b))

- w/o CCS it will be difficult (**if not impossible!**) to meet 2 °C target
- Geological CO_2 storage capacity not likely a major constraint on CCS in this century
- Coal/gas reserve exploitation via making electricity and H_2 w/CCS
- Oil reserve exploitation via BECCS* offsets (e.g., BIGCC-CCS, BTL-CCS)

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* BECCS ≡ Biomass energy with CO_2 capture and storage (CCS)

Without CCS, Coal Power Projects in non-OECD Asia Alone Will Use Up ~ ½ of Global C Budget

Coal Power Plant Capacity in non-OECD Asia at end of 2013, GW_e				
Country	Operating	UC	Planned	UC + Planned
China	805	117	381	499
India	151	106	304	409
Other	66	33	111	144
Total	1023	256	796	1052

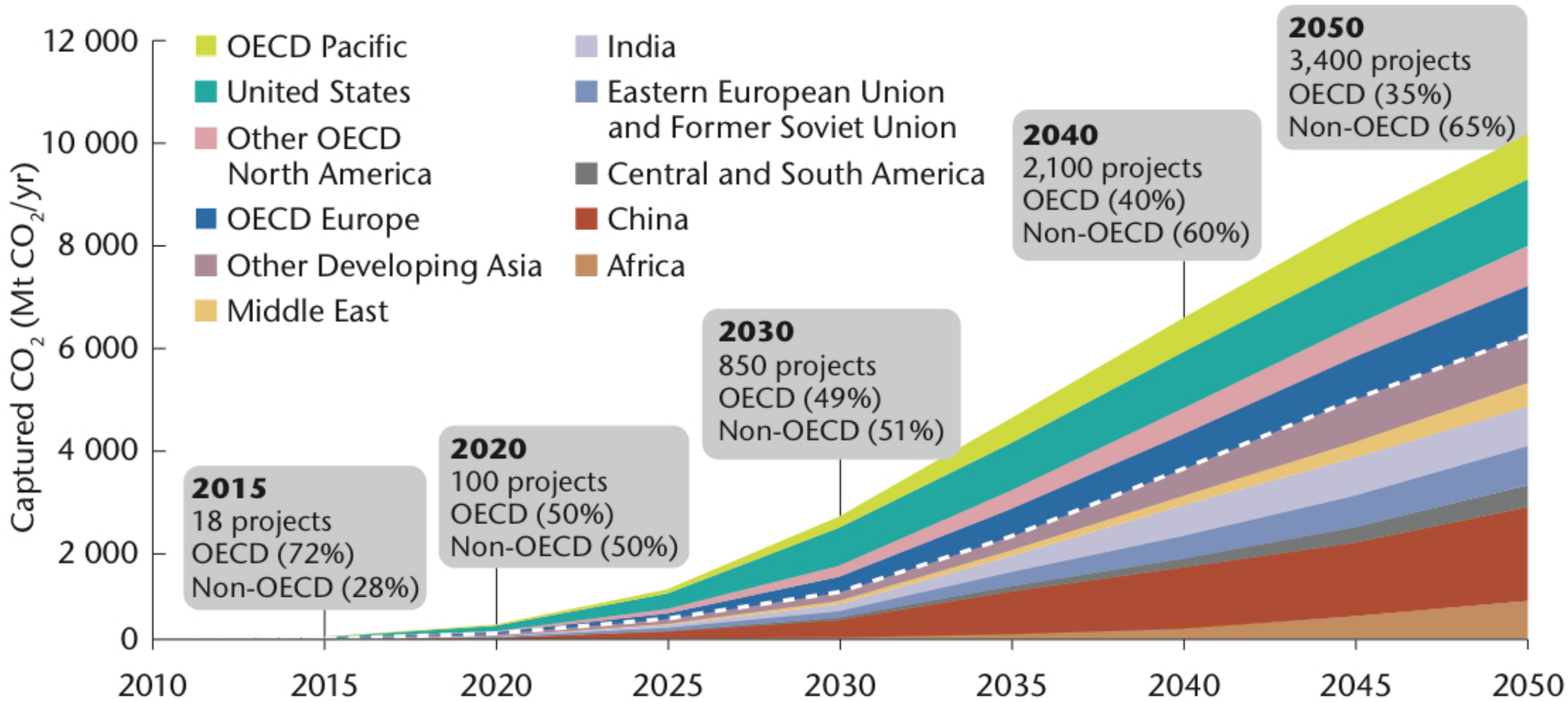
UC ≡ Under Construction

- Suppose that: (a) coal capacity built before 1990 continues to operate for 10 years, (b) capacity built during 1990-2010 continues to operate on average for more 25 years, and (c) capacity built after 2010 operates for 50 more years.
- Suppose also that all plants are supercritical units.
- Under these conditions the re-maining committed GHG emissions for the coal capacity indicated on the left is ~ 500 Gt CO_{2e}

CO_2 STORAGE OPTIONS

- Goal: store 100s to 1000s of Gt CO_2 for 100s -1000s of years
- CO_2 storage options
  - Deep ocean (*concerns about storage effectiveness, environmental impacts, legal issues, difficult access*)
  - Carbonate rocks [*100% safe, costly (huge rock volumes), long-term option*]
  - Geological media
    - **Enhanced oil recovery—CCS market-launch opportunity (huge in US)**
    - Depleted oil and gas fields (*geographically limited*)
    - **Deep saline formations located in sedimentary basins**
      - Huge potential, ubiquitous (*at least 800 m down*)
      - Such formations underly land area ≡ ½ area of inhabited continents (*2/3 onshore, 1/3 offshore*)

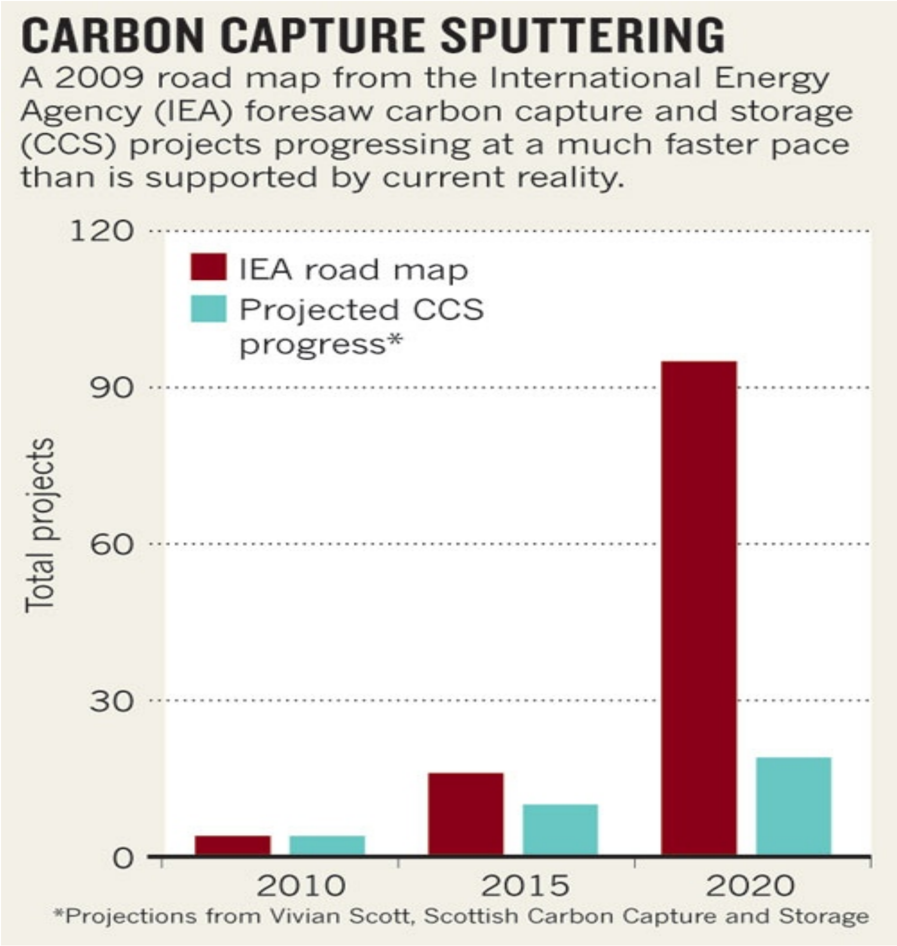
CCS Deployment Pace Goal for CCS (IEA, 2009)



Note: The dashed line indicates separation of OECD/non-OECD groupings.

- To meet 2050 goal IEA pointed out that CCS should be ready to be deployed routinely for new power systems post-2020
- To be on track IEA 2009 “CCS Roadmap” showed that ~ 100 commercial-scale integrated CCS demonstration projects should be operational by 2020

“Global CCS Enterprise” Not “On Track”



Why?

- **High cost of early-mover projects**
- Low natural gas price (US)
- Public hostility to CCS (EU)
- Public apathy about climate change
- Political antipathy to C-mitigation

Source: van Noorden (2013).

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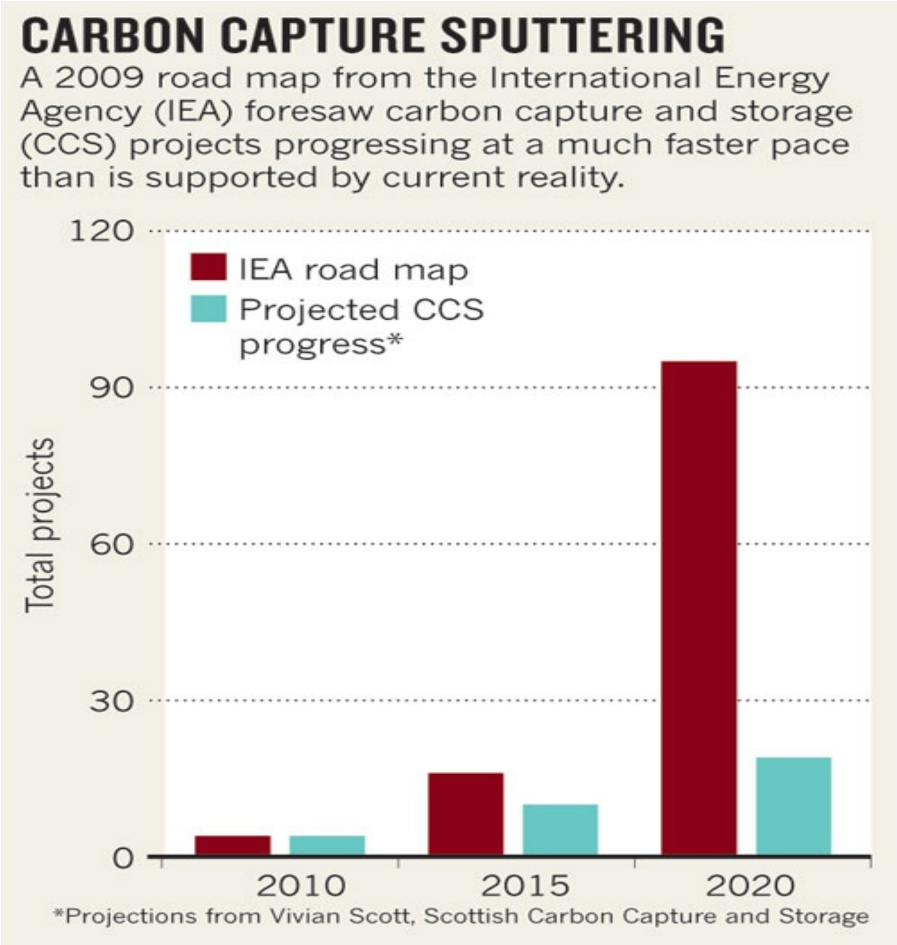

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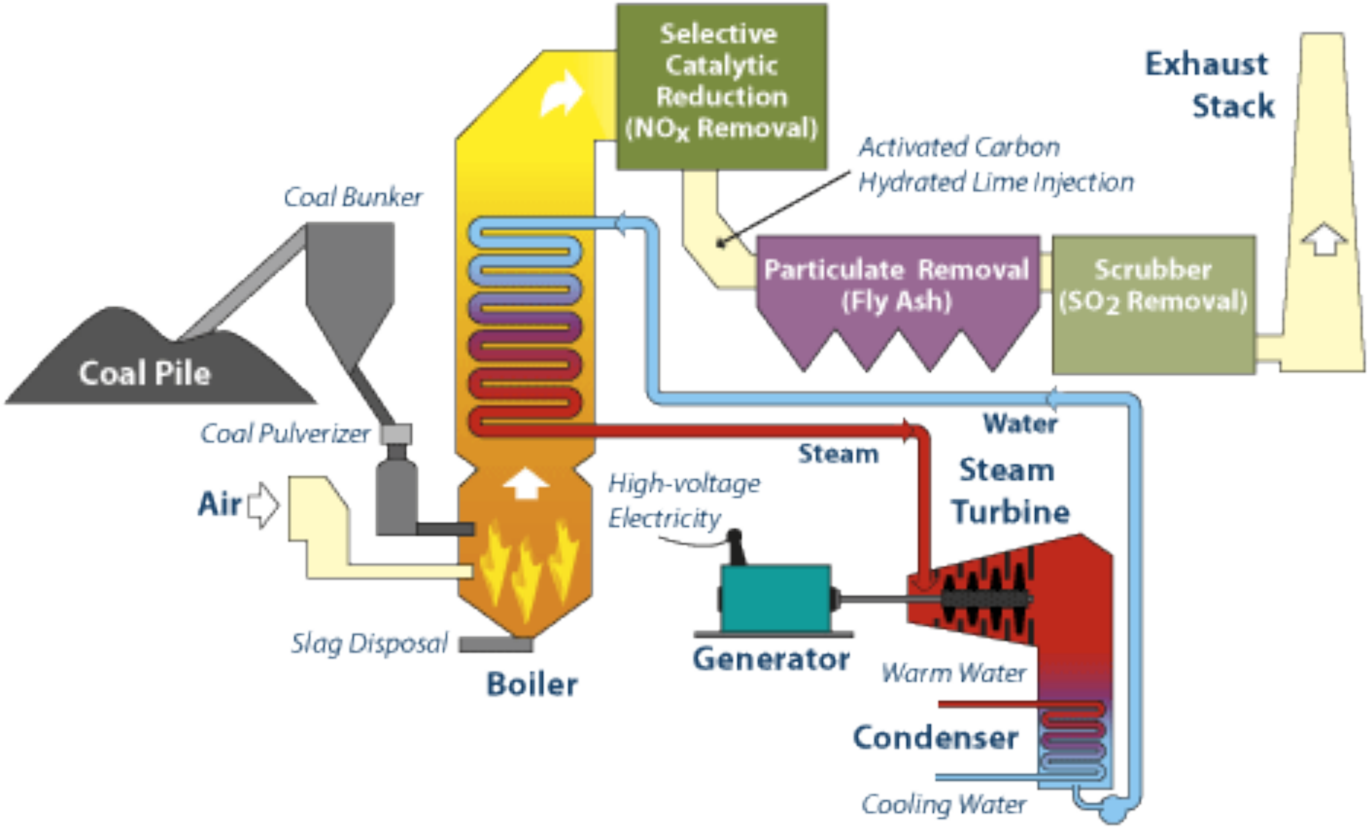
But the situation is far from hopeless!

The World's First Coal Power Plants with CCS Will Come on Line by the End of this Year

- 110 MW_e Boundary Dam Project (Canada)
  - Retrofit post-combustion capture for refurbished pulverized coal power plant (PC-CCS retrofit)
  - Captured CO_2 sold for enhanced oil recovery (EOR)
- 582 MW_e Kemper County Project (Mississippi)
  - Pre-combustion capture for new integrated gasifier combined cycle power plant (new IGCC-CCS)
  - Captured CO_2 sold for EOR

Existing Pulverized Coal Steam Power Plant (PC-V)



- In 2012 US had 307 GW_e of coal electric power capacity (30% of US generating capacity but 39% of US electricity generation)
- Average efficiency in 2012 = 32.3%
- CO_2 concentration in flue gases ~ 15% **(partial pressure = 0.15 atmosphere)**

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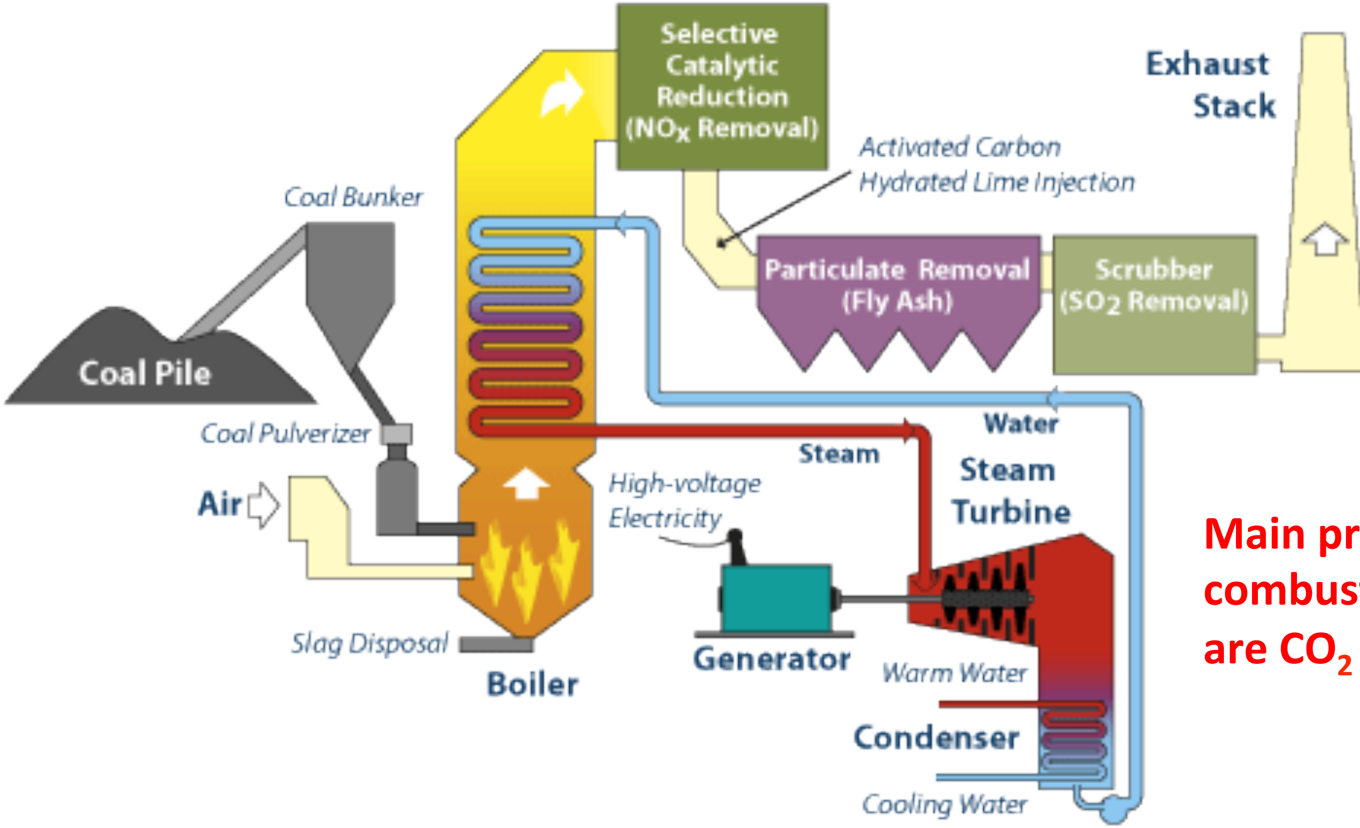

Main products of coal combustion (oxidation) are CO_2 and H_2O

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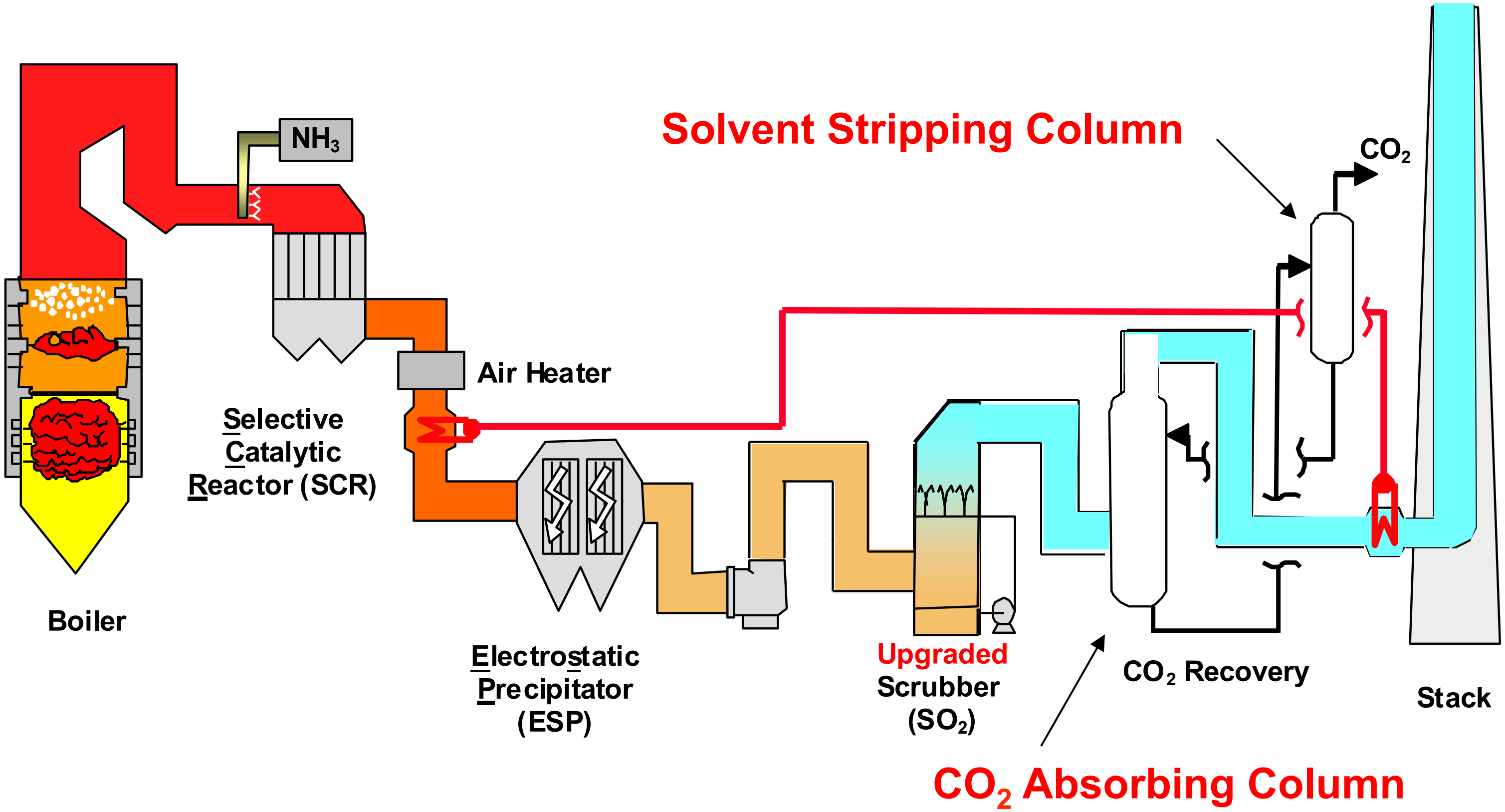
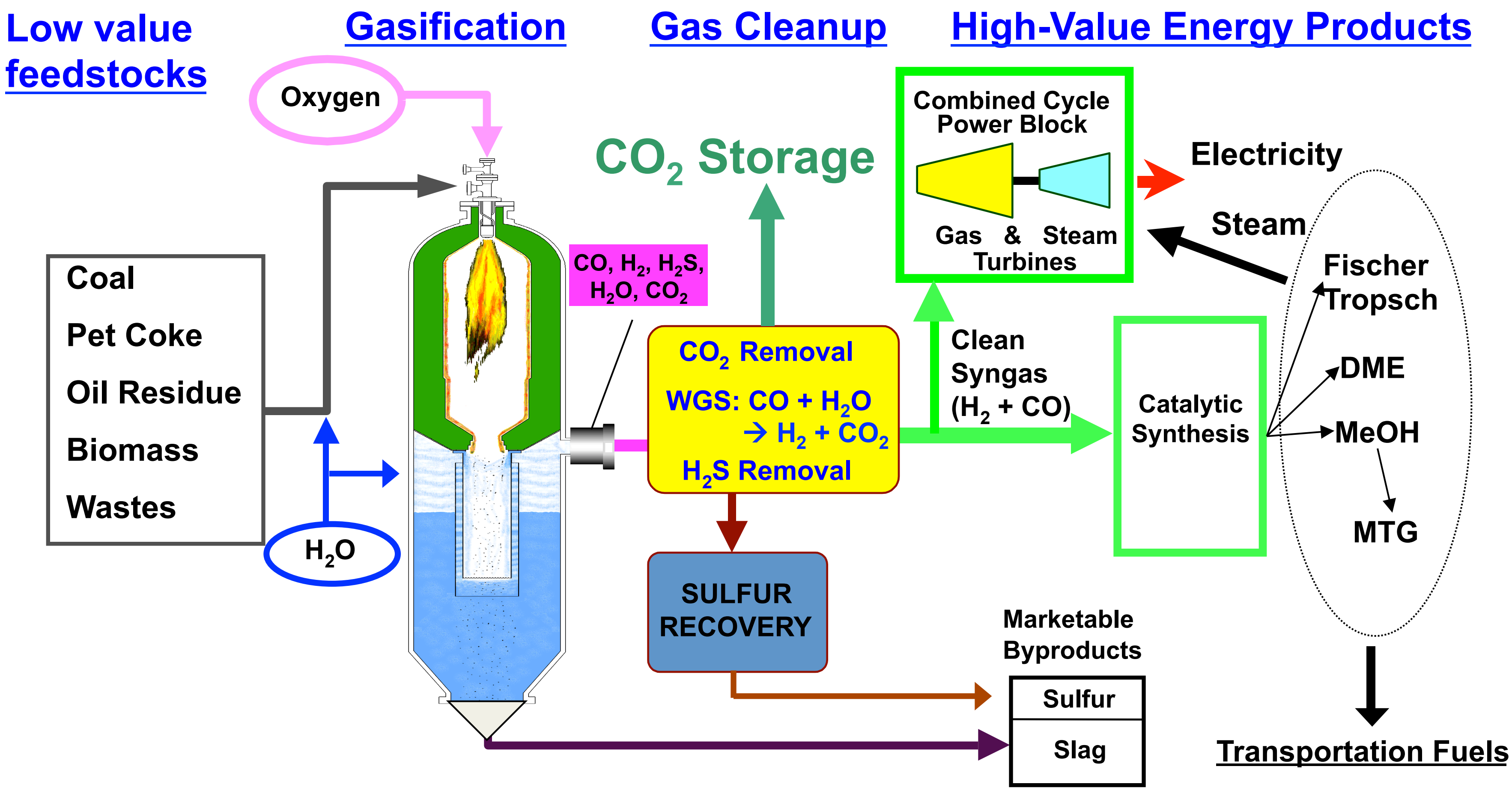
Post-Combustion Capture System for Pulverized Coal Steam Power Plant with CCS (PC-CCS retrofit)



- Strong **chemical** (amine) solvent used to extract CO_2 in **absorber** and bind it
- Large amount of steam required to release CO_2 from solvent in **stripper**
- For this (and other) capture options, captured CO_2 must be compressed (typically to ~ 150 atmospheres) for pipeline transport to storage site
- High energy penalty for CO_2 capture (loss of ~ 24% of electricity output)

Boundary Dam CCS Plant In Canada

Gasification-Based Electricity and/or Fuels Production



- Precombustion capture → lower energy penalty than for post-combustion
- Ultra-low emissions of SO_2, NO_x, PM, Hg at low incremental cost
- Reduced H_2O requirements
- Reduced solid waste management problems
- Flexibility: Can make electricity, fuels, or **combinations** thereof

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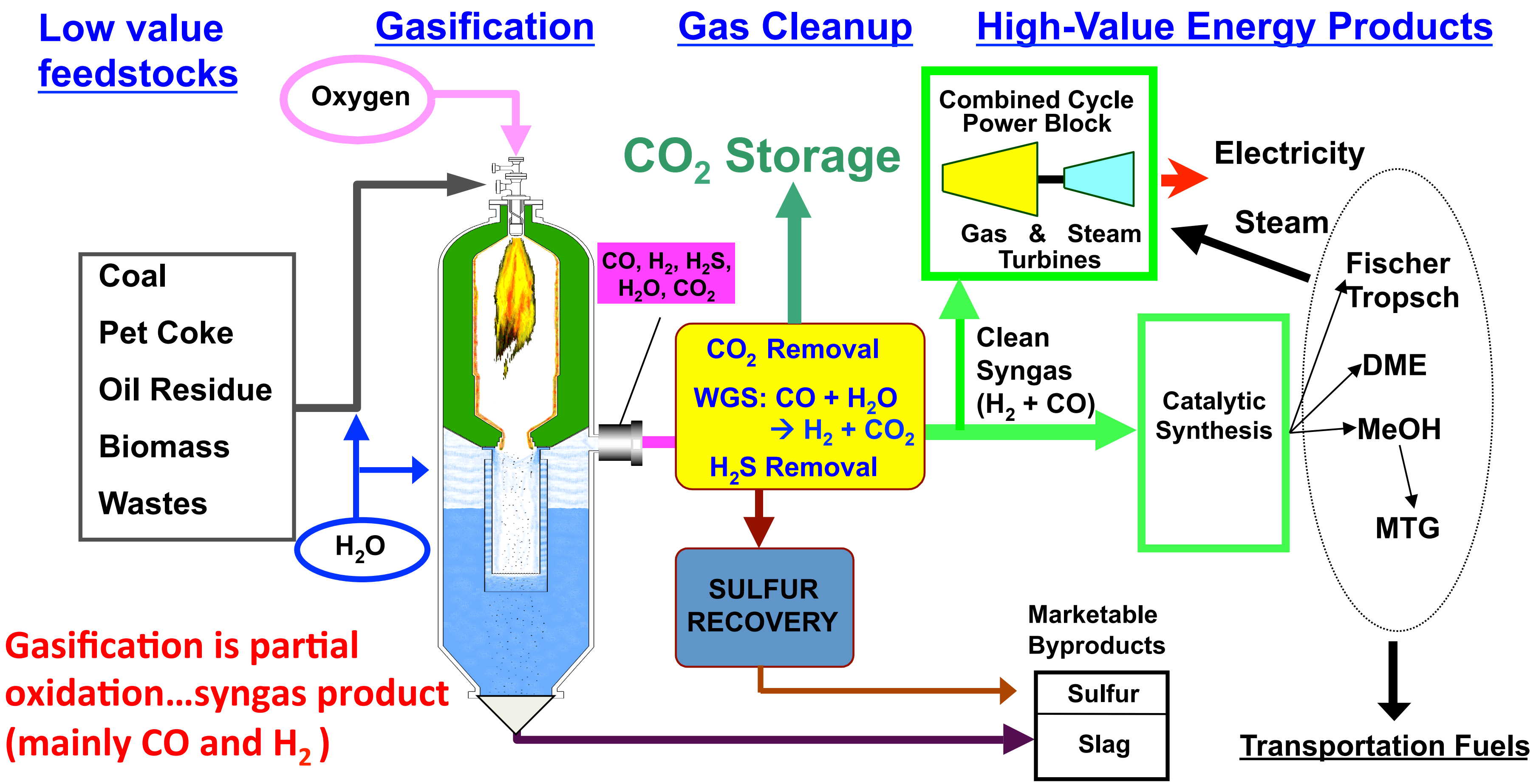

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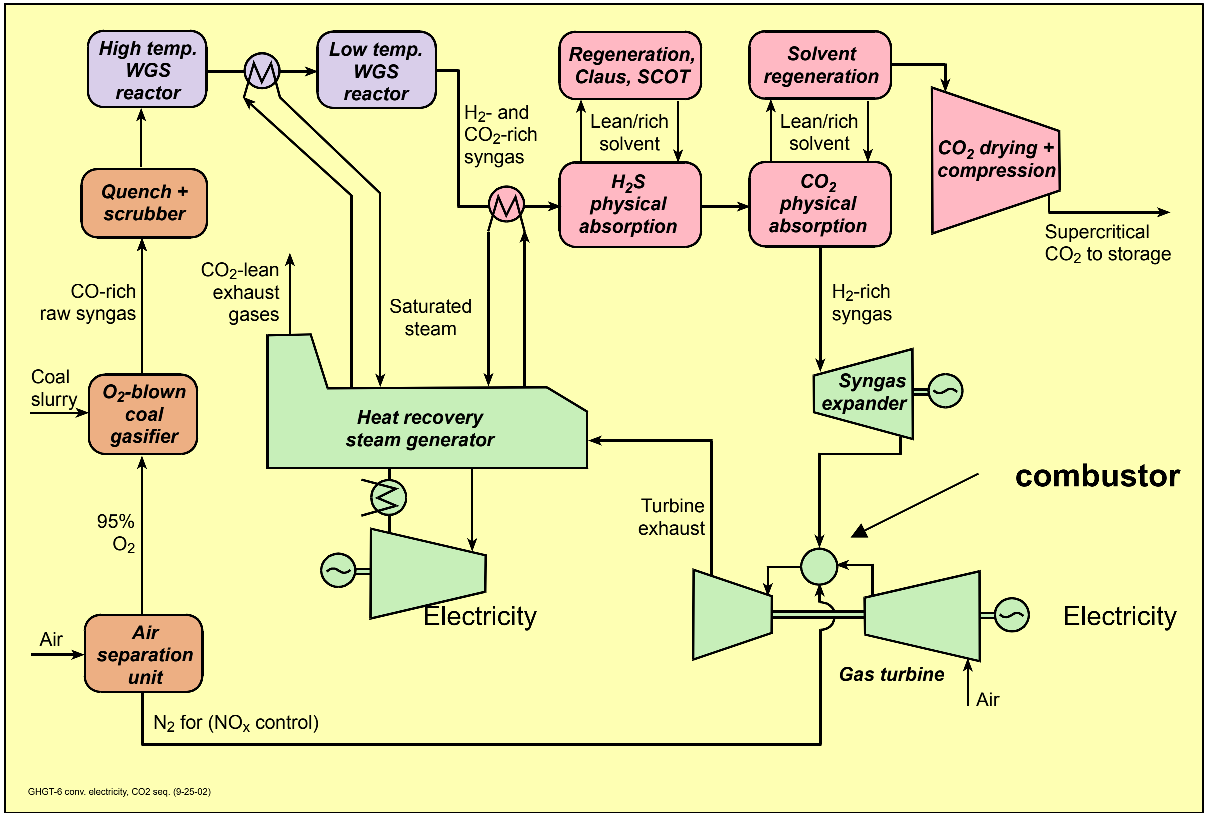
Coal Integrated Gasifier Combined Cycle, Carbon Capture and Storage (IGCC-CCS)



Water gas shift (WGS) reaction:

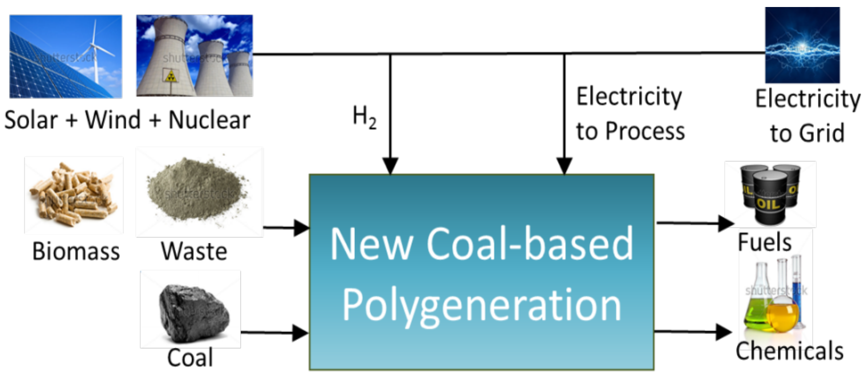
$$CO + H_2O \rightarrow CO_2 + H_2$$

- WGS reaction converts gasification-derived “syngas” into primarily H_2 (burned for power) and CO_2 (separated for underground storage)
- Pre-combustion capture at high CO_2 partial pressure (~ 10 atmospheres) ➔ can use less energy-intensive **physical** solvents (lower capture energy penalty compared to post-combustion capture)

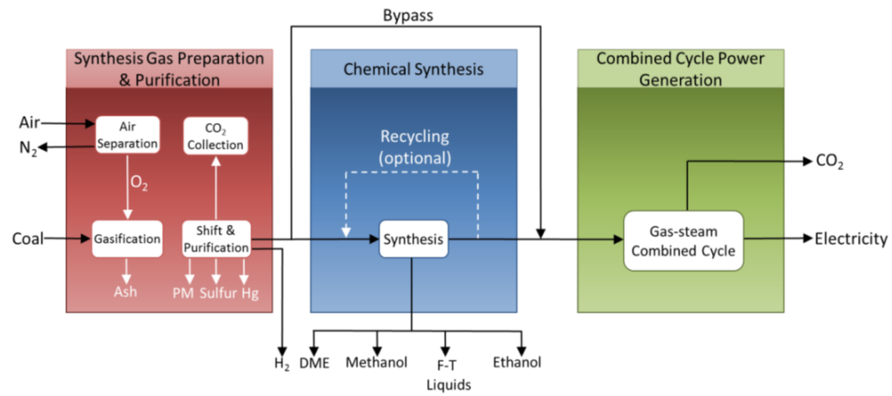
Partially Completed Kemper County IGCC-CCS Project in Mississippi

Vision for Future Coal of Dr. ZHANG Yuzhuo (President and CEO of the Shenhua Group)

Framework for coal-new energy polyproduction



Polyproduction based on coal gasification



"Clean coal conversion can lead to the realization of the transformation from high carbon, to low carbon, to carbon free coal utilization with broad prospects for technological and commercial markets in the future."

ZHANG, Yuzhuo, 2013: "Clean Coal Conversion: Road to Clean and Efficient Utilization of Coal Resources in China," *Cornerstone*, **1** (3): 4-10. This article can be accessed at http://cornerstonemag.net/clean-coal-conversion-road-to-clean-and-efficient-utilization-of-coal-resources-in-china/

Catalytic Synthesis of Fuels from Syngas

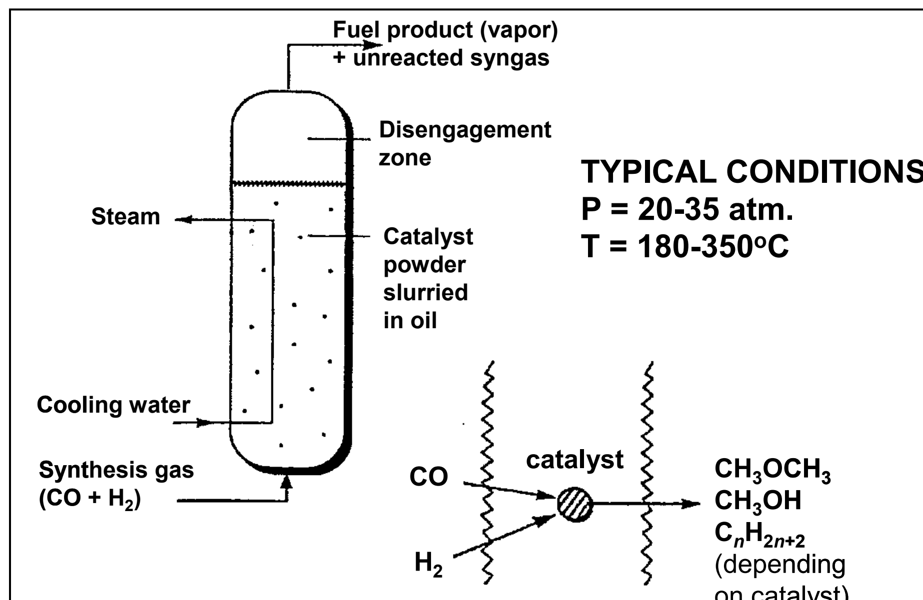
- **Basic overall reactions**:

$CO + 2H_2$ Û $-CH_2- + H_2O$ — Fischer-Tropsch liquids (FTL)

$3CO + 3H_2$ Û $CH_3OCH_3 + CO_2$ — Dimethyl ether (DME)

$CO + 2H_2$ Û CH_3OH — Methanol (MeOH)…can be converted to gasoline via MTG process

- **Three reactor designs**:
  - Fixed-bed (*gas phase*): low one-pass conversion, difficult heat removal
  - Fluidized-bed (*gas phase*): better conversion, more complex operation
  - Slurry-bed [*liquid phase* (*LP*)]: high single-pass conversion



Liquid Phase Reactor

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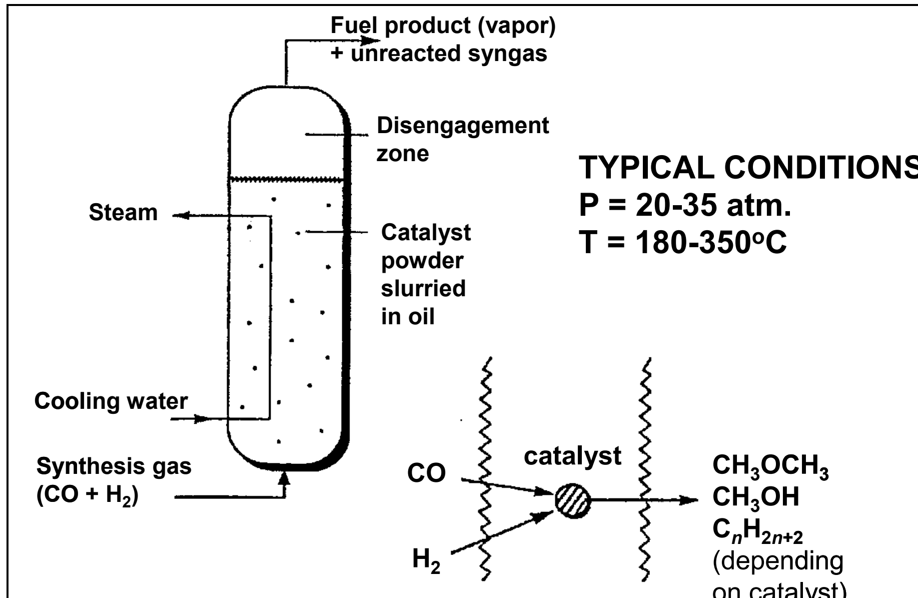


Liquid Phase Reactor

CO_2 capture costs for plants manufacturing synthetic fuels or chemicals are far lower than for power plants

Coal → SNG for $PM_{2.5}$ Air Pollution Mitigation in China

- $PM_{2.5}$ air pollution health damages from ambient air pollution—China, for 2010 (HEI, 2013; Lim et al., 2012):
  - 1.2 x 10^6 premature deaths (almost 2/5 of world total from AAP)
  - 25 x 10^6 healthy years of life lost
  - 4^{th} leading cause of premature deaths (after dietary risks, high blood pressure, tobacco smoking)
- Partial Chinese response: Make substitute natural gas (SNG) from coal to replace direct coal use in buildings, industry (sectors for which $PM_{2.5}$ emissions from coal are harder to control than at coal power plants)
- Rationale:
  - Replacing coal with SNG for heating, cooking virtually eliminates $PM_{2.5}$ air-pollution health damage concerns.
  - Gasification-based coal to SNG technology is commercially proven.
  - China has the most global experience with coal energy conversion via gasification.
- Concern: Current approach to coal → SNG is exacerbating global carbon-mitigation efforts **because CCS is not planned**

Ongoing + Planned Coal → SNG Projects, Xinjiang Province, China

Investor	Project	Capacity, 10^9 CM/y	Investor	Project	Capacity, 10^9 CM/y
Guodian Corporation	Nilka	10.0	China National Coal Group	Changji	4.0
Guanghui New Energy Co.	Yiwu	8.0	Kailuan Group	Changji	4.0
China Power Investment Co.	Qapqal, Ili	6.0	TBEA Group	Changji	4.0
China Power Investment Co.	Huocheng, Ili	6.0	Yanzhou Mining Group	Changji	4.0
Huadian Group	Changji	6.0	Guanghui New Energy Co.	Altay	4.0
Qinghua Group	Yining, Ili	5.5	Xuzhou Mining Group	Tacheng	4.0
Beikong New Energy	Qitai	4.0	Huahong Mining Co.	Changji	2.0
Henan Coal Chemical Group	Qitai	4.0	Xinwen Mining Co.	Ili	2.0
LuAn Group	Ili	4.0	Shengxin Group	Changji	1.6
China Huaneng Group	Changji	4.0	Tianlong Group	Jimusaer	1.3
Xinjiang Longyu Co.	Changji	4.0	UNIS Group	Hami	0.8
Total for 22 Ongoing and Planned SNG Projects in Xinjiang Province					**93.2**
% of Total Chinese Ongoing + Planned Coal → SNG Capacity in Xinjiang Province					**77.4**

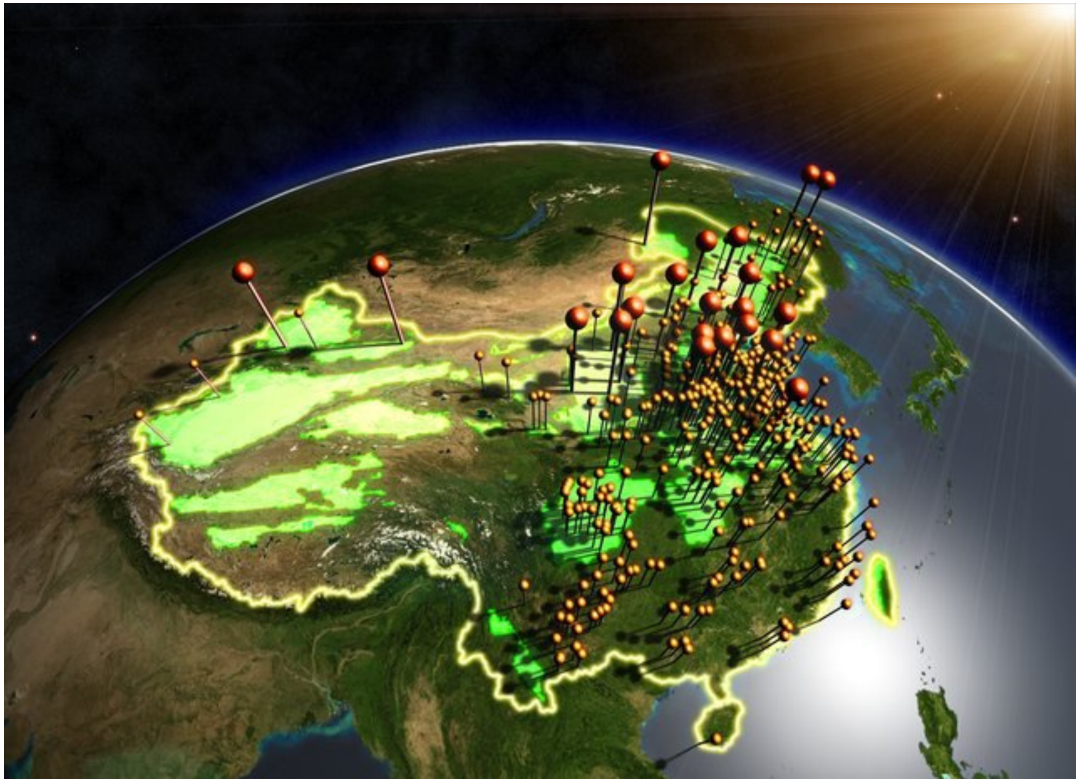
SINOPEC plan: 6000 km pipeline (22 x 10^9 USD) to transport 30 x 10^9CM/y from Xinjiang to SE China [complementing pipelines (2 existing + 1 near-finished) carrying NG from Xinjiang to East]

Ongoing + Planned Coal → SNG Projects, Other Chinese Regions

Investor	Project	Province	Capacity, 10^9 CM/y
DT International Power	Fuxin	Liaoning Province	4.0
Hongsheng New Energy	Zhangye	Gansu Province	4.0
National Ocean Oil Company	Datong	Shanxi Province	4.0
DT International Power	Hexigten Banner	Inner Mongolia	4.0
China Huaneng Group	Hulunbeier	Inner Mongolia	4.0
DT Huayin Power	Erdos	Inner Mongolia	3.6
Shenhua Group	Erdos	Inner Mongolia	2.0
Huineng Coal Power	Erdos	Inner Mongolia	1.6
Subtotal for the 8 Ongoing + Planned Coal → SNG Projects, Other Regions			**27.2**
Total for 30 Listed Ongoing + Planned Coal → SNG Projects, All China			**120.4**
% of Total Chinese Ongoing + Planned Coal → SNG Capacity in Inner Mongolia			**12.6**
% of Total Chinese Ongoing + Planned Coal → SNG Capacity in Regions Other than Xinjiang Province and Inner Mongolia			**10.0**
Production @ 90% CF for China's ongoing + planned SNG capacity, Quads/y			**3.9**
US natural gas production in 2012, Quads/y			**24.6**

As of 2013, **nine** SNG projects with a capacity of 37 x 10^9 CM/y had been approved (Yang and Jackson, 2013).

Many Low-Cost CO_2 Capture Opportunities in China



Source: ZHENG et al. (2010)

- Pins: 400 existing / planned chemical plants releasing concentrated CO_2 (low capture costs)
- Green areas: sedimentary basins where suitable storage sites might be found.
- 18 "Big Pins": plants within 10 km of deep saline formation emitting > 10^6 t/y CO_2
  ➔ many opportunities for megascale aquifer storage projects with low-cost CO_2

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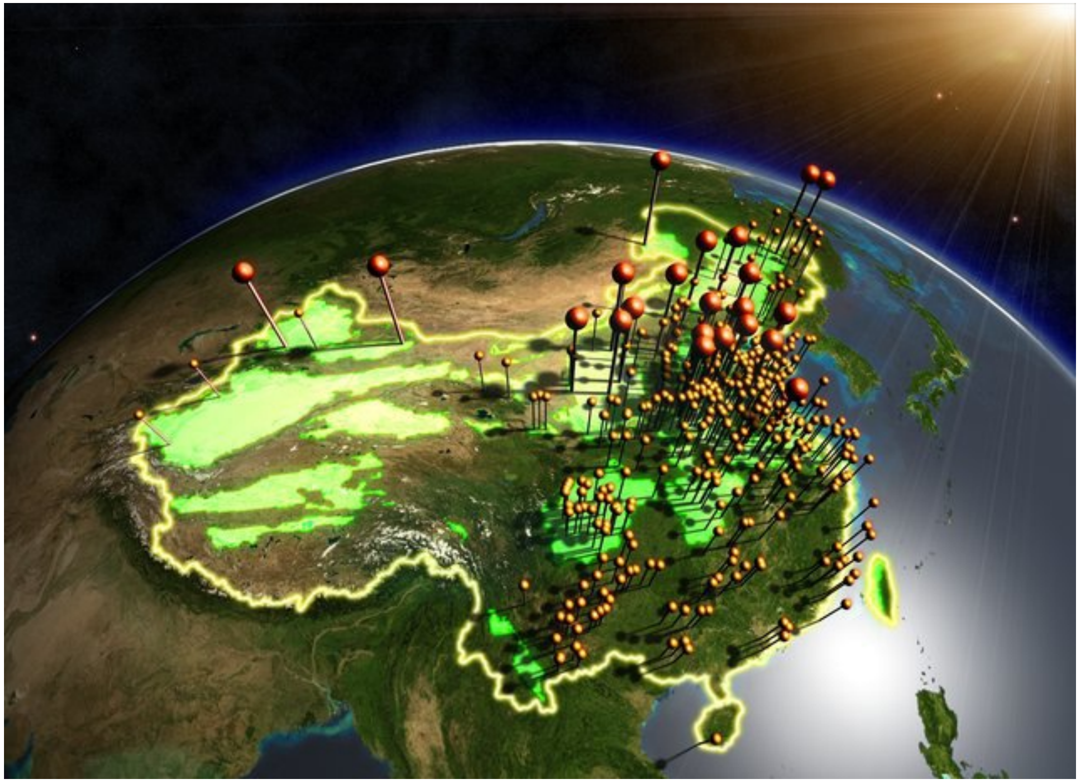

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- Pins: 400 existing / planned chemical plants releasing concentrated CO_2 (low capture costs)
- Green areas: sedimentary basins where suitable storage sites might be found. **Xin-jiang Province, where most SNG plants will be built, has large sedimentary basins.**
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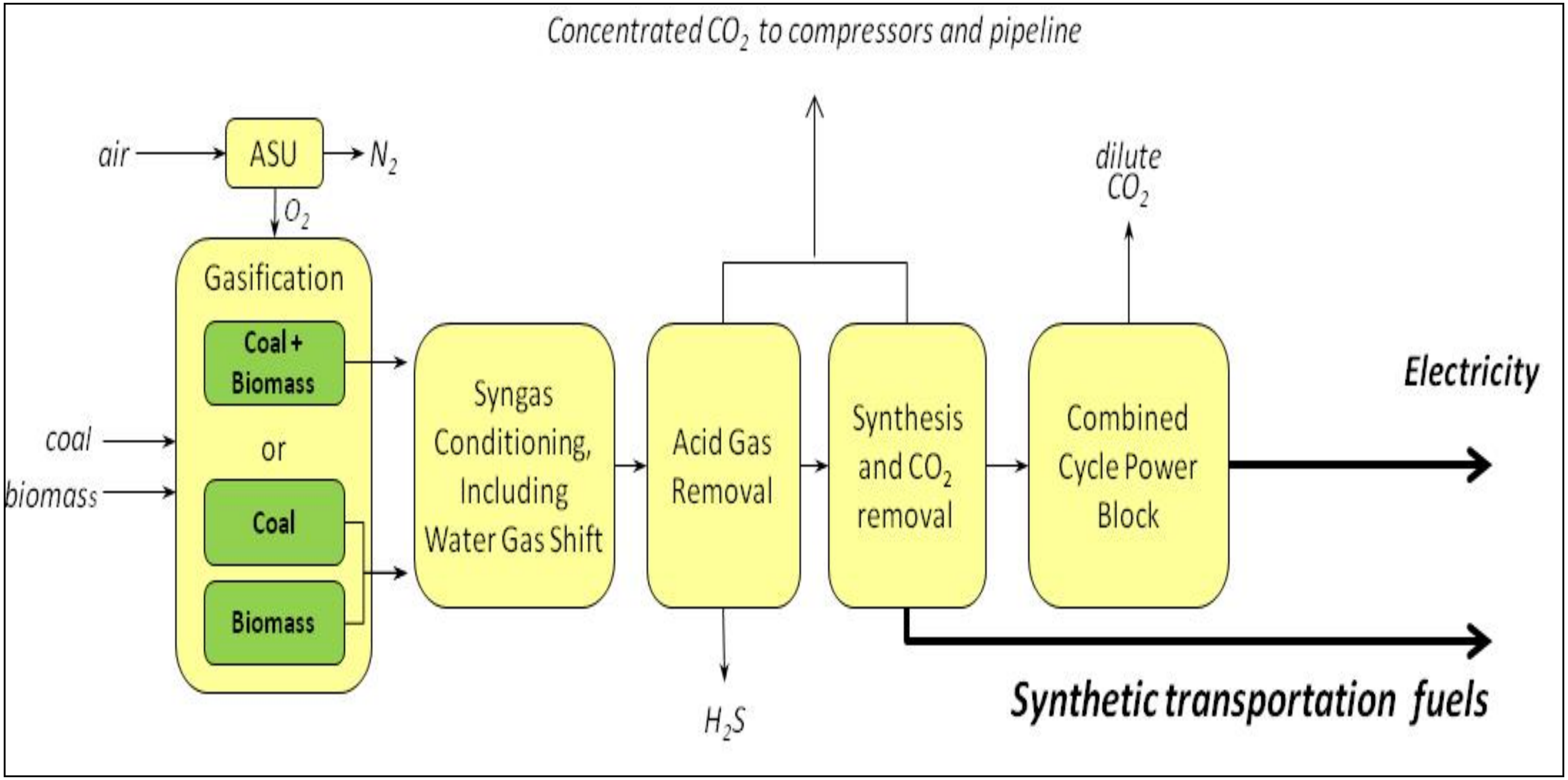
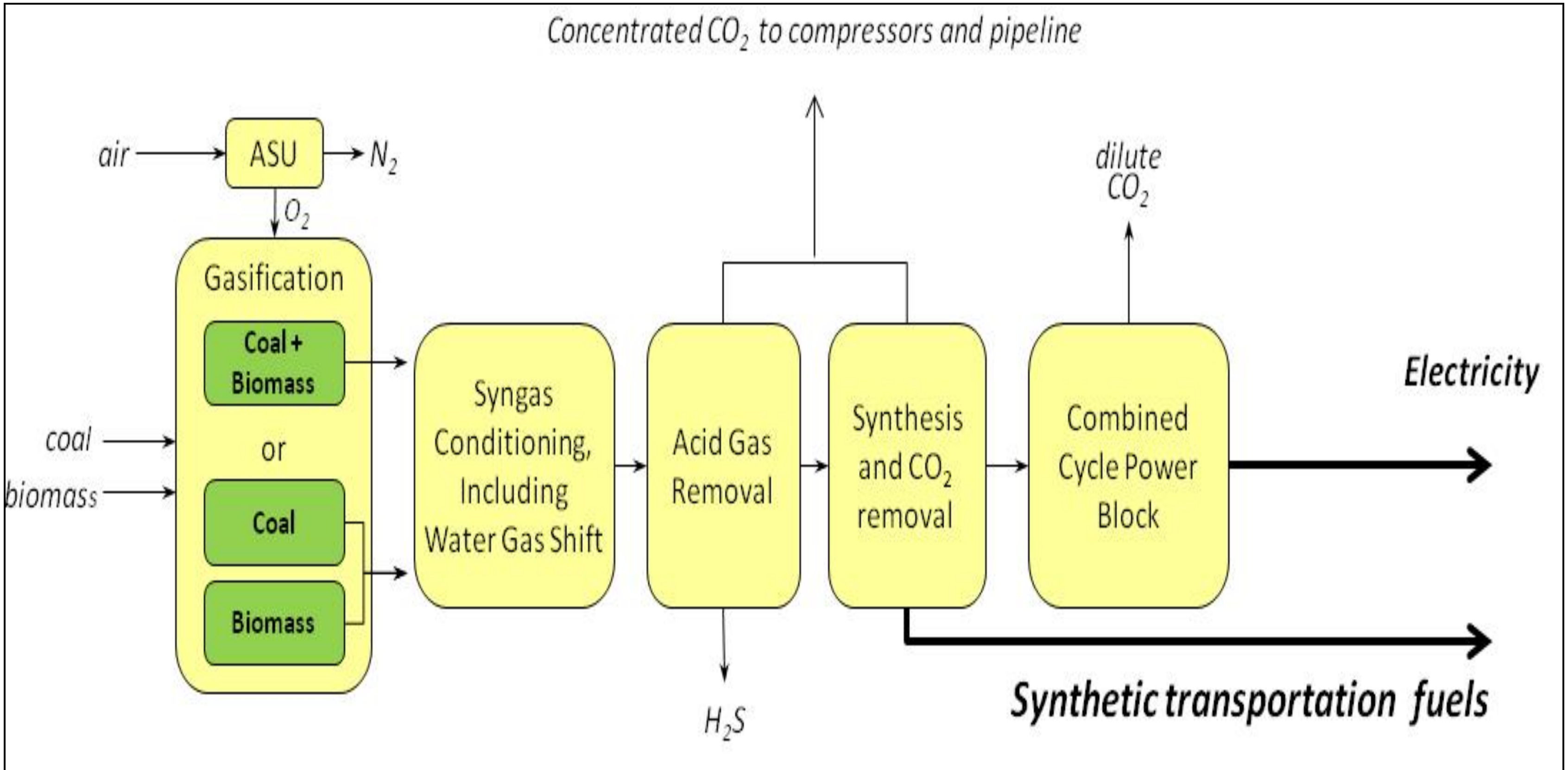
Schematic for Synthetic Fuels/Electricity Coproduction



- Feedstocks can be coal, biomass, or coal + biomass

Schematic for Synthetic Fuels/Electricity Coproduction



- Typically ½ - ⅔ of feedstock C is stored underground as CO_2

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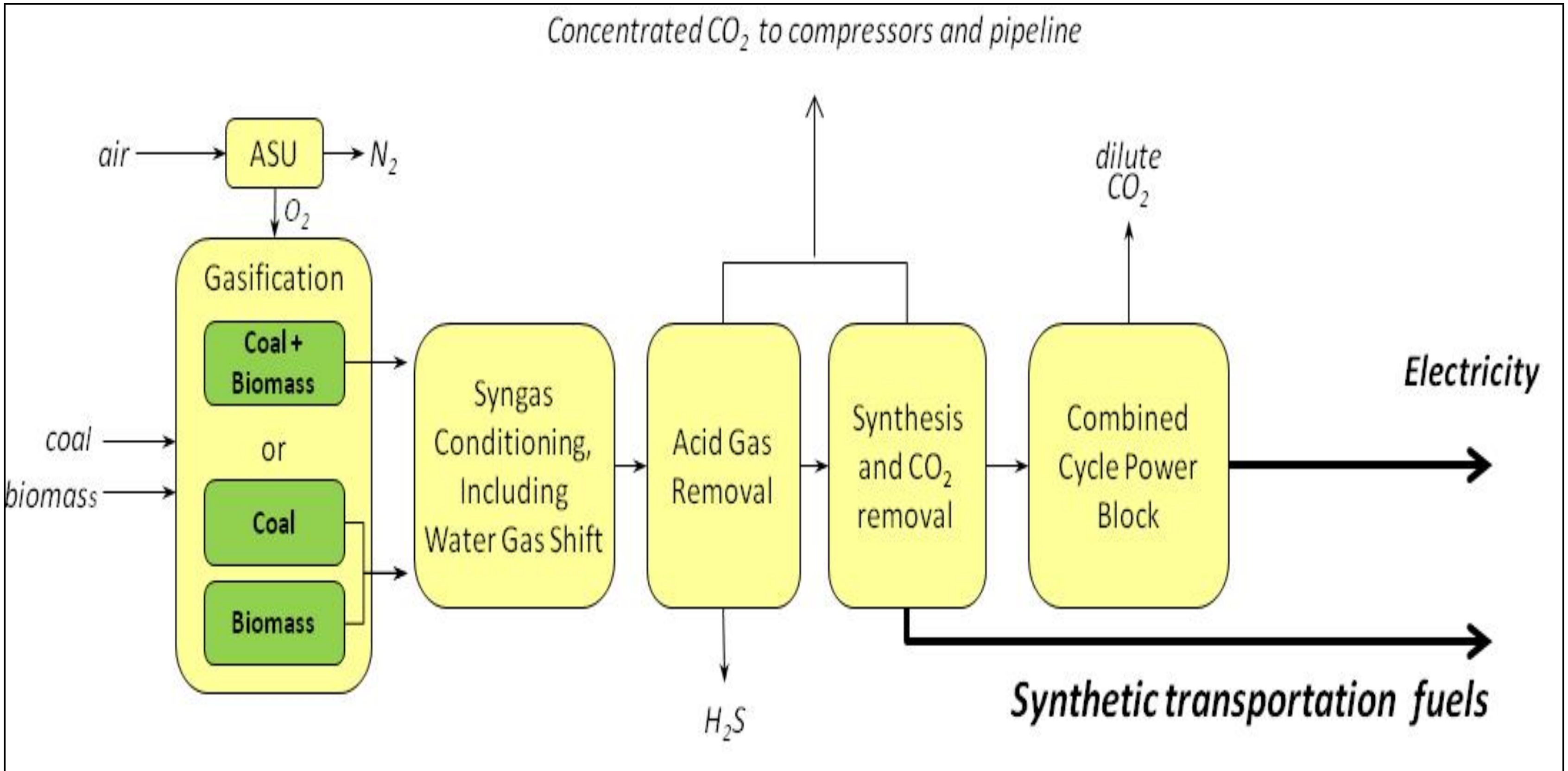
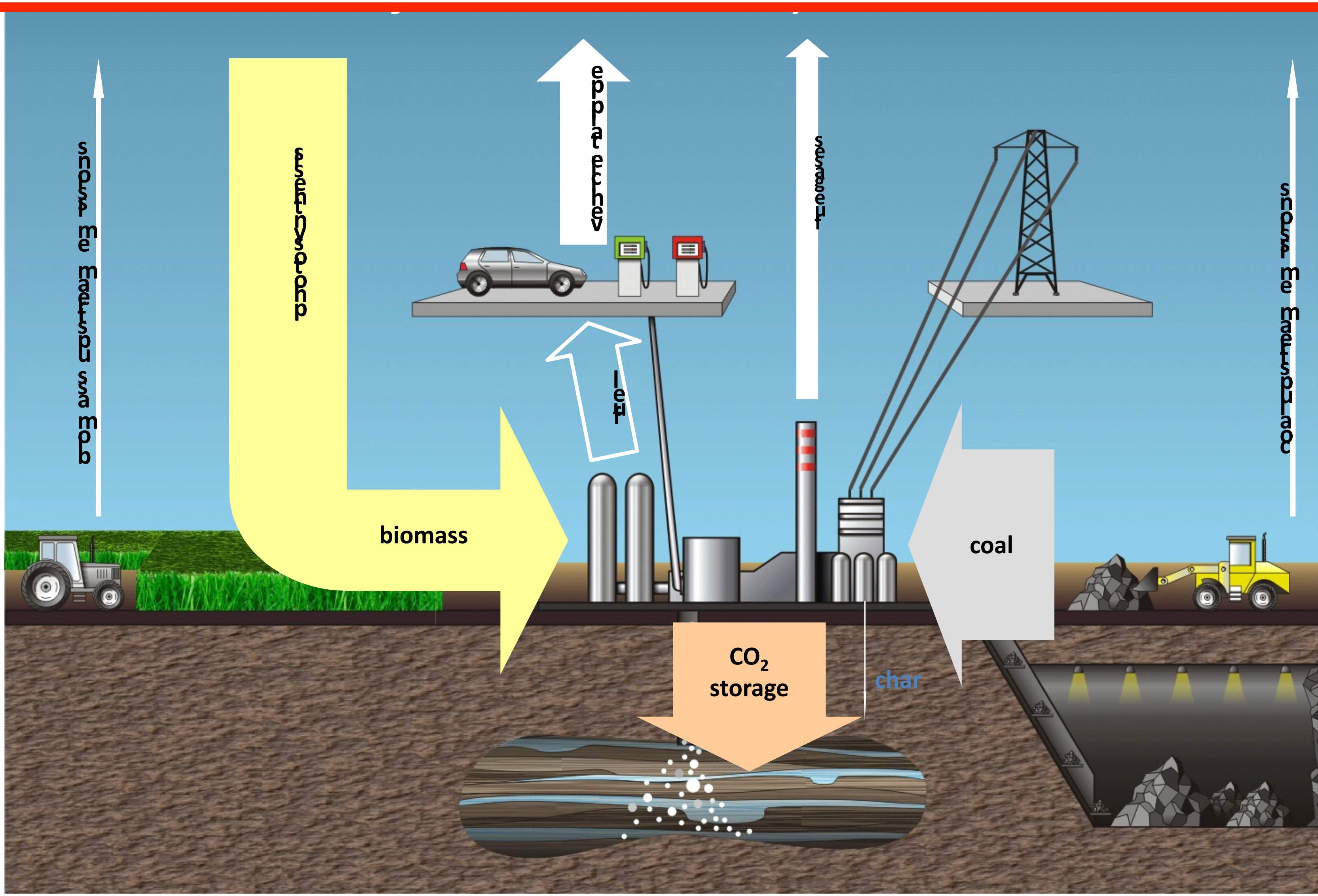


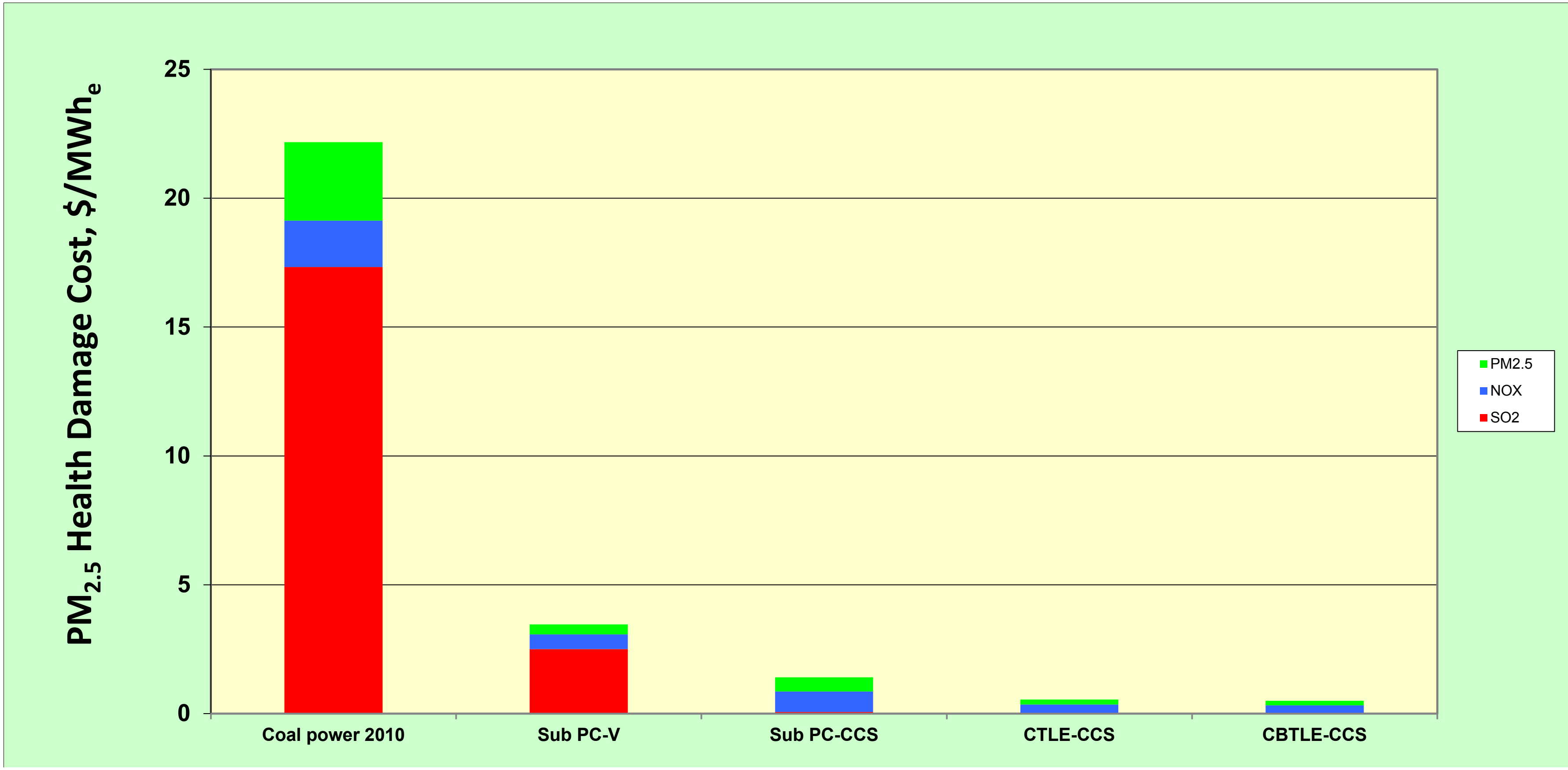
- Typically ½ - ⅔ of feedstock C is stored underground as CO_2
- Underground storage of photosynthetic CO_2 represents negative CO_2 emissions

Carbon Flows for CBTLE-CCS: Toward Zero Emissions



Sum of 4 carbon flows to atmosphere = photosynthetic carbon flow from atmosphere with ~ 34% biomass coprocessing

Health damage costs caused by $PM_{2.5}$ particles for the US average coal power plant in 2010 (on left) and alternative new power plants



$PM_{2.5}$ particles are those having diameters less than 2.5 microns that are either emitted directly or formed in the atmosphere from gaseous precursor emissions (SO_2 and NO_x).

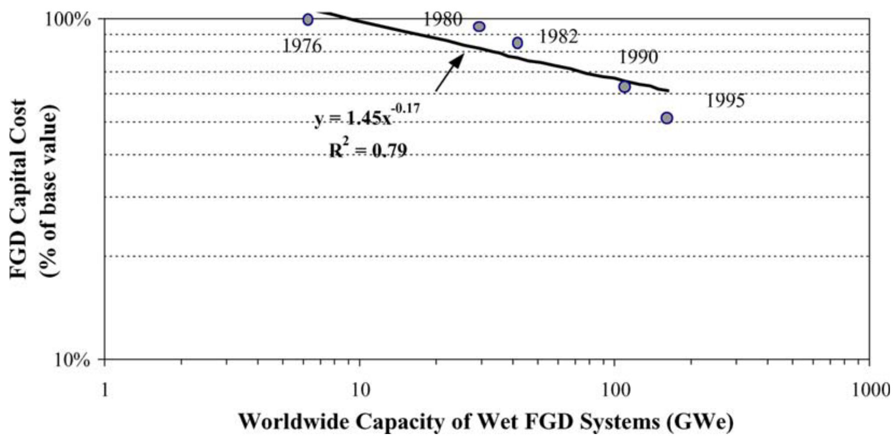
The ave. health damage cost in 2010 is equivalent to 36% of the ave. electricity generation price.

For the 3 options selected for TCB, $PM_{2.5}$ health damage costs would be low. SO_2 emissions in particular are near zero—to avoid amine solvent damage in the PC-CCS retrofit case and to avoid synthesis catalyst degradation in the CTLE-CCS and CBTLE-CCS cases.

Proposed US/China Collaborative Strategy for Getting the Global CCS Enterprise Back on Track

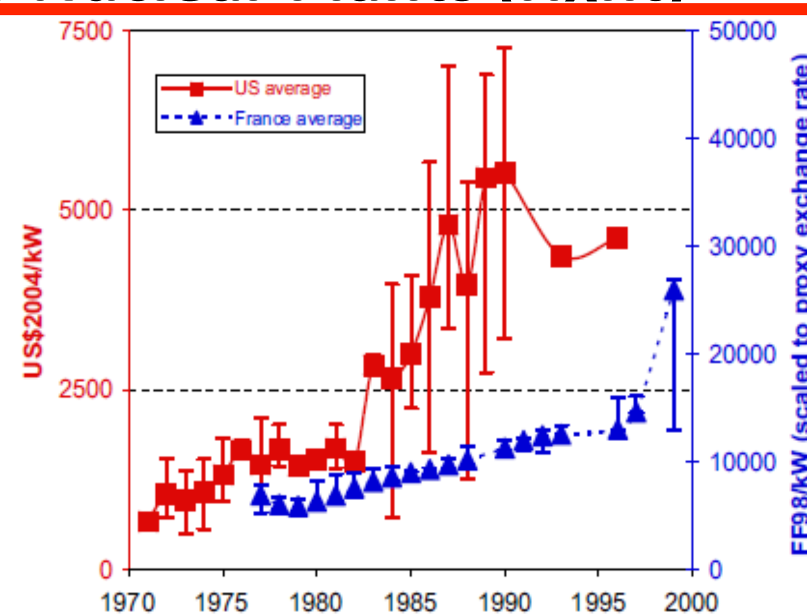
- "Buy-down" high costs of early-mover (EM) carbon capture projects through experience (LBD) for CCS systems selling CO_2 for EOR in US
- Gain extensive experience with aquifer storage by exploiting low CO_2 capture cost opportunities for chemical and synfuel plants in China
- Conduct collaborative RD&D on advanced concepts
- Exploit via collaboration:
  - More extensive technological US experience with capture and aquifer storage, and CO_2 EOR opportunities for EM projects
  - Chinese extensive experience with modern coal gasifiers, proven capability to get large projects done quickly, huge CCS retrofit market, and passion for polygeneration (key to exploitation of gasification approach to a low carbon future for coal)

Learning Rate Cannot Be Known *a Priori*. There was Positive Learning for SO_2 Scrubbers (left) but Negative Learning for Nuclear Plants (right)



FGD capital costs for a standardized coal-fired plant (500 MW, 3.5% S coal, 90% SO_2 removal) vs. cumulative installed FGD capacity worldwide. Costs declined 11% for each cumulative doubling of production.

Source: Rubin et al. (2004).



The specific investment cost of new French nuclear power plants rose with experience (though not as fast as for new US nuclear power plants).

Source: Grubler (2010).

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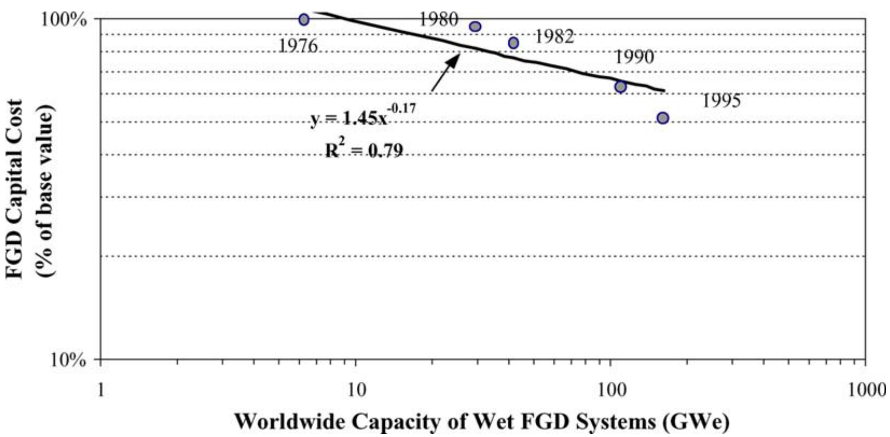

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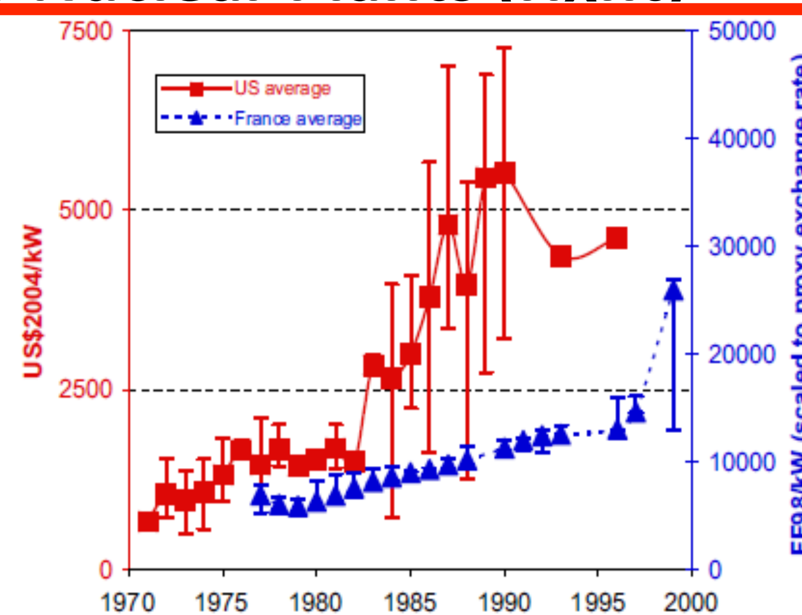

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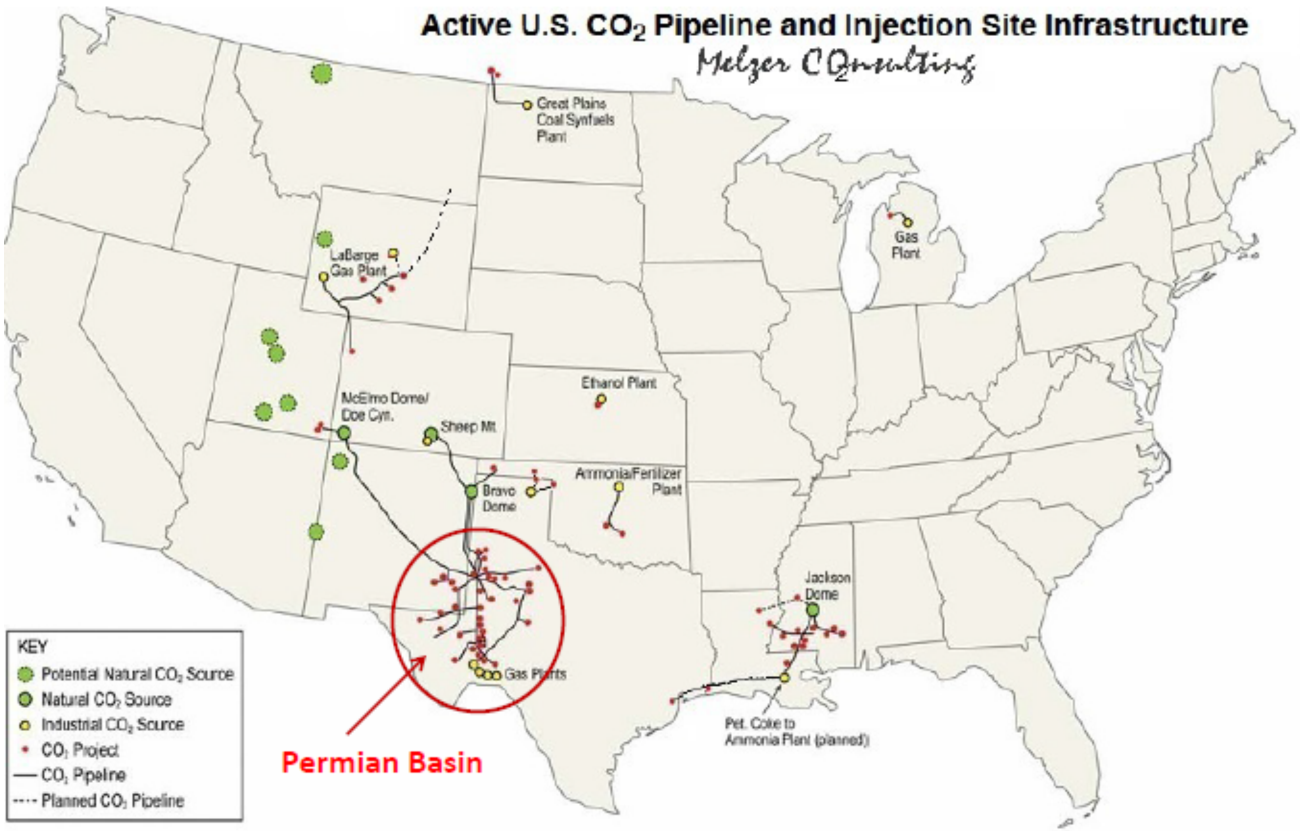
Governments can afford (to offer subsidies)to find out what learning rate is for promising CCS options when CO_2 storage is via EOR

CO_2 Pipelines & Injection Sites for Enhanced Oil Recovery (EOR) in US

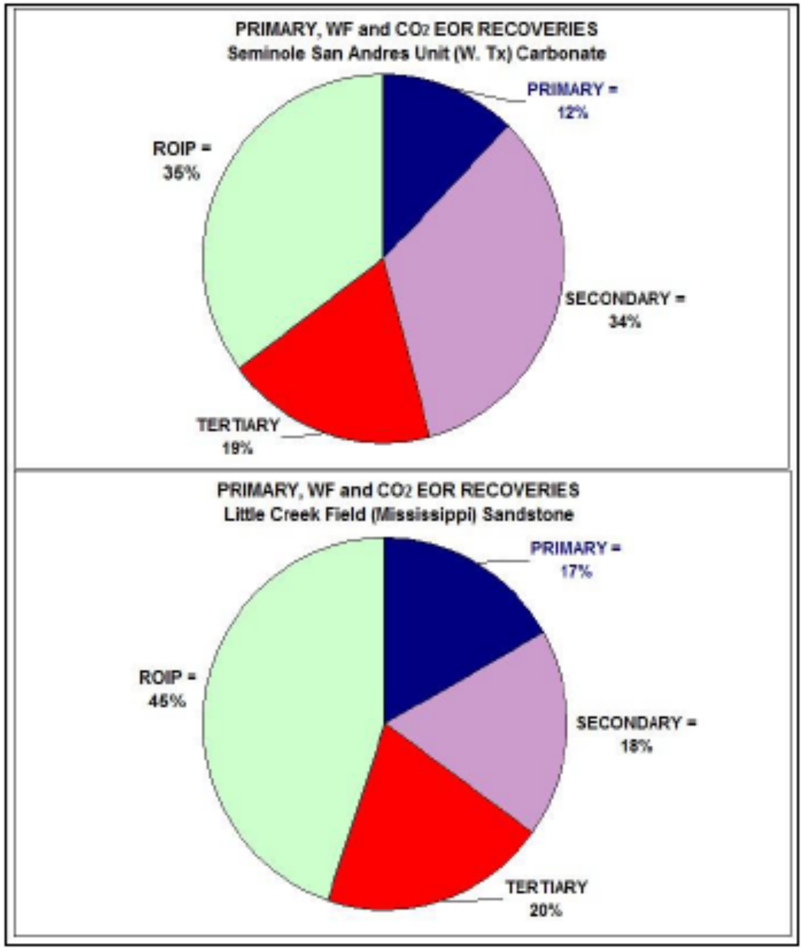


CO_2 EOR technology is well established in the US—providing, in 2011, 5% of US crude oil production or 280,000 bbls/day (EIA, 2013) using ~ 60 million tonnes per year of CO_2 delivered to injection sites via 6000 km of pipelines. Most CO_2 comes from natural sources.

CO_2 Enhanced Oil Recovery (EOR): Early Opportunity for CCS

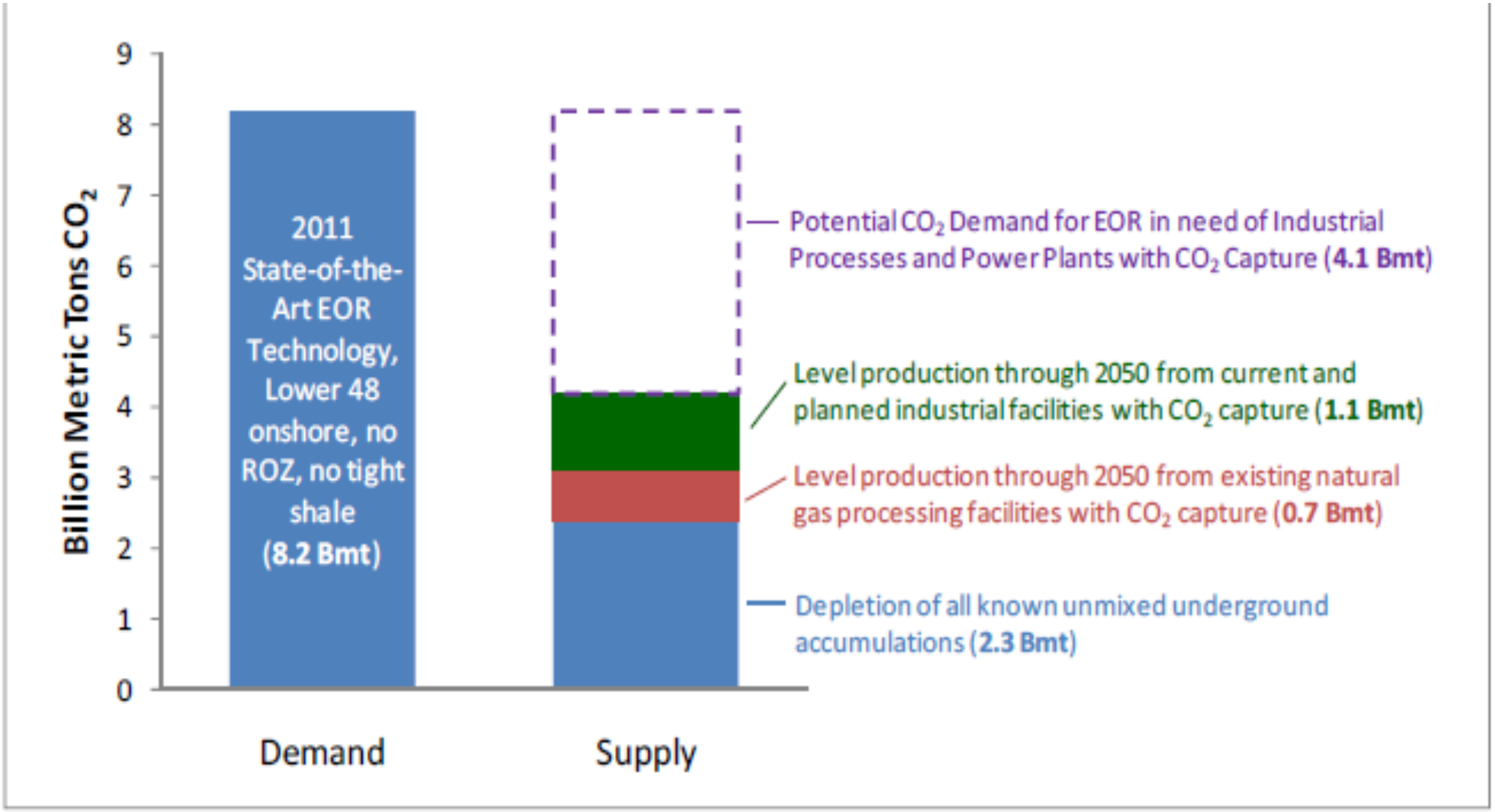
US Examples of Primary Oil Recovery + Secondary Oil Recovery + Tertiary Oil Recovery via EOR

CO_2 enhanced oil recovery is well suited for tertiary light oil recovery from depths > 800 m, making possible recovery of an additional 10-20% of original oil in place (OOIP) after recovery of 35%-45% of OOIP via primary and secondary recovery.



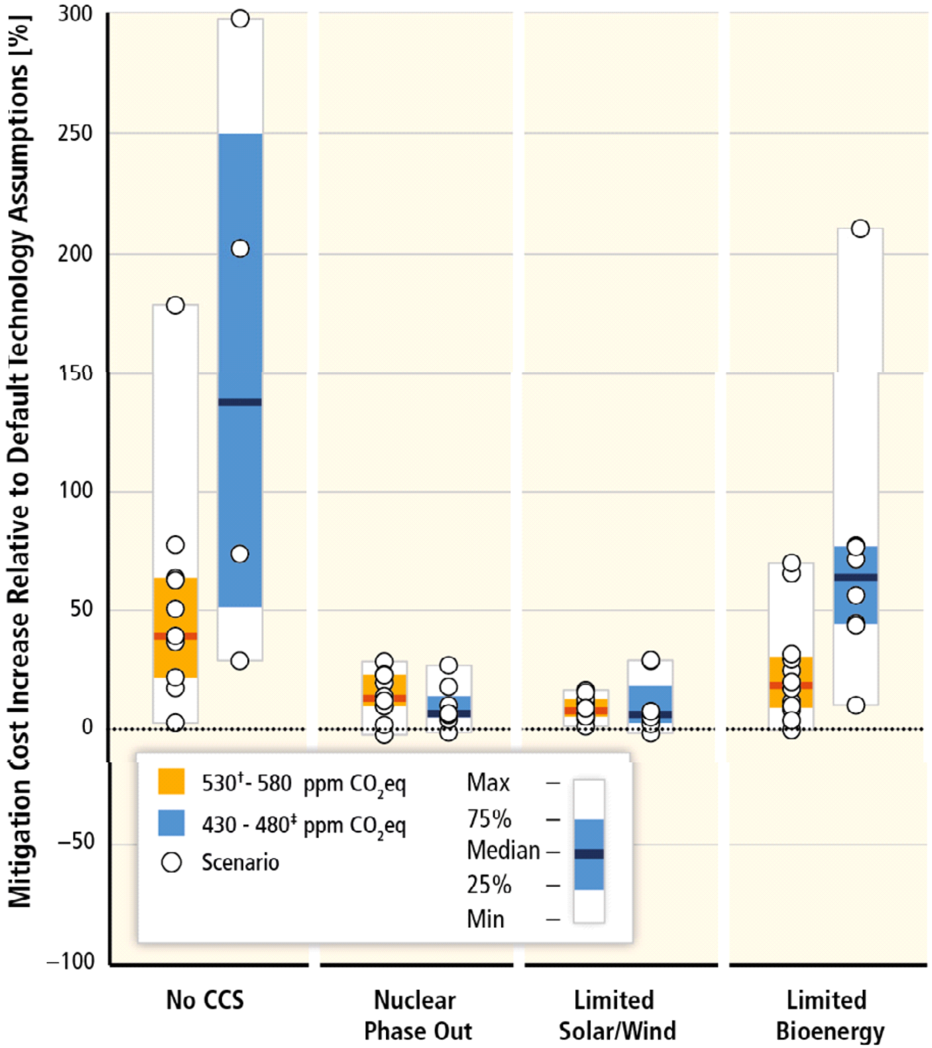
<u>Source</u>: NCC (2012).

US CO_2 Demand & Supply for EOR (NETL, 2011)



- With adequate supply of low-cost anthropogenic CO_2, US crude oil production via CO_2 EOR could increase from 280,000 bbls/day to 3.6 million bbls/day (ARI, 2010) by 2030—6X the level projected in the Reference Scenario of EIA (2013). Assuming state-of-the-art CO_2 EOR technology (0.4 tonnes of CO_2 purchased per incremental bbl of crude oil), realization of this target implies an EOR market opportunity of almost 440 million tonnes/year of CO_2 by 2030.
- Regulatory regime spelling out how CO_2 EOR qualifies as secure storage urgently needed—MMV protocols, etc. (CSLF, 2013)

IPCC Estimates That if CCS Is Excluded as a C-Mitigation Option, Realizing 2DS Would Be Far More Costly



Mitigation costs would rise far less if nuclear power were phased out or if solar, wind, or biomass mitigation options prove to be limited.

Source: IPCC (2014)

Overview of CO_2 Storage Issues

INTERGOVERNMENT PANEL ON CLIMATE CHANGE (2005) ON CO_2 STORAGE

- On geological storage capacity for CO_2:

  …worldwide, it is virtually certain that there is 200 Gt CO_2 of geological storage capacity and likely that there is at least about 2000 Gt CO_2…

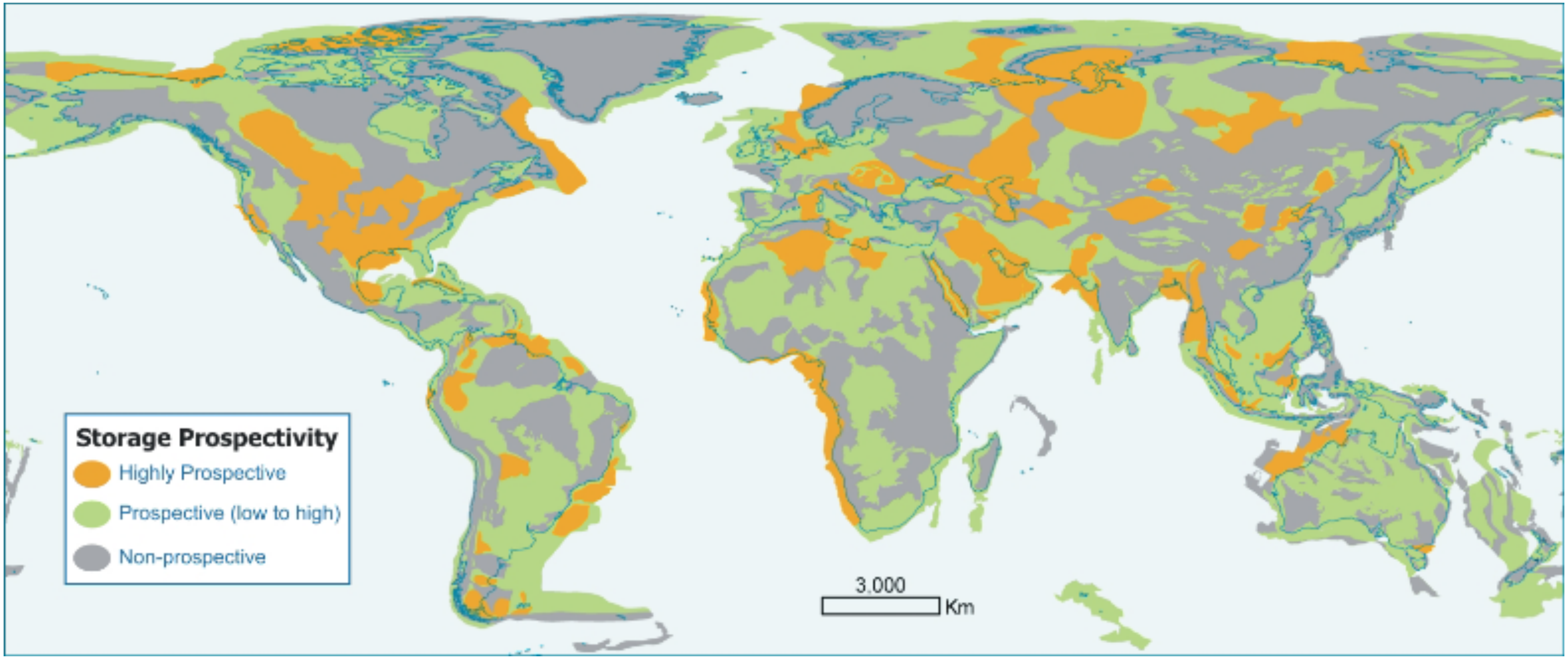
- On geography of sources and sinks for CO_2:

  …there is potentially good correlation between major sources and prospective sedimentary basins, with many sources lying either directly above, or within reasonable distances (*less than 300 km*) from areas with potential for geological storage…

- On security of CO_2 storage:

  …based on observations and analysis of current CO_2 storage sites, natural systems, engineering systems, and models, the fraction [*of injected* CO_2] retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1000 years…

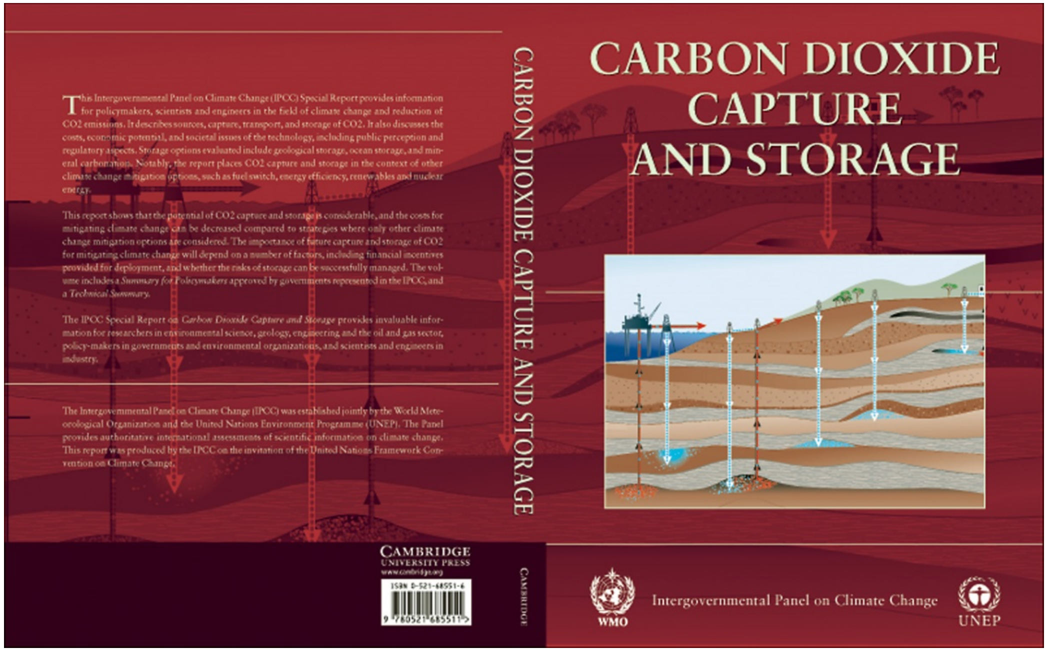
STORAGE POTENTIAL FOR CO_2 IN SEDIMENTARY BASINS OF THE WORLD



Source: J. Bradshaw and T. Dance, 2004: Mapping geological storage prospectivity of CO_2 for the world's sedimentary basins and regional source to sink matching. *Proceedings of the 7th International Conference on Greenhouse Gas Technologies*, September 5-9, 2004, Vancouver, Canada.

Is CO_2 Storage Safe? According to the IPCC (2005):

" With **appropriate site selection** informed by available subsurface information, a **monitoring program** to detect problems, a **regulatory system**, and the **appropriate use of remediation methods** to stop or control CO_2 releases if they arise, the **local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas**."

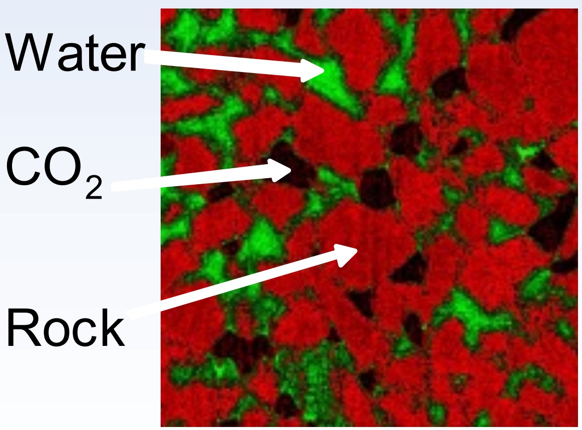


What Keeps the CO_2 Underground?

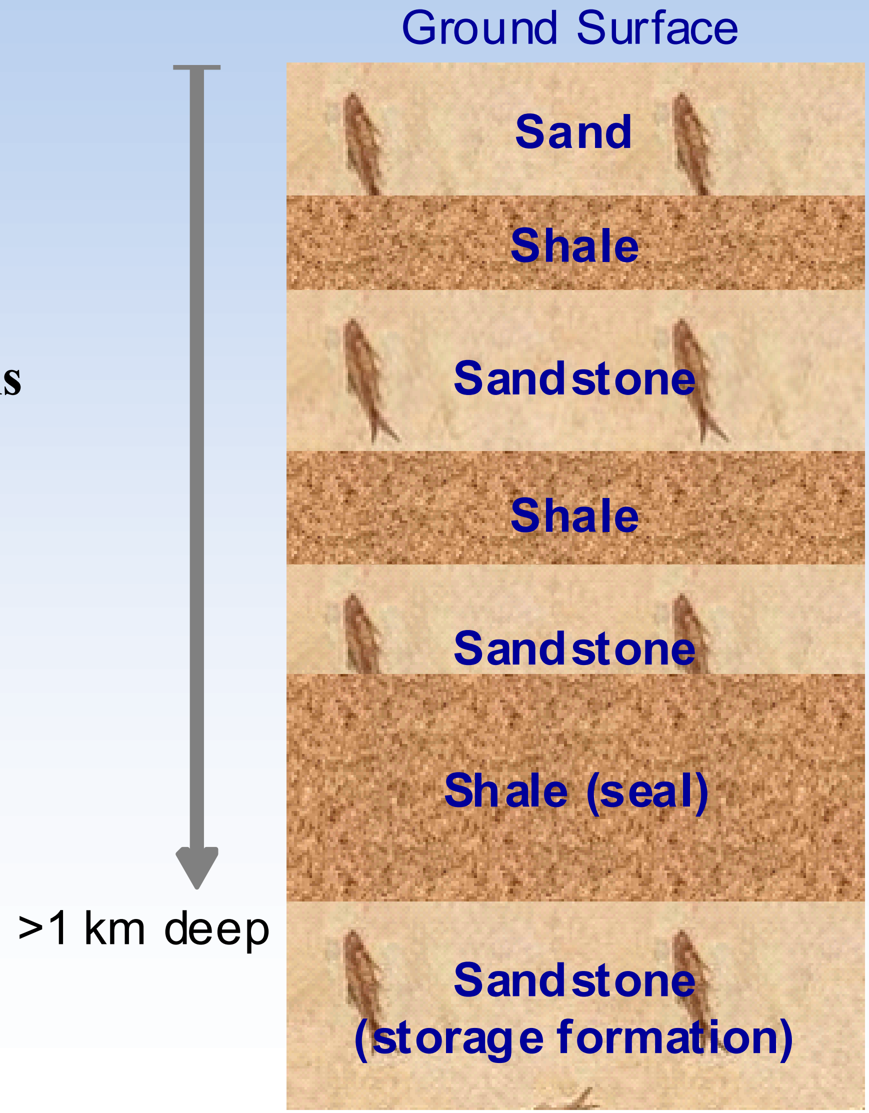
CO_2 Trapping Mechanisms

- CO_2 is physically trapped beneath seals
- CO_2 is trapped by capillary forces

X-ray of CO_2 in sandstone

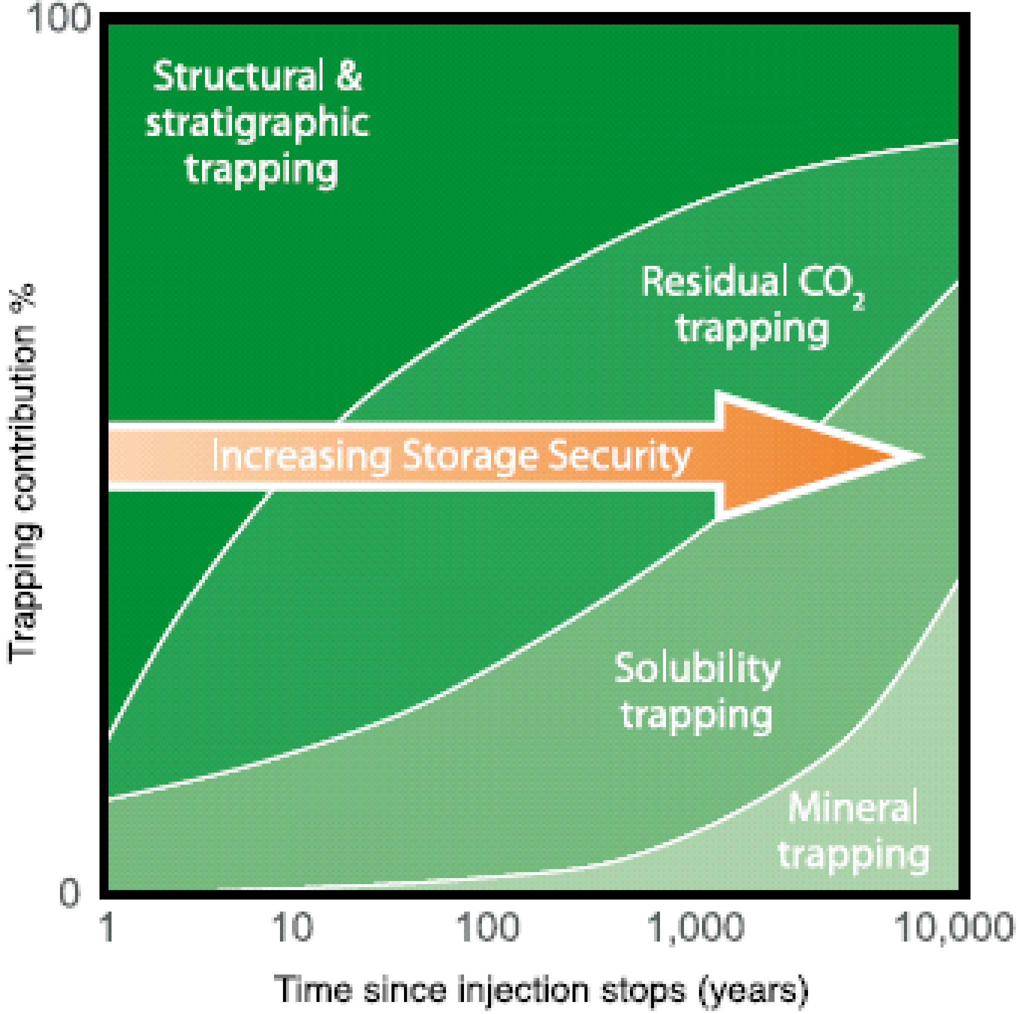


- CO_2 dissolves in water
- CO_2 converts to solid minerals



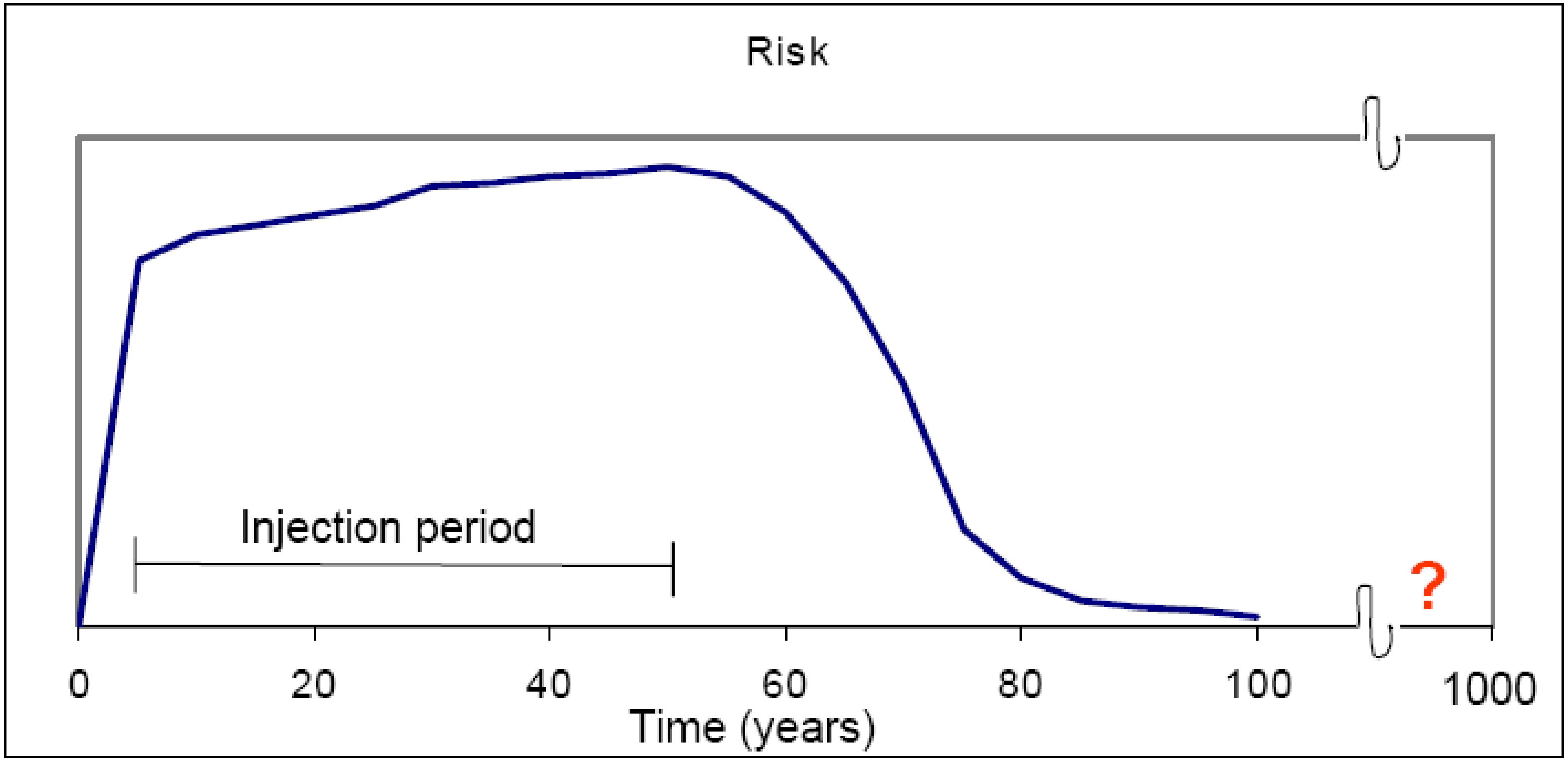
<u>Source</u>: Sally Benson, Stanford University

Security of CO_2 Storage as Function of Time



IPCC, 2005: Chapter 5 (Underground Geological Storage), *Special Report on Carbon Dioxide Capture and Storage*

The risk timeline for leakage is heavily-laden in early times.



Why does it look like this?

- Pressure driver during and post injection
- Most "changes" occur in early phase
- Long-term effects trap larger quantities of CO_2
- Seals may be affected over long-term

Taken from Grant Bromhal's presentation RECS conf. 2007

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