Fischer-Tropsch Fuels from Coal and Biomass

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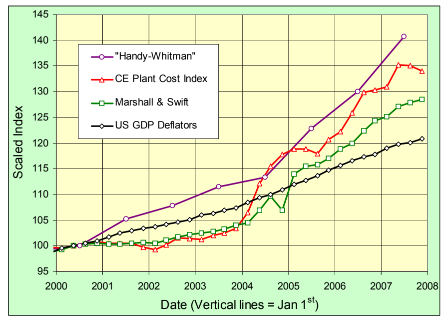
FTL Analytical Framework

- 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.
- "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
  - 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

Capex Estimates

- Aspen mass/energy/carbon balance simulations used as basis for power-law scaling of Capex for:
  - Most major plant areas: from NETL coal power study (*2007*).*
  - Biomass gasification: from Fluor studies (*1984,1985*) + NETL coal power study (*2007*)
  - F-T island: Bechtel work** from 1990s—including upgrading to finished fuels
- Costs include BOP, indirects, and contingencies
- N^{th} plant design philosophy (*for equipment train sizes and costs*)
- All costs escalated to mid-year 2007$ using *Chemical Engineering Plant Cost* index.



* *Cost and Performance Baseline for Fossil Energy Plants: Volume 1: Bituminous Coal and Natural Gas to Electricity*, DOE/ NETL-2007/1281, Rev. 1, August 2007, National Energy Technology Laboratory.

** Bechtel, *Baseline Design/Economics for Advanced Fischer-Tropsch Technology*, report under contract DE-AC22-91PC90027, April 1998, Federal Energy Technology Center.

Feedstock Assumptions

Feedstock	Type	Delivered price, $/GJ$_{HHV}$
Coal	Bituminous, Illinois #6	1.71
Biomass	Switchgrass/mixed prairie grasses	5.0

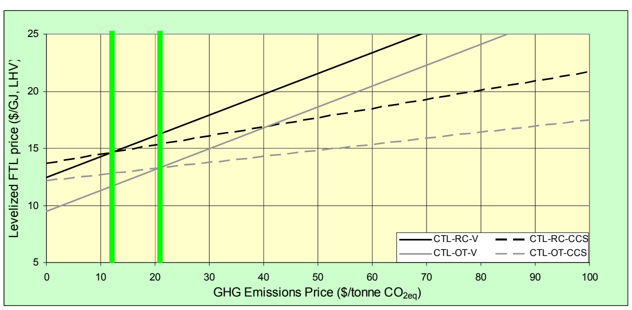
Acronyms

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
OTA	Autothermal reformer and extra CO_2 capture equipment added to OT system downstream of FT synthesis to increase CO_2 capture/storage
V	Coproduct CO_2 is vented
CCS	Coproduct CO_2 is captured and piped to underground storage site
S	Biomass feedstock is mixed prairie grasses grown on C-depleted soils. Soil/root C buildup as biomass C storage mechanism complements underground storage of supercritical CO_2

Sixteen Process Designs

CTL-RC-V	50,000 barrels/day of finished FTL fuels (diesel/jet and gasoline)
CTL-RC-CCS	Same coal input and same FTL outputs as CTL-RC-V
CTL-OT-V	Same coal input as CTL-RC-V
CTL-OT-CCS	Same coal input as CTL-RC-V, same FTL outputs as CTL-OT-V
CTL-OTA-CCS	Same coal input as CTL-RC-V, same FTL outputs as CTL-OT-V
BTL-RC-V	CBIR (*Common Biomass Input Rate = 10^6 dry metric tonnes/yr processed*)
BTL-RC-CCS	CBIR, same FTL outputs as BTL-RC-V
CBTL-RC-V	CBIR, same coal input, FTL outputs as CBTL-RC-CCS
CBTL-RC-CCS	CBIR, coal/biomass ratio that yields FTL with zero GHG emission rate
CBTL-OT-V	CBIR, same coal input, FTL outputs as CBTL-OT-CCS
CBTL-OT-CCS	CBIR, coal/biomass ratio that yields FTL with zero GHG emission rate
CBTL2-OT-CCS	CBIR, same FTL outputs as CTL-OT-CCS
CBTL-OTS-CCS	CBIR, coal/biomass ratio that yields FTL with zero GHG emission rate
CBTL-OTA-V	CBIR, same coal input, FTL outputs as CBTL-OTA-CCS
CBTL-OTA-CCS	CBIR, coal/biomass ratio that yields FTL with zero GHG emission rate
CBTL-OTAS-CCS	CBIR, coal/biomass ratio that yields FTL with zero GHG emission rate

Some CTL Options: V vs CCS; RC vs OT

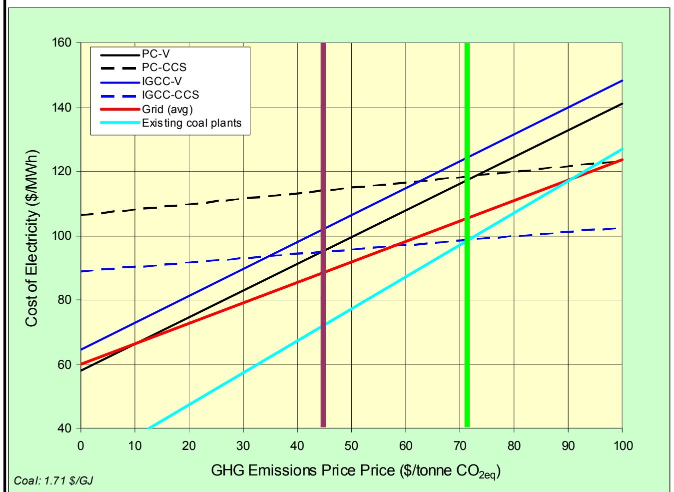


Minimum GHG emissions price to induce CCS

- η_{HHV} = efficiency of making FTL + electricity (HHV basis)
- GHGI (*GHG emissions index*) = FTL GHG emissions relative to emissions for COPD when electricity assigned C-IGCC-CCS GHG emission rate
- CI (*capture index*) = CO_2 captured as fraction of feedstock C not in FTL
- BECOP = Breakeven crude oil price (*$/barrel*) at $0/t of CO_{2eq}

System	Outputs	η_{HHV}	GHGI	CI	CAPEX ($\$10^9$)	BECOP
CTL-RC-V	50,000 B/D + 427 MW_e	0.500	2.2	0	4.88	56
CTL-RC-CCS	50,000 B/D + 317 MW_e	0.486	1.0	0.78	4.95	63
CTL-OT-V	36,700 B/D + 1279 MW_e	0.493	2.8	0	4.41	40
CTL-OT-CCS	36,700 B/D + 1075 MW_e	0.467	1.3	0.68	4.60	55

Electric Generation Cost vs GHG Emissions Price



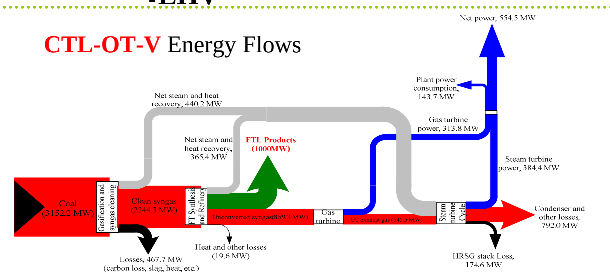
- For FTL systems coproduct electricity is valued at **average electric grid price**
- Minimum GHG emissions price needed to induce CCS for coal power depends on whether electricity demand is **growing** or **not**
- (IGCC/PC costs estimated using same methodologies as for FTL systems)

Minimum GHG emissions price to induce CCS for coal power if electricity demand is:
growing —— constant or declining ——

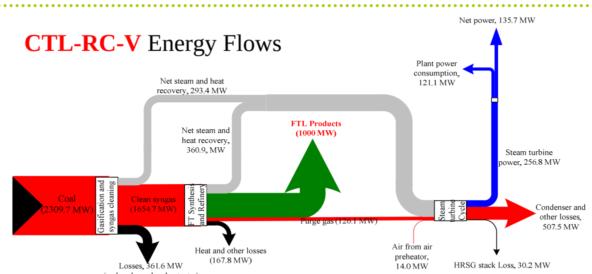
Marginal electric generation efficiency (MEGE) for CTL-OT-V >> η_{LHV} for C-IGCC-V

- **FTL = 1000 MW**
- Δ E_{coal} = 3152.2 - 2309.7 = 842.5 MW
- Δ Power = 554.5 - 135.7 = 418.8 MW_e
- MEGE = **49.7%**
- η_{LHV} for C-IGCC-V = **39.3%**

CTL-OT-V Energy Flows



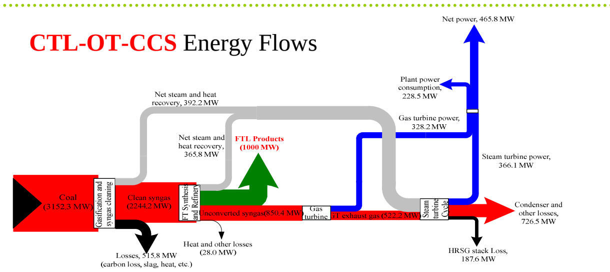
CTL-RC-V Energy Flows



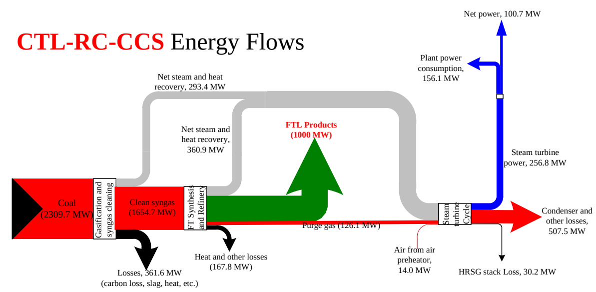
Marginal electric generation efficiency (MEGE) for CTL-OT-CCS >> η_{LHV} for C-IGCC-CCS

- **FTL = 1000 MW**
- Δ E_{coal} = 3152.3
- \- 2309.7 = 842.6 MW
- Δ Power = 465.8 - 100.7 =365.1 MW_e
- MEGE = **43.3%**
- η_{LHV} for C-IGCC-CCS = **33.2%**

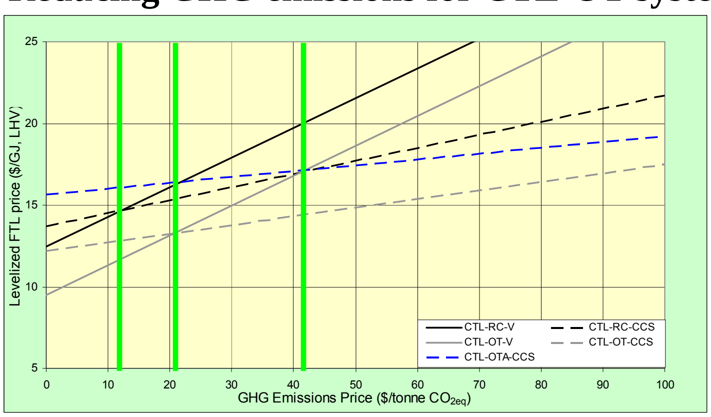
CTL-OT-CCS Energy Flows



CTL-RC-CCS Energy Flows



Reducing GHG emissions for CTL-OT systems via ATR

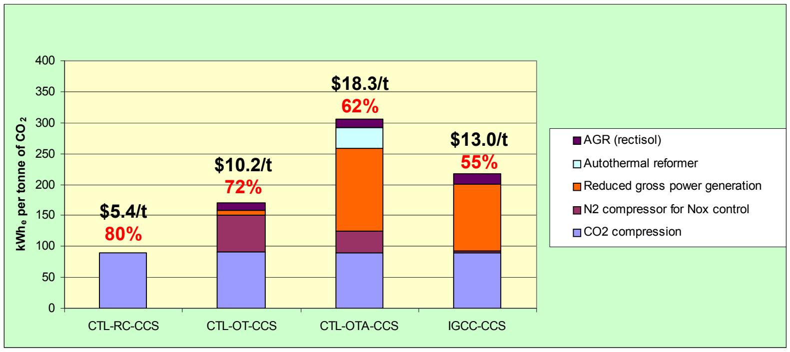


Minimum GHG emissions price to induce CCS

- Adding ATR reduces GHGI to < 1 but…
- BECOP is much higher
- Minimum GHG emissions price needed to induce CCS ~ same as for C-IGCC-CCS when electricity demand is rising

System	Outputs	η_{HHV}	GHGI	CI	CAPEX ($\$10^9$)	BECOP
CTL-OT-V	36,700 B/D + 1279 MW_e	0.493	2.8	0	4.41	40
CTL-OT-CCS	36,700 B/D + 1075 MW_e	0.467	1.3	0.68	4.60	55
CTL-OTA-CCS	36,700 B/D + 818 MW_e	0.433	0.9	0.85	5.10	73

Energy Penalty for CO_2 Capture

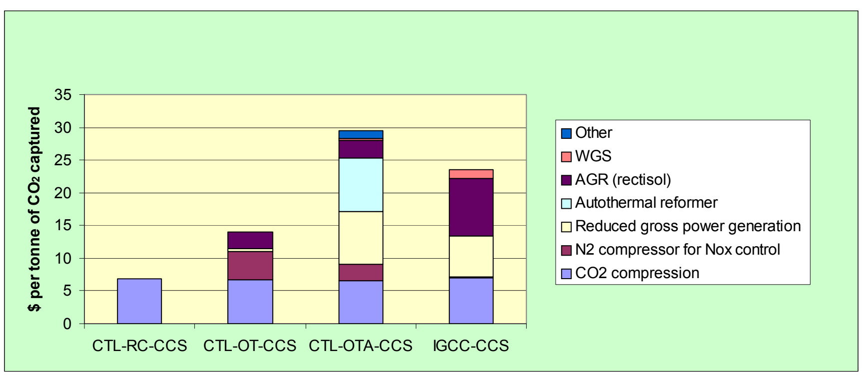


Value of Energy Penalty for CO2 Capture @ $60MWh (*$/t*)

Value of Energy Penalty (*as % of Total Capture Cost*)

- <u>CTL-RC-CCS</u>: CO_2 compression is only penalty
- <u>CTL-OT-CCS</u>: N_2 compression for NO_x control accounts for most of added penalty
- <u>CTL-OTA-CCS</u>: Penalties (*beyond CO_2 compression penalty*) consist mainly of:
  - Huge loss of gross power output from chemical energy loss via syngas burning for ATR
  - Electric energy penalty (*ASU*) for providing O_2 to ATR
  - About same level of N_2 needed per unit of GT expander output as for CTL-OT-CCS

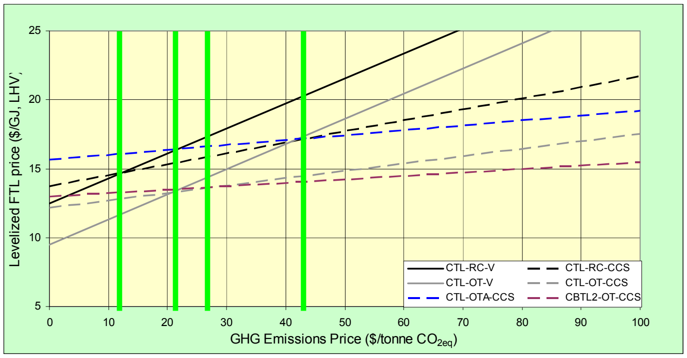
CO_2 Capture Cost



Capture cost penalty for CTL-OT-CCS is:

- 48% of penalty for CTL-OTA-CCS
- 60% of penalty for IGCC-CCS
- 35% of post-combustion capture penalty for PC-CCS (*not shown*)

Reducing CTL-OT emissions by cofiring some biomass

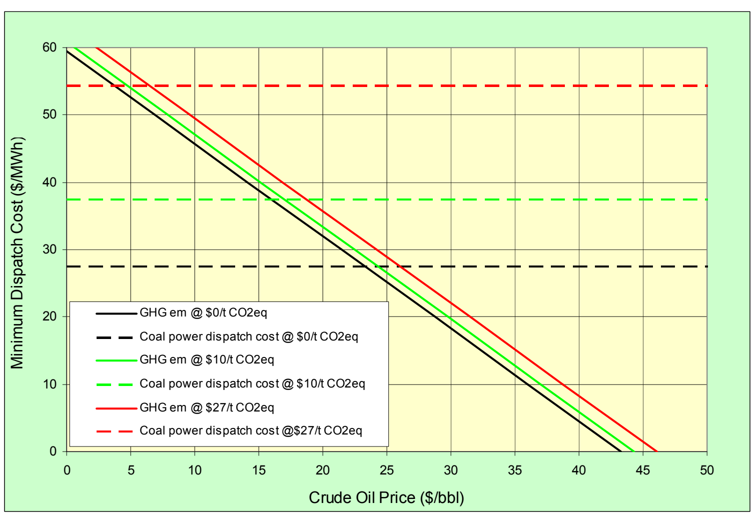


- With 9% biomass feed, GHGI → 1.0
- BECOP for CBTL2-OT-CCS << than for CTL-OTA-CCS
- CBTL2-OT-CCS offers early route for decarbonizing coal power

Minimum GHG emissions price to induce CCS

System	Outputs	η_{HHV}	GHGI	CI	BECOP
CTL-OT-CCS	36,700 B/D + 1075 MW_e	0.467	1.3	0.68	55
CTL-OTA-CCS	36,700 B/D + 818 MW_e	0.433	0.9	0.85	73
CBTL2-OT-CCS (*9% bio*)	36,700 B/D + 1113 MW_e	0.469	1.0	0.68	59

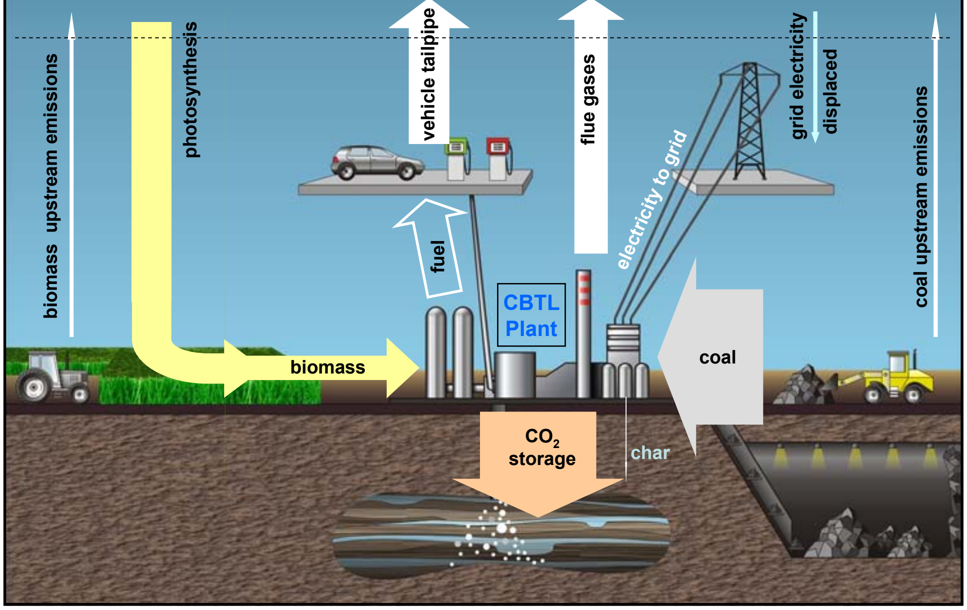
Dispatch competition: CBTL2-OT-CCS as generator of decarbonized power vs old coal power plants



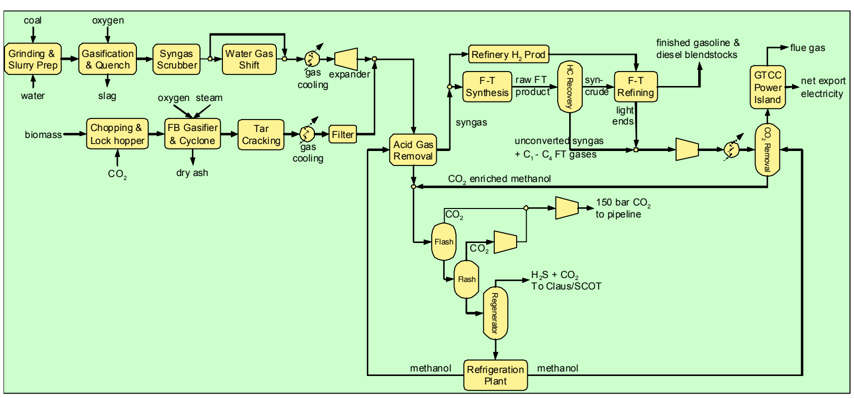
@ $27/t CO_{2eq} CBTL2-OT-CCS plants could beat old coal power plants in economic dispatch at crude oil prices down to ~ $7 a barrel

➔ This/other CBTL-OT-CCS options very effective in backing out old coal plants

C Flows for CBTL Plants Making FTL with Zero Net GHG Em + Decarbonized Electricity



CBTL-OT-CCS

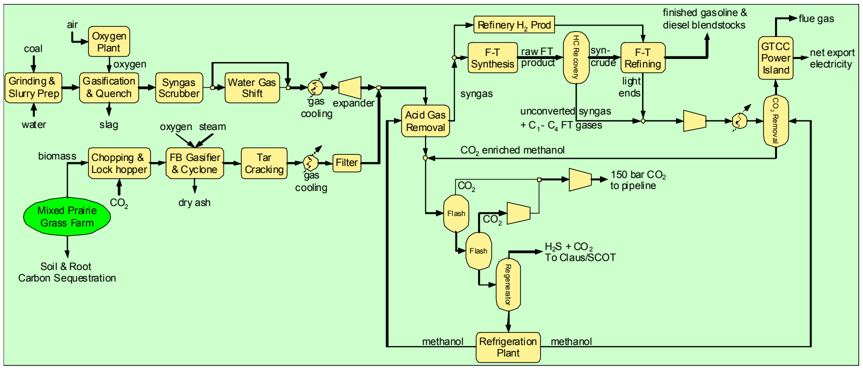


Candidate feedstocks: lignocellulosic biomass that would not lead to "C-debt" issue described in Searchinger et al. (2008): crop residues, forest biomass [*logging residues, forest thinnings* (*pine-bark beetle tree kills, fuel treatment/productivity enhancement thinnings*)], urban wood wastes

CBTL-OT-CCS is designed with just enough biomass to reduce GHGI to zero

System	Outputs	η_{HHV}	GHGI	CI	BECOP
CBTL-OT-CCS (38% bio)	8,100 B/D + 276 MW_e	0.476	0.0	0.67	101

CBTL-OTS-CCS



Assumed feedstock: mixed prairie grasses (**MPGs**) grown on land not suitable for food production (*e.g., CRP land*) with C-depleted soils

Assumed 30-y soil/root C storage rate: 0.3 tC/dt of MPG (Tilman et al., 2006).

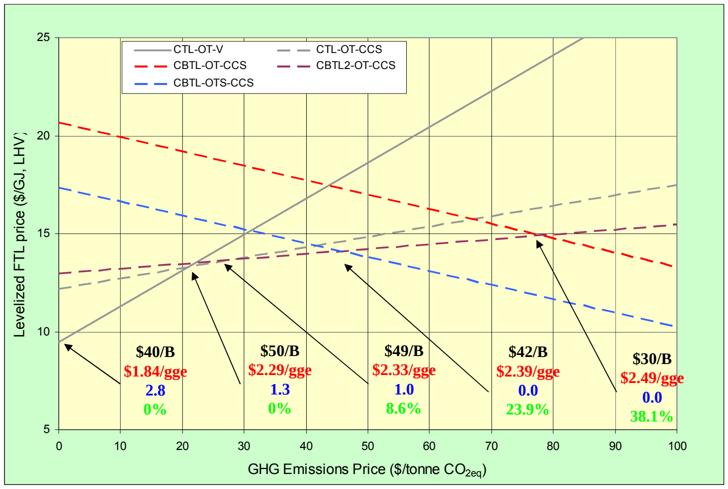
GHGI = 0 is realized with less biomass input than in CBTL-OT-CCS case

System	Output	η_{HHV}	GHGI	CI	BECOP
CBTL-OTS-CCS (24% bio)	13,000 B/D + 406 MW_e	0.467	0.0	0.67	83

FTL via CBTL with CCS vs Alternatives

- Assume deployment of CBTL systems with CCS providing decarbonized power & FTL to displace crude oil derived products + existing coal power
- Assume GHG emissions price = \$50/t CO_{2eq} under serious C-policy
- Each set of 100 CBTL-OT-CCS plants (*each plant consuming 10^6 dt/y of biomass*) could:
  - Provide at plant gate FTL w/GHGI = 0 @ \$2.0/gge and electricity @ \$92/MWh
  - *Net* coal = 22% of coal for CTL-RC-CCS plants offering FTL w/GHGI = 1.0
  - Require 59% as much lignocellulosic biomass as would be required for *future* cellulosic ethanol plants providing same amount of gasoline-equivalent fuel
  - Provide decarbonized power equivalent to 11% of US coal power in 2007
- Each set of 100 CBTL-OTS-CCS plants (*each plant consuming 10^6 dt/y of biomass*) could:
  - Provide at plant gate FTL w/GHGI = 0 @ \$1.7/gge and electricity @ \$92/MWh
  - Net coal = 50% of coal for CTL-RC-CCS plants offering FTL w/GHGI = 1.0
  - Require 37% as much lignocellulosic biomass as would be required for *future* cellulosic ethanol plants providing same amount of gasoline-equivalent fuel
  - Provide decarbonized power equivalent to 16% of US coal power in 2007

LEAST-COSTLY FTL OPTIONS



Breakeven crude oil price *($/barrel*)
FTL pump price (*$/gge…assuming $0.70/gge markup for distribution/retail taxes*)
FTL GHG emission rate relative to rate for crude oil products displaced
% biomass in feedstock (*HHV basis*)

Conclusion

- Largely because of their high marginal power generation efficiencies, OT systems are more cost-competitive than RC systems in making synfuels
- OT CBTL plants with CCS offer attractive opportunity for decarbonizing liquid fuels and power generation simultaneously
  - Require ¼ to ½ as much *net coal* for making synfuels as CTL-RC-CCS plants
  - Require ½ or less lignocellulosic biomass than for making cellulosic ethanol
- OT CBTL "must-run" power plants with CCS would be highly competitive in economic dispatch and thus able to back out existing coal power plants
- Such plants fueled with modest biomass inputs offer early route to CCS for power because CO_2 capture costs are much less than for stand-alone power plants
  - Strong candidates for 3-10 megascale integrated CCS projects during next decade to:
    - Establish gigascale viability of CCS as C-mitigation option
    - Establish strong scientific/engineering basis for regulations of subsequent commercial CO_2 storage projects
  - Competitive options for providing CO_2 for enhanced oil recovery projects
- Investments in OT CBTL plants with CCS would be shielded against financial risk of oil price collapse by a strong C-mitigation policy (*manifest by GHG emissions value ~ $50/t CO_{2eq}*)