Potential of Biorefinery as Large-Scale Production Plant for Liquid Fuels in the Forest and Pulp Industry

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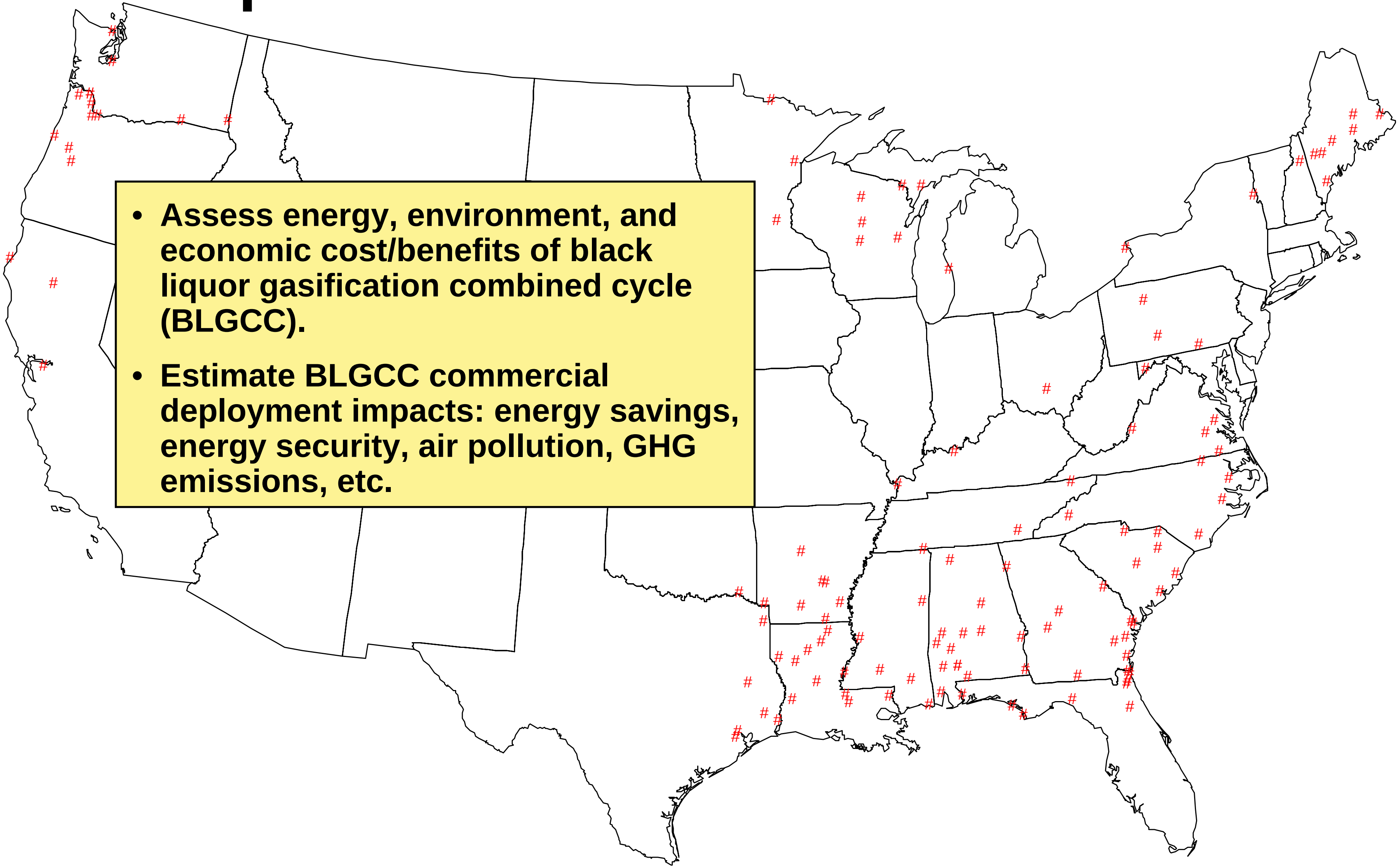
Outline of this talk

- Background: prior work assessing black liquor gasification combined cycle (BLGCC) power and chemical recovery for U.S. pulp mills.
- A new study to assess costs and benefits of gasification-based pulpmill biorefinery.
- Gasification-based conversion of woody residues.
- “Back of the envelope” economics of a pulpmill-biorefinery co-producing dimethyl ether (DME) and electricity.
- How large could a forest-based biorefinery industry become in the U.S.?

Cost-Benefit Assessment of Kraft Black Liquor Gasification Power for USA*



- **Assess energy, environment, and economic cost/benefits of black liquor gasification combined cycle (BLGCC).**
- **Estimate BLGCC commercial deployment impacts: energy savings, energy security, air pollution, GHG emissions, etc.**

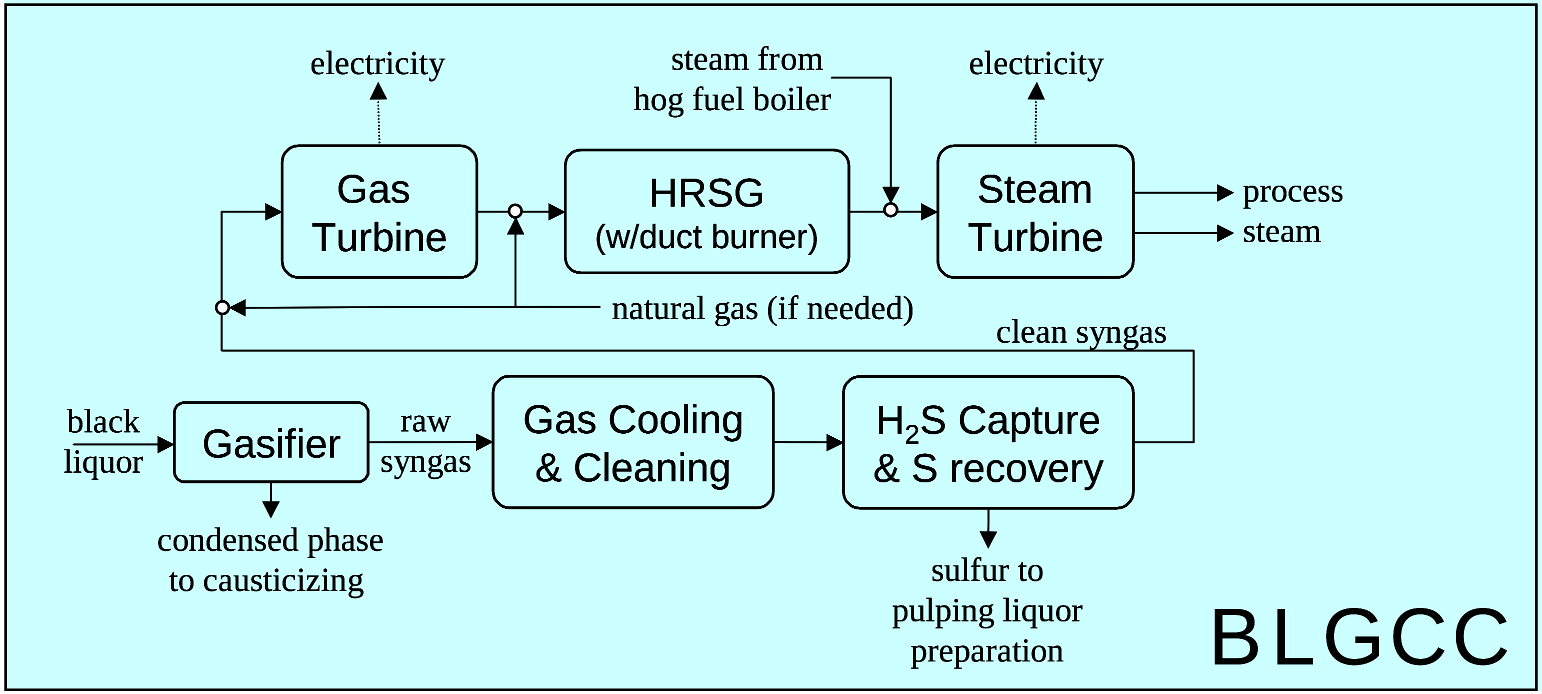
E.D. Larson, S. Consonni, and R. Katofsky (2003), “A Cost-Benefit Assessment of Biomass Gasification Power Generation in the Pulp and Paper Industry, Final Report,” prepared with support from AFPA and USDOE (downloadable via http://www.princeton.edu/~energy).

Reference Mill, Southeast USA ~ 2010

POWER/RECOVERY SYSTEM →		Tomlinson BASE	Tomlinson HERB	BLGCC
PULPING CHEMISTRY →		Conventional		Polysulfide
Product flow (uncoated freesheet paper)	Machine-dry metric tons/day	1,725		
Unbleached pulp rate	Bone dry short tons/day	1,580		
Mill hardwood/softwood mix	% HW, % SW	65% HW, 35% SW		
Digester yield	% for softwood	45.5		48.75
	% for hardwood	46.5		49.75
Wood to process (91% of total)		3,434		3,208
Hog fuel (9% of total)	Bone dry short tons/day	340		317
Total wood used		3,774		3,525
BLACK LIQUOR SOLIDS CONCENTRATION (%)		80	85	80
BL solids flow rate	lb BLS per day	6,000,000		5,419,646
	kg BLS per day	2,721,555		2,458,311
	MW, HHV	437.6		394.7
BL solids composition, mass%	C	33.46%		32.97%
	H	3.75%		3.70%
	O	37.35%		36.88%
	S	4.10%		4.27%
	Na	19.27%		20.03%
	K	1.86%		1.93%
	Ash/chlorides	0.21%		0.22%
HOG FUEL ENERGY CONTENT	MJ / kg of fuel (HHV)	10		10
	Btu / lb of fuel (HHV)	4,300		4,300
	MWth, HHV	71.3		66.6
MILL STEAM USE, 55 psig steam	kg / kg of paper	3.384	3.362	3.207
(including evaporators, but excluding	MWth	142.8	141.8	135.3
power/recovery area)	MJ / mt of paper	7,149	7,100	6,774
MILL STEAM USE, 175 psig steam	kg / kg of paper	1.760	1.817	1.648
(including evaporators, but excluding	MWth	69.3	71.5	64.8
power/recovery area)	MJ / mt of paper	3,469	3,581	3,247
TOTAL MILL STEAM	MWth	212.1	213.3	200.1
MILL ELECTRICITY USE (ex power/recovery)	kWh / mt of paper	1,407	1,406	1,407

- **Integrated pulp/paper mill making uncoated freesheet.**
- **Nominal 6 million lbs/d black liquor solids (BLS) to recovery area.**
- **Tomlinson boiler at end of life.**
- **Process steam demand ~10% below current U.S. “best practice”.**
- **Polysulfide pulping (with BLGCC) reduces wood input (and black liquor flow) for same product output as with conventional pulping.**

BLGCC Power/Recovery Systems



electricity

Gas Turbine

steam from hog fuel boiler

HRSG (w/duct burner)

electricity

Steam Turbine

process steam

natural gas (if needed)

clean syngas

black liquor

Gasifier

raw syngas

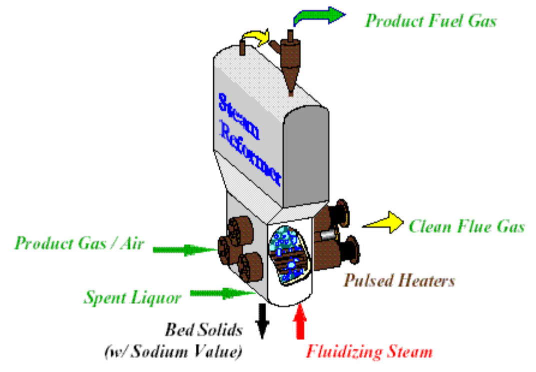
Gas Cooling & Cleaning

H_2S Capture & S recovery

condensed phase to causticizing

sulfur to pulping liquor preparation

BLGCC

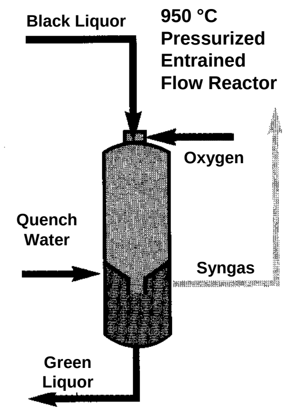


High-Temperature Gasifier ➔

- **Pressurized, O_2-blown, smelt-phase solids removal, ~ 50% of sulfur leaves in gas phase, lower-energy product gas (~ 9 MJ/kg).**
- **Chemrec (Sweden) leading developer**

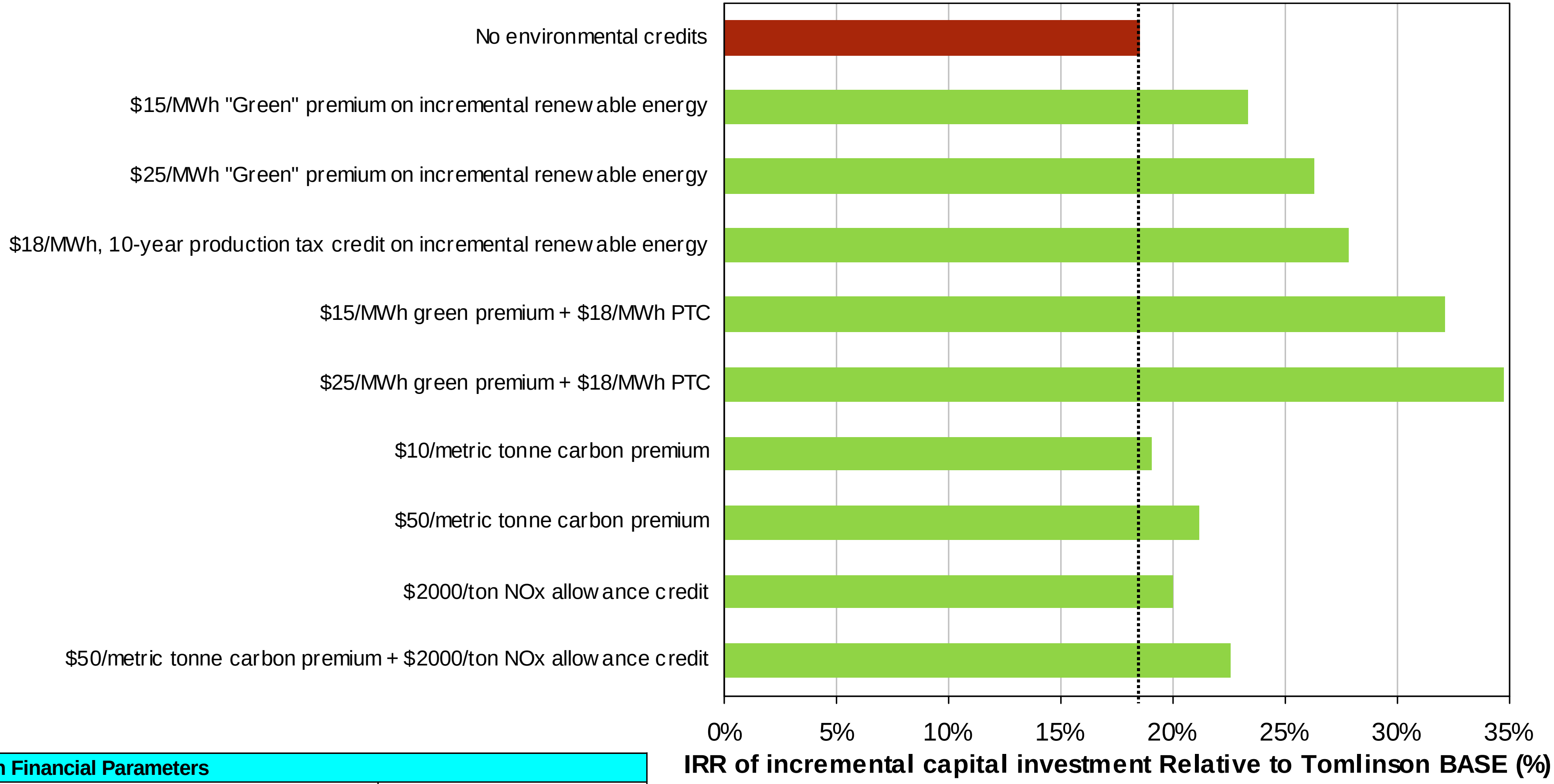
🡐Low-Temperature Gasifier

- **Steam reforming, atmospheric pressure, dry solids removal, ~ 90% of sulfur leaves in gas phase, higher-energy product gas (~ 21 MJ/gk).**
- **MTCI/TRI (USA) is leading developer**



Economics of BLGCC

(high-temperature gasifier, “mill-scale” gas turbine)



Main Financial Parameters	
Debt/equity	50% / 50%
Interest on Debt/Return on Equity	8% / 15%
Income Tax / Property tax + insurance	40% / 2%
Property Tax & Insurance	2%
Economic Life (years)	25
Depreciation Method	20-year MACRS
Effective capital charge rate	17.9%
Annual Operating Hours	8,330

Baseline Levelized Fuel and Feedstock Prices[c] (2002$)	
Utility Natural Gas ($/MCF) [$/MMBtu]	$3.86 [$3.76]
Industrial #6 Oil ($/gallon) [$/MMBtu]	$0.59 [$3.96]
Industrial Retail Electricity ($/MWh)[d]	$43.16
Exported Electricity ($/MWh)[e]	$40.44
Hog Fuel/Bark ($/MMBtu)	$1.50
Pulpwood ($/dry ton)	$51.26

Biorefinery Cost-Benefit Analysis

- US Department of Energy and American Forest & Paper Association are co-supporting a detailed technology analysis and cost-benefit assessment of gasification-based fuels production from black liquor and woody residues at U.S. kraft pulp mills
- Building on previous BLGCC analysis.
- 18-month effort kicked-off in January 2005.
- Analytical team: Princeton, Politecnico di Milano, Inst. of Paper Science & Technology, and Navigant Consulting.
- Candidate products: dimethyl ether (DME), methanol, mixed alcohols, Fischer-Tropsch, chemicals.
- Consider DME for some preliminary analysis, drawing on RBAEF results.

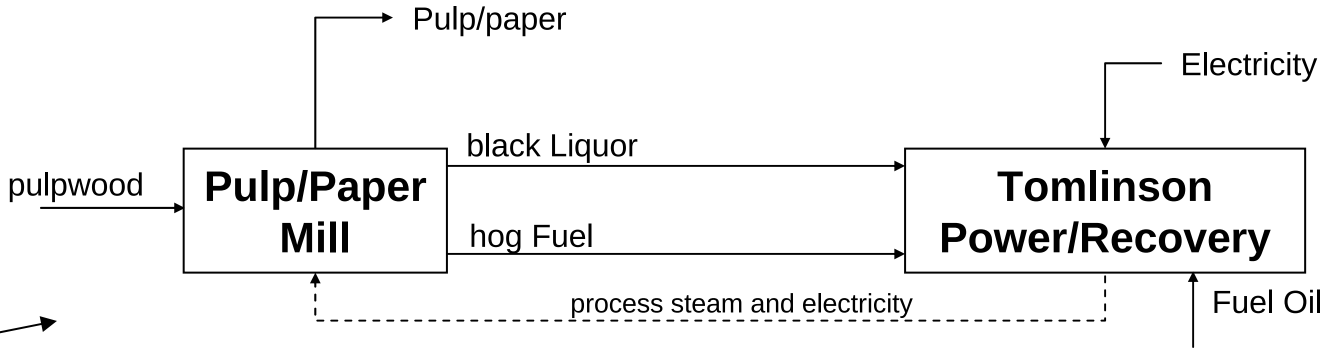
The RBAEF Project

(Renewable Biomass for America's Energy Future)

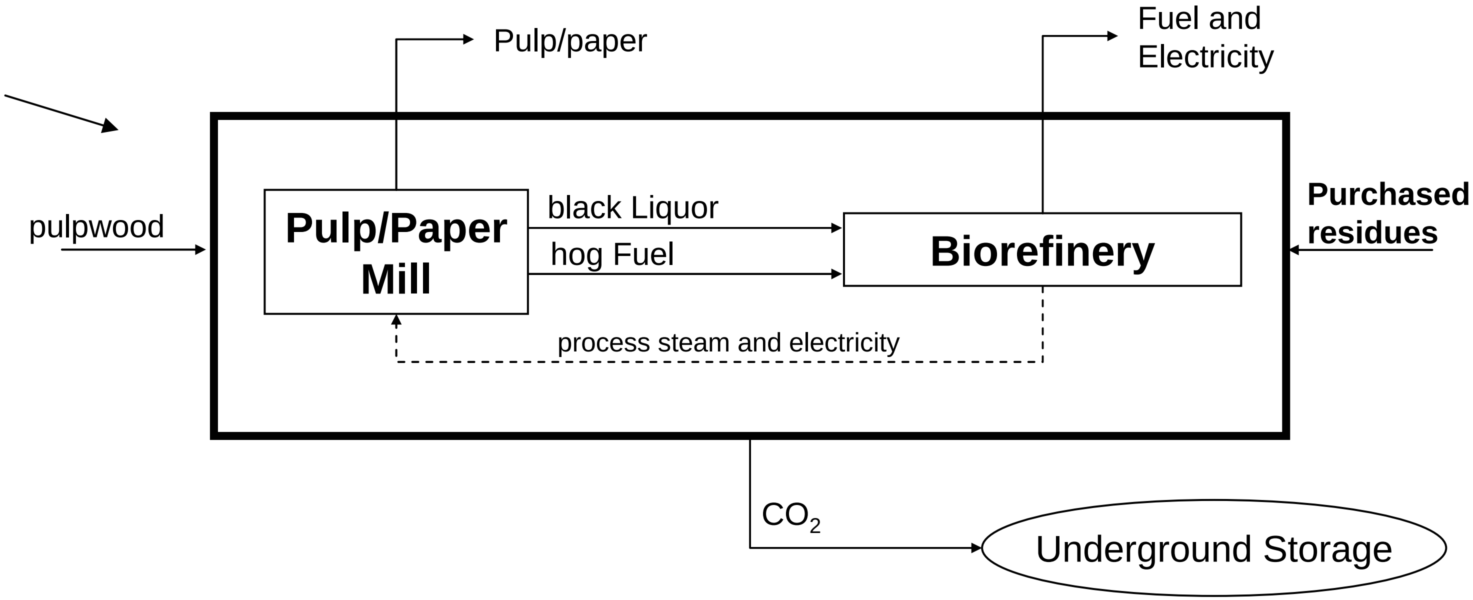
- **Questions Posed:**
  - How can biomass make large contributions to future U.S. demand for energy services, especially transportation?
  - How to accelerate biomass energy use and associated benefits?
- **Ten Participating Organizations:**
  - Dartmouth College, Princeton U., Michigan State U., U. of Tennessee
  - Argonne National Lab, National Renewable Energy Lab, Oak Ridge National Lab, USDA Agricultural Research Service
  - Union of Concerned Scientists, Natural Resources Defense Council
- **Sponsors:**
  - US DOE, Energy Foundation, National Commission on Energy Policy
- **Detailed analysis effort during 2003-2005:**
  - Energy crops, land use, farm economics, biological and thermochemical conversion, process economics, lifecycle environmental impacts, vehicle technologies, policies.
- **Recent public document:**
  - N. Greene (principal author), *Growing Energy: How Biofuels Can Help End America's Oil Dependence*, December 2004, 86 pp. (available online)

Biorefinery Schematic

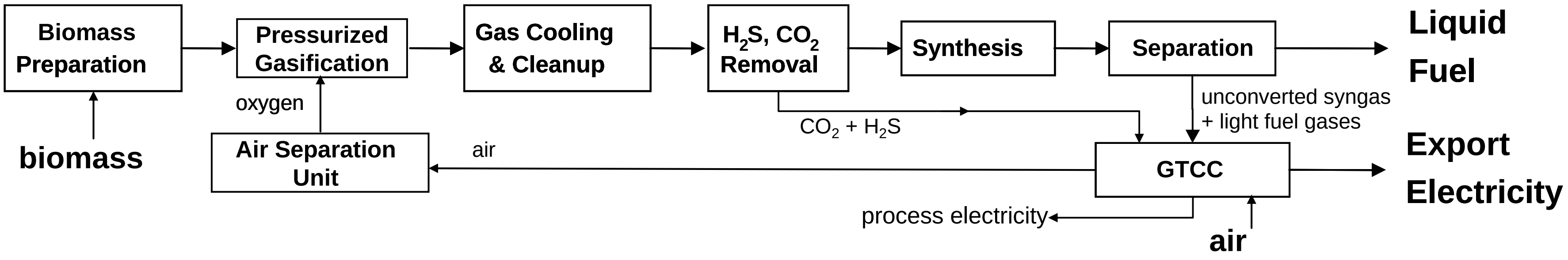
Current



Future ?



Synfuels from Woody Biomass Residues



Biomass Preparation

biomass

Pressurized Gasification

oxygen

Air Separation Unit

air

Gas Cooling & Cleanup

H_2S, CO_2 Removal

$CO_2 + H_2S$

Synthesis

Separation

unconverted syngas + light fuel gases

GTCC

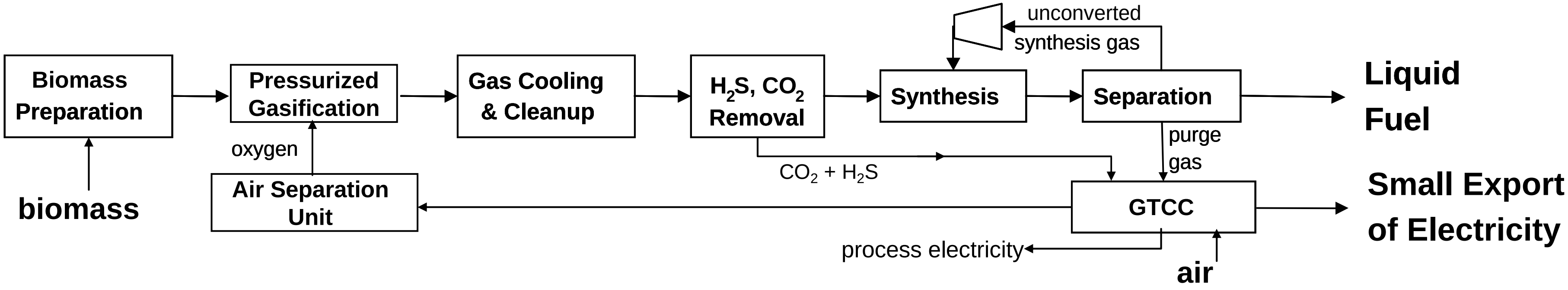
process electricity

air

Liquid Fuel

Export Electricity

Once-through (OT) processing of syngas



Biomass Preparation

biomass

Pressurized Gasification

oxygen

Air Separation Unit

Gas Cooling & Cleanup

H_2S, CO_2 Removal

$CO_2 + H_2S$

Synthesis

unconverted synthesis gas

Separation

purge gas

GTCC

process electricity

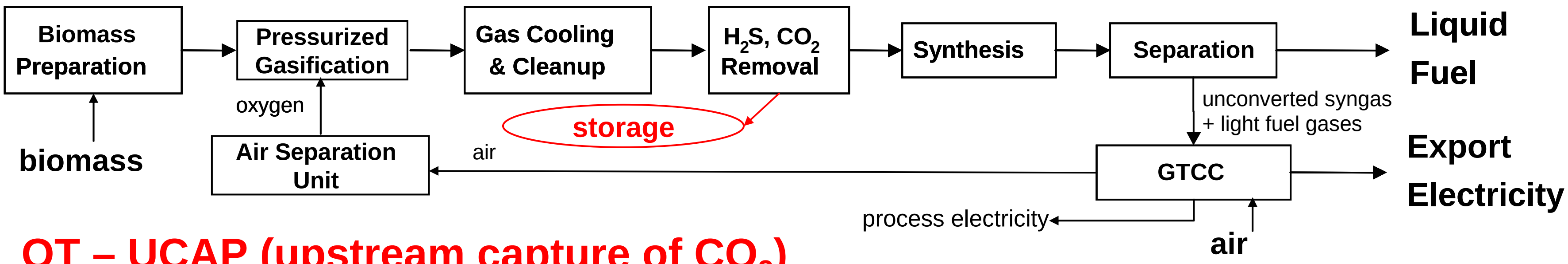
air

Liquid Fuel

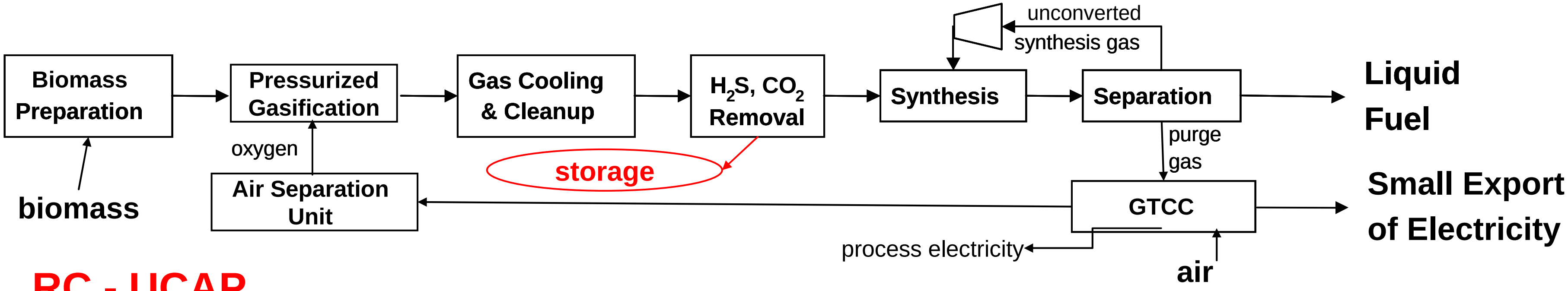
Small Export of Electricity

Recycle (RC) processing of syngas

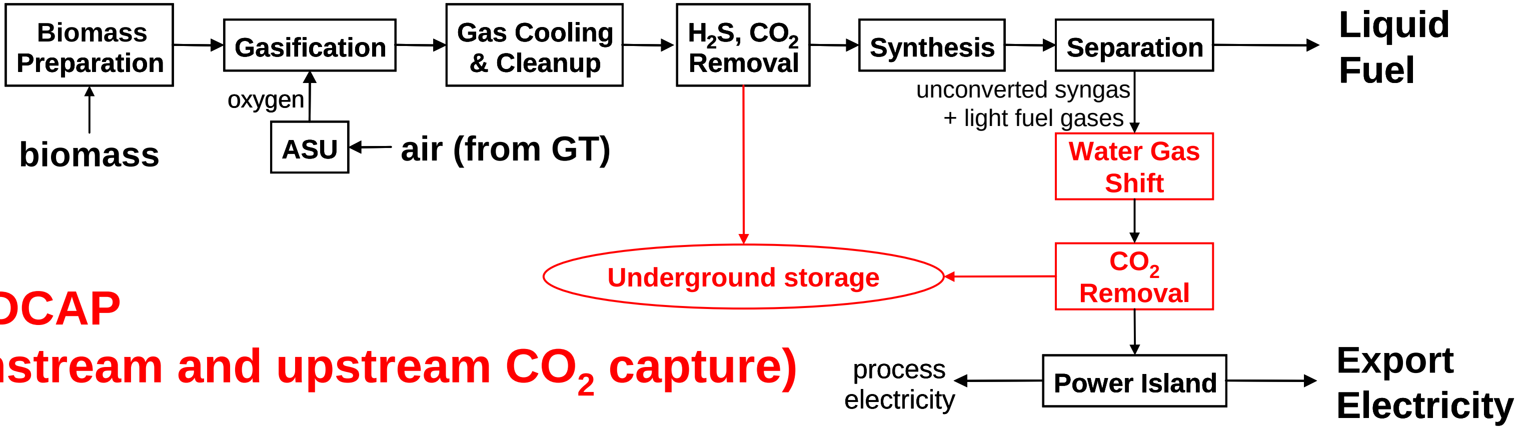
Beyond Carbon-Neutral Biomass



OT – UCAP (upstream capture of CO_2)



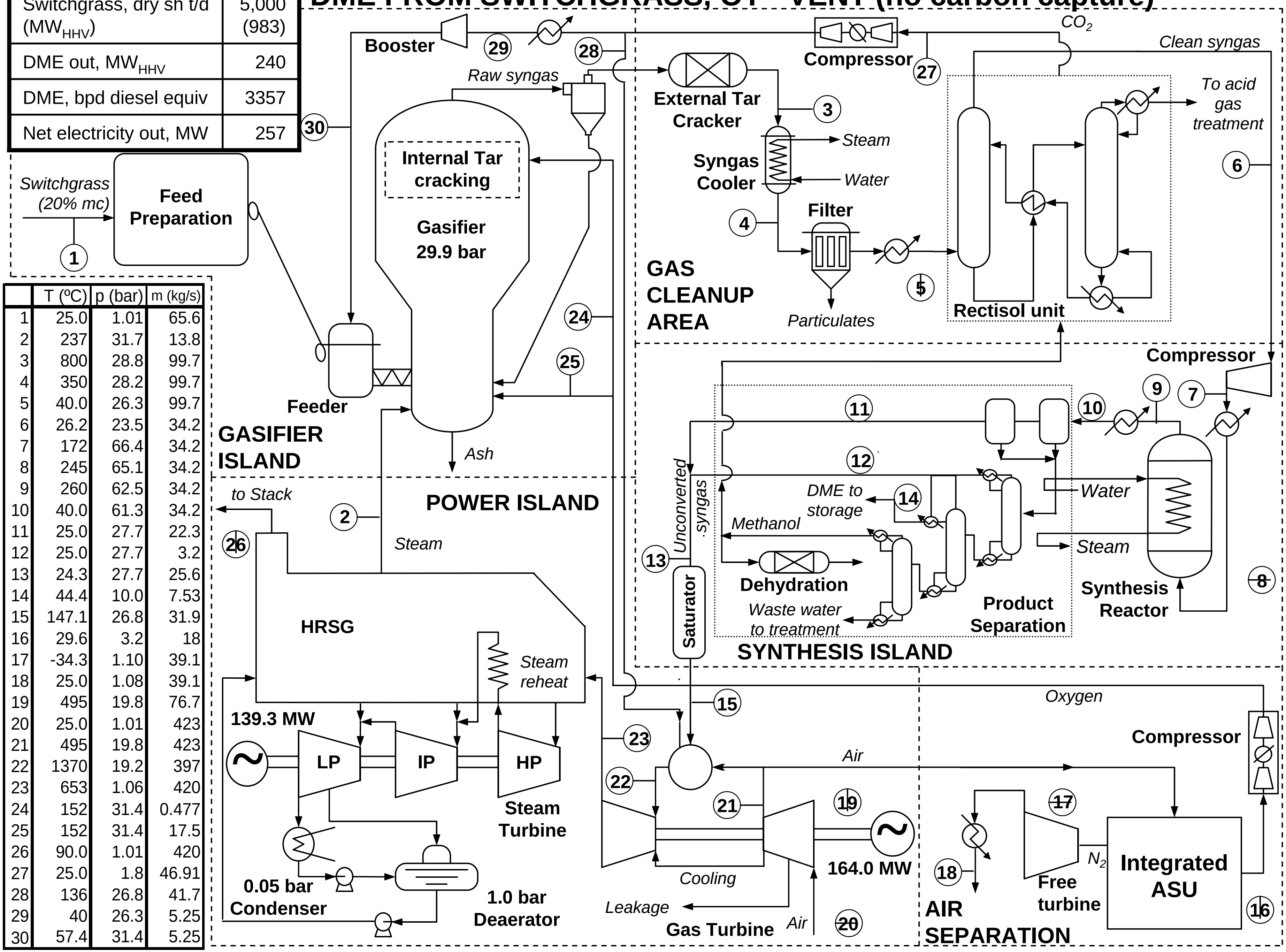
RC - UCAP



OT – DCAP
(downstream and upstream CO_2 capture)

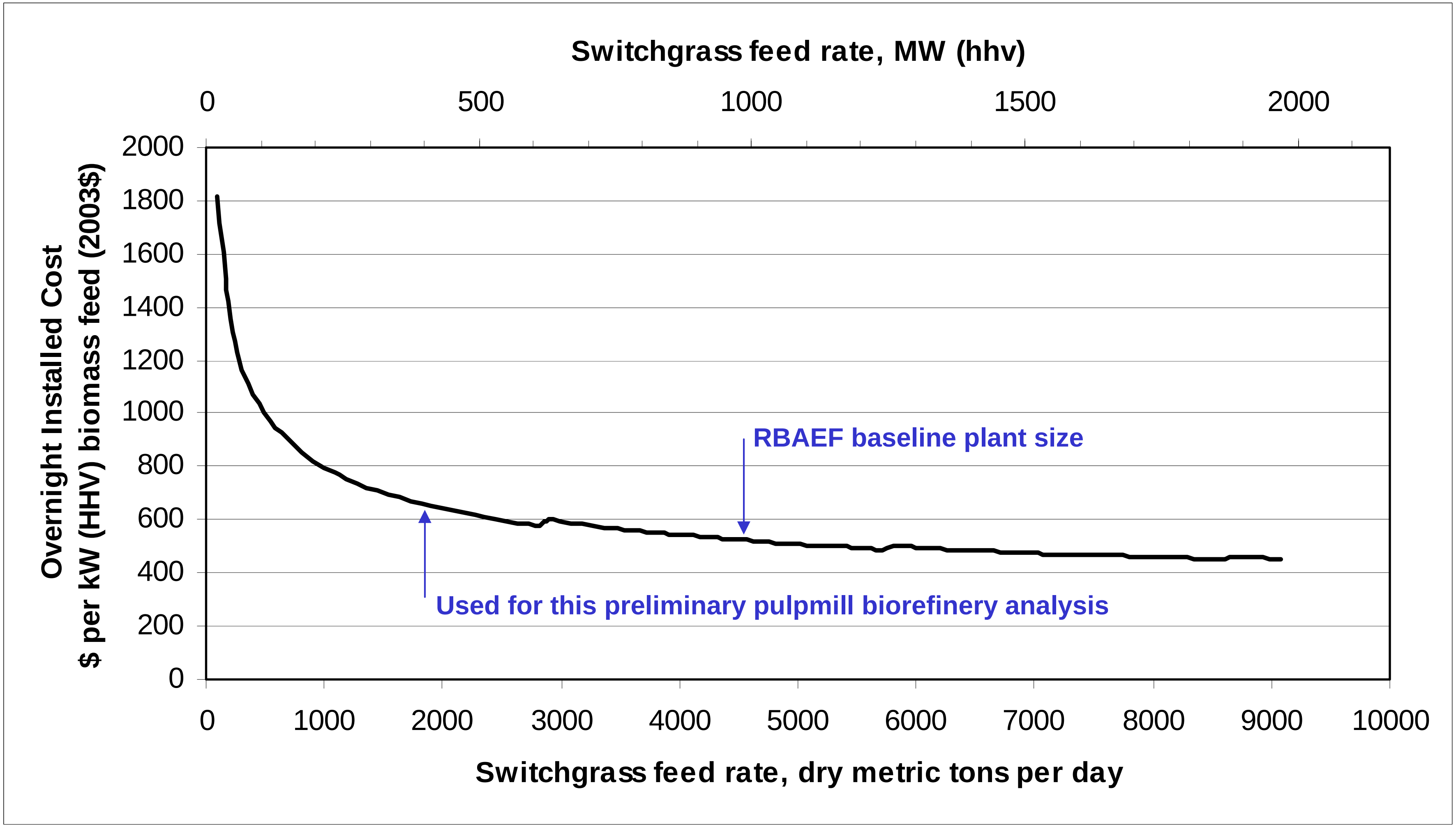
DME FROM SWITCHGRASS, OT - VENT (no carbon capture)

Switchgrass, dry sh t/d (MW_{HHV})	5,000 (983)
DME out, MW_{HHV}	240
DME, bpd diesel equiv	3357
Net electricity out, MW	257



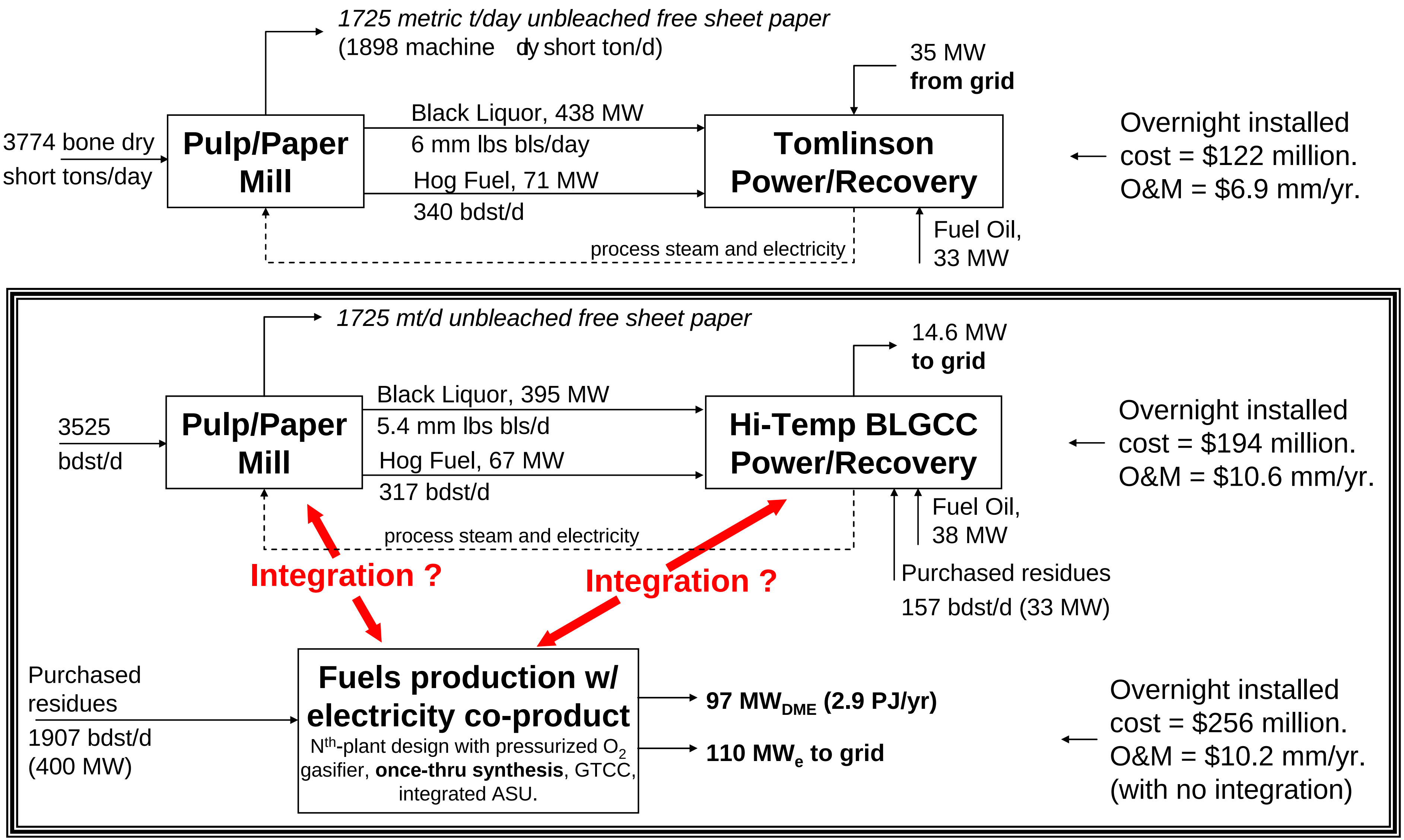
	T (ºC)	p (bar)	m (kg/s)
1	25.0	1.01	65.6
2	237	31.7	13.8
3	800	28.8	99.7
4	350	28.2	99.7
5	40.0	26.3	99.7
6	26.2	23.5	34.2
7	172	66.4	34.2
8	245	65.1	34.2
9	260	62.5	34.2
10	40.0	61.3	34.2
11	25.0	27.7	22.3
12	25.0	27.7	3.2
13	24.3	27.7	25.6
14	44.4	10.0	7.53
15	147.1	26.8	31.9
16	29.6	3.2	18
17	-34.3	1.10	39.1
18	25.0	1.08	39.1
19	495	19.8	76.7
20	25.0	1.01	423
21	495	19.8	423
22	1370	19.2	397
23	653	1.06	420
24	152	31.4	0.477
25	152	31.4	17.5
26	90.0	1.01	420
27	25.0	1.8	46.91
28	136	26.8	41.7
29	40	26.3	5.25
30	57.4	31.4	5.25

Installed Capital Cost for OT-VENT Plant Configuration for DME vs. Plant Size



For additional information about these estimates, see Larson Jin, Williams, and Celik, "Gasification-Based Liquid Fuels and Electricity from Biomass with Carbon Capture and Storage," presentation at National Energy Technology Lab's 4th Annual Conf. on Carbon Capture & Sequestration, 2-5 May 2005, Alexandria, Virginia, USA

Pulpmill Biorefinery Cost Analysis (preliminary)



1725 metric t/day unbleached free sheet paper
(1898 machine dry short ton/d)

3774 bone dry short tons/day

Pulp/Paper Mill

Black Liquor, 438 MW
6 mm lbs bls/day

Hog Fuel, 71 MW
340 bdst/d

35 MW **from grid**

Tomlinson Power/Recovery

Fuel Oil, 33 MW

process steam and electricity

Overnight installed cost = $122 million.
O&M = $6.9 mm/yr.

1725 mt/d unbleached free sheet paper

3525 bdst/d

Pulp/Paper Mill

Black Liquor, 395 MW
5.4 mm lbs bls/d

Hog Fuel, 67 MW
317 bdst/d

14.6 MW **to grid**

Hi-Temp BLGCC Power/Recovery

Fuel Oil, 38 MW

Purchased residues 157 bdst/d (33 MW)

process steam and electricity

Overnight installed cost = $194 million.
O&M = $10.6 mm/yr.

Integration ?

Integration ?

Purchased residues
1907 bdst/d
(400 MW)

Fuels production w/ electricity co-product
Nth-plant design with pressurized O_2 gasifier, **once-thru synthesis**, GTCC, integrated ASU.

97 MW_{DME} (2.9 PJ/yr)

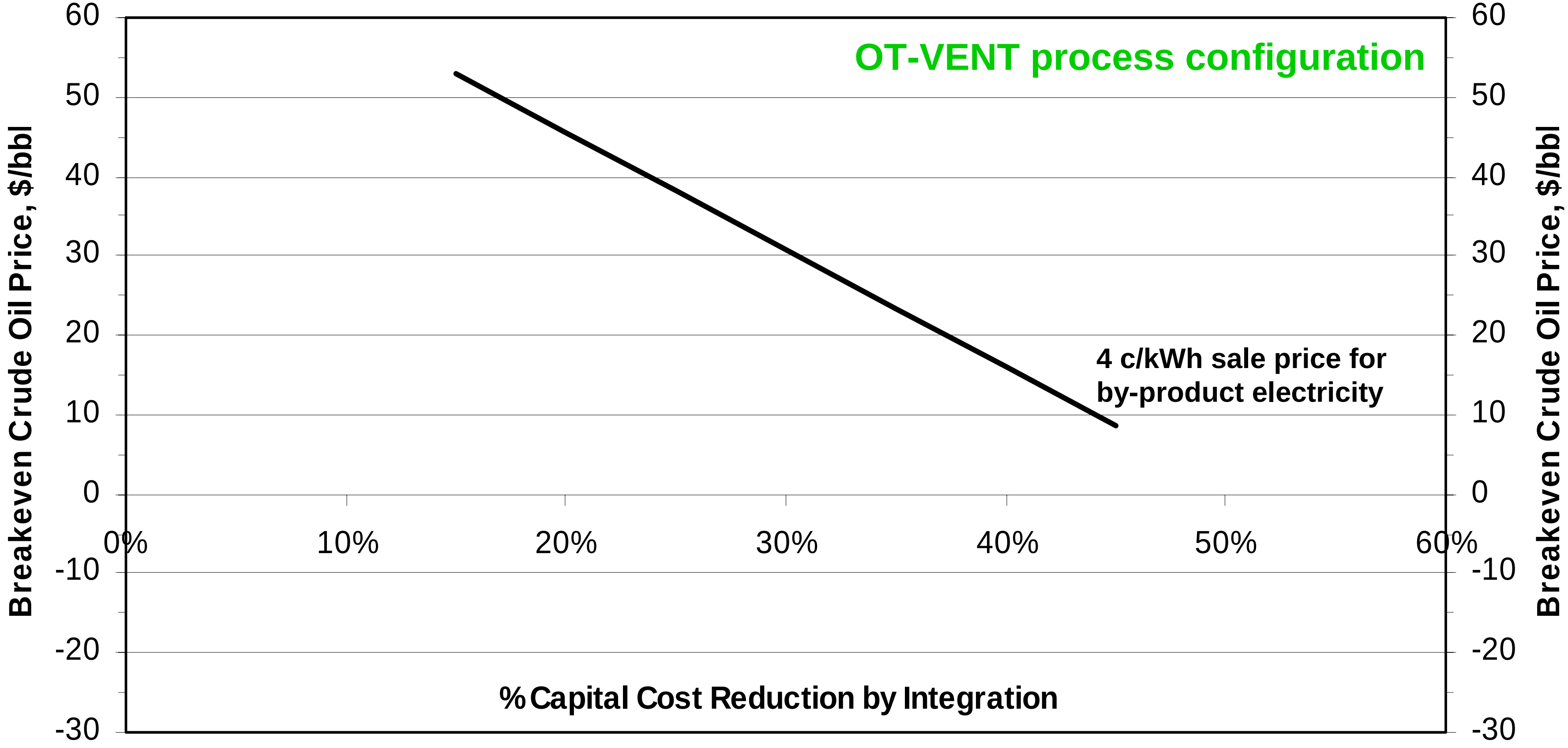
110 MW_e to grid

Overnight installed cost = $256 million.
O&M = $10.2 mm/yr.
(with no integration)

All fuel energy contents are given on higher heating value basis

Based on: E.D. Larson, S. Consonni, & R.E. Katofsky, 2003. *A Cost-Benefit Assessment of Biomass Gasification Power Generation in the Pulp and Paper Industry*, October.
E.D. Larson, H. Jin & F.E. Celik,*2005. Gasification-Based Fuels and Electricity Production from Biomass, with and without Carbon Capture and Storage*, RBAEF report, forthcoming.
E.D. Larson and T. Ren, 2003. "Synthetic Fuels Production by Indirect Coal Liquefaction," *Energy for Sustainable Development*, **VII**(4): 79-102.

DME Costs (incremental to new Tomlinson) from a Pulpmill Biorefinery



Input Assumptions *(same as Larson, Consonni, Katofsky 2003 BLGCC study)*			
Pulpwood, $/dry short ton	51.3	Annual operating hours	8330
# 6 fuel oil, $/GJ (HHV)	3.75	Debt/Equity mix	50/50
Natural gas, $/GJ (HHV)	3.56	Interest rate on debt	8%
Avoided electricity value, c/kWh	4.30	Return on equity	15%
Electricity sales, c/kWh	4.00	Capital charge rate, %/yr	17.9%
Purchased residues, $/mmBtu, hhv	1.5		

Notes

- Breakeven $/bbl is oil price at which refinery-gate price of petroleum diesel equals DME plant-gate cost on $/GJ basis.
- Other’s analysis suggests cost of DME delivery and refueling about equals diesel-vehicle avoided pollution control costs.
- All financial parameter assumptions same as for BLGCC study.

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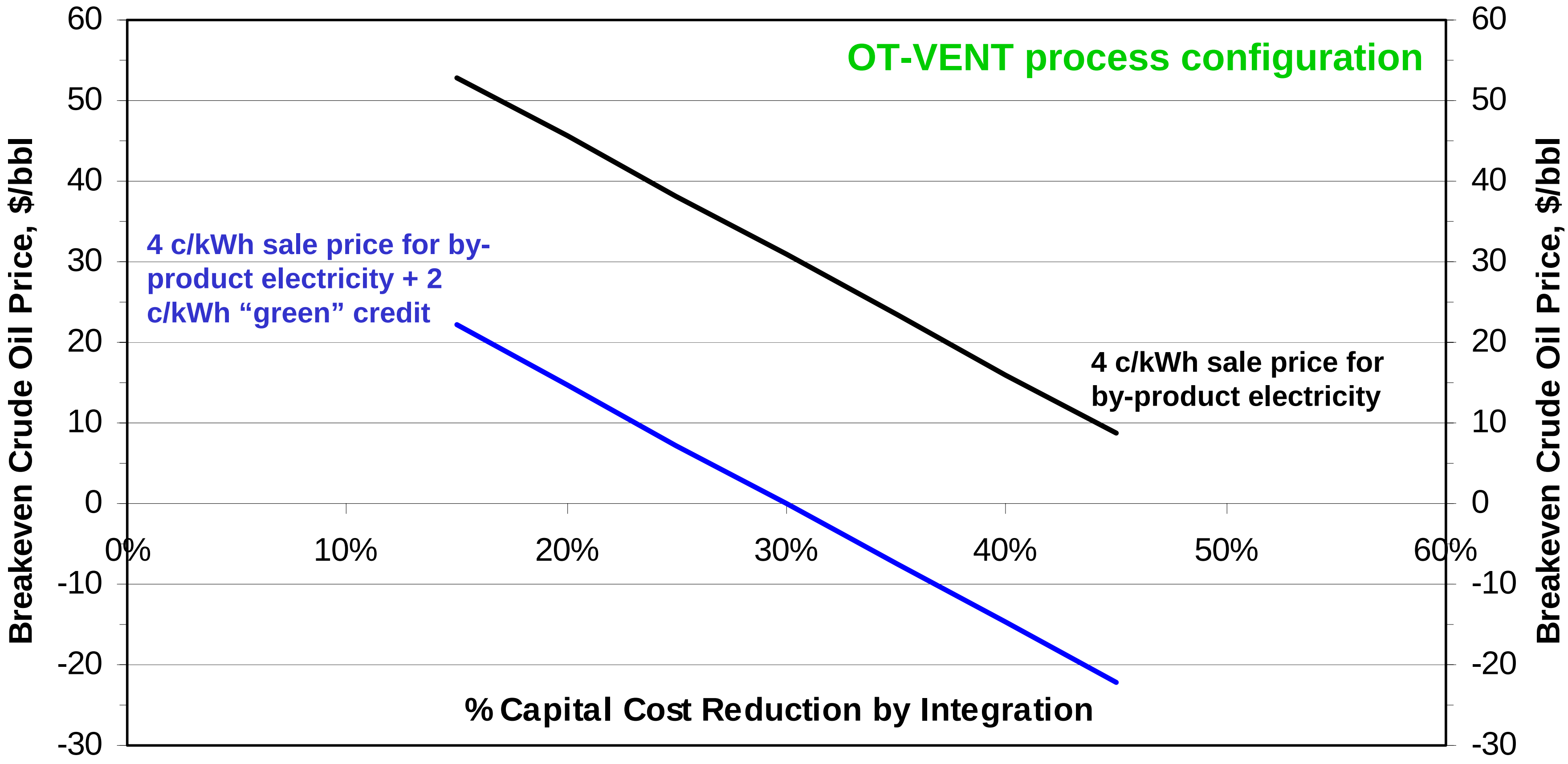

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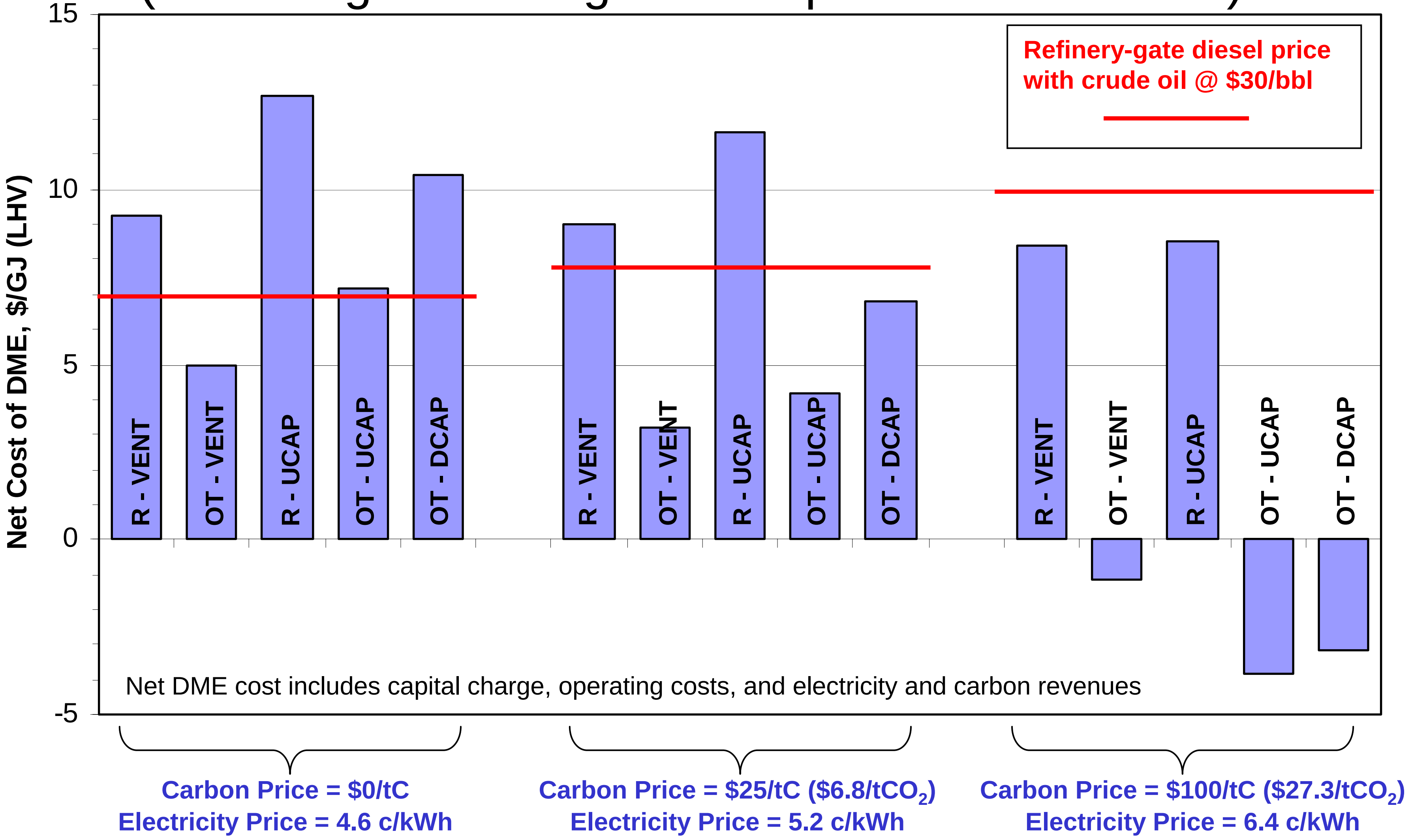
Net DME Cost for Alternative Configurations

(assuming 30% integration capital cost reduction)



Capital charge rate, 17.9%/yr

Purchased biomass, $1.42/$GJ_{HHV}$

CO_2 tpt/storage, $5/t$CO_2$

Electricity @ coal-IGCC cost

How Large Could a U.S. Pulpmill Biorefinery Industry Become?

- 73 million t/yr BLS processed by U.S. industry today.
- For each tonne of black liquor solids (BLS), a pulpmill biorefinery could produce 0.56 barrels diesel-equivalent plus 1222 kWh export electricity.
- A pulpmill-biorefinery industry would require ~55 million tonnes/year purchased biomass.
- Such an industry could
  - Produce 4.4% of current U.S. petroleum-diesel + 4.6% of coal-electricity.
  - Avoid CO_2 emissions of 37 million tC/yr (without using CCS), or 2.3% of all U.S. carbon emissions today.
  - Generate carbon revenues of $0.93 billion/yr, assuming a carbon price of $25/tC ($6.8/tCO_2).

The Potential Sustainable Biomass Supplies in U.S.A. are Large*

	Million dry tonnes/yr
Currently-Available (and unused) Forest Resources	**139**
Logging and other residues	37
Thinnings (for fuel treatment)	55
Fuelwood	15
Forest products industry mill wastes (excludes black liquor)	7
Urban wood residues	25
Future forest growth	**81**
Potential Agricultural Resources	**582 - 997**
Crop residues	286 – 446
Dedicated perennial crops	156 – 377
Crop processing residues	84 – 87
Grains to biofuels	56 – 87
TOTAL	**802 - 1,217**
	1,217 mt/yr ≈ 23 EJ/yr (*current U.S. primary energy use = 103 EJ/yr*)

* Source: Perlack, Wright, Turhollow, Graham, Stokes, and Erbach, *Biomass as Feedstocks for a Bioenergy and Bioproducts Industry: the Technical Feasibility of a Billion-Ton Annual Supply*, jointly sponsored by USDOE and USDA, Oak Ridge National Lab, April 2005.

How Large Could a Forest-Based Biorefinery Industry Become?

- Consider pulpmill-based industry that grows into a forest-based industry using most the available forest-based biomass residues in U.S. (195 million tonnes/yr).
- Such an industry could
  - Produce 16% of current U.S. petroleum-diesel, plus 15% of coal-electricity.
  - Avoid CO_2 emissions of 107 million tC/yr (without using CCS), or 6.8% of current total U.S. carbon emissions.
  - Generate carbon revenues of $2.7 billion/yr, assuming a carbon price of $25/tC ($6.8/tCO_2).
- With such an industry, the infrastructure would be in place for utilizing non-forest biomass resources, which are potentially 2 to 4 times bigger than forest resources.