Toward Decarbonization of Power as Well as Fuels via Co-Production with CCS & Coal/Biomass Coprocessing

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Systems Analysis for Synthetic Fuels Production

- Alternative FTL system configurations were investigated in detail in the following PCC report (*available on request*):

  T. Kreutz, E. Larson, G. Liu, and R. Williams, "Fischer-Tropsch Fuels from Coal and Biomass," *Proc. 25th Annual Pittsburgh Coal Conference*, 2008.

- Research Support:
  - Princeton University's Carbon Mitigation Initiative (BP/Ford-supported)
  - NetJets
  - Hewlett Foundation
  - NRC contract

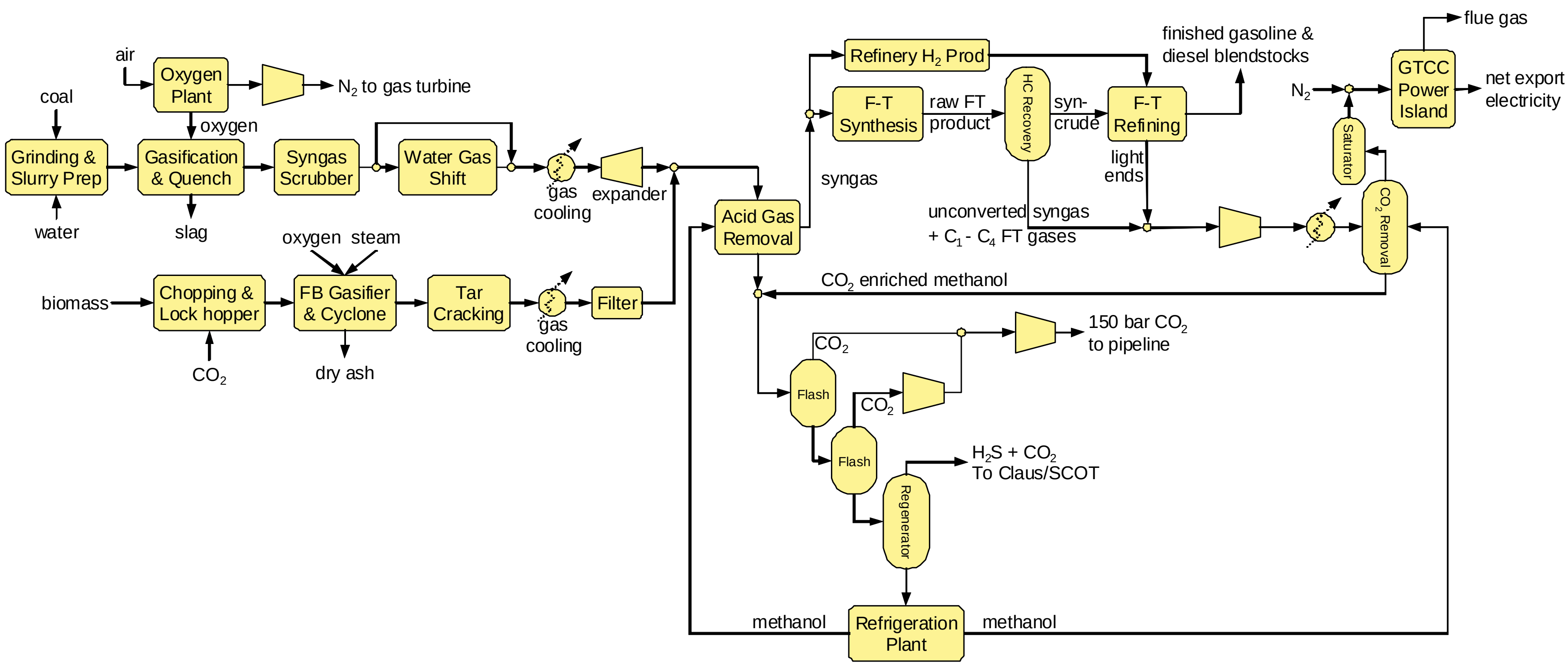
Feedstock Assumptions

Feedstock	Type	Delivered price, $\$/GJ_{HHV}$
Coal	Bituminous, Illinois #6	1.7
Biomass	Switchgrass	5.0

Acronyms

CTL	Coal to finished FTL fuels (diesel/jet, gasoline) and electricity
BTL	Biomass to finished FTL fuels (diesel/jet, gasoline) and electricity
CBTL	Coal + biomass to finished FTL fuels (diesel/jet, gasoline) and electricity
RC	FTL synthesis with recycle (RC) of unconverted syngas for maximum FTL output
OT	FTL synthesis with once through (OT) synthesis; unconverted syngas used to make coproduct power in a combined cycle
V	Coproduct CO_2 is vented
CCS	Coproduct CO_2 is captured and piped to underground storage site
GHGI	*GHG emissions index* = FTL emissions relative to emissions for crude oil products displaced when electricity is assigned rate for coal IGCC with 90% capture
CI	*capture index* = CO_2 captured as fraction of feedstock C not in products

Once-Through FT Synthesis + CCS via Coal/Biomass Co-Processing



Focused attention has been given to these systems

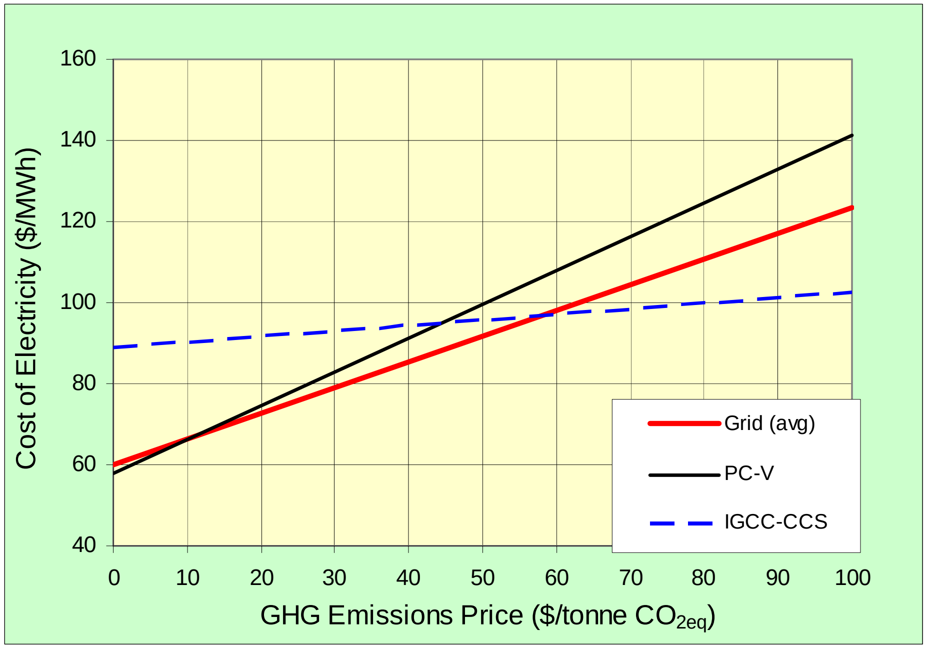
FTL Analytical Framework

- Consistent and detailed analytical framework applied to compare 16 FTL process designs using coal and/or biomass as feedstocks.
- Aspen Plus for estimating mass/energy/carbon balances and then using these to estimate CAPEX, component by component as of mid-2007.
- "Nth" plant ($N \approx 5$) performance/cost estimates
- Key technology components:
  - GE quench gasifier for coal
  - GTI (O_2 + *steam*)-blown fluid-bed gasifier + tar cracking for biomass
  - Rectisol for acid gas removal
  - low-temperature slurry-phase FT reactor (*Fe catalyst*)
  - Onsite FT refining to finished diesel/jet fuel *and* high-octane gasoline blendstocks
  - power island with:
    - steam turbine power for FT recycle cases that maximize FTL production
    - combined cycle power with "F" class gas turbines for FTL once-through cases
- GREET model in estimating fuel-cycle-wide GHG emissions outside plant boundaries

Some Major Findings of PCC Study

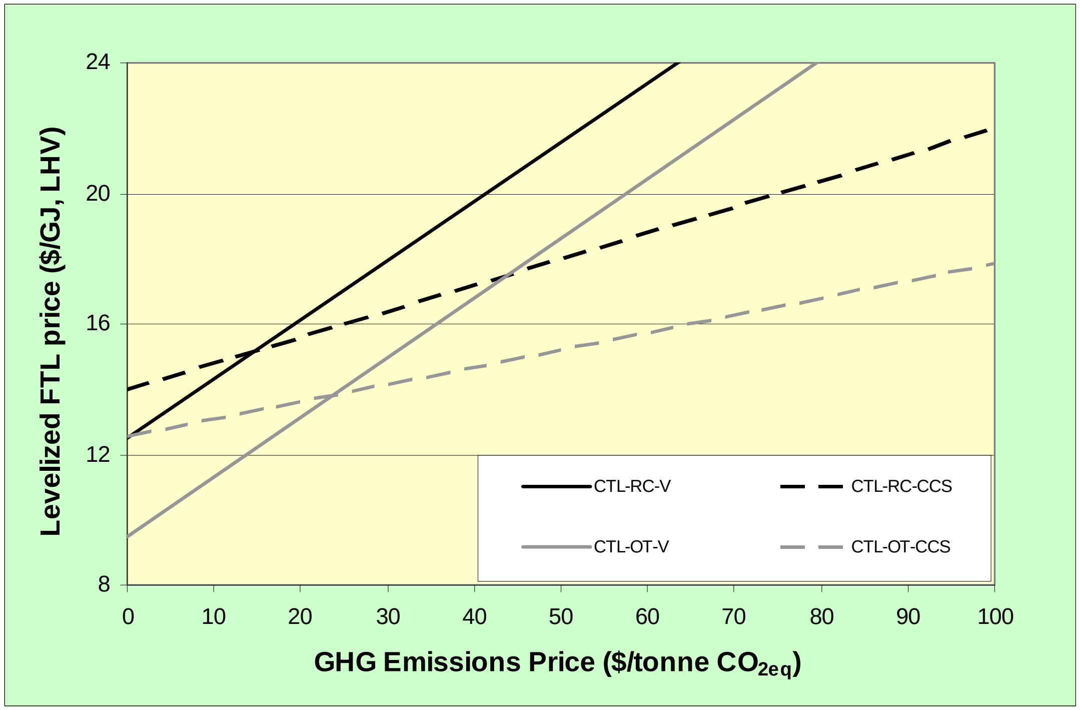
- Co-production [*once-through (OT)*] plants can provide FTL at lower cost than recycle (RC) plants designed to maximize FTL output.
- Coprocessing biomass with coal in co-production plants with CCS enables a major role for coal in providing synfuels in a carbon-constrained world
- Co-production plants can provide decarbonized electricity at far lower costs of GHG emissions avoided than can stand-alone fossil fuel power plants
- These widely held tenets of conventional wisdom are probably wrong:
  - RC systems offer the most profitable route to synfuels production
  - It is easier to decarbonize electric power than liquid fuels for transportation
  - Electric power will be decarbonized mainly in stand-alone power plants

When Evaluating FTL Systems as Fuel Producers, How Should Co-Product Electricity Be Valued?



- Assumed value of electricity coproduct of FTL plants ( ) = average US grid price in 2007 + value of 2007 US average grid GHG emission rate (*636 kgCO_{2eq}/MWh*).
- For reference, generation costs are shown for:
  - PC-V (*pulverized coal supercritical steam-electric plant with CO_2 vented*)
  - IGCC-CCS (*coal integrated gasifier combined cycle plant with CCS*).

OT Options Outperform RC Options Economically



Production costs are 10-24% less for CTL-OT systems compared to CTL-RC systems at zero GHG emissions price.

Economic advantage of CTL-OT-CCS grows with GHG emissions price.

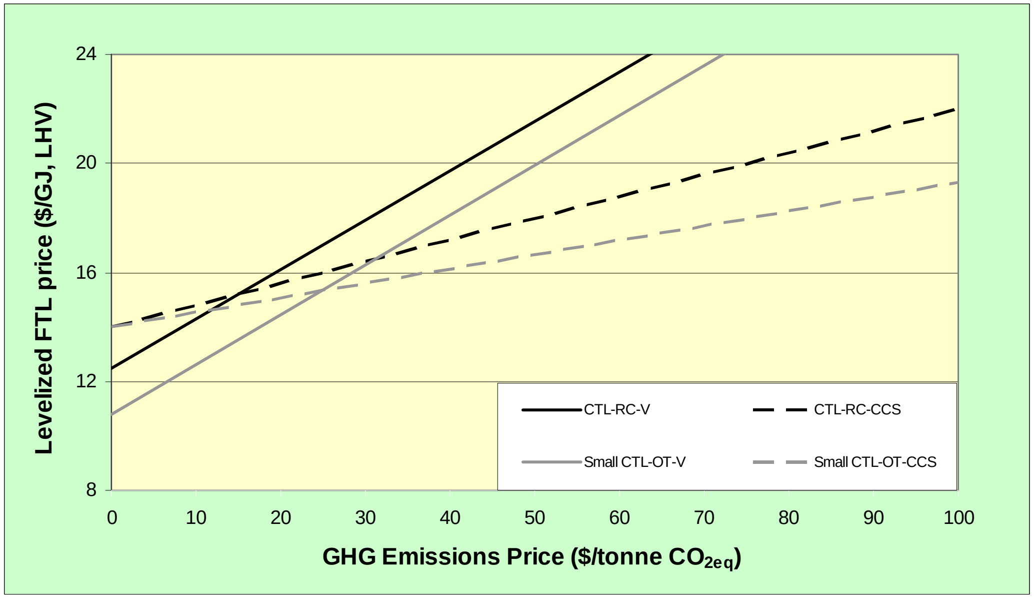
FTL System (*same coal input rates for all*)	Outputs	GHGI	CI	CAPEX	
				$\$10^3$ per B/D	$\$10^9$
CTL-RC-V	50,000 B/D, 427 MW_e	2.2	0	97.6	4.88
CTL-RC-CCS	50,000 B/D, 317 MW_e	1.0	0.78	98.9	4.95
CTL-OT-V	36,700 B/D, 1279 MW_e	2.8	0	120.2	4.41
CTL-OT-CCS	36,700 B/D, 1075 MW_e	1.3	0.68	125.4	4.60

Why Do OT Options Outperform RC Options?

- Consider OT & RC plants with same FTL outputs
- 1 OT advantage: high marginal efficiency (ME) of power generation:

  ME = (Δ net electric output)/(Δ coal input, LHV)
- For CTL-OT systems: MEs for power are ~ 10 percentage points higher than for stand-alone power via coal IGCC.
- High MEs arise because gas turbine exhaust in downstream combined cycle power plant offers enough high-quality "waste heat" to both:
  - Superheat for power saturated steam from synthesis, other upstream exotherms,
  - Generate additional steam for power generation.
- High MEs manifest by ST/GT output ratios for OT FTL ~ 1.1 – 1.2 (*vs ~ 0.6 for typical stand-alone coal IGCC plant*).
- In RC systems, not enough high-quality "waste heat" is available.
- Also, incremental specific capital for extra power ($\$/kW_e$) < ½ of capital for stand-alone power

OT Systems: Favorable Economics at Smaller Scales



CAPEX ~ 40% less for Small CTL-OT-CCS systems offering FTL at same cost as for CTL-RC-CCS systems @$0/t CO_{2eq}

FTL System	Outputs	GHGI	CI	CAPEX	
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CTL-RC-V	50,000 B/D, 427 MW_e	2.2	0	97.6	4.88
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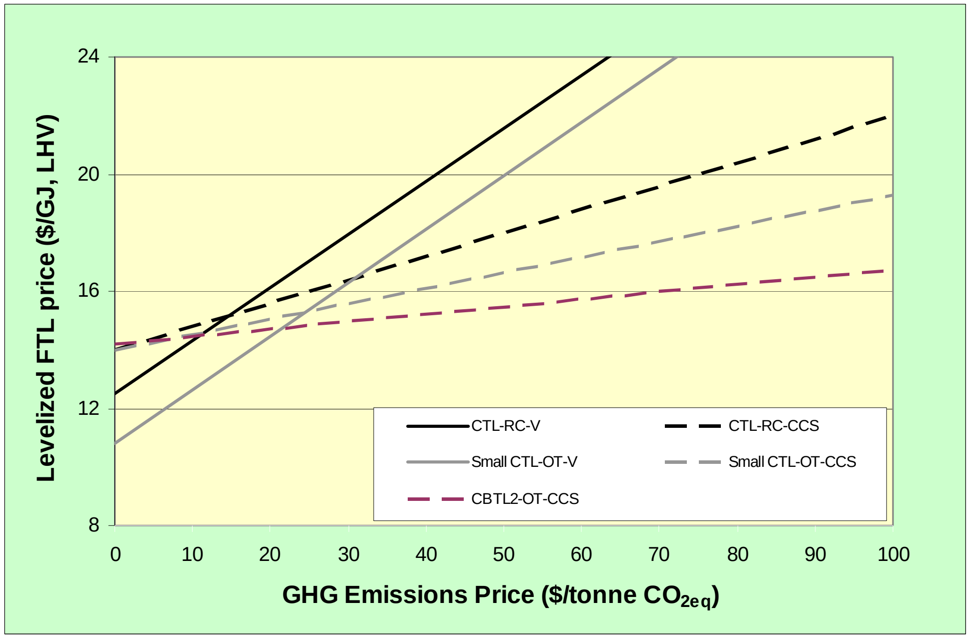
Small CTL-OT-V	19,300 B/D, 674 MW_e	2.8	0	132.5	2.56
Small CTL-OT-CCS	19,300 B/D, 566 MW_e	1.3	0.68	137.0	2.65

Benefits of Coprocessing Modest Amount of Biomasss



Coprocessing ~ 9% biomass reduces GHGI by 23%

Resulting CBTL2-OT-CCS system provides less costly FTL than CTL-OT-V for GHG emission prices > $22/t CO_{2eq}

FTL System	% Bio, HHV	Outputs	GHGI	CI	CAPEX	
					$\$10^3$ per B/D	$\$10^9$
CTL-RC-V	0	50,000 B/D, 427 MW_e	2.2	0	97.6	4.88
CTL-RC-CCS	0	50,000 B/D, 317 MW_e	1.0	0.78	98.9	4.95
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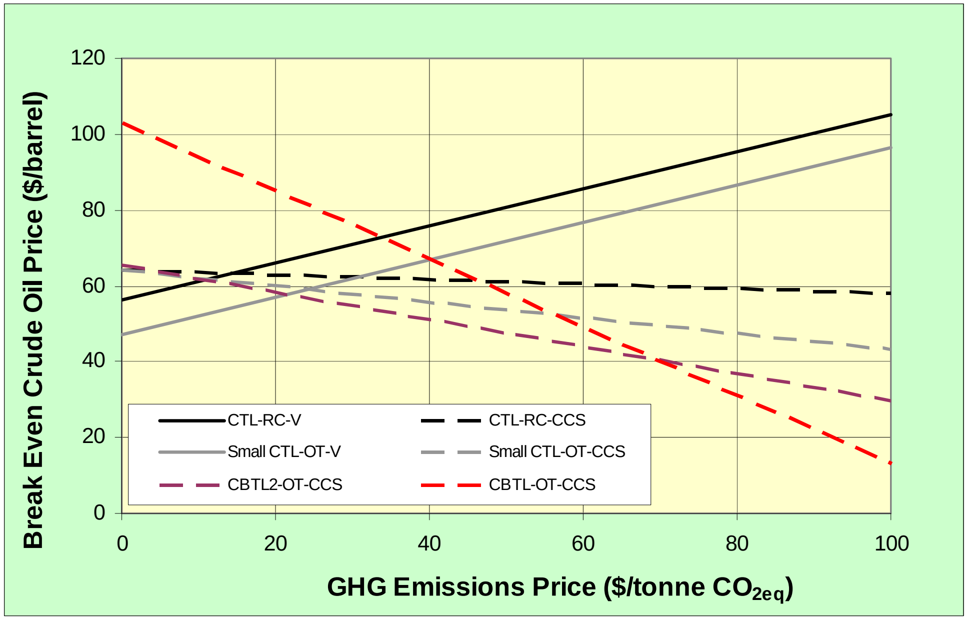
CBTL2-OT-CCS	8.6	19,300 B/D, 583 MW_e	1.0	0.68	132.3	2.56

C Mitigation + Investment Security via Coprocessing



If biomass share → ~ 38%, FTL GHG emission rate → 0

Resulting CBTL-OT-CCS system provides high degree of protection against risk of oil price collapse under serious C-mitigation policy

FTL System	% Bio, HHV	Outputs	GHGI	CI	CAPEX	
					$10^3 per B/D	$10^9
CTL-RC-V	0	50,000 B/D, 427 MW_e	2.2	0	97.6	4.88
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CBTL2-OT-CCS	8.6	19,300 B/D, 583 MW_e	1.0	0.68	132.3	2.56
CBTL-OT-CCS	38.1	8,100 B/D, 276 MW_e	0.0	0.67	170.1	1.38

How Can Even Modest Biomass Inputs Have Such Significant Impacts in Reducing Costs Under C Policy?

(*assumed \$5.0/GJ biomass price = 3X coal price*)

- For FTL systems ~ ½ of C in feedstock is available as CO_2 at high partial pressure—can be captured for geological storage at low incremental cost.
- Biomass derived CO_2 stored underground represents negative emissions that can be used to offset positive CO_2 emissions from coal.
- Decarbonized electricity coproduct credit for OT increases with GHG emissions price ➔ FTL cost falls rapidly with GHG emissions price.
- For perspective, IEA's *World Energy Outlook 2008* projection of GHG emissions price in 2030 (*in OECD countries*):
  - \$90/t for 550 ppmv Stabilization Scenario
  - \$180/t for 450 ppmv Stabilization Scenario

When Evaluating CTL-OT Systems As Power Generators Instead of Fuel Producers:

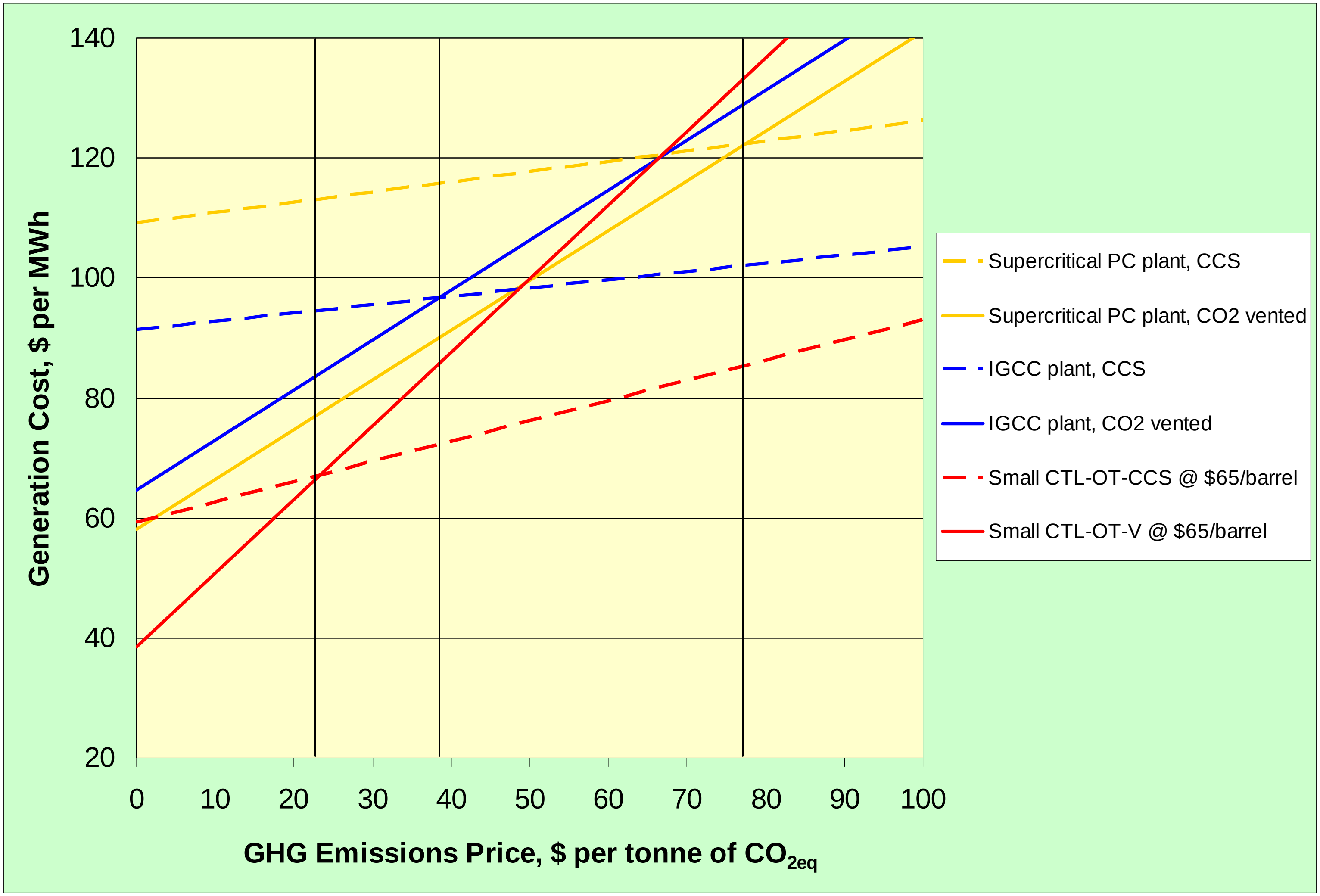
- Assign to FTL products:
  - System-wide GHG emission rates for crude oil products displaced
  - Economic worth = refinery-gate prices of crude oil-derived products displaced
- Thus, levelized generation cost ($ per MWh of electricity) =

= [Levelized system cost ($/year) – levelized economic worth of synfuel products ($/year)]/[levelized generation rate (MWh/year)]

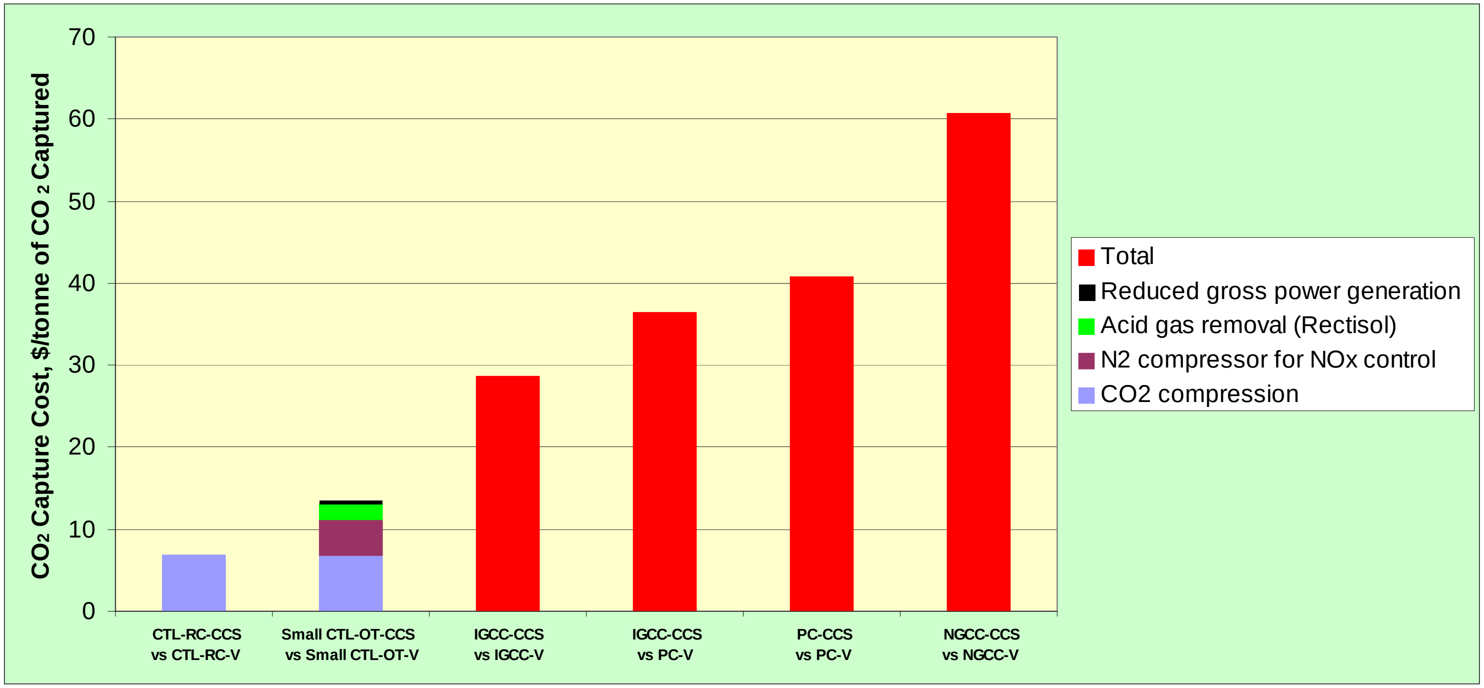
Cost of GHG Emissions Avoided

- Cost of GHG emissions avoided
  = [(production cost, CCS) – (production cost, CO_2 vented)]
  /[(GHG emissions, CO_2 vented) – (GHG emissions, CCS)]
- Cost of GHG emissions avoided = GHG emissions price at which generation costs are the same for V and CCS options

Cost of GHG Emissions Avoided for FTL OT Plants << Than for Stand-Alone Power Plants



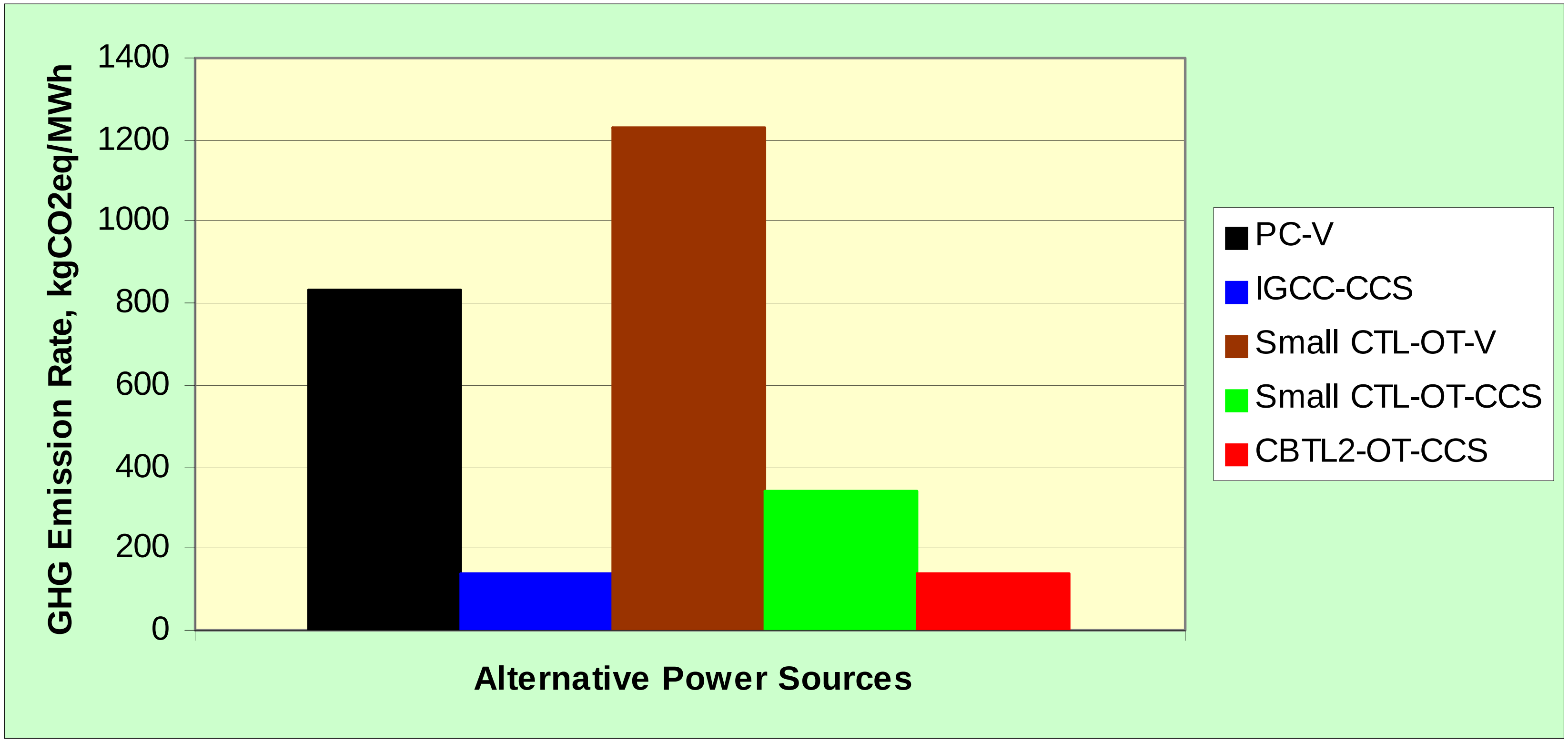
Why do OT Systems Out-Perform Stand-Alone Power Systems in Reducing GHG Emissions for Power?



FTL systems produce concentrated CO_2 streams as core element of synthesis process ➔ inherently low cost of CO_2 capture:

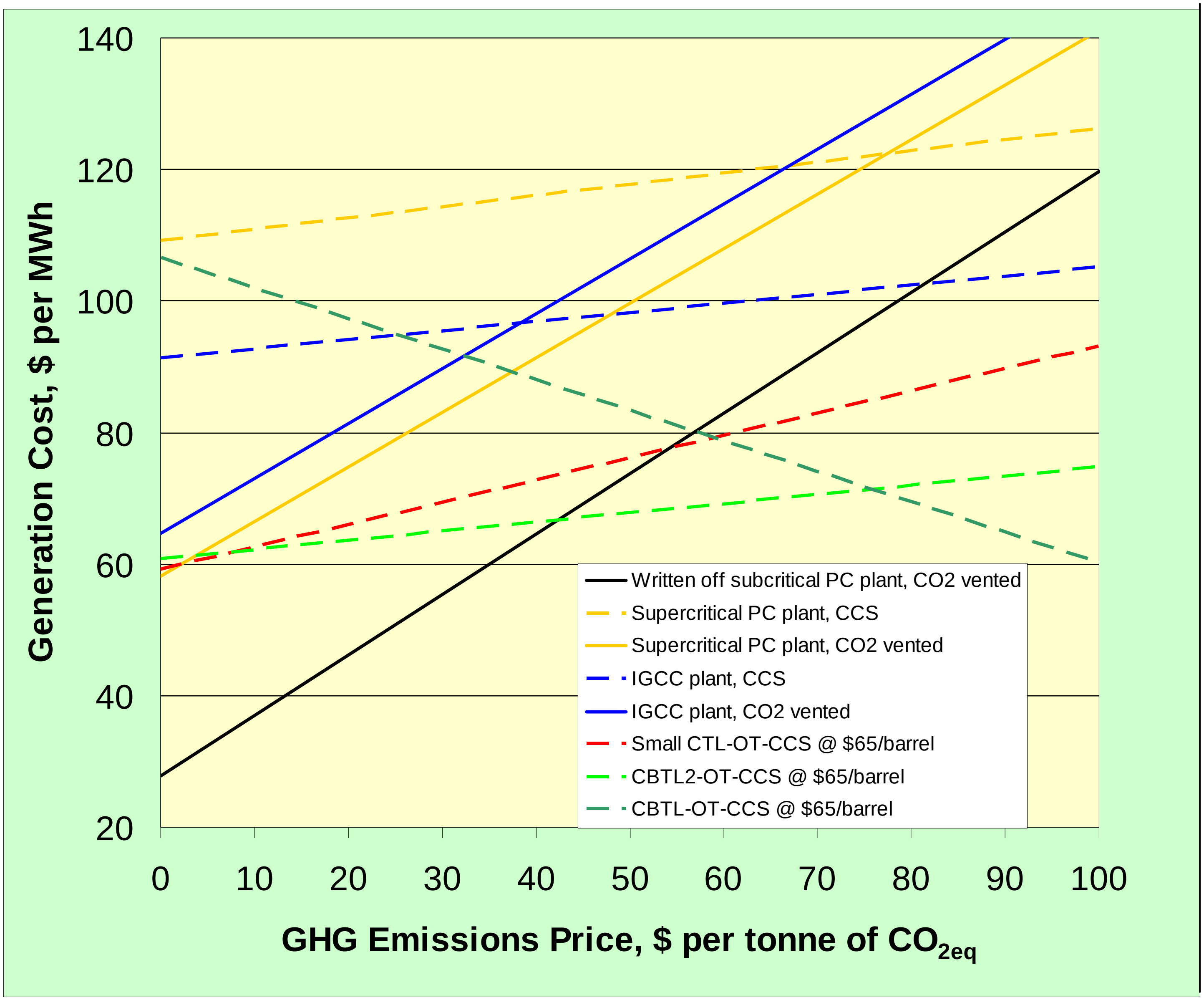
- CTL-RC-CCS: capture cost is for CO_2 drying/compression
- Small CTL-OT-CCS: most additional cost for N_2 compression for NO_x emissions control
- In making FTL via Co catalyst OT capture cost likely to be not much more than for RC (*Fe catalyst assumed for displayed FTL system*)

GHG Emission Rates for Alternative Power Options



- GHG emission rate (*electricity*) relative to IGCC-CCS (*90% capture*):
  - 2.5 for Small CTL-OT-CCS
  - 1.0 for CBTL2-OT-CCS
- What are the COEs for these alternative power options?

Generation Cost: Co-Production vs Stand-Alone Power



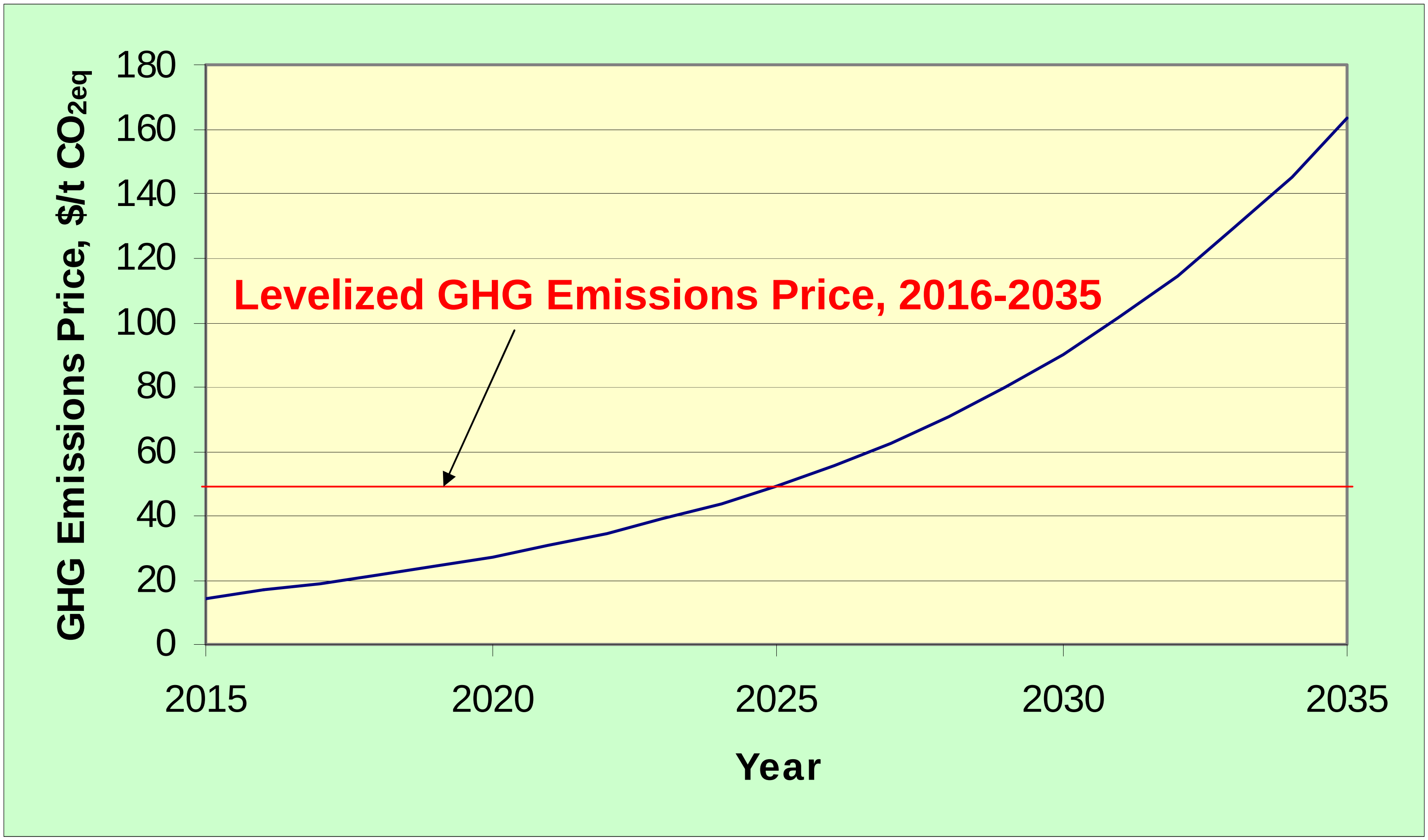
Reflections on Co-Production Systems

- OT-CCS systems offer opportunity to decarbonize electricity at much lower costs than for stand-alone coal power plants
- OT-CCS systems that coprocess biomass:
  - Enable simultaneous decarbonization of both synfuels and electricity at attractive costs and GHG emissions prices < those envisioned for 2030 in *WEO 2008 Stabilization Scenarios* of the International Energy Agency and thereby
  - Enable a major role for coal in mitigating climate change
- Technical hurdles
  - CCS must be viable as a carbon mitigation strategy at "gigascale"…need ASAP many "megascale" integrated CCS projects with storage in deep saline formations
  - Large biomass gasification systems must be commercialized
- Institutional hurdles: formidable…facilitating public policy needed

Proposed DoD/DoE CCS Early Action Initiative (CEAI)

- Urgency to carry out "megascale" integrated CCS projects
- G8 Summit (*Japan 2008*)
  - G8 agreement to sponsor 20 projects globally (*up & running ~ 2016*)
  - US commitment to sponsor 10
- Do economic crisis/budget deficit concerns jeopardize G8 goal?
- CEAI (*enabling goal realization at low cost to government*) would:
  - Allow co-production systems to compete with power only systems for subsidies
  - Require produced synfuels to comply with Section 526 of EISA of 2007
  - Specify that winning projects are those with least CEAs (e.g., reverse auction)
- For winning projects:
  - Government would pay incremental cost for CCS for 5 years
  - Air Force would offer 20-year procurement contracts for jet fuel

Assumed GHG Emissions Price Trajectory for CEAI



- Consistent with WEO 2008 550 Stabilization Scenario (*$90/t in 2030*)
- CBTL2-OT-CCS would be profitable w/o CCS subsidy after 5 years

Cost of CEAI Incentives to Government If All 10 Winning Projects Were CBTL2-OT-CCS Systems

(*cost valuation for co-production systems from "fuels perspective"*)

Levelized crude oil price, \$/barrel	35	45	55	65
PW of subsidy for incremental CCS Cost, $\$10^9$	0.39			
PW of synthetic jet fuel procurement, $\$10^9$	6.46	2.60	- 1.27	- 5.13
Present worth (PW) of total obligation, $\$10^9$	6.84	2.98	- 0.88	- 4.74

- By 2016:
  - 5.8 GW_e of decarbonized power capacity on line
  - 1700 million gallons/year of synthetic diesel would be produced/procured
- By 2021:
  - ~ 0.25 Gt CO_2 stored in deep saline formations
  - Biomass supply logistics technologies would be established in the market.
- Negative net cost to government if oil price > \$55/barrel.

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