Coal Synfuel and CO_2 Enhanced Oil Recovery Opportunities for Early CCS Projects

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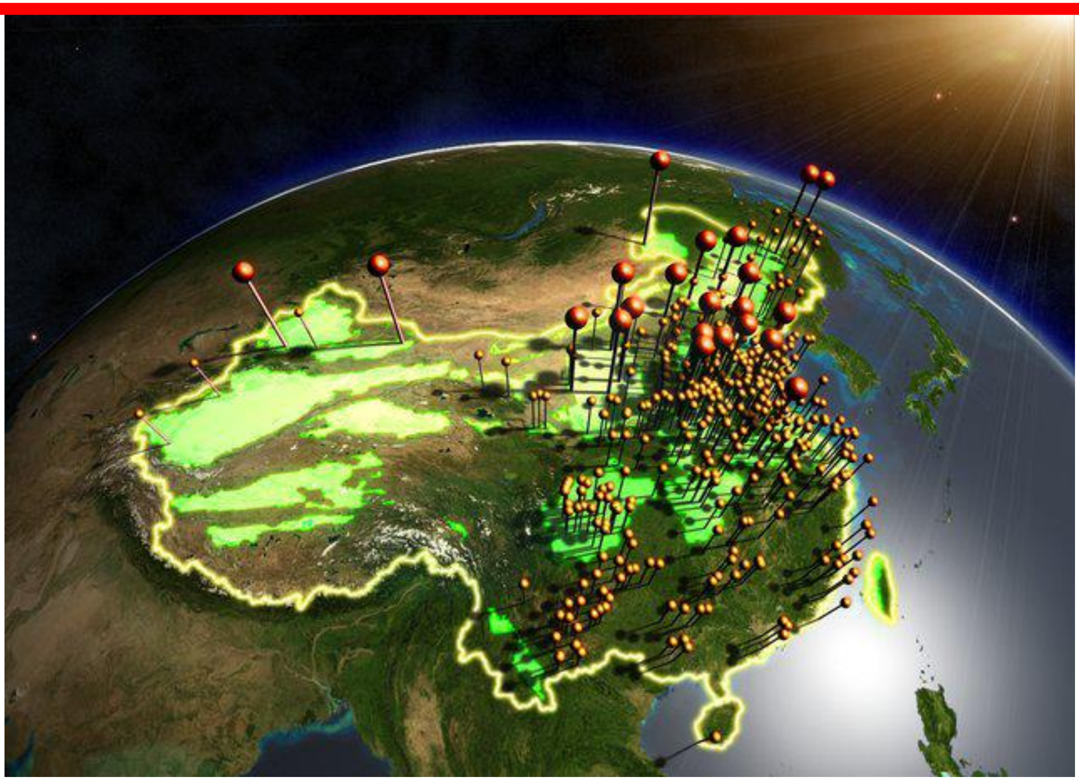
Outline

- Widespread deployment of CCS technology requires a strong carbon-mitigation policy or an equivalent incentive.
- In the absence of such policies there are two promising approaches for going forward in the near term with no or only modest government subsidies—by taking advantage of:
  - The inherently low CO_2 capture cost at chemical and synfuel plants (at which CO_2 has to be removed before synthesis—even in absence of a carbon policy);
  - The market value of captured CO_2 if used for enhanced oil recovery (EOR) applications.
- Chinese opportunities in both areas are reviewed.
- The economic aspects of exploiting CO_2 EOR opportunities is explored for systems that make electricity from coal, synfuels from coal, and synfuels + electricity from coal in the US.

Low-Cost CO_2 Capture Opportunities in China (Chemical and Synfuel Plants)



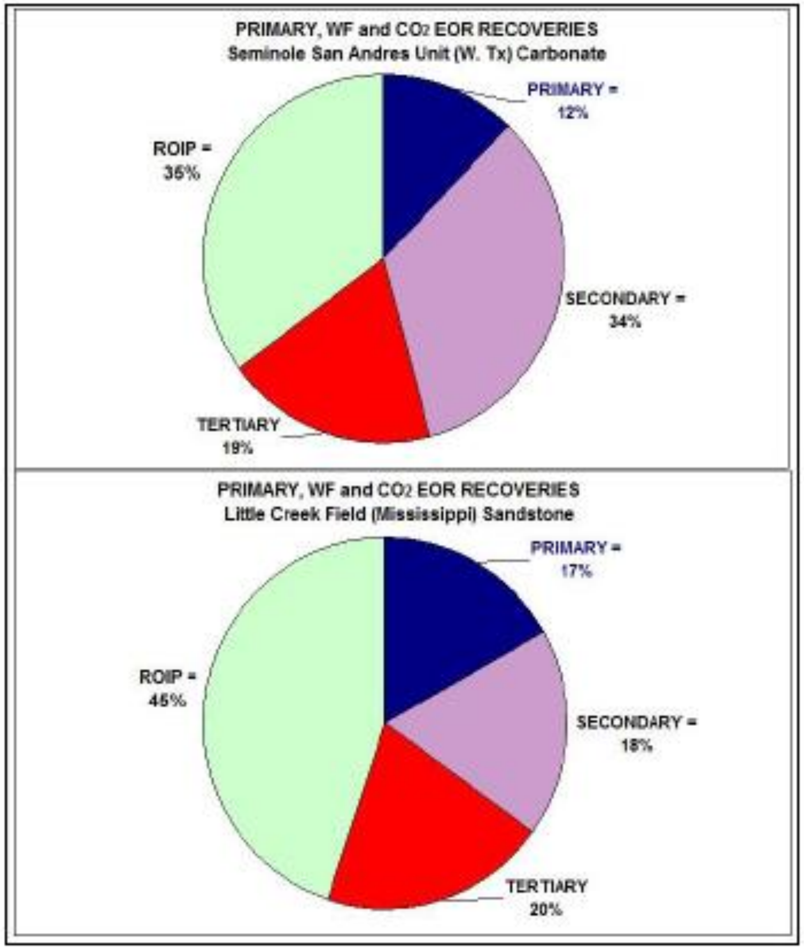
- Pins: 400 existing & planned chemical plants releasing concentrated CO_2 (low capture costs)
- Green areas: sedimentary basins where suitable storage sites might be found
- 18 "Big Pins": plants within 10 km of deep saline formation emitting > 10^6 t/y CO_2
  ➔ many opportunities for megascale aquifer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

Source: Zheng et al. (2010).

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

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

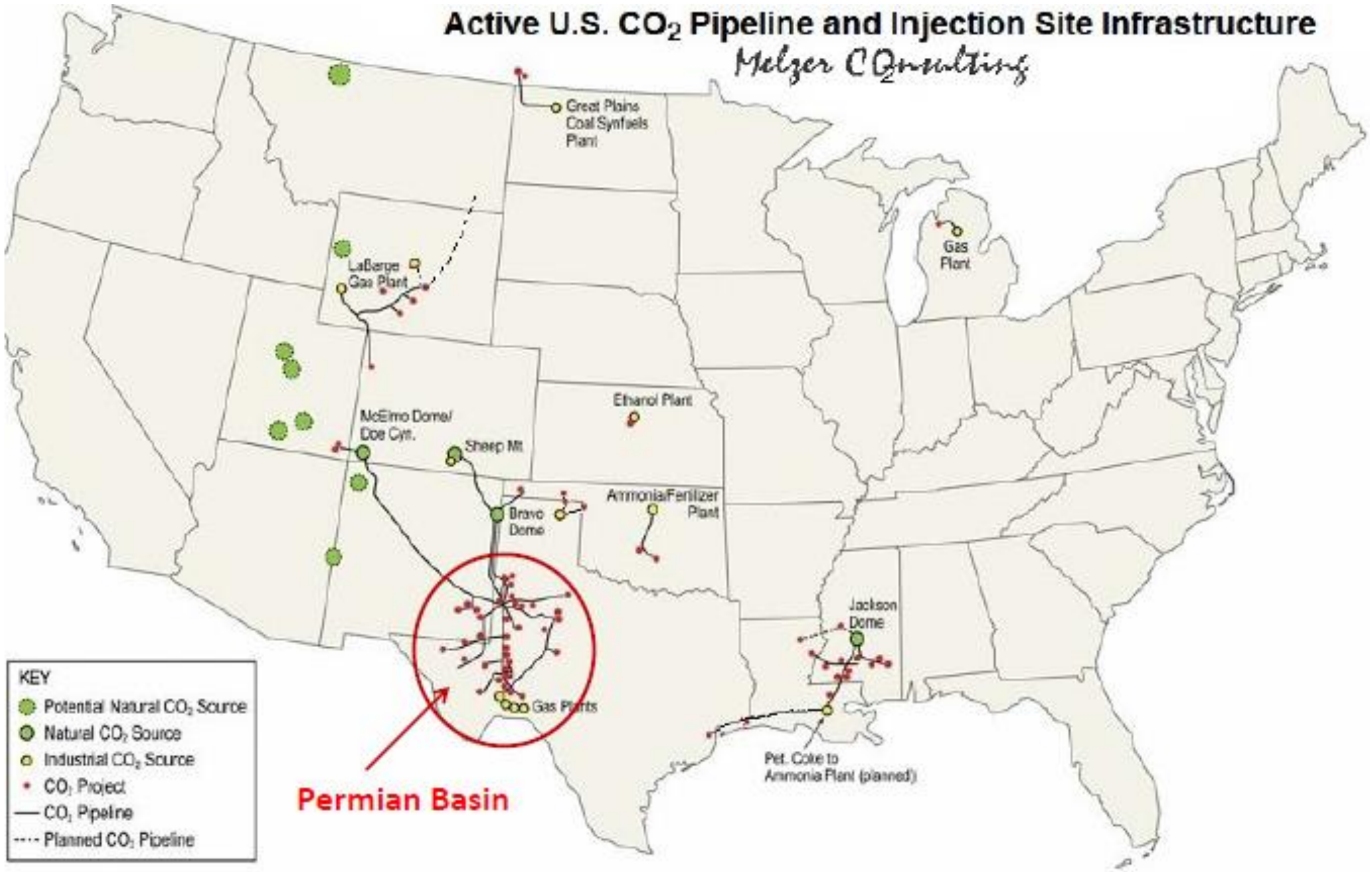
CO_2 enhanced oil recovery is well suited for tertiary light oil recovery from depths > 800 m, making possible recovery of up to an additional ~ 20% of original oil in place (OOIP) after recovery of 35%-45% of OOIP via primary and secondary recovery. Source: NCC (2012).



Aside from enabling early CCS projects, impact of new crude oil via EOR on atmospheric CO_2 depends on behavior of world oil market:

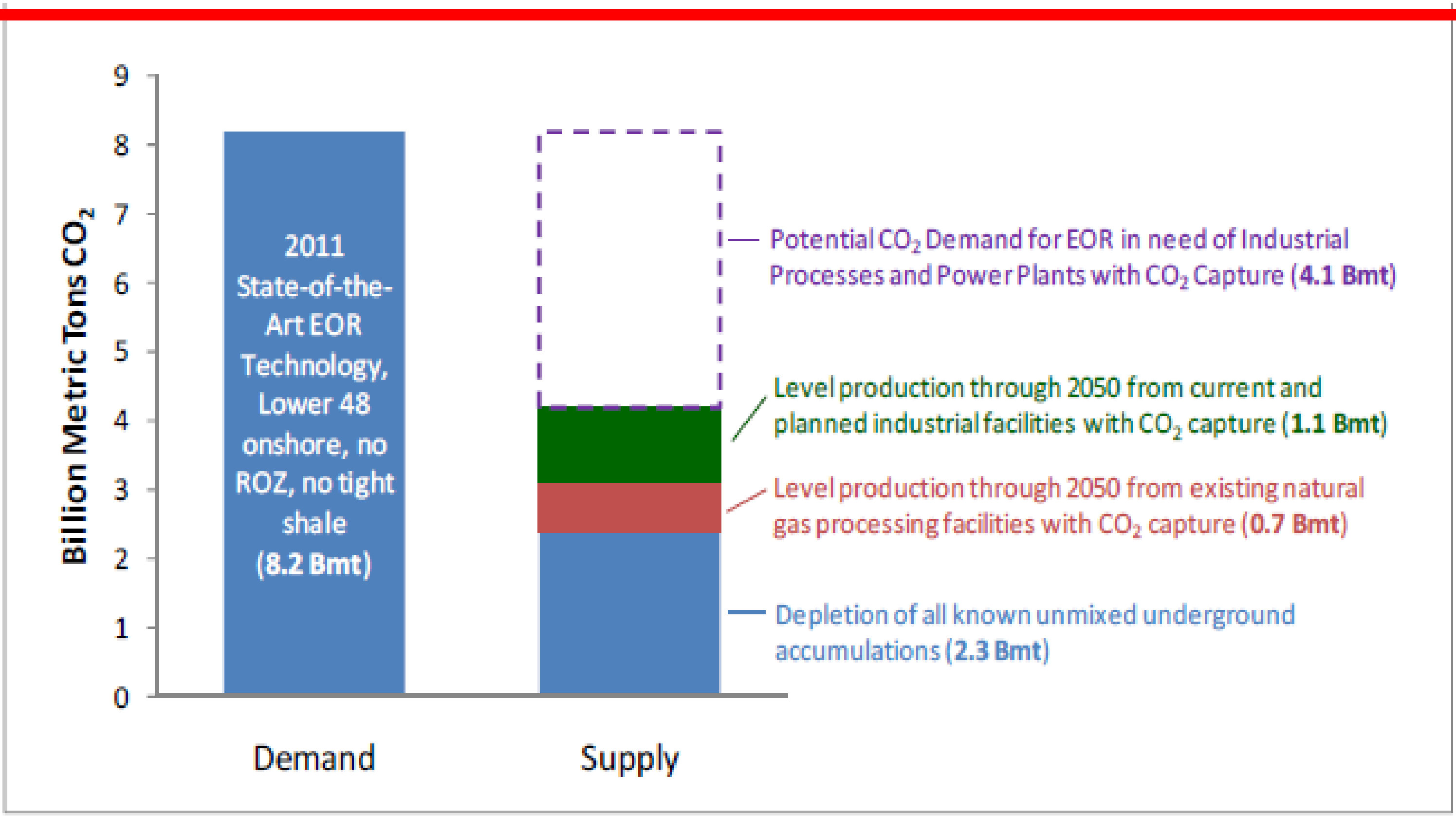
Under what conditions is total oil consumption the same without and with CO_2 EOR?

CO_2 Pipelines & Injection Sites for EOR in US



CO_2 EOR technology is well established in the US—providing 280,000 bbls/d of crude oil (6% of US crude oil production) 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.

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 3.7 million bbls/day (NETL, 2011), plausibly by 2030
- If realized via next generation CO_2 EOR technology (NETL, 2011), cumulative storage, 2020-2030: ~ 1.7 Gt CO_2 [80% of cumulative 2030 North American storage goal in IEA (2013b)]
- Regulatory regime spelling out how CO_2 EOR qualifies as secure storage urgently needed—MMV protocols, etc. (CSLF, 2013)

Planned CO_2 EOR Projects for China

Project leader	**CO_2 supply**	**Oil field (City, Province)**	**Pipeline length, km**	**Targeted storage rate, 10^6 t/y (expected storage for project life, 10^6 t)**	**Expected year for reaching targeted injection rate**
PetroChina	Natural gas processing	Jilin (Songyuan, Jilin)	151-200	0.8 to 1.0 (11 - 20)	2015
Shaanxi Yanchang Petroleum Group	Coal to acetic acid plant	Jingbian (Yulin, Shaanxi)	200-250	0.36 (6 - 8)	2016
Sinopec	FBB Post-combustion capture retrofit	Shengli (Dongying, Shandong)	51-100	1.0 (21 - 30)	2017
Huaneng GreenGen	Capture from IGCC	Tianjin (SE of Beijing)	51-100	Up to 2 (41 - 50)	2020

Data largely from publications of the Global CCS Institute

Opportunity for CCS via EOR expected to be much less for China than for US

GHGI—a “Carbon Footprint” Metric

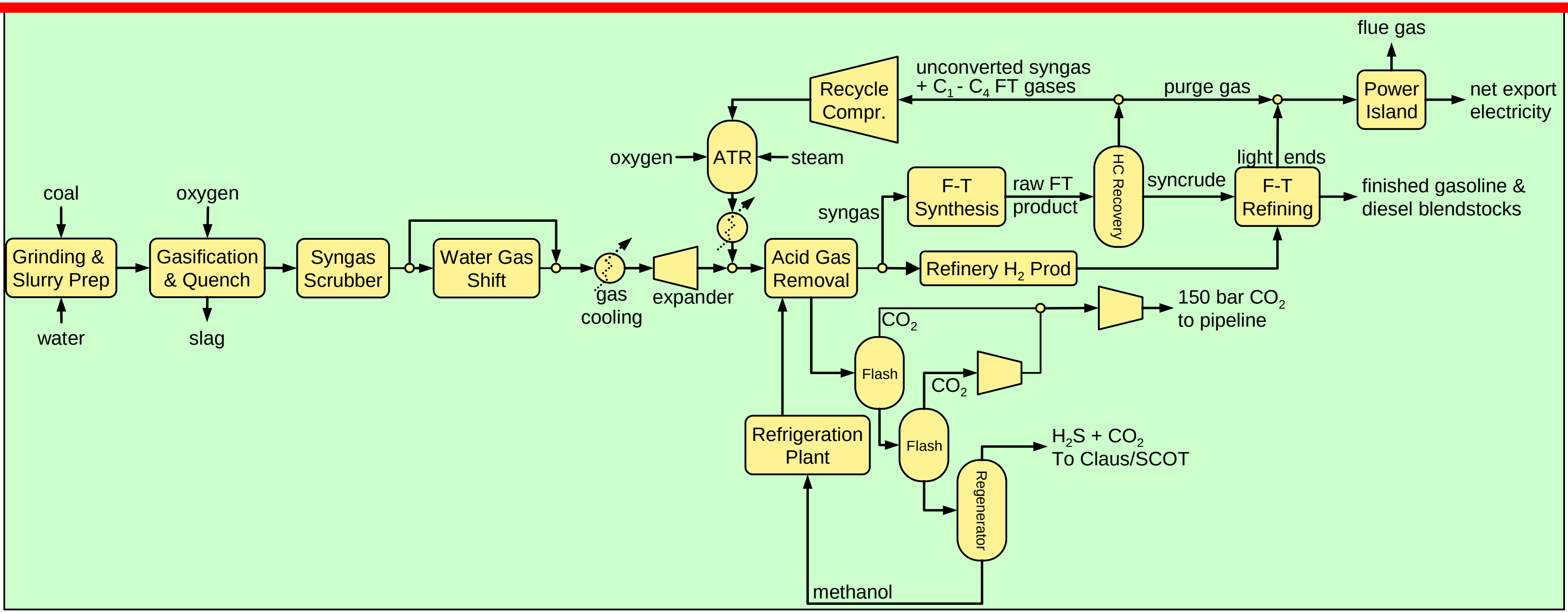
A widely applicable metric for measuring GHG emissions mitigation that is especially helpful in understanding the carbon mitigation benefits of coproduction systems is the greenhouse gas emissions index:

$$GHGI \equiv \frac{\left(\textbf{total GHG emissions for energy production}\,\&\,\textbf{consumption}\right)}{\left(\textbf{total GHG emissions for fossil energy displaced}\right)}$$

For systems making liquid transportation fuels and/or electricity, fossil energy displaced is assumed to be equivalent crude-oil-derived products + electricity from new super-critical coal plants venting CO_2.

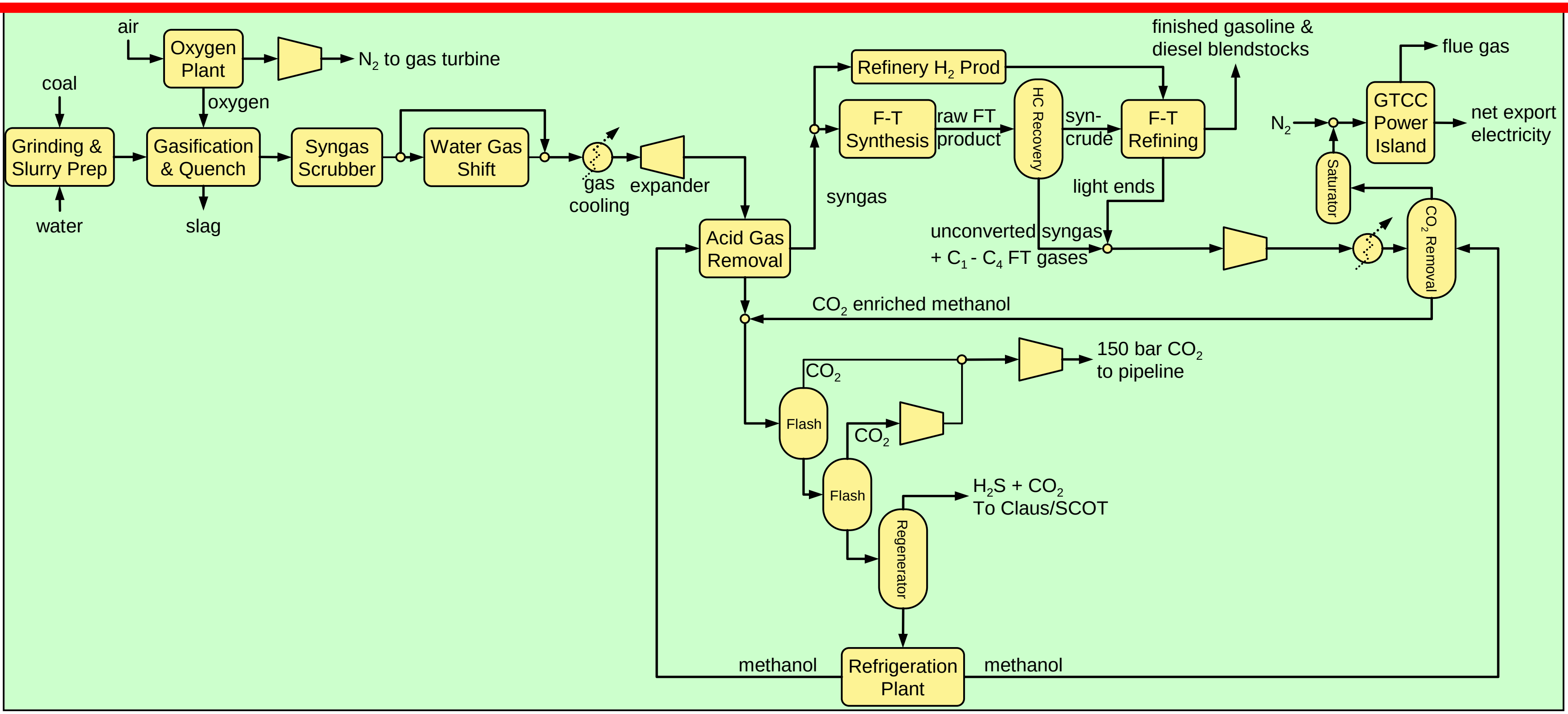
GHG emissions arising outside energy conversion plant boundaries are based on the GREET model of the Argonne National Laboratory.

CTL-RC-CCS System Schematic



Synthesis gas from an entrained-flow coal gasifier is used to make synthetic fuels and electricity with CO_2 capture. A water gas shift reactor upstream of synthesis adjusts the H_2/CO ratio in synthesis gas to 1.0. Shifted synthesis gas is passed (after CO_2 and H_2S removal) to a liquid-phase Fischer-Tropsch (F-T) synthesis reactor with an iron catalyst operated in a "recycle " (RC) system configuration: syngas unconverted in a single pass through the synthesis reactor is recycled back to the synthesis reactor with the aim of maximizing liquid fuel output. An auto-thermal reformer (ATR) is included in the recycle loop to convert C_1 - C_4 gases into CO and H_2 to further increase liquid fuel output. Electricity is generated in a steam turbine power plant from purge gases removed from the recycle loop (to prevent the buildup of inerts) and from light ends recovered from the F-T refinery. Source: Liu et al. (2011).

CTL-OT-CCS System Schematic



This system is like CTL-RC-CCS except that F-T production is via a “once-through” (OT) system configuration: syngas unconverted in a single pass through the synthesis reactor is delivered to a gas turbine combined cycle (GTCC) to provide electricity as a major coproduct after CO_2 is removed from syngas exiting the synthesis reactor (this syngas contains CO_2 because the iron catalyst has water gas shift activity). CO_2 is removed both upstream and downstream of synthesis (each accounting for ~ ½ of total captured CO_2). Source: Liu et al. (2011).

Alternative Energy Conversion Options

Technology feature	**CTL-RC -CCS**[a]	**CTL-OT -CCS**[a]	**NGCC -V**[b]	**PC-CCS retrofit**[c]	**IGCC -CCS**[b]
Electric output capacity, MW_e (% of energy output)	98.2 (8.5)	391 (32)	555 (100)	398 (100)	543 (100)
FTL capacity, bbls/day	16,650	13,200	0	0	0
Energy output capacity, MW (LHV)	1150	1220	555	398	543
Efficiency (HHV), %	48.9	46.1	50.2	24.7	32.6
GHGI (**in declining order**)	**0.89**	**0.70**	**0.57**	**0.23**	**0.17**
CO_2 storage rate, 10^6 t/y (% of feedstock C stored as CO_2)	3.2 (52)	3.6 (52)	0 (0)	3.5 (90)	3.4 (88)
Capital, NOAK plant, $\$10^6$	**2.7**	**2.7**	0.44	0.93	2.0

[a] Based on: Liu et al. (2011).

[b] From: NETL (2010).

[c] From: NCC (2012).

CTL plants are scaled to have same capital cost—to facilitate investment choice by CTL project developer

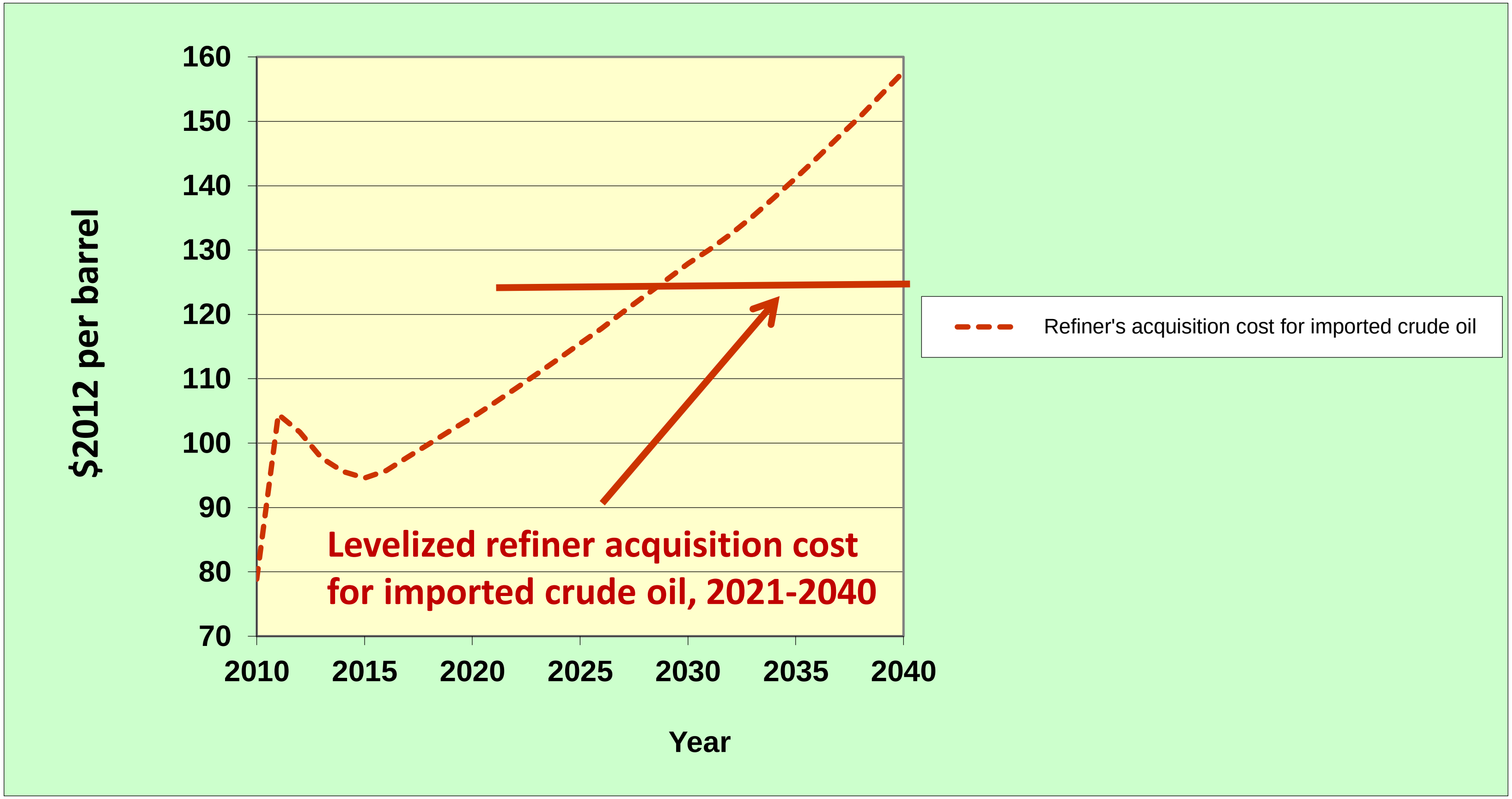
NOAK Capital cost = Total Plant Cost (TPC) + Owner’s Cost (OC)—see A.1, Appendix for details.

Crude Oil Production via Use of Captured CO_2 for EOR

Technology feature	**CTL-RC -CCS**	**CTL-OT -CCS**	**PC-CCS retrofit**	**IGCC -CCS**
Ave. crude oil production via state-of-the-art CO_2 EOR technology (bbls per day)	21,700	27,100	23,800	23,300
Bbls of crude oil per bbl of FTL				
State-of-the-art CO_2 EOR technology	1.45	2.28	-	-
Next-generation CO_2 EOR technology	1.94	3.04	-	-
CO_2 capture rate, tonnes per hour	403	451	467	457
CO_2 capture cost for NOAK plants, \$ per tonne of CO_2	11.6	25.6	51.0	34.3

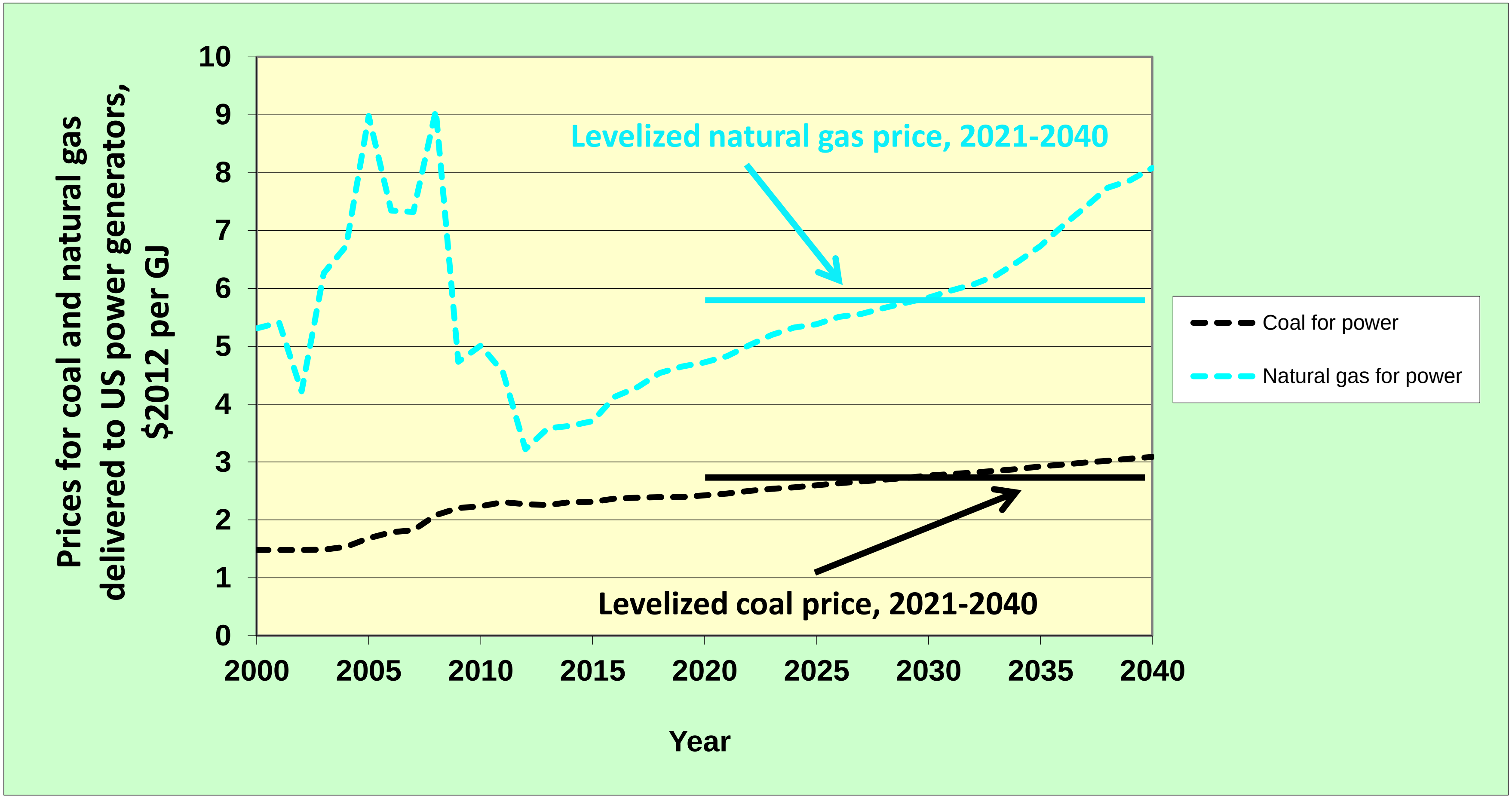
The amount of purchased CO_2 for EOR is 0.4 t and 0.3 t per incremental bbl of crude oil produced for state-of-the-art CO_2 and next-generation EOR technologies, respectively (NETL, 2011). In slides that follow, the economics are carried out for state-of-the-art CO_2 EOR technology.

US Average Imported Crude Oil Price



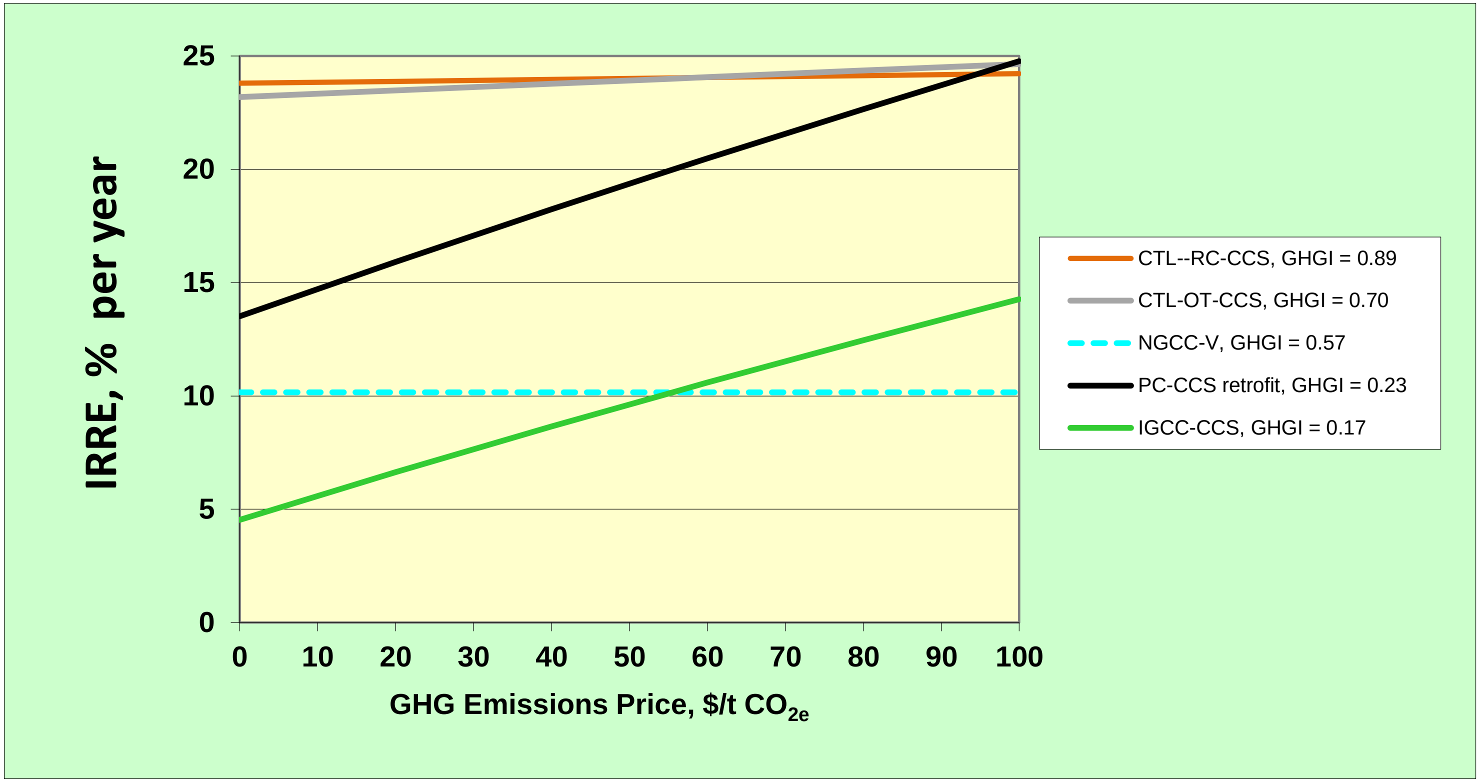
Prices for 2010-2012 are historical data from EIA (2013b). Prices for 2013-2040 are projections for *Annual Energy Outlook 2013* Reference Scenario (EIA, 2013c).

Prices for Coal and Natural Gas Delivered to to US Power Plant Sites



Prices for 2000-2012 are historical data from EIA (2013b). Prices for 2013-2040 are projections for *Annual Energy Outlook 2013* Reference Scenario (EIA, 2013c).

IRRE for NOAK Plants (Nearby EOR), $124/bbl Crude Oil



Internal rate of return on equity (IRRE) when the crude oil price is levelized value, 2021-2040, of imported crude oil price for *AEO 2013* Reference Scenario (EIA, 2013c).

IRRE values are low for new IGCC-CCS power-only plants but are acceptably high at all GHG emissions prices for PC-CCS retrofit.

CTL-RC-CCS and CTL-OT-CCS IRRE values are comparable and far higher than for all stand-alone power plants ➔ CTL-OT-CCS considered as a power generator represents a promising approach to coal power generation in a carbon-constrained world.

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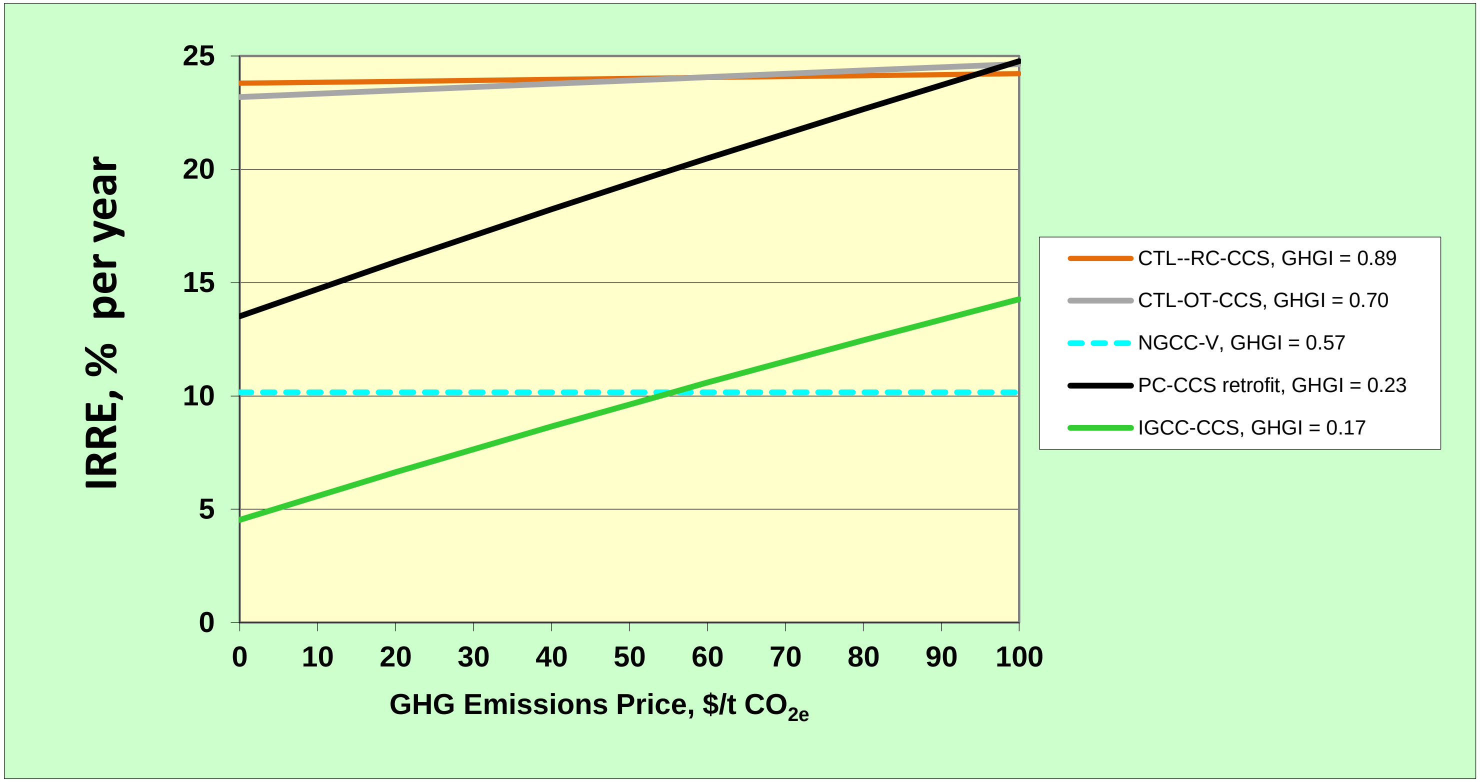

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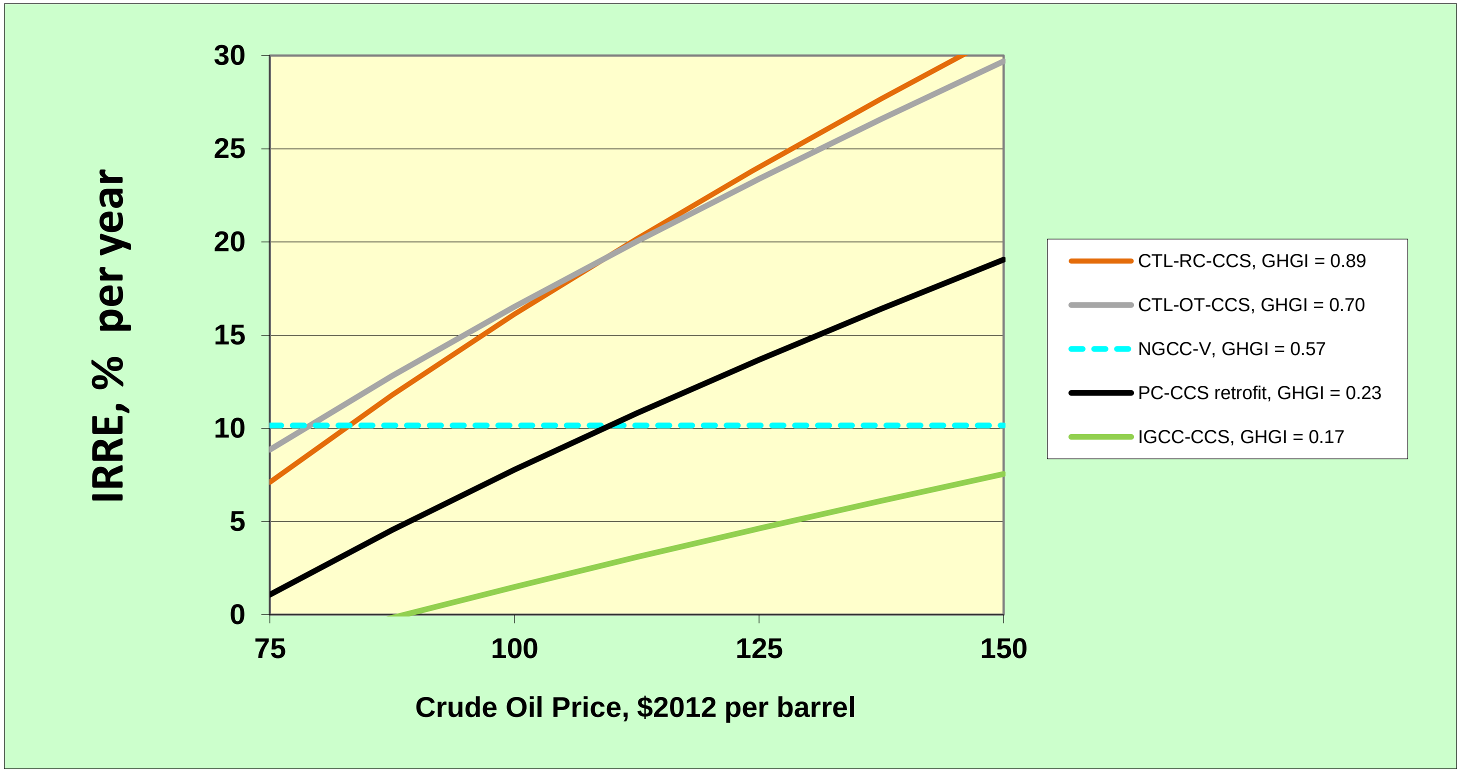
CTL-RC-CCS and CTL-OT-CCS IRRE values are comparable and far higher than for all stand-alone power plants ➔ CTL-OT-CCS considered as a power generator represents a promising approach to coal power generation in a carbon-constrained world**…but if oil prices turn out to be lower?**

IRRE for NOAK Plants (Nearby EOR), $0/t GHG Emissions Price



- The CTL options remain more profitable than any of the power-only options down to crude oil prices ~ $80/bbl.
- Notably IGCC-CCS with captured CO_2 used for EOR is not acceptably profitable at any crude oil price in the absence of a price on GHG emissions.

FOAK vs NOAK Plants

- Much lower IRRE values are expected for more costly first-of-a-kind (FOAK) plants [perhaps up to 2X as costly as NOAK plants described above (Williams, 2013a)]
- But early-mover plant costs are expected to decline with experience [learning by doing (LBD)] (Rubin et al., 2004).
- In absence of a substantial price on GHG emissions subsidies probably be needed for early-mover projects to facilitate technology cost buydown (TCB).
- NOAK plant IRRE analysis can be screening analysis for choosing best TCB candidates:
  - CTL-RC-CCS, CTL-OT-CCS, and PC-CCS retrofit are the more promising candidates
  - Because it is about as profitable as CTL-RC-CCS and far more profitable than any other stand-alone power option for crude oil prices > $80/bbl, CTL-OT-CCS (considered as a power plant) stands out as the leading candidate for technology cost buydown
- Williams (2013a) estimates that in the TCB process for CTL-OT-CCS linked to CO_2 EOR and a crude oil price = AEO 2013 levelized (2021-2040) Reference Scenario oil price:
  - Subsidies for early-mover projects would be large if it is required that the LCOE be as low as for NGCC-V
  - Only a few (~ 3) plants would require subsidy before CTL-OT-CCS plants could compete without subsidy
  - If subsidies are financed from the new federal corporate income tax revenues/royalties arising from deployment of these systems, new federal revenues net of subsidies would be +tive for the very first plant—at so that needed subsidies would be affordable even for fiscally constrained governments.

Toward Deep Reductions in GHG Emissions

- Despite attractive prospective CTL economics, these synfuel systems are characterized by carbon footprints only modestly less than for conventional energy:

  (GHGI = 0.89 for CTL-RC-CCS and 0.70 for CTL-OT-CCS)
- Between now and 2050, deep reductions in GHG emissions will be needed to realize the aspirational goal of keeping the global mean temperature increase from pre-industrial levels below 2°C [as all countries agreed to in Cancun (COP 16, December 2010)].
- Deep reductions in GHG emissions are realizable by coprocessing sustainably grown biomass with coal in CBTL systems similar to CTL systems: negative GHG emissions associated with photosynthetic CO_2 storage is exploited in CBTL systems to offset positive emissions from coal-derived carbon (Liu et al., 2011; Williams, 2013a, 2013b):
  - Coproduction systems coprocessing ~ ¼ biomass (CBTL systems) could be designed to have same carbon footprint (GHGI) as IGCC-CCS; NOAK versions might be highly profitable at the social cost of carbon (Williams, 2013a).
  - CCS via CBTL systems is likely to be more profitable than for BTL systems…a result of scale economies and lower average feedstock cost (Williams, 2013b).
  - For low-rank coals (lignite or subbitiuminous coal) the coprocessing of > ¼ biomass has been demonstrated for the transport gasifier ➔ biomass coprocessing might well go forward first for low-rank coals (Williams, 2013c).
  - The # of costly early-mover systems coprocessing ~ ¼ biomass requiring subsidy in CO_2 EOR applications in the absence of a price on GHG emissions higher than for CTL-OT-CCS but still modest (~ 6) at same projected crude oil price (Williams, 2013a).

Summary of Findings

- There are large opportunities in China for CO_2 storage projects using low-cost CO_2 from chemical and synfuel plants—attractive opportunities for international collaboration.

- What are prospects that CO_2 EOR opportunities can be exploited for CO_2 capture technology market launch without CO_2 emissions price?
  - Poor for new plants producing only electricity;
  - Good for NOAK PC-CCS retrofits; outstanding for NOAK CTL plants;
  - Subsidies will be needed for more costly early-mover plants—but only for a small # of plants in CTL cases.

- CTL coproduction plants are likely to be very profitable in providing electricity as well as liquid fuels with reduced GHG emissions.

- But coprocessing ~ ¼ biomass needed to reduce coproduction system carbon footprint (GHGI) to IGCC-CCS level; such CBTL coproduction plants are likely to be quite profitable at the social cost of carbon.

Appendix with Supporting Materials

A.1: Assumed Exogenous Prices (2012$) & Financial Assumptions

Levelized fuel prices, 2021-2040, for US average power generators from EIA (2013c) [a], ($\$/\mathrm{GJ}_{\mathrm{HHV}}$)	
Coal	2.7
Natural gas	5.8
Price of biomass (switchgrass) delivered to conversion plants ($\$/\mathrm{GJ}_{\mathrm{HHV}}$)	5.4
Levelized crude oil price, 2021-2040, from EIA (2013c)[a], $/bbl	124
Capacity factors for power (FTL) plants are assumed to be design CFs, %	85 (90)
Economic life of energy conversion plants (years)	20
Construction time for energy conversion plants (years)	3
[OC (owner's cost)]/TPC for new plants[b]	0.228
Corporate income tax rate, % per year	39.2%
Property tax & insurance (PTI) as % of TPC assuming zero inflation	2.0
Debt/equity ratio	55/45
Real (inflation-corrected) rate of return on debt (ROD), %/year	4.4
Real rate of return on equity (ROE) for capture cost calculations, %/year	10.2
Selling price for electricity, $\$/\mathrm{MWh}_e$	$59.7/MWh[c] + value of GHG emissions for an NGCC-V plant
Selling prices for synfuels	Refinery-gate price of equivalent crude oil-derived products, including value of fuel-cycle-wide GHG emissions
Net CO_2 required per incremental barrel of crude oil, tonnes/barrel	0.4 (state-of-the art value)
Plant-gate CO_2 selling price, $\$/\mathrm{t}$	0.444*(Crude oil price, $\$/\mathrm{bbl}$)[d] – CO_2 transport cost ($\$/\mathrm{t}$)
CO_2 transport cost, $\$/\mathrm{t}$	10 (corresponds to nearby EOR)

[a] EIA (2013c).

[b] This is the average OC/TPC ratio for power systems analysed in NETL (2010).

[c] This is the LCOE for NGCC-V at the levelized NG price, 2021-2040, in the absence of a price on GHG emissions.

[d] The CO_2 price ($\$/\mathrm{t}$) at EOR sites in West Texas averaged 0.265 to 0.624 x (crude oil price, $\$/\mathrm{bbl}$), 2008-2011 (Wehner, 2011). In the present analysis, the midrange value of the coefficient is assumed.

A.2: Estimated Landed LNG Prices ($/MMBTU), November 2013

Source: Waterborne Energy, Inc., 7 October 2013.

For comparison, in 2012 the US average refiner acquisition price for crude oil in 2012 was $17.7/MMBTU ($103/bbl) and the average US Henry Hub natural gas price was $2.67/MMBTU.