Pulp Mill Integrated Gasification-Based Liquid Biofuels Production

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presentation prepared for
TAPPI International Renewable Energy Conference, 10-11 May 2007

Abstract
Commercialization of black liquor and biomass gasification technologies is anticipated in the 2010-2015 timeframe, and synthesis gas from gasifiers can be converted into liquid fuels using catalytic synthesis technologies that are already commercially established today in the gas-to-liquids or coal-to-liquids industries. This paper describes key results from a major assessment of the prospective energy, environmental, and financial performance of commercial gasification-based biorefineries integrated with kraft pulp and paper mills. Seven detailed biorefinery designs were developed for a reference mill in the Southeastern U.S., together with the associated mass/energy balances, air emissions estimates, and capital investment requirements. The biorefineries provide chemical recovery services and co-produce process steam for the mill, some electricity, and one of three liquid fuels: a Fischer-Tropsch synthetic crude oil (which would be refined to vehicle fuels at existing petroleum refineries), dimethyl ether (a diesel engine fuel or propane substitute), or an ethanol-rich mixed-alcohol product.

Compared to installing new Tomlinson power/recovery systems, biorefineries would require more capital investment and greater purchases of woody residues for energy use. However, because biorefineries would be more efficient, have lower air emissions, and produce a more diverse product slate, for nearly all cases examined, the internal rate of return (IRR) on the incremental capital investment lies between 14% and 18%, assuming a $50/bbl world oil price. The IRRs would more than double if plausible federal and state financial incentives are assumed to be captured. Industry-wide adoption of such biorefining in the United States could provide significant energy and environmental benefits to the country.

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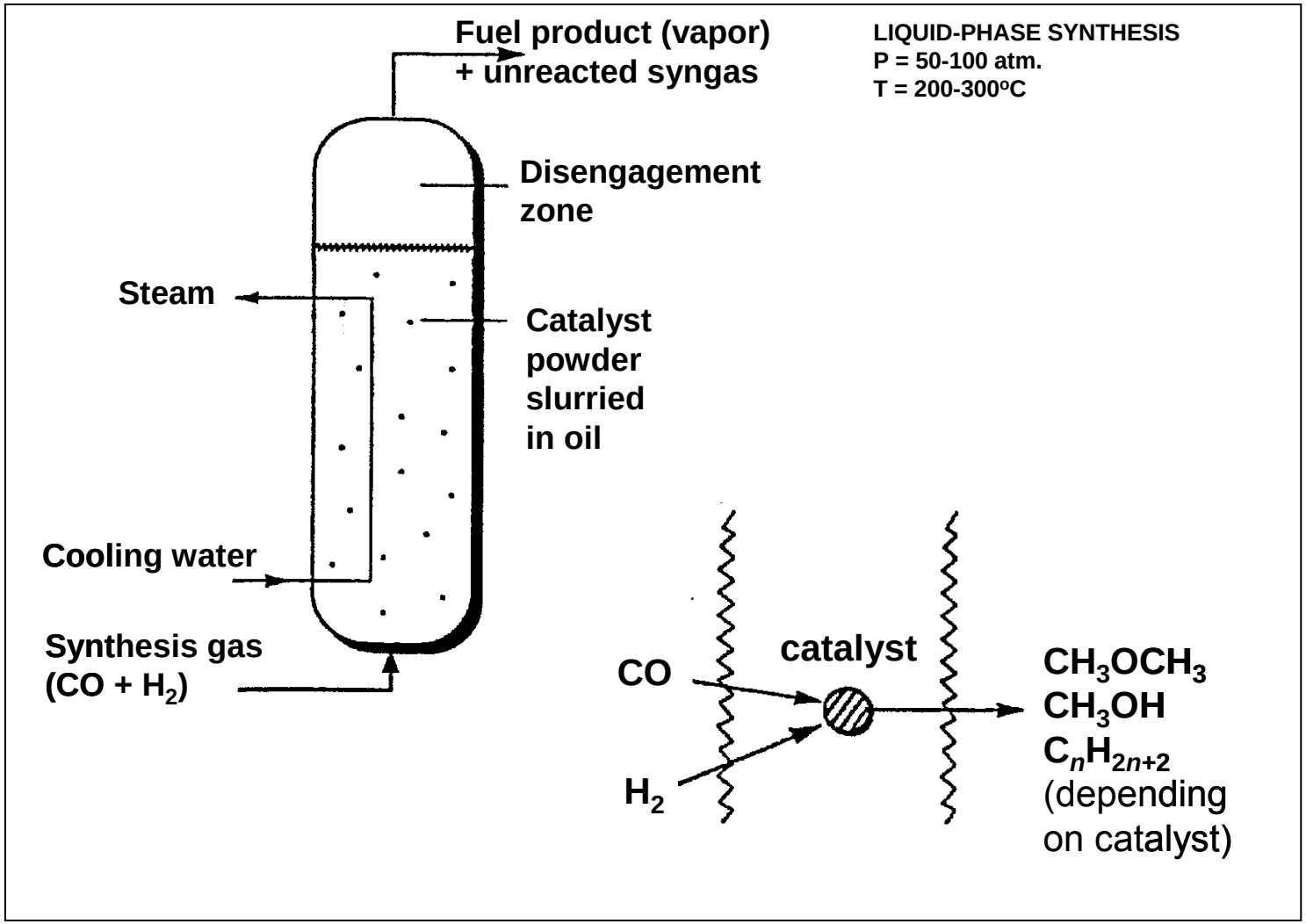
Synthesis of Liquid Fuels from Synthesis Gas ($CO+H_2$)



Gasification-Based Liquid Fuels

Fischer-Tropsch Liquids (FTL)

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

Dimethyl Ether (DME) (first cousin of methanol)

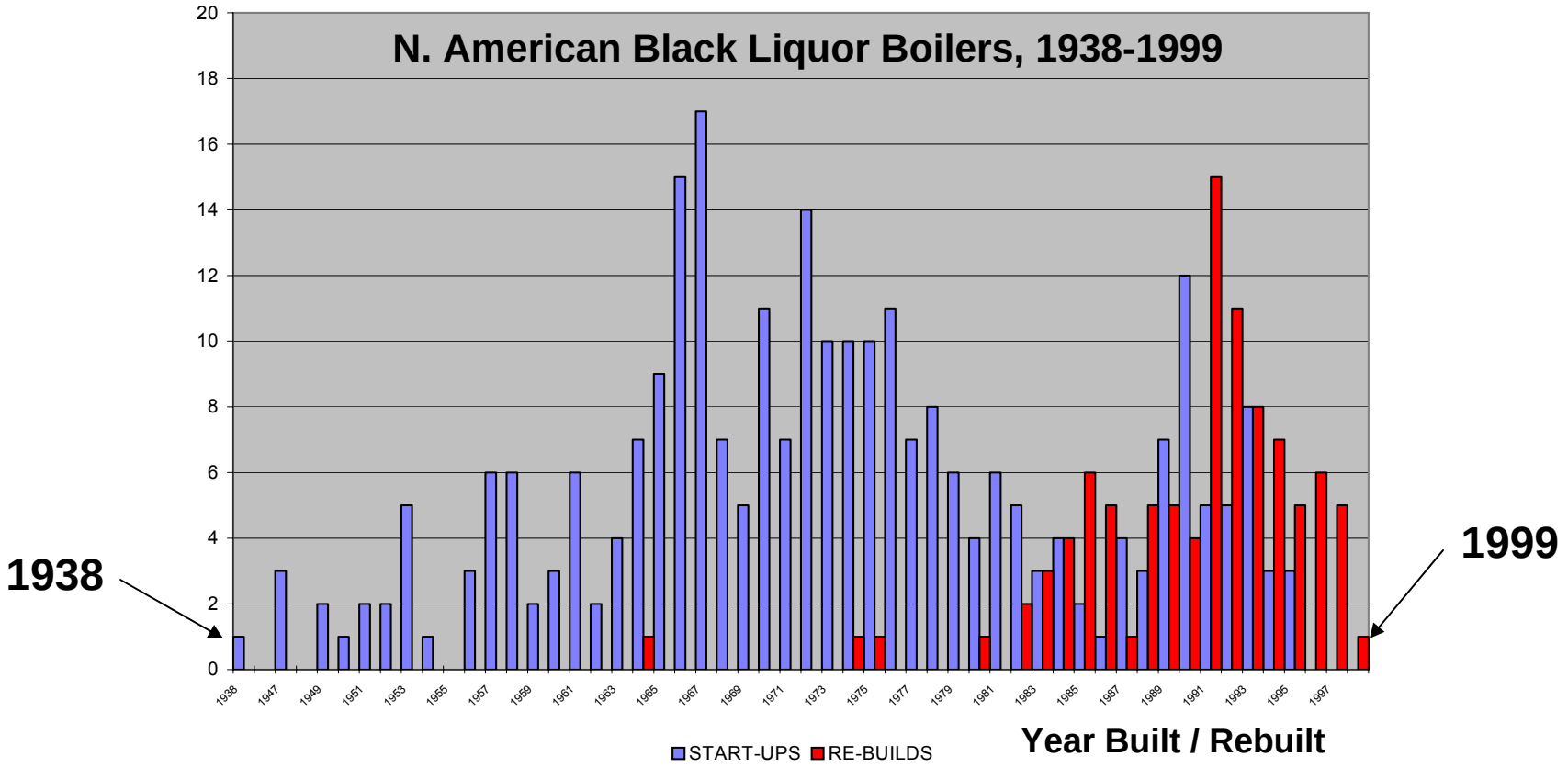
- Propane substitute/blendstock or zero-S, zero-PM, high-cetane diesel fuel.
- Huge commercial investments in DME and methanol from coal in China;
- Growing investments in DME from gas in Iran, China, and (as buyer) Japan;
- Swedish interest in DME from biomass.

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.

Bioenergy in the Kraft Pulp Industry

- United States kraft pulp industry generates and uses over 1.5 quads/year of bioenergy: ~80% black liquor and ~20% woody residues.
- Fleet of Tomlinson black liquor boilers is aging and approaching retirement.



- Tough global competition for northern-hemisphere pulp industry ➔ Diversify to stay competitive, e.g., fuels/chemicals production?
- Window of opportunity for introducing gasification/biorefining.

Reference 2010 Kraft Pulp/Paper Mill

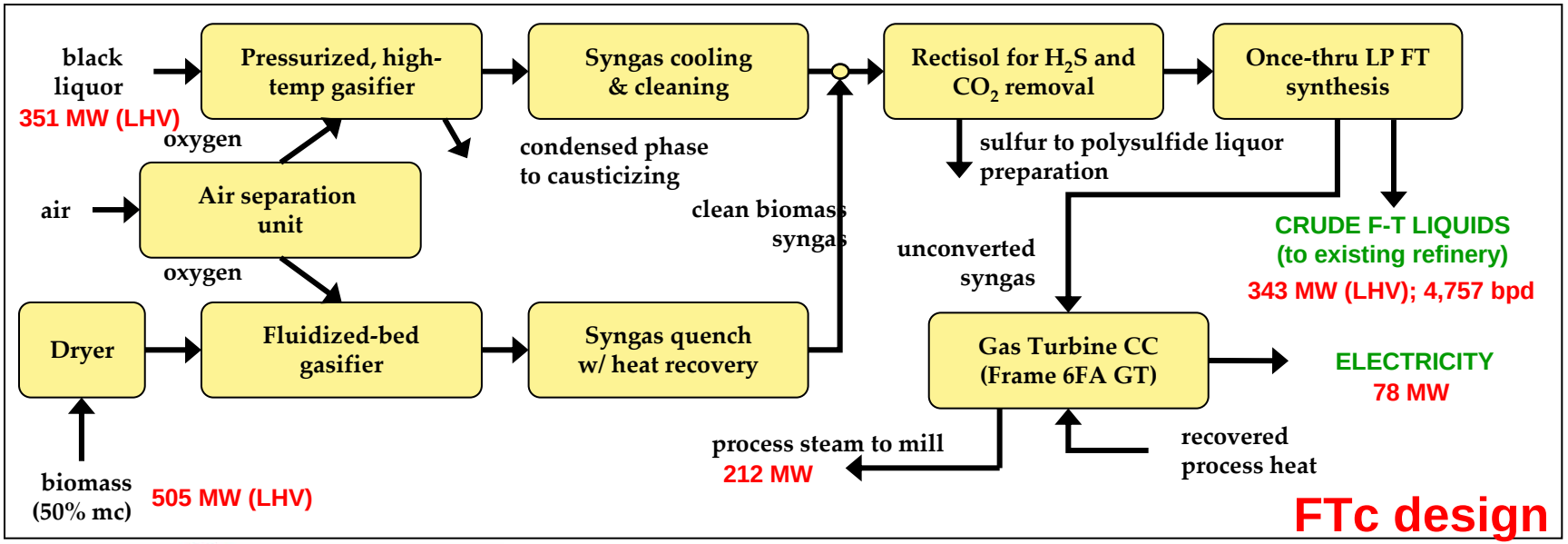
Same reference mill as in 2003 BLGCC study:

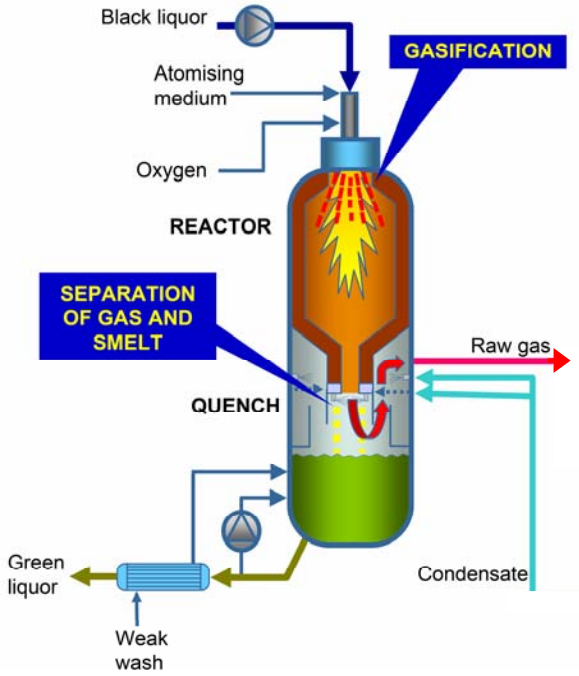
- Uncoated freesheet (65% HW, 35% SW), Southeast USA
  - 1,580 metric t/d unbleached pulp rate (bone dry)
  - 1,725 metric t/d paper rate (machine dry).
- Process steam use for projected state-of-art 2010 mill.
- Pulping technology adopted
  - Conventional kraft with Tomlinson chemical recovery.
  - Polysulfide with gasification chemical recovery.

Power/fuels/recovery area:

- 6 x 10^6 lbs/day black liquor solids (2721 metric t/d) with conventional kraft; 5.4 x 10^6 lbs/day with polysulfide.
- Hog fuel from pulpwood + purchased residues if needed.
- Delivers all mill process steam and some electricity.

Pulp Mill-Integrated Biorefining

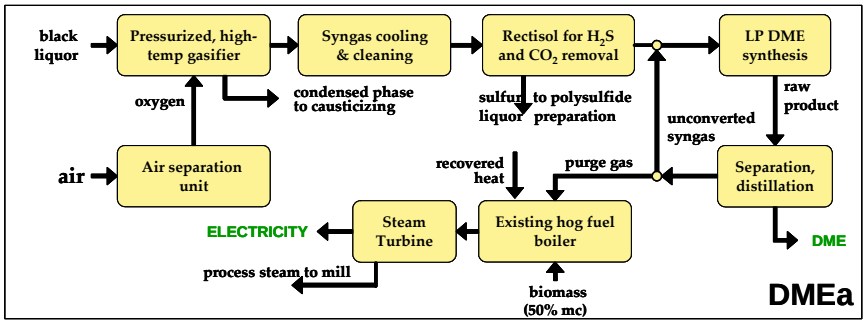


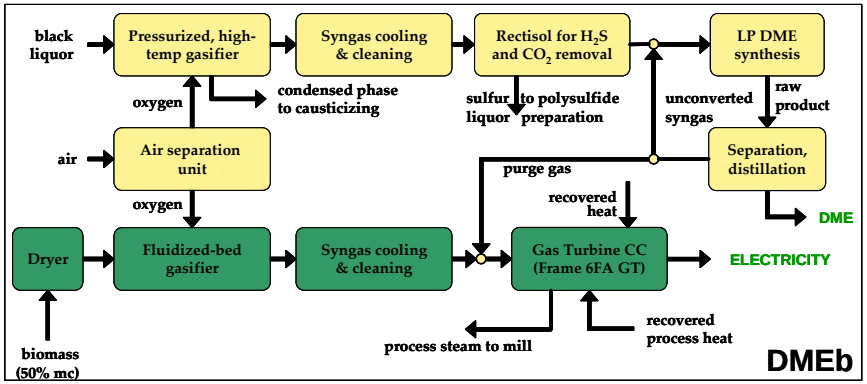


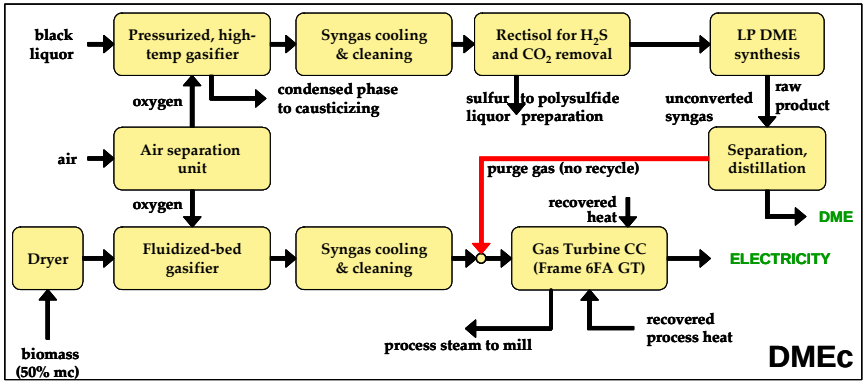
Pressurized, high-temperature, O_2-blown (Chemrec) black liquor gasifier adopted in our biorefinery designs:

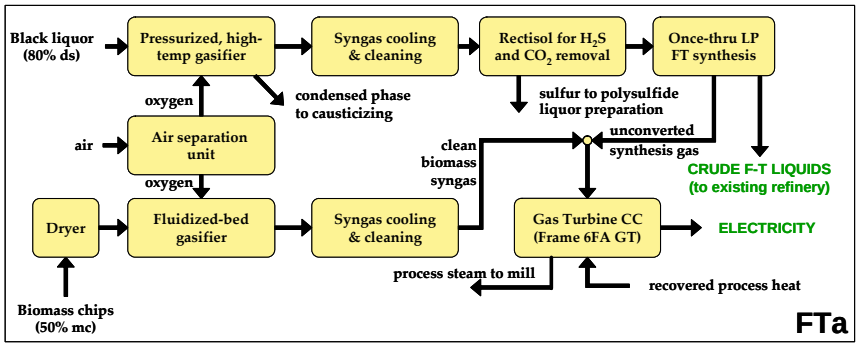
- Pilot-scale (20 tpd BLS) pressurized gasifier tests ongoing in Sweden since mid-2006.
- Commercial demo under planning for implementation by 2010 in Sweden.
- American company (VantagePoint Venture Partners) is major owner.

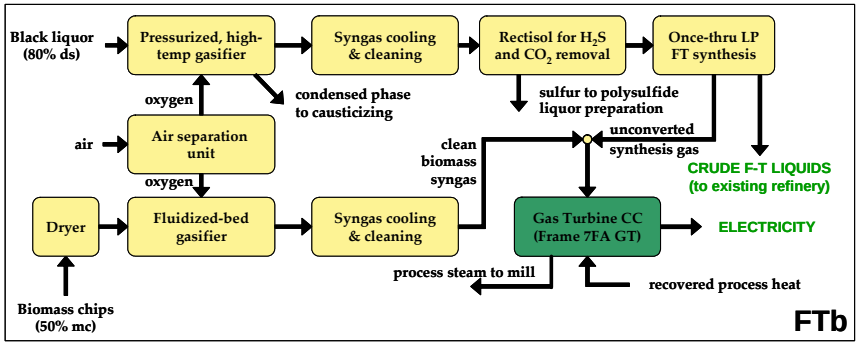
7 Detailed Biorefinery Designs Developed

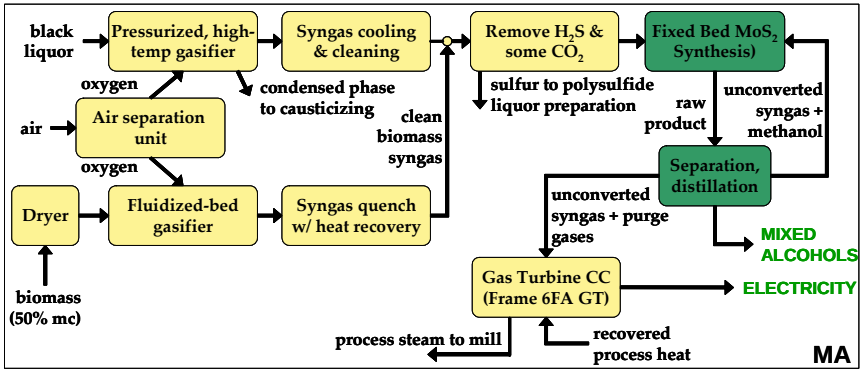










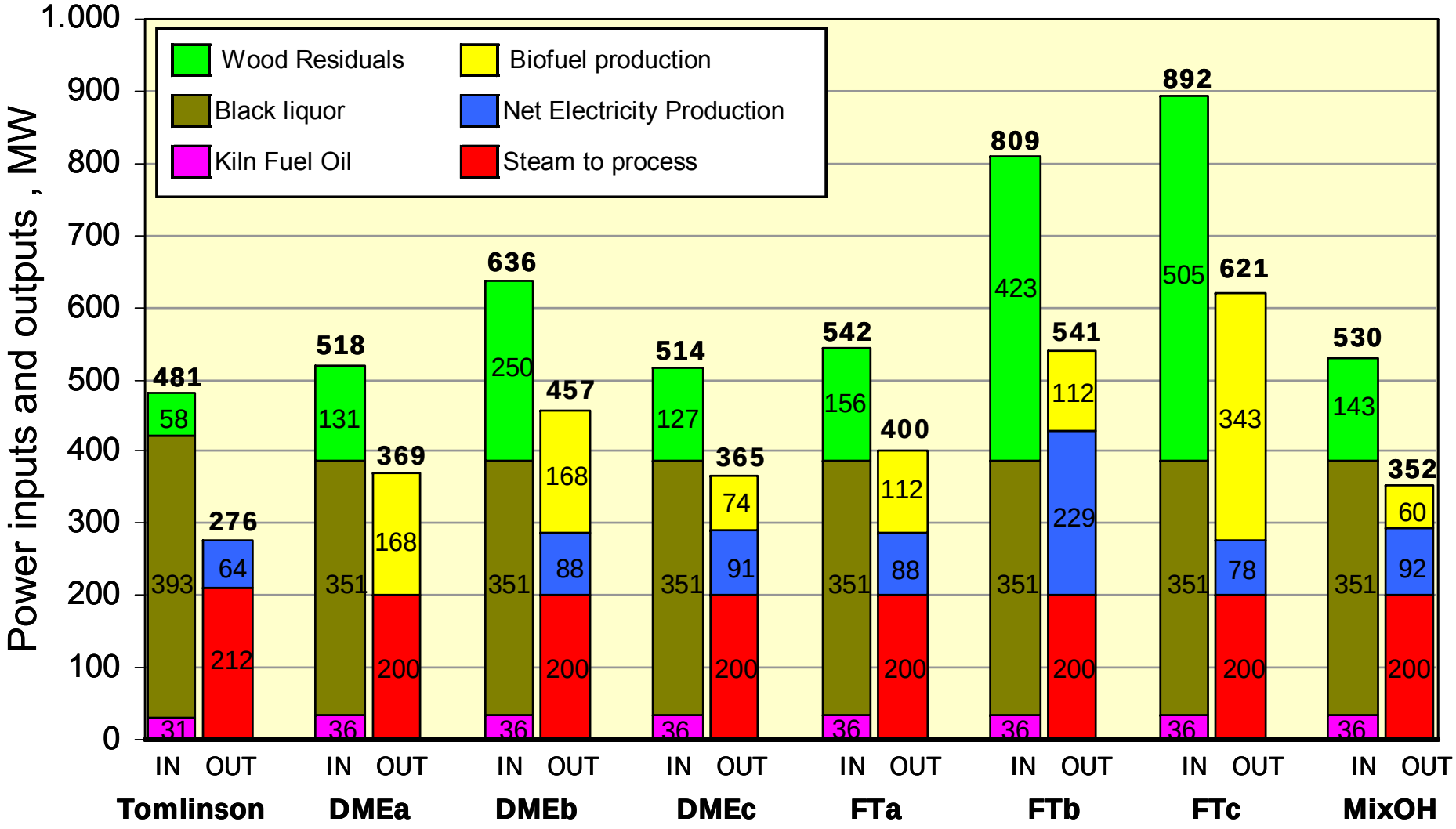


Technology in Our Biorefinery Designs

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

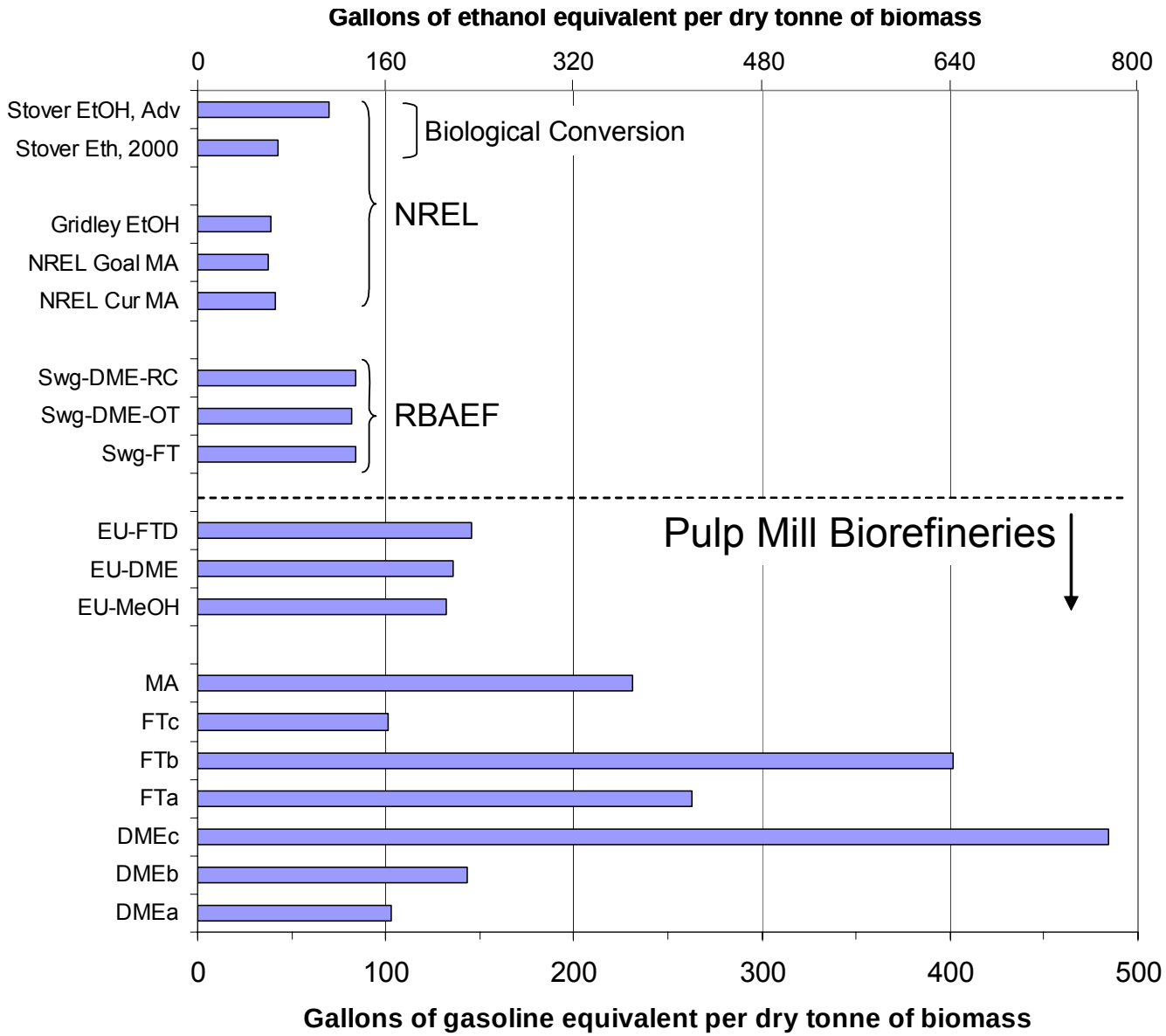
Overall Energy In and Out



"Nth 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



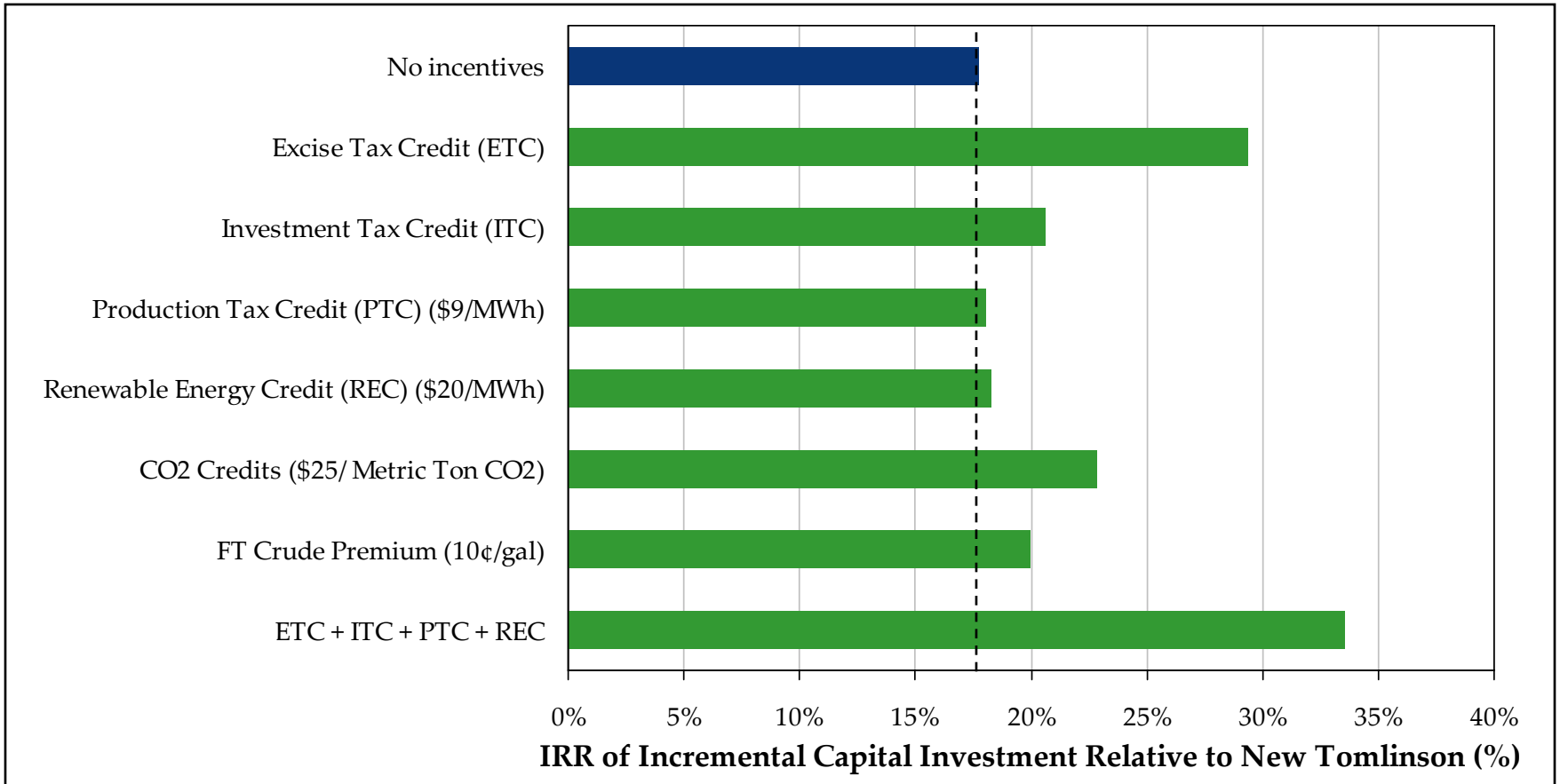
- A biorefinery integrated with a pulp mill effectively requires much less biomass per unit of liquid fuel produced vs. “stand-alone” biofuel production
- The reason is that black liquor (and some biomass) are charged against services provided to the mill (chemical recovery, process steam and power)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

“Nth Plant” Installed Capital Costs

- New Tomlinson boiler system: ~$140 million.
- New gasification-based biorefinery: $250-500 million.

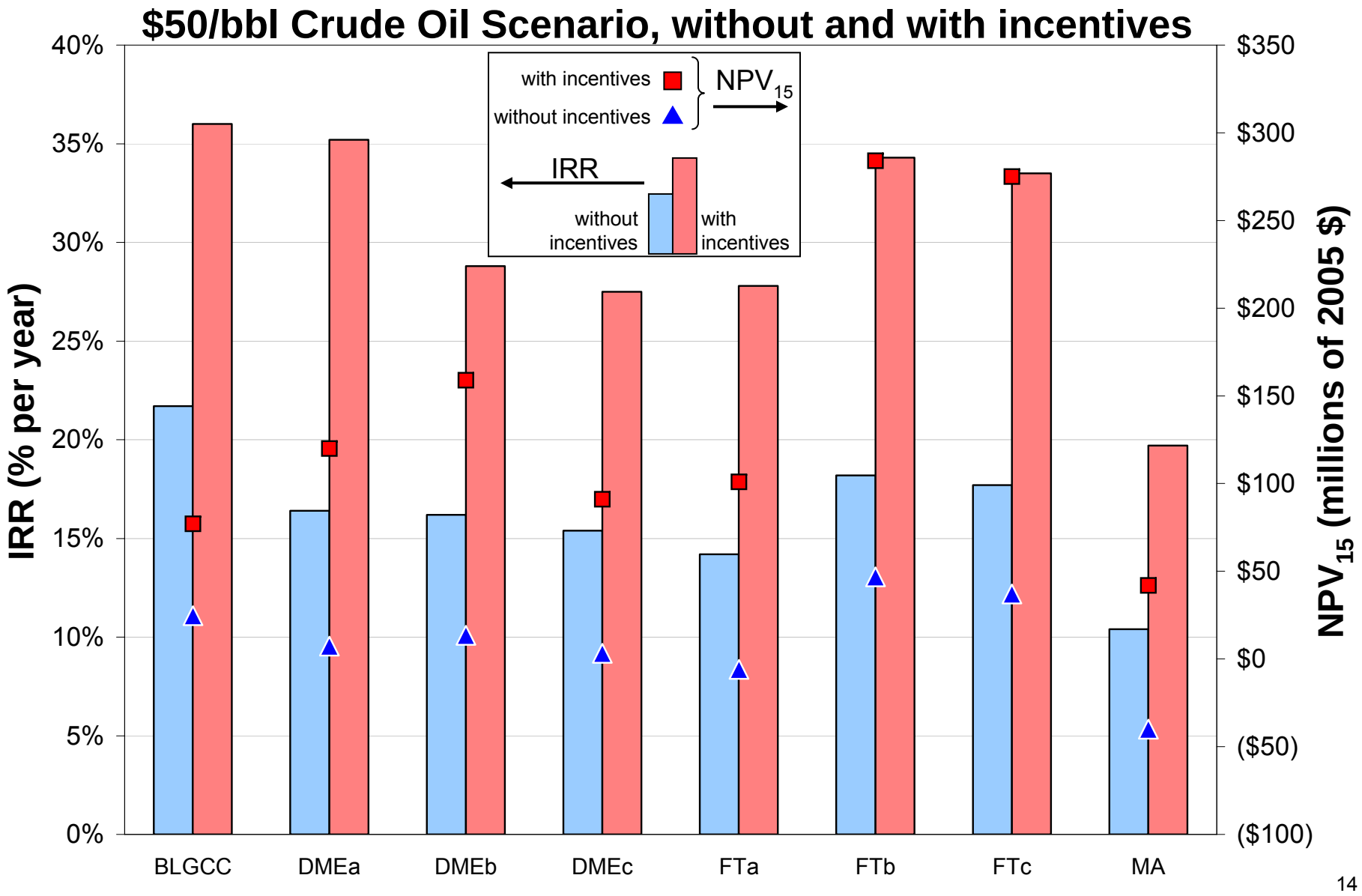
THOUSAND 2005$	Power/Steam[a]		Biorefinery -- Power/Steam/Liquid Fuel						
	Tomlin.	BLGCC	DMEa	DMEb	DMEc	FTa	FTb	FTc	MA
Recovery boiler	125,018	0	0	0	0	0	0	0	0
Steam system modifications[b]	11,136	0	3,000	0	0	0	0	0	0
Air separation unit (ASU)	0	42,628	43,053	61,561	52,933	55,001	72,762	77,823	54,080
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**

Internal Rate of Return Analysis: FTc

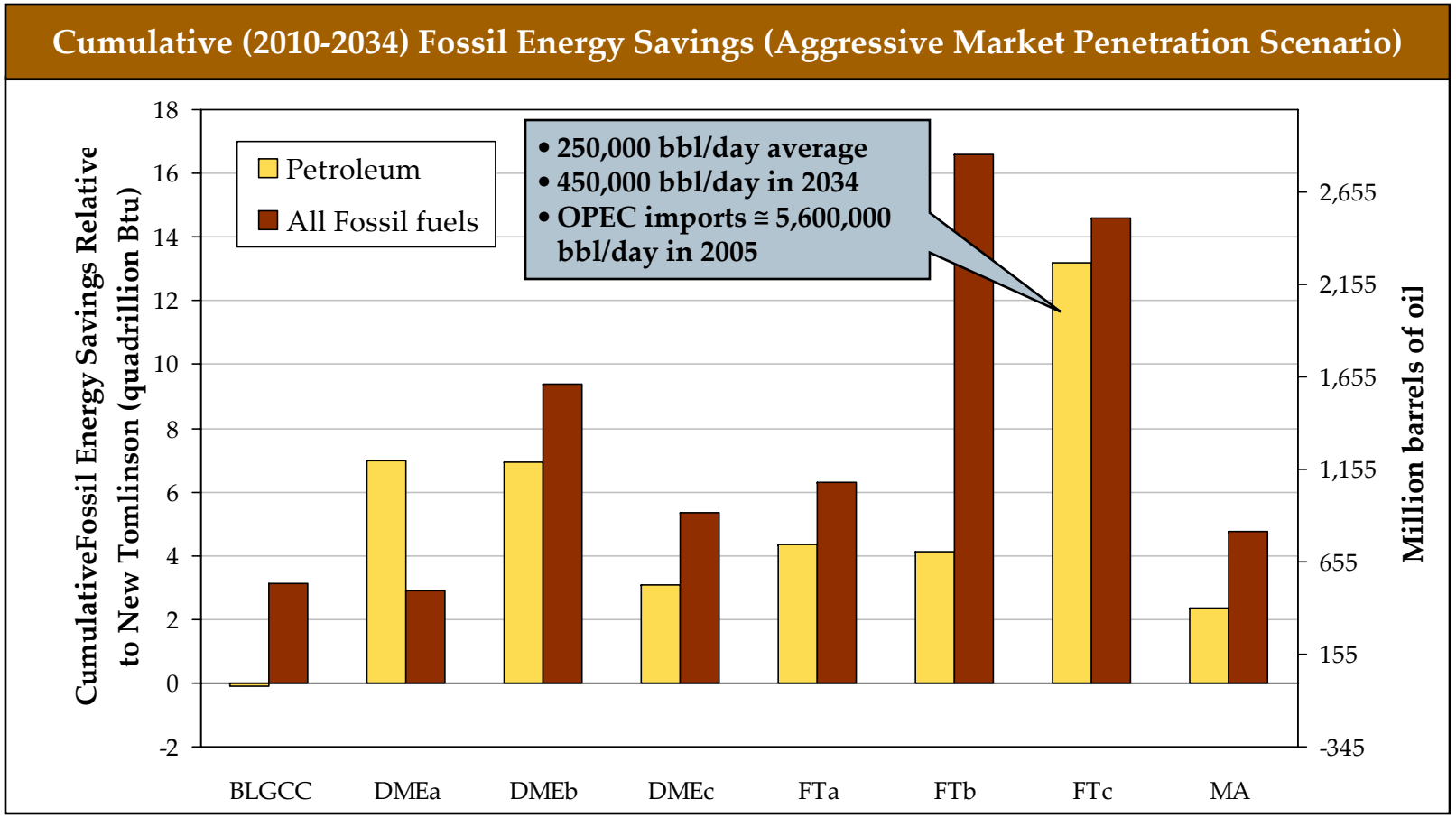


- $330 million incremental capital investment
- $50/bbl Crude Oil Scenario (AEO '06 Reference Projection)
- Electricity sale price: 5.3 c/kWh (without incentives)
- Incentives examined:
  - Excise Tax Credit (ETC): Equivalent to existing $0.51/gal for ethanol on energy basis.
  - Investment Tax Credit (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



25-Year Fossil Energy Savings
Up to 16 quads, Mostly Petroleum



Notes

- Transportation of the crude FT product to the oil refinery included in FT cases.
- Vehicle end use: FT cases assume FT gasoline blend in gasoline engines and FT diesel blend in CIDI engines. MA case assumes low-level blend with gasoline.

U.S. Pulp/Paper Industry Technical Potential for Biofuel Production in 2034

(billion gallons per year ethanol equivalent)

- FT configurations: 5 to 14 billion gal/yr
- DME configurations: 3 to 7 billion gal/yr
- For comparison:
  - 2005 corn ethanol production: 4 billion gallons
  - Latest administration goal: 35 billion gallons in 2017

Final Comments

- Pulpmill-integrated N^{th}-plant biorefinery economics are favorable due to integration ➔ capital cost shared with mill and low effective feedstock costs.
  - Production cost of FT syncrude or of DME ranges from $0.7 to $1.3 per gallon ethanol equivalent.
- Most needed technology is already commercial (in other industries), gasification is not (yet) off-the-shelf, so there are risks for the 1^{st} or 2^{nd} full-scale biorefinery.
- How to get started?
  - Woody biomass gasification for IGCC-electricity and/or liquid fuels, and/or
  - Partial BLG (Weyerhaeuser New Bern model).
  - Partnership with energy-industries and government to help manage risk and also bring in energy-industry competences.

Thank you !

Steering Committee
- Craig Brown/Del Raymond – Weyerhaeuser
- Theo Fleisch/Mike Gradassi – BP
- Paul Grabowski – U.S. Department of Energy
- Jennifer Holmgren – UOP
- Tom Johnson – Southern Company
- Mike Pacheco – National Renewable Energy Laboratory
- Steve Kelley – North Carolina State University
- Lori Perine – American Forest & Paper Association
- David Turpin – MeadWestvaco

Additional Resource Persons
- Ron Reinsfelder – Shell Global Solutions
- Gord Homer – Air Liquide

Many Others!

Primary funding from
- U.S. Department of Energy, Office of the Biomass Program
- American Forest and Paper Association
- Georgia Tech/IPST Gasification and Biorefinery Development Program

www.princeton.edu/~energy

1. 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 U.S. Department of Energy and the American Forest & Paper Association, DOE contract DE-FG26-04NT42260, December 2006.
2. Larson, Consonni, Katofsky, “A Cost-Benefit Assessment of Biomass Gasification Power Generation in the Pulp and Paper Industry,” final report to U.S. Department of Energy, October 2003.

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