Advanced Gasification-Based System Concepts for Biorefining

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Gasification-Based Liquid Fuels

Fischer-Tropsch Liquids (FTL)

- Synthetic crude refinable to zero-sulfur, high-cetane, low-particulate diesel blendstock and gasoline blendstock.
- Explosion of global investment in gas-to-liquids GTL (e.g., Qatar, Nigeria)
- Growing investment in coal-to-liquids, CTL (China, USA).
- Initial commercial investment in biomass-to-liquids, BTL (Germany)

Dimethyl Ether (DME) (cousin of methanol)

- Propane substitute/blendstock or zero-S, zero-PM, high-cetane diesel fuel.
- Exploding commercial investment in DME from coal in China;
- Long-standing methanol from coal production in China and USA;
- Growing investment in DME from gas in Iran, China, and (as buyer) Japan;
- Swedish interest in DME from biomass.

Mixed alcohols (MA)

- Mixture of ethanol and higher alcohols as a gasoline blendstock.
- No commercial synthesis technology available today.
- Demonstrated catalyst performance (modified methanol or modified FTL catalysts) does not yet approach MeOH or FTL catalyst performance.
- Interest exclusively in U.S.A., driven largely by policy emphasis on ethanol.

Princeton Analyses of Gasification-Based Liquid Fuels Production Systems

- Stand-alone switchgrass biorefinery: FTL, DME.[1,2]
- Biorefining integrated with kraft pulp/paper mill, with black liquor and wood chips as feedstocks: FTL, DME, MA.[3]
- Switchgrass and coal dual gasification system for FTL.[4,5]
- CO_2 capture and storage (aquifer or enhanced oil recovery, EOR)
- Modeling tools
  – Aspen Plus (+ pinch analysis for heat integration).
  – "GS" (with Politecnico di Milano colleagues)
  – Capital cost and financial models.

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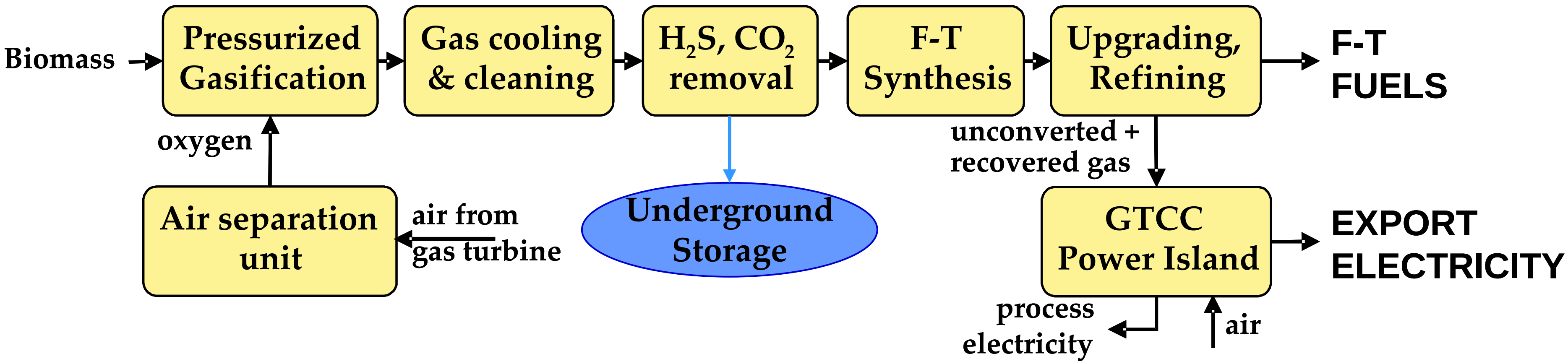
1. E.D. Larson, H. Jin, and F.E. Celik, "Gasification-Based Fuels and Electricity Production from Biomass, without and with Carbon Capture and Storage," Princeton Environmental Institute, Princeton University, Princeton, NJ, October 2005, 77 pages.
2. E.D. Larson, R.H. Williams, and H. Jin, "Fuels and electricity from biomass with CO2 capture and storage," *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies* (forthcoming), Trondheim, Norway, 19-22 June 2006.
3. Larson, Consonni, Katofsky, Iisa, and Frederick, "A Cost-Benefit Assessment of Gasification-Based Biorefining in the Kraft Pulp and Paper Industry," final report in 4 volumes to DOE and AFPA, DOE contract DE-FG26-04NT42260, 21 Dec. 2006.
4. R.H. Williams, E.D. Larson, and H. Jin, "Synthetic Fuels in a World with High Oil and Carbon Prices," *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies* (forthcoming), Trondheim, Norway, 19-22 June 2006.
5. R.H. Williams, E.D. Larson, H. Jin, "Comparing Climate-Change Mitigating Potentials of Alternative Synthetic Liquid Fuel Technologies Using Biomass and Coal," *Proceedings of the Fifth Annual Conference on Carbon Capture and Sequestration,* Alexandria, VA, 8-11 May 2006.

FTL (+ Co-Product Electricity) from Switchgrass Without or With CCS



- Switchgrass gasified in pressurized O_2-CFB (GTI design).
- Rectisol® for removal of trace H_2S and bulk CO_2.
- Iron based slurry FT synthesis (H_2/CO in = 1.7).
- Refine raw FTL to diesel/gasoline (62%/38%) blendstocks.
- Co-produce electricity with GTCC using unconverted syngas.
- ~5000 dry metric t/d switchgrass. (1990s Princeton analysis showed biomass transport costs with increasing plant size more than offset by scale-economy gains in conversion capital costs.)
- Compress the captured CO_2 to 150 bar for pipeline transport.
- CO_2 injection in deep saline aquifer or for enhanced oil recovery (EOR).

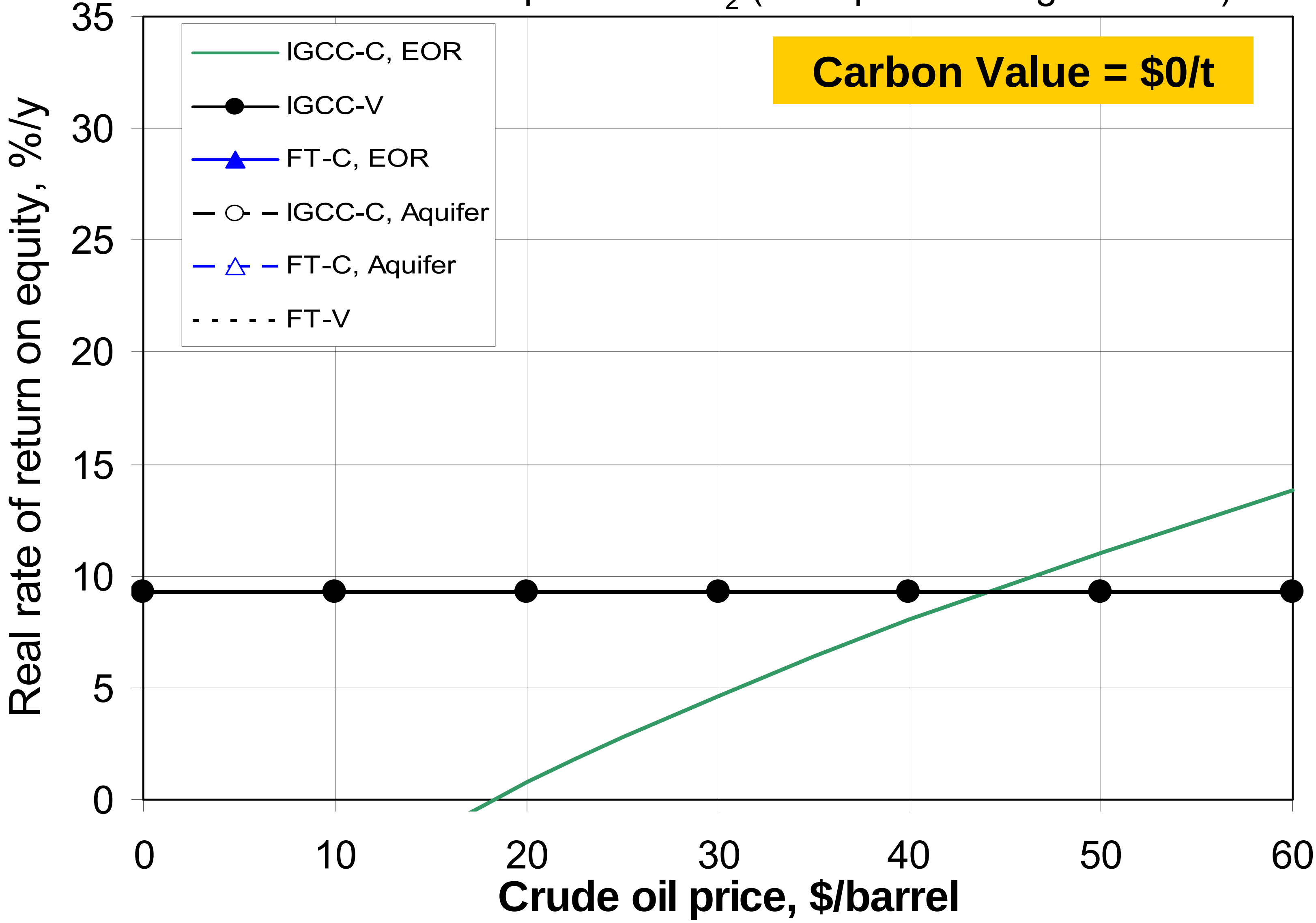
"N^th" Plant Performance and Costs

	FTL + ELECTRICITY						IGCC ELECTRICITY					
PERFORMANCE AND CAPITAL COST	CO_2 VENTED		CO_2 CAPTURED				CO_2 VENTED		CO_2 CAPTURED			
Switchgrass input, dry t/day [MW_{LHV}]	4535 [893]											
FTL out, MW_{LHV} [bbl/day gasoline equiv]	305 [5272]		306 [5285]									
Electric power output, MW	207		191				442		352			
CO_2 emissions from plant, kgC/s	18.5		6.2				24.7		2.4			
Overnight construction cost, $\$10^6$	541		557				427		503			
PRODUCTION COSTS (2003 $)	**FTL Production Cost, $/GJLHV**						**Elec. Generation Cost, ¢/kWh**					
CO_2 storage mode	none		aquifer		EOR		none		aquifer		EOR	
Price of GHG emissions, $\$/tC_{equiv}$	0	100	0	100	0	100	0	100	0	100	0	100
Capital (80% capacity factor)	11.85		12.17				2.33		3.44			
O&M plus switchgrass @ $\$3/GJ_{HHV}$	12.48		12.53				2.95		3.83			
CO_2 tpt/storage + GHG emissions cost	0	0.60	1.39	1.99	0.87	1.47	0	0.15	0.68	0.87	0.36	0.55
Electricity co-product credit	-8.93	-13.0	-8.23	-12.0	-8.23	-12.0						
Credit for CO_2 sold for EOR					-4.80	-1.75					-2.73	-1.00
Credit for bio-CO_2 storage			0	- 4.02	0	-4.02				-2.28		-2.28
Net production cost, $\$/GJ_{LHV}$ or ¢/kWh	15.4	11.9	17.9	10.7	12.5	8.4	5.3	5.4	8.0	5.9	4.9	4.6

- Electricity sale price assumed equal to generating cost of least costly coal-IGCC: 4.75 ¢/kWh @ $0/tC, 6.94 ¢/kWh @ $\$100/tC_{eq.}$
- CO_2 cost/price: $\$5.9/t_{CO2}$ 100 km tpt; $\$3.5/t_{CO2}$ aquifer injection. Sale price for EOR ($/kSCF) = 3% of oil price in $/bbl.

Financial Results: Bio-FTL and Bio-IGCC

V = Venting of CO_2
C = Capture of CO_2 (for aquifer storage or EOR)



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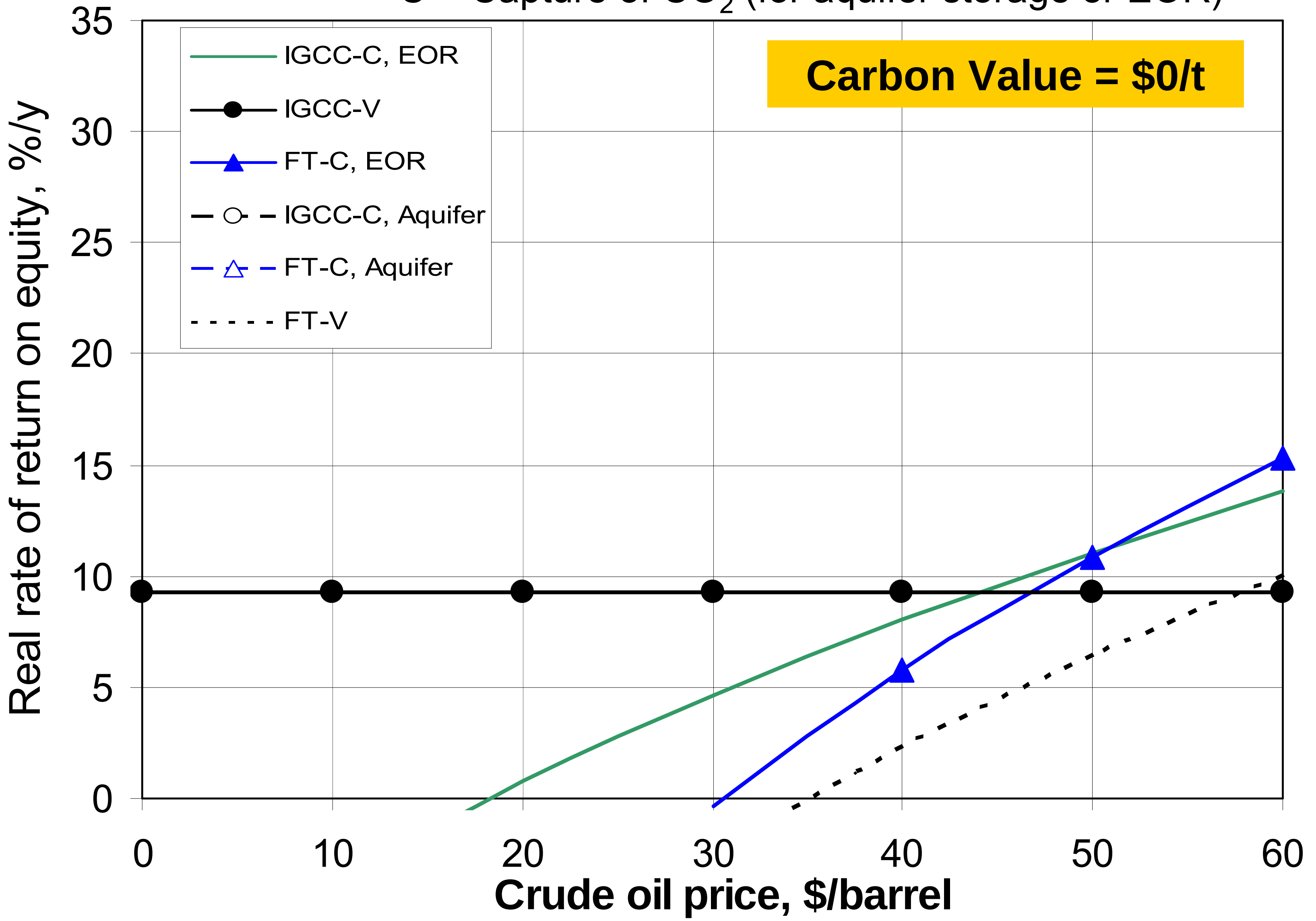

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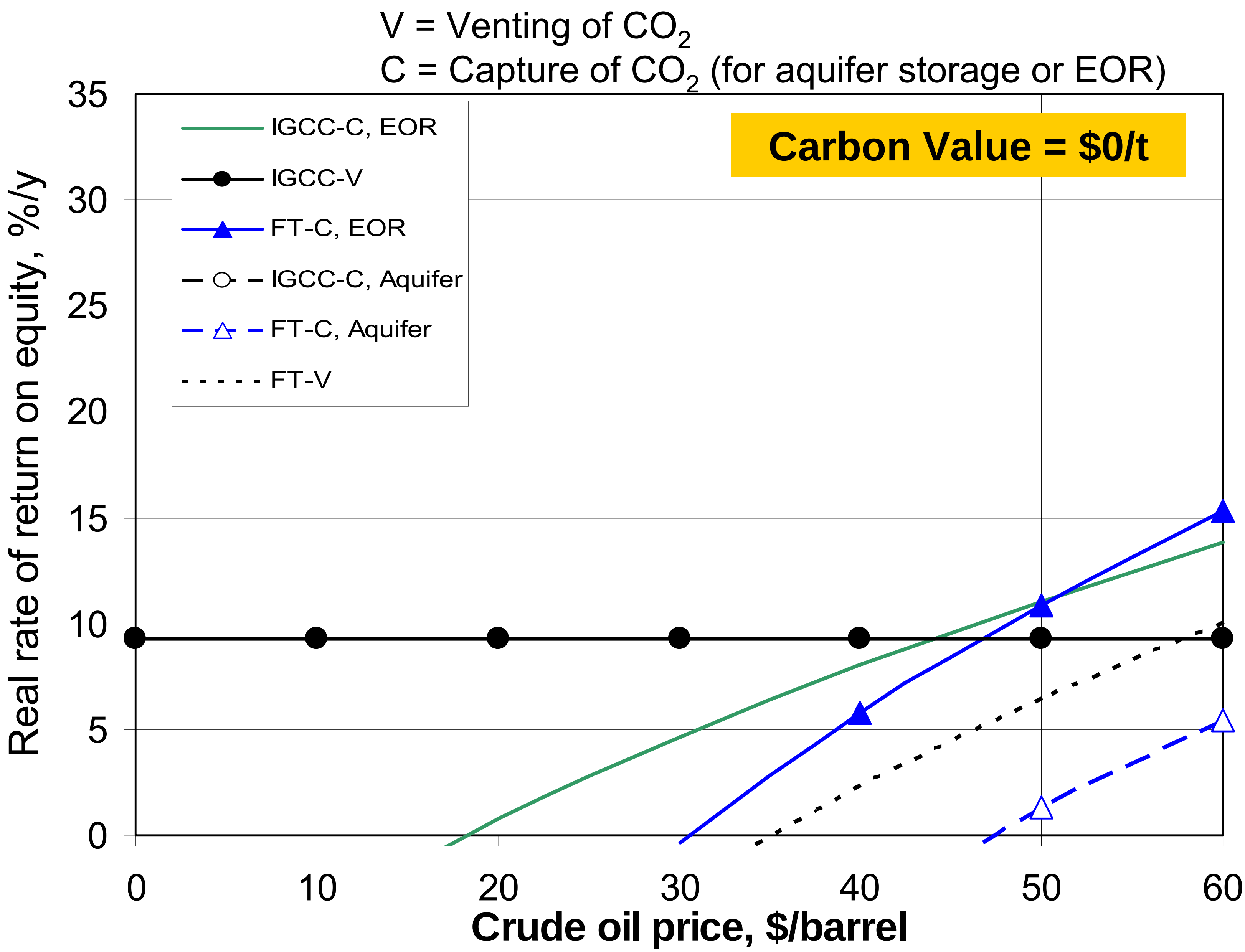

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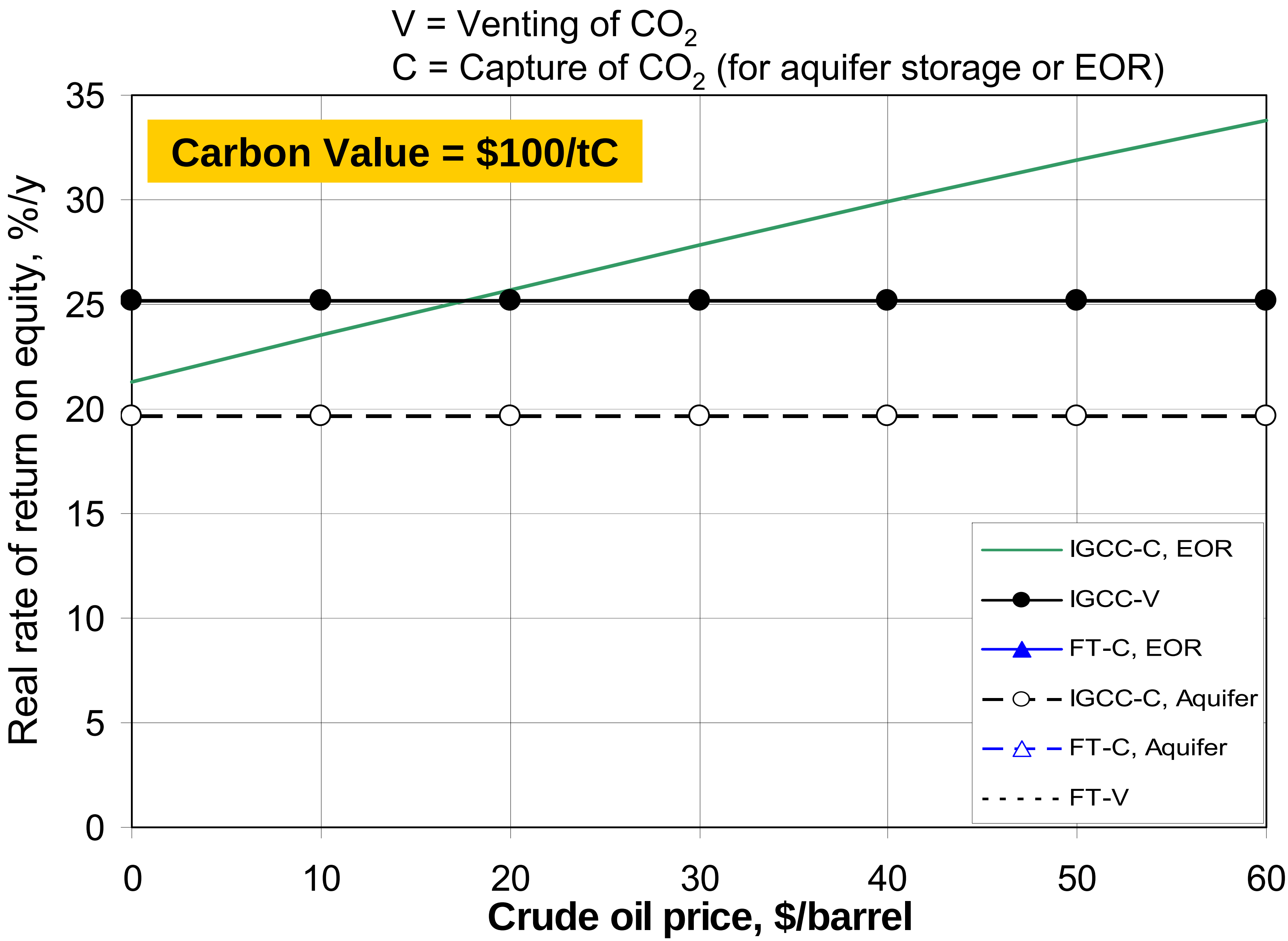

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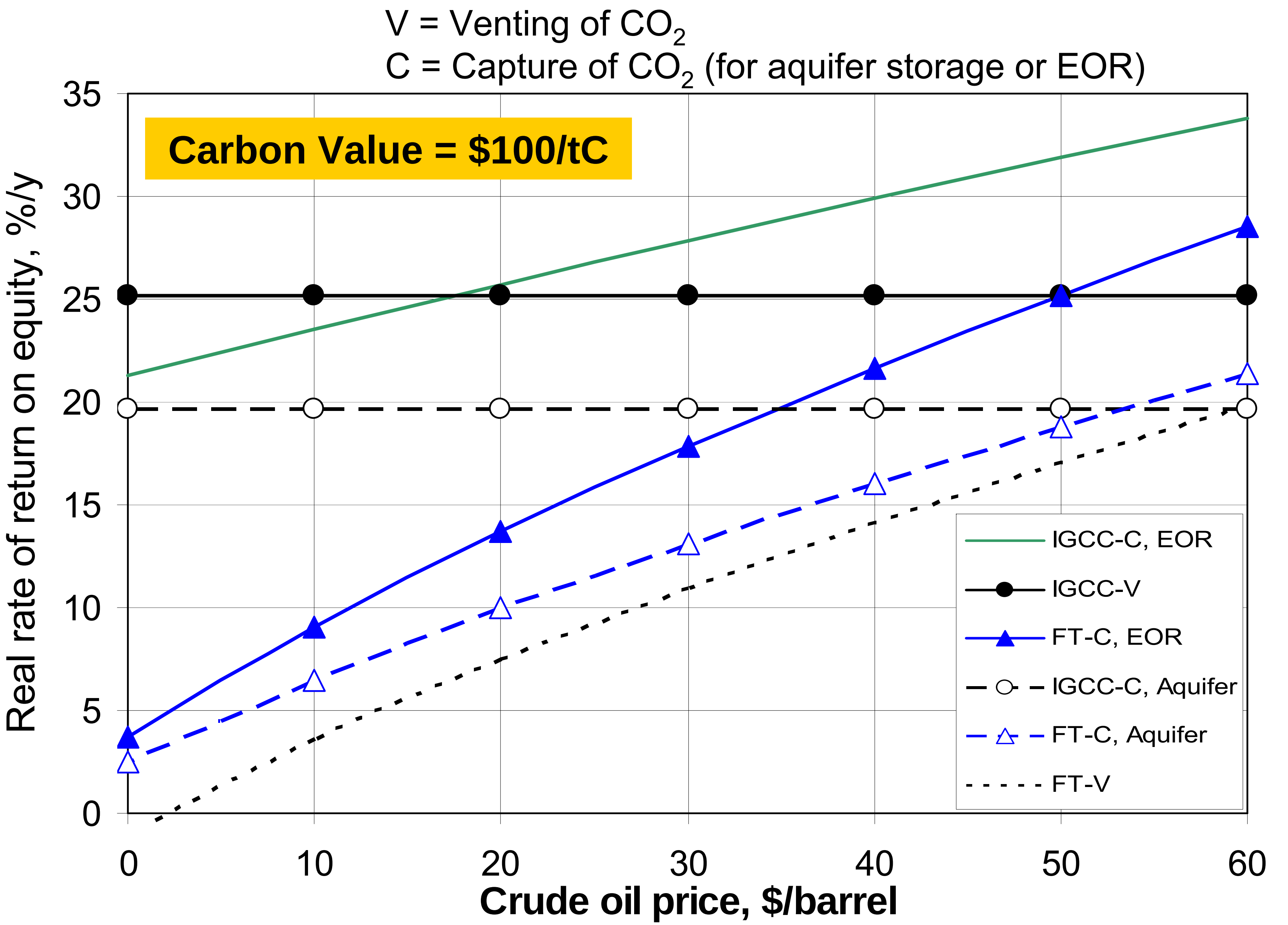
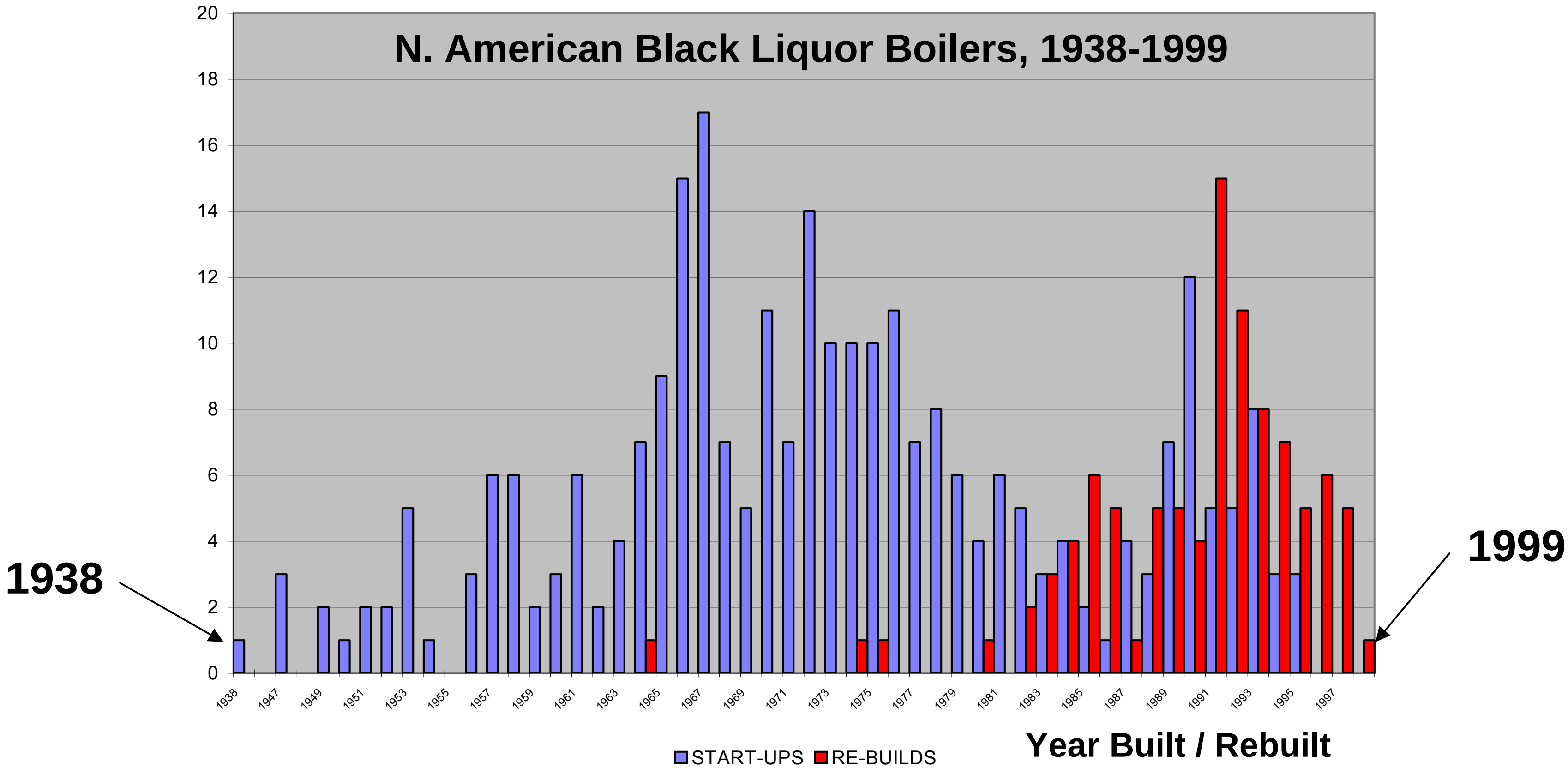


Summary of Stand-Alone Bio-FTL

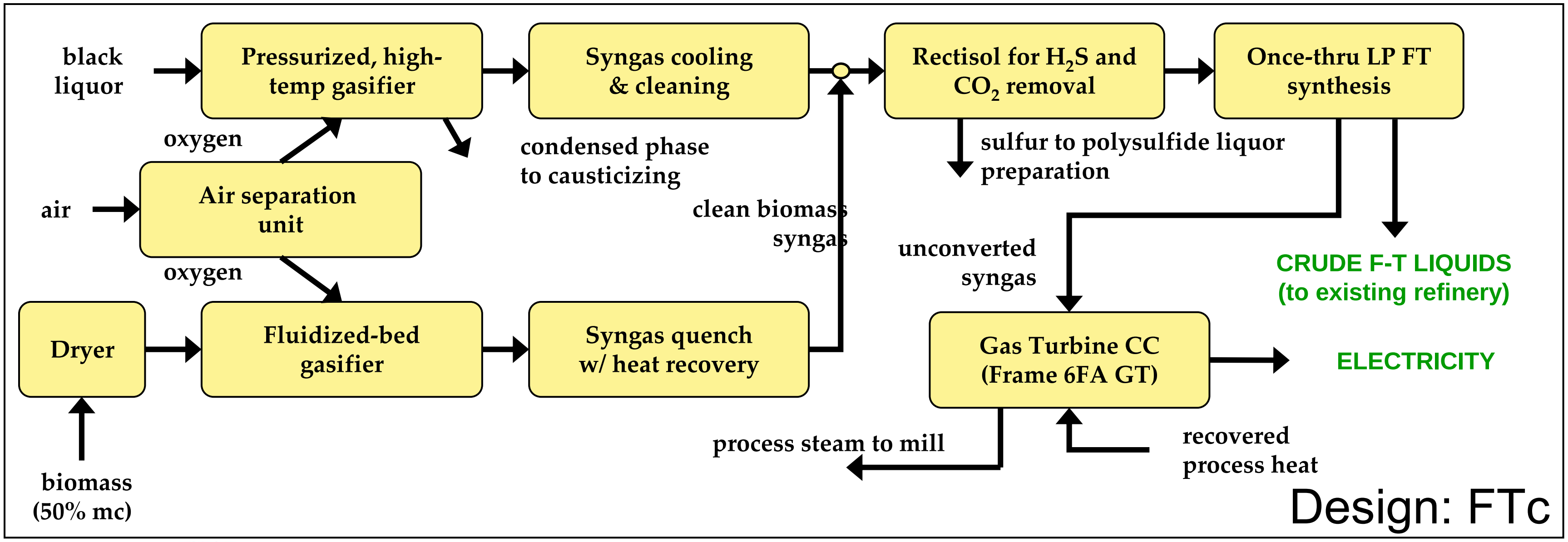
- Technology is near-commercially ready.
- Economics (with switchgrass) are not promising in the absence of a value on GHG emissions.
- With value on GHG emissions, large-scale facilities will be desirable for best economics (but logistics of biomass supply will be challenging).
- How to get started today with gasification-based liquid biofuels?

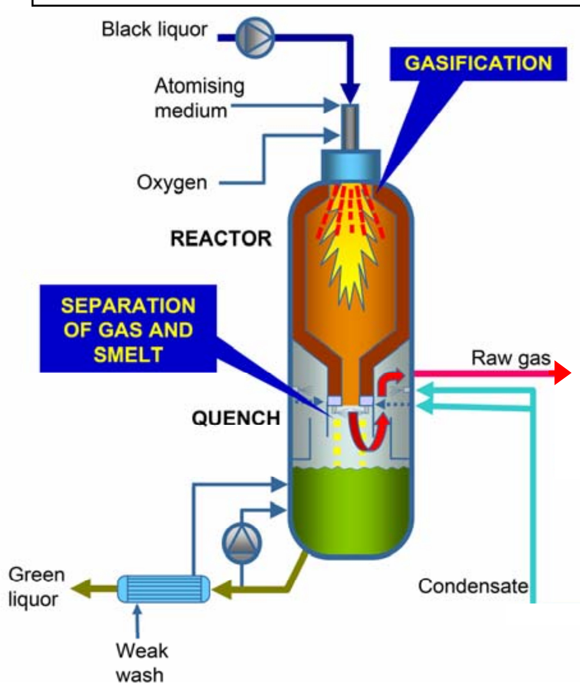
Kraft Pulp Mills as Biorefineries?

- U.S. industry uses >1.5 EJ/yr bioenergy, mostly black liquor.
- Tough global competition in pulp production is spurring northern-hemisphere pulp industry interest in diversification via integrated biorefining to make fuels and chemicals.
- Aging black liquor boiler fleet provides window of opportunity for introducing new energy technology such as gasification.



Pulp Mill-Integrated Biorefining

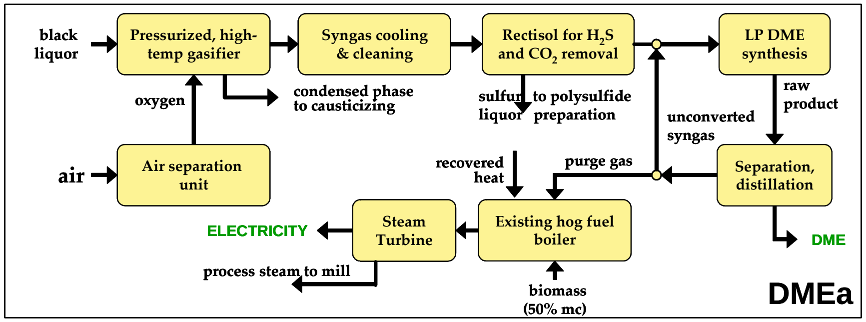


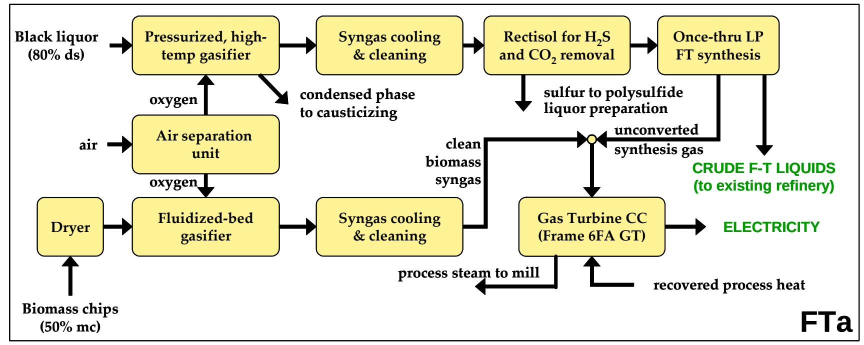


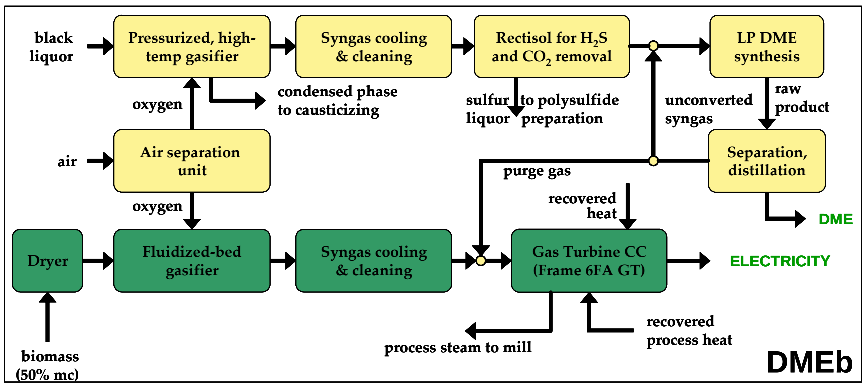
Pressurized, high-temperature, O_2-blown (Chemrec) black liquor gasifier adopted in our biorefinery designs:

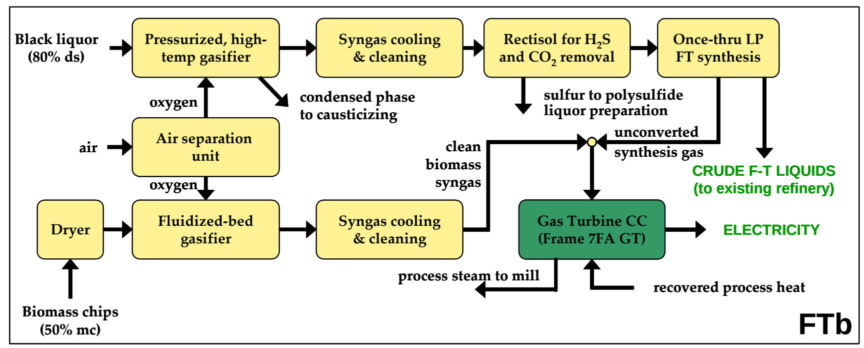
- Pilot-scale (20 tpd BLS) pressurized gasifier tests ongoing in Sweden since mid-2006.
- Commercial demo under planning for implementation by 2010 in Sweden.

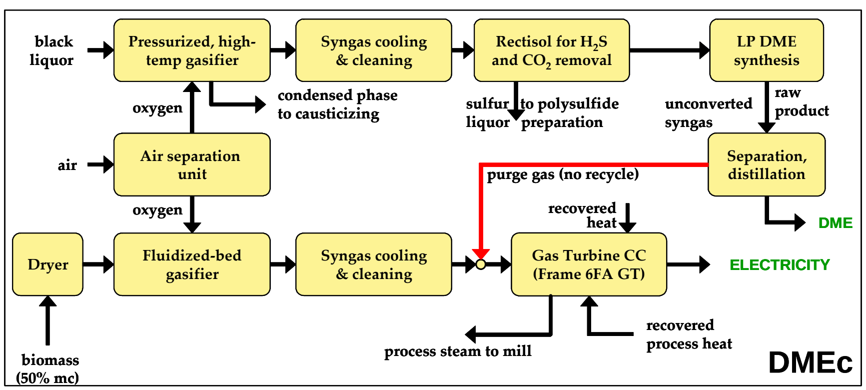
7 Biorefinery Designs Developed

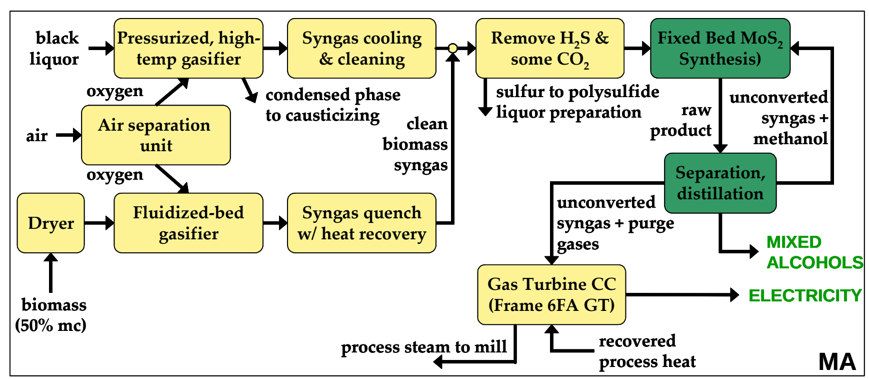












Technology in Our Designs

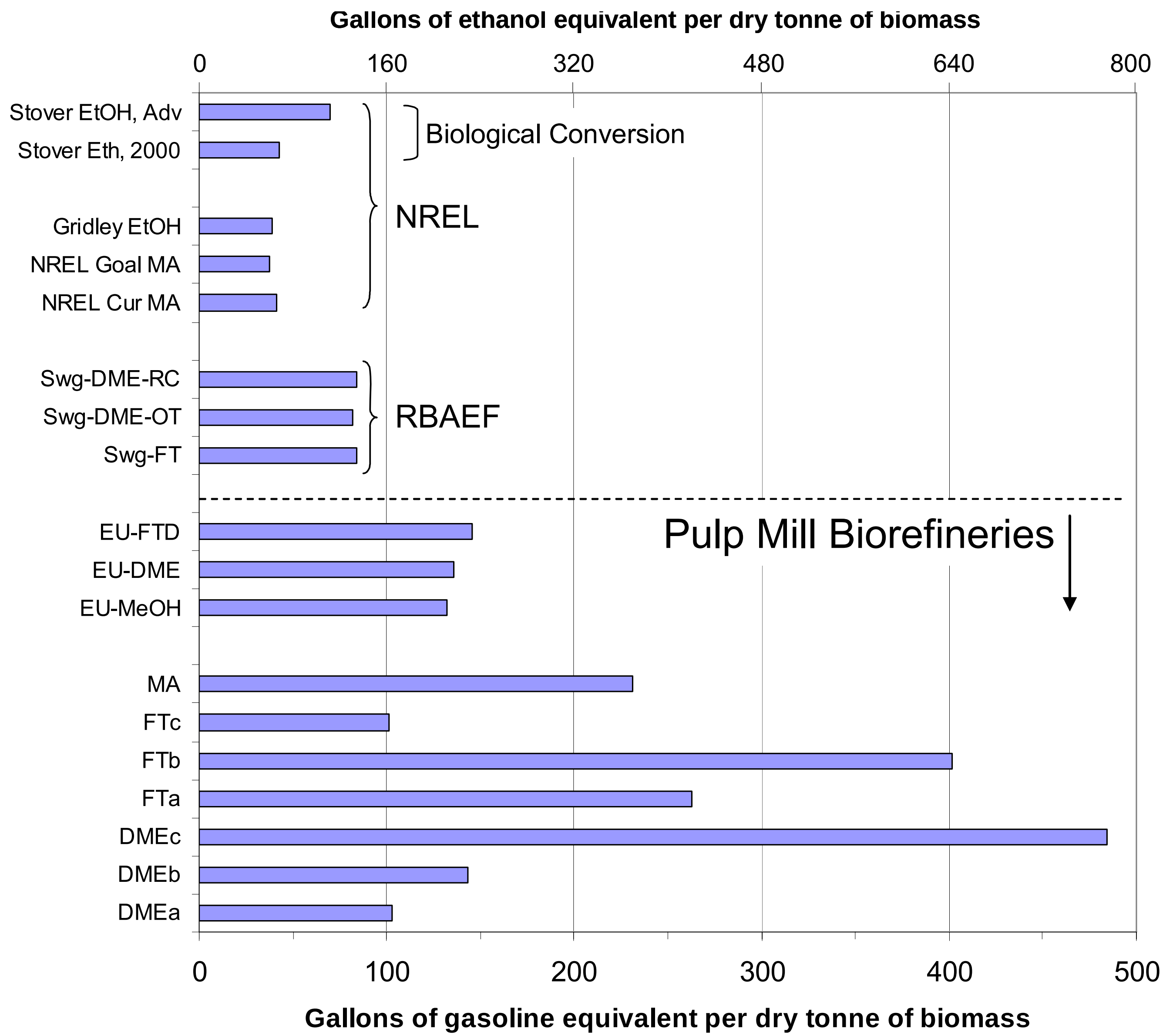
Technology		Status*	FTa	FTb	FTc	DMEa	DMEb	DMEc	MA
Black Liquor Gasification Island	Entrained flow gasifier	Pilot	♦	♦	♦	♦	♦	♦	♦
	Quench	Pilot	♦	♦	♦	♦	♦	♦	♦
	O_2 feed	Com	♦	♦	♦	♦	♦	♦	♦
Woody Biomass Conversion	Fluid-bed gasifier	Pilot	♦	♦	♦		♦	♦	♦
	Syngas cooler	Pilot	♦	♦		♦	♦	♦	
	Hot gas filter	Pilot	♦	♦			♦	♦	
	Quench cleanup	Com			♦				♦
	O_2 feed	Com	♦	♦	♦		♦	♦	♦
	Boiler	Com				♦			
H_2S Capture and Recovery	Rectisol®	Com	♦	♦	♦	♦	♦	♦	
	Selexol®	Com							♦
	Claus/SCOT	Com	♦	♦	♦	♦	♦	♦	♦
Fuel Synthesis Island	Slurry bed reactor	Com	♦	♦	♦	♦	♦	♦	
	Fixed-bed reactor	Lab							♦
	Syngas recycle	Com				♦	♦		♦
Power Island	Gas turbine	Com	♦	♦	♦		♦	♦	♦
	Back pressure ST	Com	♦			♦	♦	♦	♦
	Condensing ST	Com		♦	♦				

* Com = commercially-offered; Pilot = Demonstrated at pilot scale; Lab = Demonstrated in Laboratory

"N^th Plant" Performance Predictions

		Tomlinson	BLGCC	FTa	FTb	FTc	DMEa	DMEb	DMEc	MA
Energy Inputs										
Black liquor dry solids	kg/s	31.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5
Dry solids fraction in black liquor	%	80	80	80	80	80	80	80	80	80
Total black liquor	kg/s	39.4	35.6	35.6	35.6	35.6	35.6	35.6	35.6	35.6
	MWt LHV	393	351	351	351	351	351	351	351	351
Total wood residuals (50% mc)	kg/s	7.12		19.2	52.0	62.2	16.2	30.7	15.7	17.6
	MWt LHV	57.7	54.0	156	423	505	131	250	127	143
from mill	MWt LHV	57.74		54.0	54.0	54.0	54.0	54.0	54.0	54.0
purchased	MWt LHV	0.00		102	369	451	77.0	196	73.0	89.0
Lime kiln fuel oil	MWt LHV	31.1	35.9	35.9	35.9	35.9	35.9	35.9	35.9	35.9
Power/Recovery/Refinery Outputs										
	kg/s	-		2.75	2.75	9.06	6.20	6.20	3.20	5.75
FT crude or DME	MWt LHV			112.0	112.0	343.0	168.0	168.0	74.0	60.0
	bbl/dau petroleum product equiv.	-		1549	1549	4757	2362	2362	1043	948
Electricity										
Steam turbine gross output	MWel	72.0	48.2	34.0	87.9	48.6	32.9	42.0	38.7	40.8
Gas turbine output	MWel	-	87.0	83.9	186.5	89.7	-	89.5	82.9	89.7
Biomass syngas expander output	MWel	-	-	1.7	4.3		2.6	5.0	2.0	3.0
Total gross production	MWel	72.0	135.1	119.5	278.7	138.3	35.5	136.5	123.6	133.5
Recovery/power/biorefinery consumption	MWel	7.7	20.5	31.3	49.2	60.4	34.3	48.1	32.4	41.1
Mill demand	MWel	100.10	100.1	100.1	100.1	100.1	100.1	100.1	100.1	100.1
Net power available for export	MWel	-35.8	14.6	-12.4	128.8	-22.8	-99.6	-12.3	-9.6	-8.2

Comparing Effective Liquid Fuel Yields



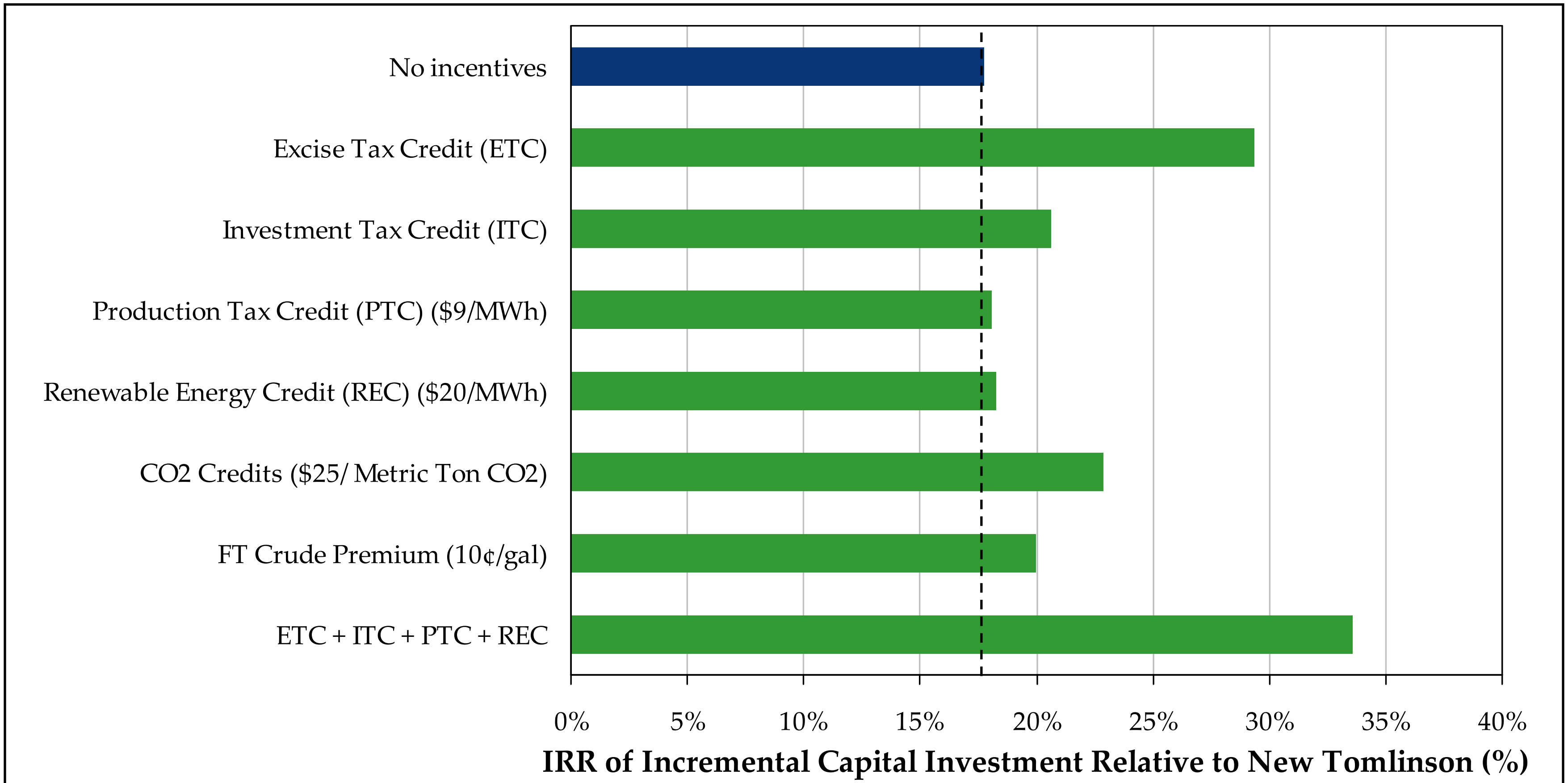
- A biorefinery integrated with a pulp mill effectively requires much less biomass per unit of liquid fuel produced vs. "stand-alone" biofuel production
- The reason is that black liquor (and some biomass) are charged against services provided to the mill (chemical recovery, process steam and power) – not against liquid fuel.

"Nth Plant" Installed Capital Costs

THOUSAND 2005$	Power/Steam[a]		Biorefinery -- Power/Steam/Liquid Fuel						
	Tomlin.	BLGCC	DMEa	DMEb	DMEc	FTa	FTb	FTc	MA
Recovery boiler	125,018	0	0	0	0	0	0	0	0
Steam system modifications[b]	11,136	0	3,000	0	0	0	0	0	0
Air separation unit (ASU)	0	42,628	43,053	61,561	52,933	55,001	72,762	77,823	54,080
ASU increment for O_2 delig.[c]	0	1,118	1,061	879	954	933	805	776	948
BL gasifier & green liquor filter[d]	0	63,720	63,720	63,720	63,720	63,720	63,720	63,720	63,720
Nitrogen compressor	0	0	0	1,188	810	1,071	1,757	2,013	5,181
Acid gas removal & sulfur recovery	0	19,003	37,732	37,732	27,321	27,321	27,321	42,164	24,529
Synthesis island	0	0	49,344	49,344	16,287	22,019	22,019	38,767	83,548
Combined cycle power island	0	89,243	0	105,303	100,091	90,018	171,895	104,300	90,348
Wood yard expansion[e]			867	2,697	789	1,303	4,832	5,788	1,077
Biomass dryer, including RTO[f]	0	0	0	50,295	32,523	37,286	72,507	45,558	31,383
Biomass gasifier & tar cracker	0	0	0	28,354	18,320	20,867	41,365	47,063	22,949
Biomass syngas cooler & filter	0	0	0	8,484	4,998	5,666	11,372	0	0
Biomass syngas cooler & wash	0		0	0	0	0	0	34,425	16,092
Biomass syngas expander	0	0	0	3,778	2,661	2,670	9,410	0	0
Hog fuel boiler	0	0	50,736	0	0	0	0	0	0
Other[g]	0	2,359	2,359	2,359	2,359	2,359	2,359	2,359	2,359
Overnight Installed Capital Cost	**136,154**	**218,072**	**251,873**	**415,695**	**323,766**	**330,234**	**502,125**	**464,755**	**396,215**
Annual non-fuel O&M cost[h]	**5,446**	**8,723**	**10,075**	**16,628**	**12,951**	**13,209**	**20,085**	**18,590**	**15,849**

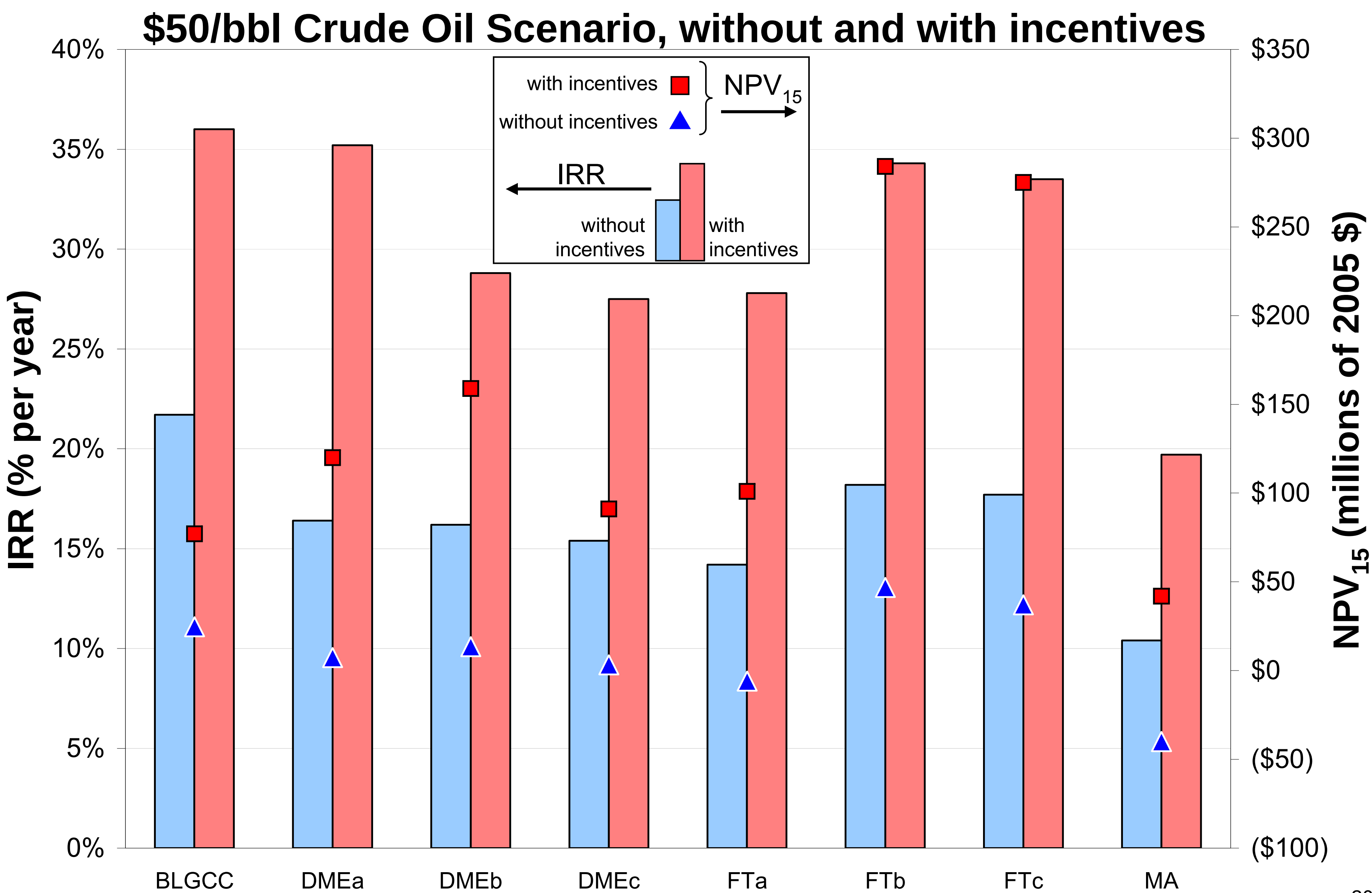
(a) From 2003 BLGCC study, with costs originally in 2002$ escalated to 2005$. The BLGCC costs shown here are for the case with "mill-scale" gas turbine and high-temperature BLG.

Financial Analysis: FTc



- $330 million incremental capital investment
- $50/bbl Crude Oil Scenario (AEO '06 Reference Projection)
- Electricity sale price: 5.3 c/kWh (without incentives)
- Incentives examined:
  - Excise Tax Credit (ETC): Equivalent to existing $0.51/gal for ethanol on energy basis.
  - Investment Tax Credit (ITC): 20% gasification tax credit (under EPAct 2005).
  - Production Tax Credit (PTC): $9/MWh for 10 years (on incremental electricity relative to Tomlinson).
  - Renewable Energy Credit (REC): $20/MWh (e.g., under RPS or green credits). Applies only to incremental electricity.
  - CO_2 Credits: $25/tCO2 applied to net reductions (including grid offsets and petroleum displaced)
  - FT Crude Premium: $4.2/bbl for superior performance

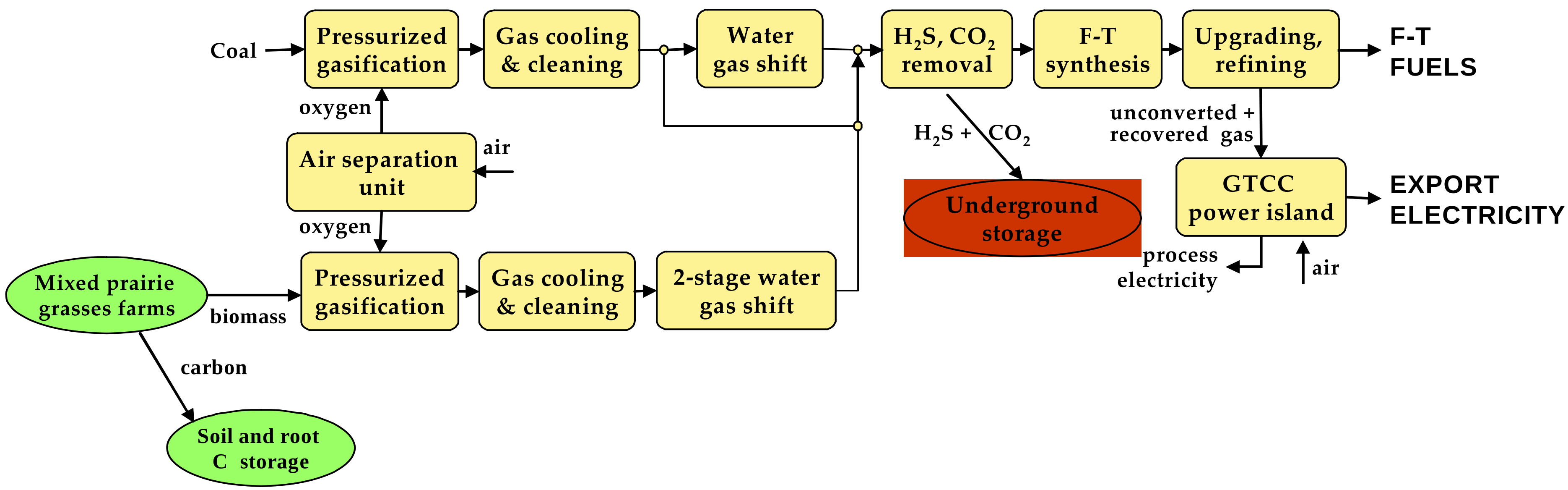
Pulpmill Biorefinery Financial Performance



Pulpmill Biorefinery Summary

- Pulpmill-integrated liquid biofuel economics much better than stand-alone production due to capital cost-sharing with pulp mill and low bio-feedstock costs.
- But the pulp industry is conservative and technology risk-averse ➔ pulp mill operation requires >95% on-stream time for black liquor chemical recovery system.
- Pulp industry needs energy-industry partners to help manage risk and contribute know-how to move forward with biorefining.
- Woody biomass gasification (for IGCC and/or liquid fuels) could be a way to start for minimizing risk to pulp mill.
- Co-gasifiy woody biomass with coal to gain scale economies and improve economics?

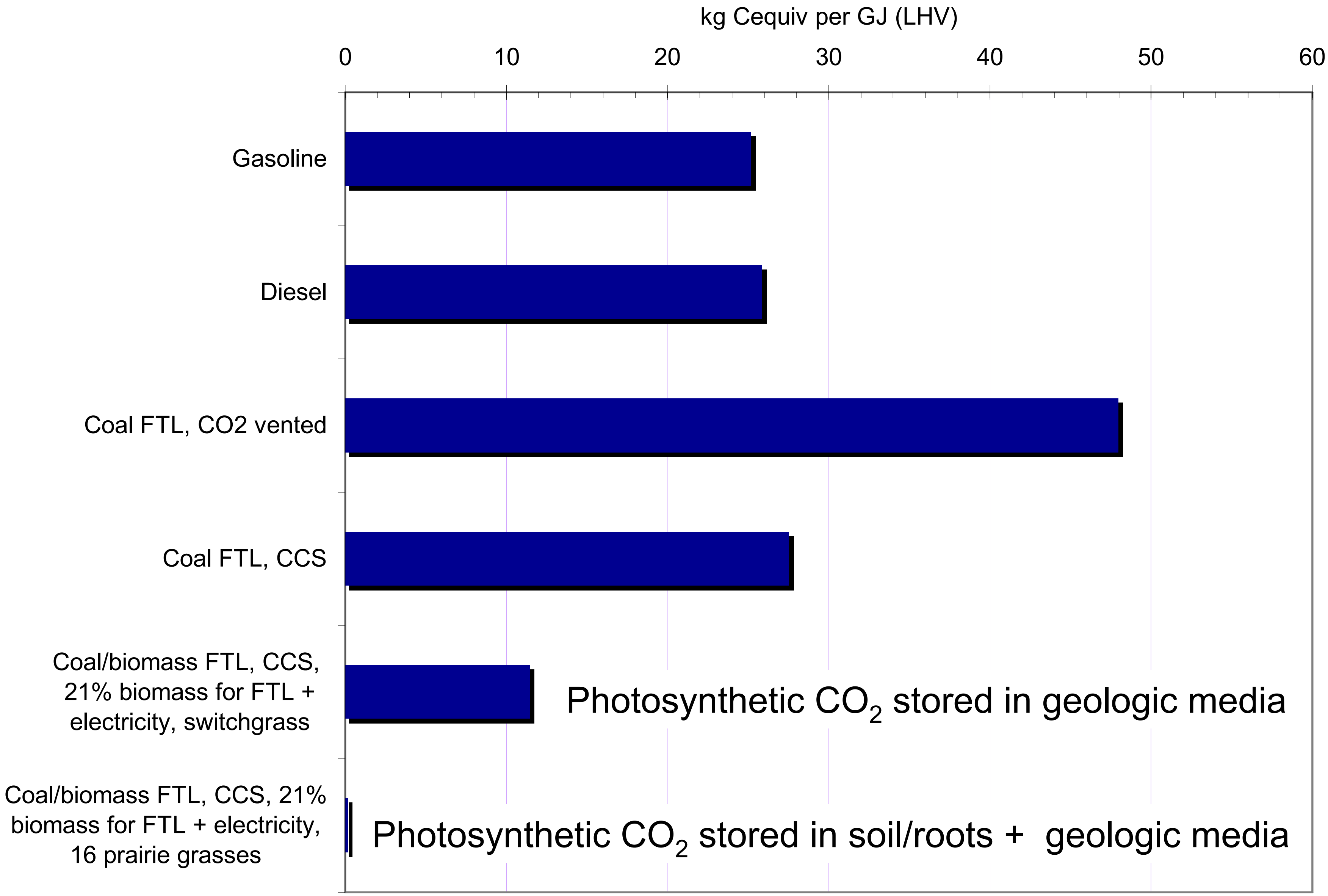
FTL/Electricity from Coal + Prairie Grasses with Two Carbon Storage Mechanisms



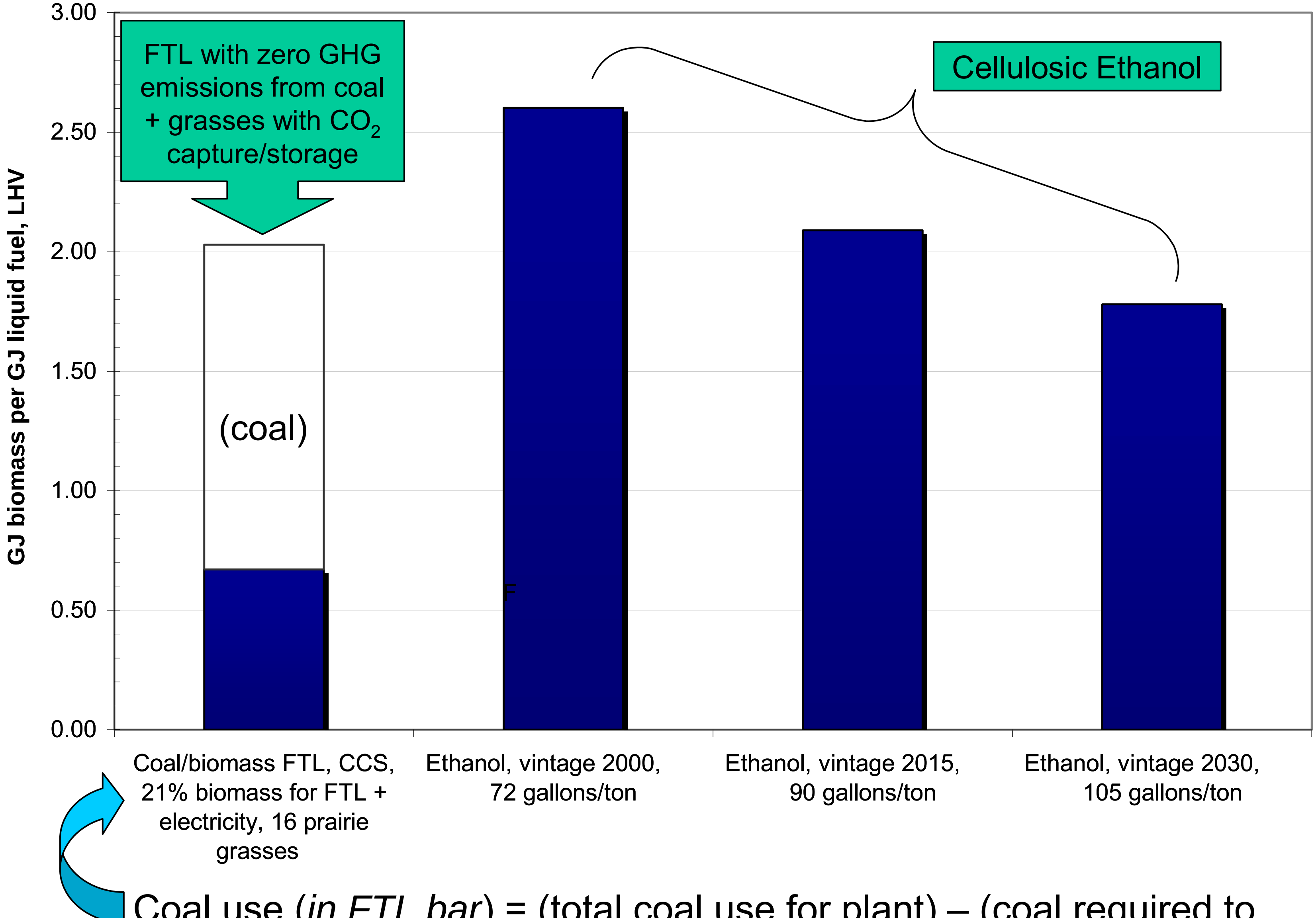
- Mixed prairie grasses are grown on C-depleted soils ➔ substantial build-up of C in roots/soils…up to 0.6 tC per tC in harvested biomass.*
- H_2 is made from biomass via gasification to compensate for H_2 deficit in coal syngas in manufacture of FTL.
- Photosynthetic CO_2 coproduct (~ 90% of C in harvested biomass) is stored with coal-derived CO_2 in deep geological formations.

* D. Tilman, J. Hill, and C. Lehman, "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass," *Science*, 314: 1598-1600, 8 December 2006.

GHG Emissions for Fuel Production + Use



Biomass to Make One GJ of Liquid Fuel



Coal use (*in FTL bar*) = (total coal use for plant) – (coal required to make same amount of electricity in stand-alone IGCC with CCS) www.princeton.edu/~energy