Fourth Annual Conference on Carbon Capture & Sequestration

Developing Potential Paths Forward Based on the Knowledge, Science and Experience to Date

Advanced Concepts – Biomass Offsets

Gasification-Based Liquid Fuels and Electricity from Biomass with Carbon Capture and Storage

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Outline of talk

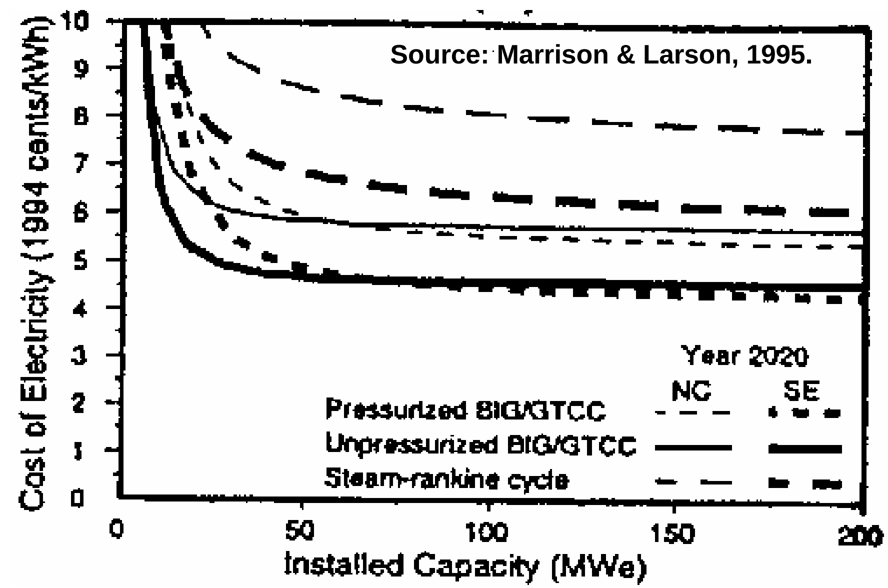
1. Motivation for this work.
2. Economic rationale for large-scale biomass conversion facilities (favored for CCS).
3. Approach to our analysis.
4. Process overviews for electricity and synfuels from switchgrass.
5. Energy and carbon balances.
6. Capital cost estimates and their calibration.
7. Electricity and synfuel economics, including impact of carbon price.

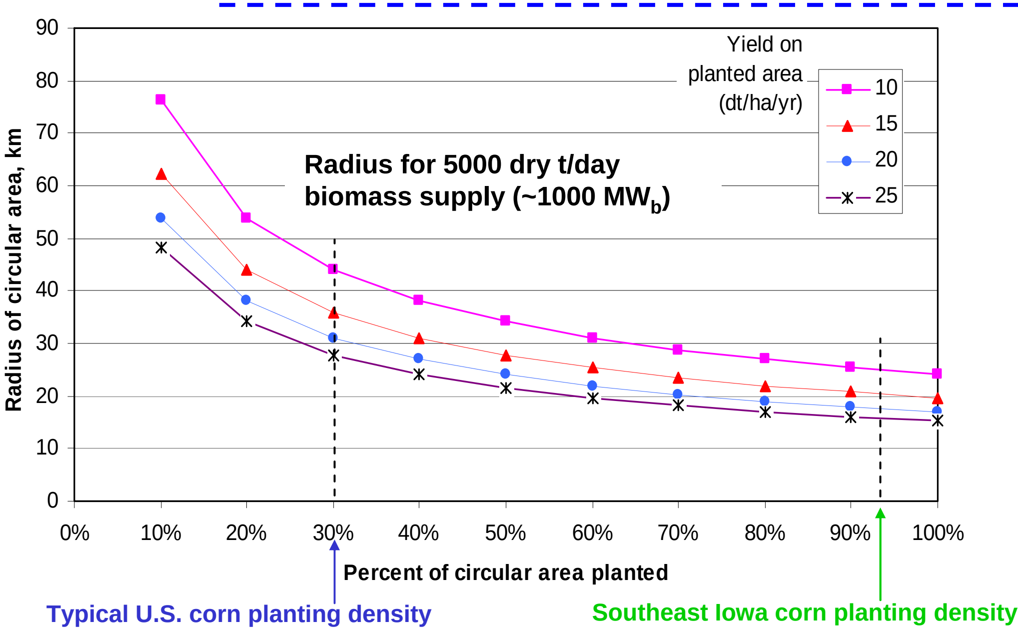
Motivation: Beyond carbon-neutral biomass

- Sustainble biomass ➔ little/no net CO_2 emissions.
- Biomass with CCS ➔ negative CO_2 emissions.
- Gasification-based electricity or fuels from biomass, without or with CCS, similar to coal-based systems:
  - Chiesa, Consonni, Kreutz & Williams, "Co-Production of Hydrogen, Electricity and CO_2 from Coal with Commercially Ready Technology. Part A: Performance and Emissions" and "Part B: Economic Analysis" (Kreutz, Williams, Consonni & Chiesa), *International Journal of Hydrogen Energy*, 2005, forthcoming.
  - Celik, Larson & Williams, "Transportation Fuel From Coal With Low CO_2 Emissions," *7th International Conf. on Greenhouse Gas Control Technologies*, Vancouver,2004.
  - Larson & Ren, "Synthetic fuels production by indirect coal liquefaction," *Energy for Sustainable Development*, **VII**(4): 79-102, 2003.
- As with coal, economics of CCS with biomass will favor large-scale biomass conversion facilities.

Rationale for large-scale conversion

- With a dedicated energy crop like switchgrass, scale-economy benefits of larger conversion facilities outweigh added feedstock transport costs. (Not true for biomass residues.)





- High yields and/or high planting densities reduce transportation distances.
- Estimated costs (2003$) for transporting switchgrass*:
  - 20 km: \$8.5/dry t (\$0.45/GJ_{hhv})
  - 80 km: \$22.6/dry t (\$1.2/GJ_{hhv})

* Marrison & Larson, 1995, “Cost vs. Scale for Advanced Plantation-Based Biomass Energy Systems in the U.S.A. and Brazil,” Proceedings of 2nd Biomass Conf. of Americas, NREL, Golden, CO, pp. 1272-1290.

Analysis approach

Objective

- Compare performance and cost on self-consistent basis of future, commercially-mature, Nth-plant processes for producing synfuels, co-producing synfuels and electricity, and producing electricity alone, without and with carbon capture and storage (CCS) – from switchgrass energy crops in the U.S.

Approach

- Assume key technical R&D hurdles have been overcome in Nth plant:
  - Efficient and high reliability feeding & operation of large-scale pressurized (~30 bar), O_2 gasifier.
  - Gas cleanup (including complete tar cracking) to specifications for downstream processing (particulates, alkali, sulfur and other trace contaminants).
  - Gas turbine performance on low heating value gases comparable to today's state-of-the-art turbines burning natural gas (e.g., GE 7FB).
  - Good process heat integration and process control achieved, including GT-integrated ASU.
- Design conversion facilities with input of 5,000 dry short tons per day (983 MW, HHV)
- Simulate heat/mass balances using Aspen^{+} and Pinch analysis, with input values based on extensive literature review and discussion with industry experts.
- Assume for capital costs no major technology breakthroughs leading to dramatic cost reductions -- Nth plant costs are estimated for scaled-up versions of technologies that have been demonstrated at least at pilot scale (e.g., gasifiers), or are commercially established (e.g, gas turbines, waste heat boilers, steam turbines, synthesis reactors).
- Capital and operating cost estimates developed based on extensive literature review, own prior work, and discussions with industry experts.
- Consistent financial parameters and accounting framework for all cases.

Two synthetic liquid fuels of interest

Fischer-Tropsch Fuels

(straight-chain C_nH_{2n} , C_nH_{2n+2})

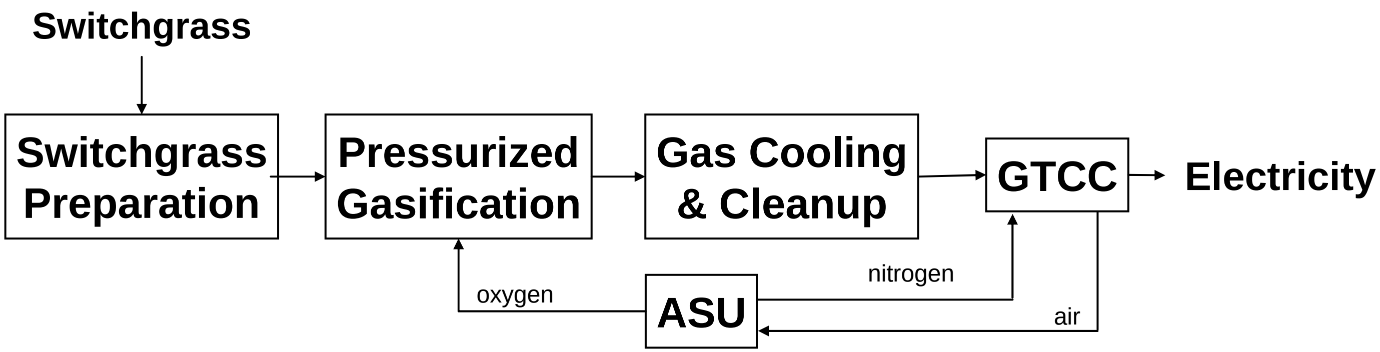
- F-T fuels of interest include high-cetane, low-aromatic, no-sulfur diesel substitute and naphtha as chemical feedstock upgradable to gasoline blendstock.
- F-T fuels production is commercially established, and growing rapidly.
- From coal:
  - Since 1950s in South Africa, 175k bbl/day (bpd) total capacity
  - 20k bpd, Inner Mongolia (2007)
  - 120k bpd, China letter of intent signed
  - 5k bpd demo, Gilberton, Pa (2008)
  - 33k bpd, Wyoming (in planning)
  - 57k bpd, Wyoming (proposed)
- From stranded natural gas:
  - From 1990s in Malaysia: 13k bpd
  - Planned:
    - Qatar, 2005: 34k bpd
    - Nigeria, 2006: 34k bpd
    - Qatar, 2009: 140k bpd
    - Qatar, 2011: 154k bpd

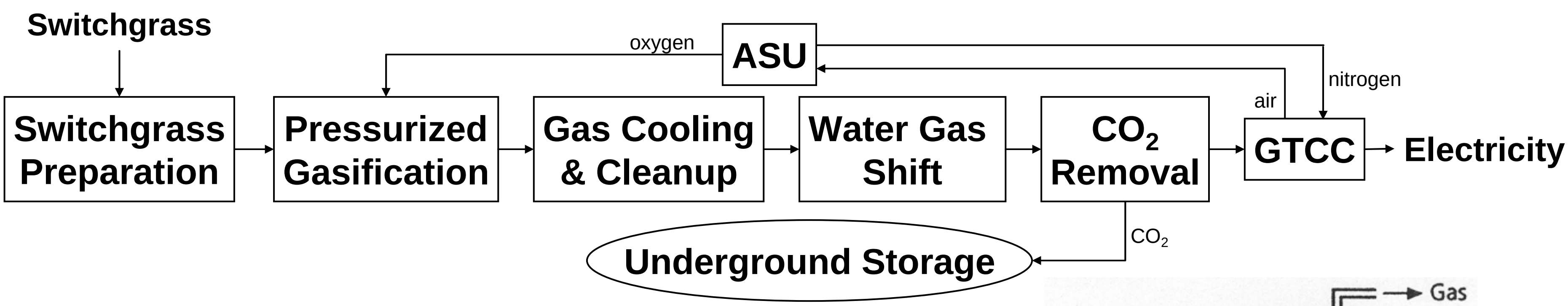
Dimethyl Ether

(CH_3OCH_3)

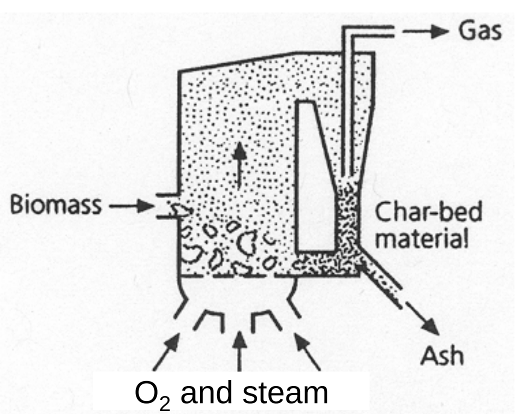
- Ozone-safe aerosol propellant, chemical feedstock.
- Current global production ~150,000 tons/year by drying methanol (CH_3OH).
- Similar to LPG – mild pressure needed to keep as liquid.
- Good diesel-engine fuel: high cetane #, no sulfur, lower NO_x, near-zero soot.
- Rapidly expanding production worldwide to supply (initially) markets for cooking and heating fuel (LPG substitute).
  - 110,000 tpy (from NG) facility to start in China, 2005
  - 800,000 tpy (from NG) facility to start in Iran, 2006
  - At least two 800,000 tpy (from coal) facilities in planning in China.
- Sweden bio-DME activities at Varnamo gasification pilot-plant facility – aiming at heavy-vehicle applications.

Electricity from biomass without and with CCS

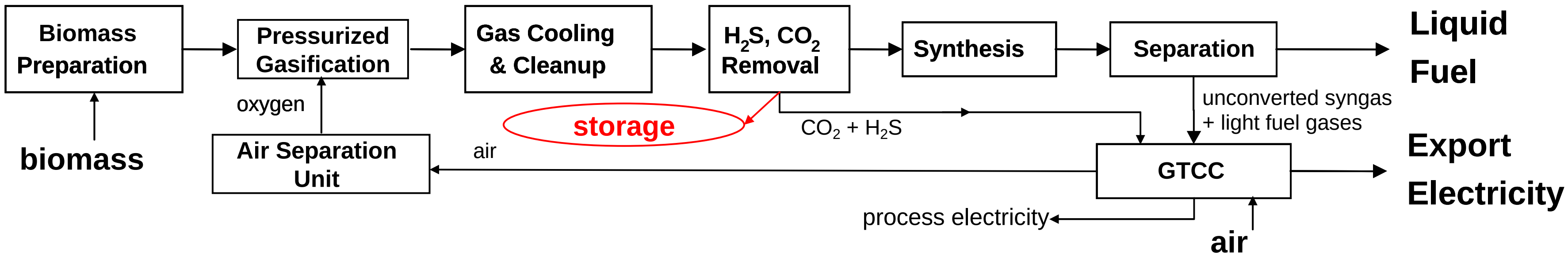




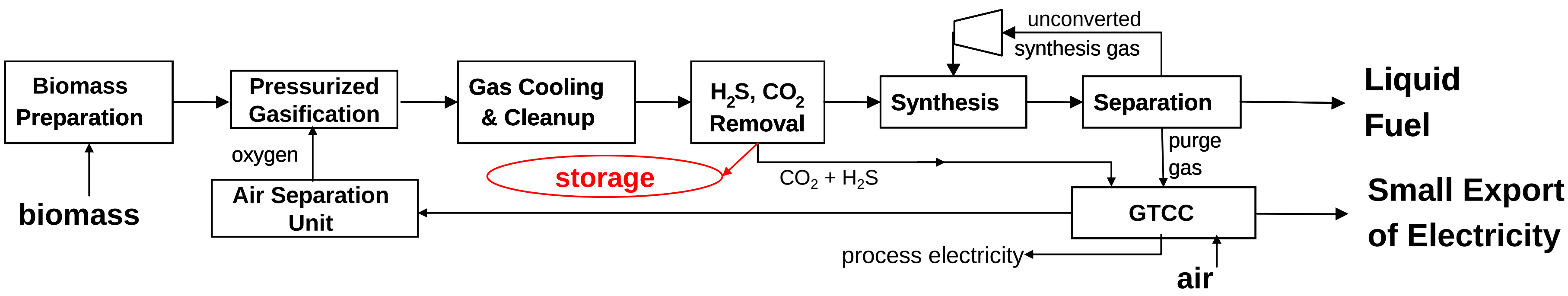
- Pressurized fluidized-bed O_2-blown gasification preferred at large scales ➔



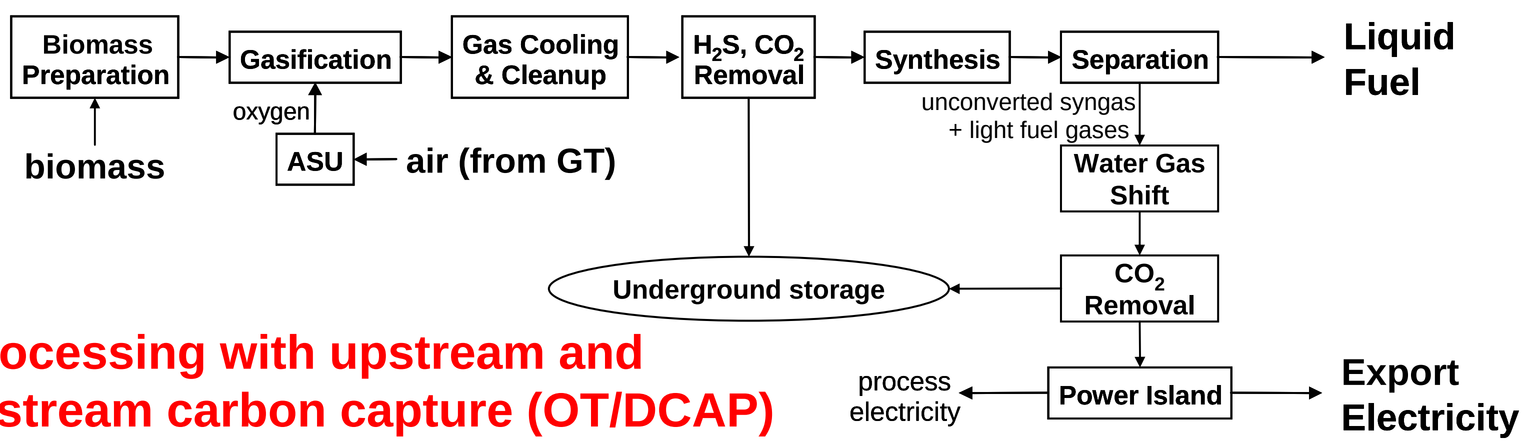
Synfuels from biomass without and with CCS



Once-through processing of syngas: OT/VENT, OT/UCAP



Recycle processing of syngas: RC/VENT, RC/UCAP



OT processing with upstream and downstream carbon capture (OT/DCAP)

Catalytic synthesis of fuels from $CO+H_2$

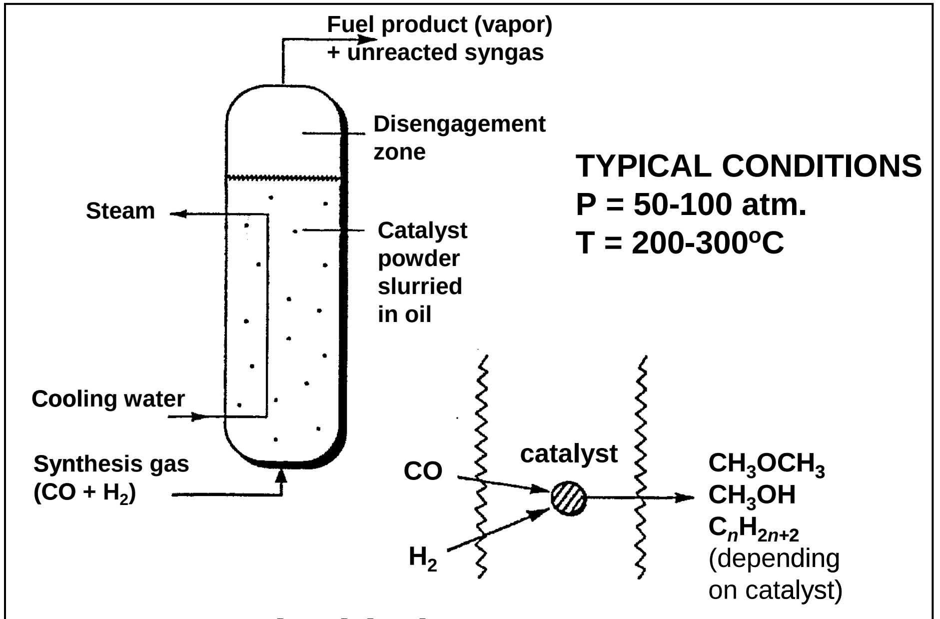
- **Basic overall reactions**:

$$CO + 2H_2 \Leftrightarrow -CH_2- + H_2O$$ Fischer-Tropsch liquids

$$3CO + 3H_2 \Leftrightarrow CH_3OCH_3 + CO_2$$ Dimethyl ether

$$CO + 2H_2 \Leftrightarrow CH_3OH$$ Methanol

- **Three reactor designs**:
  - Fixed-bed (gas phase): low one-pass conversion, difficult heat removal
  - Fluidized-bed (gas phase): better conversion, more complex operation
  - Slurry-bed (liquid phase): much higher single-pass conversion (e.g., 80% vs. 40% for F-T)➔ Once-through designs favored when electricity can be sold
    - Liquid phase FT reactors are commercial
    - LP-MeOH commercially demonstrated
    - LP-DME near commercial
  - Focus here on OT process designs with LP synthesis.

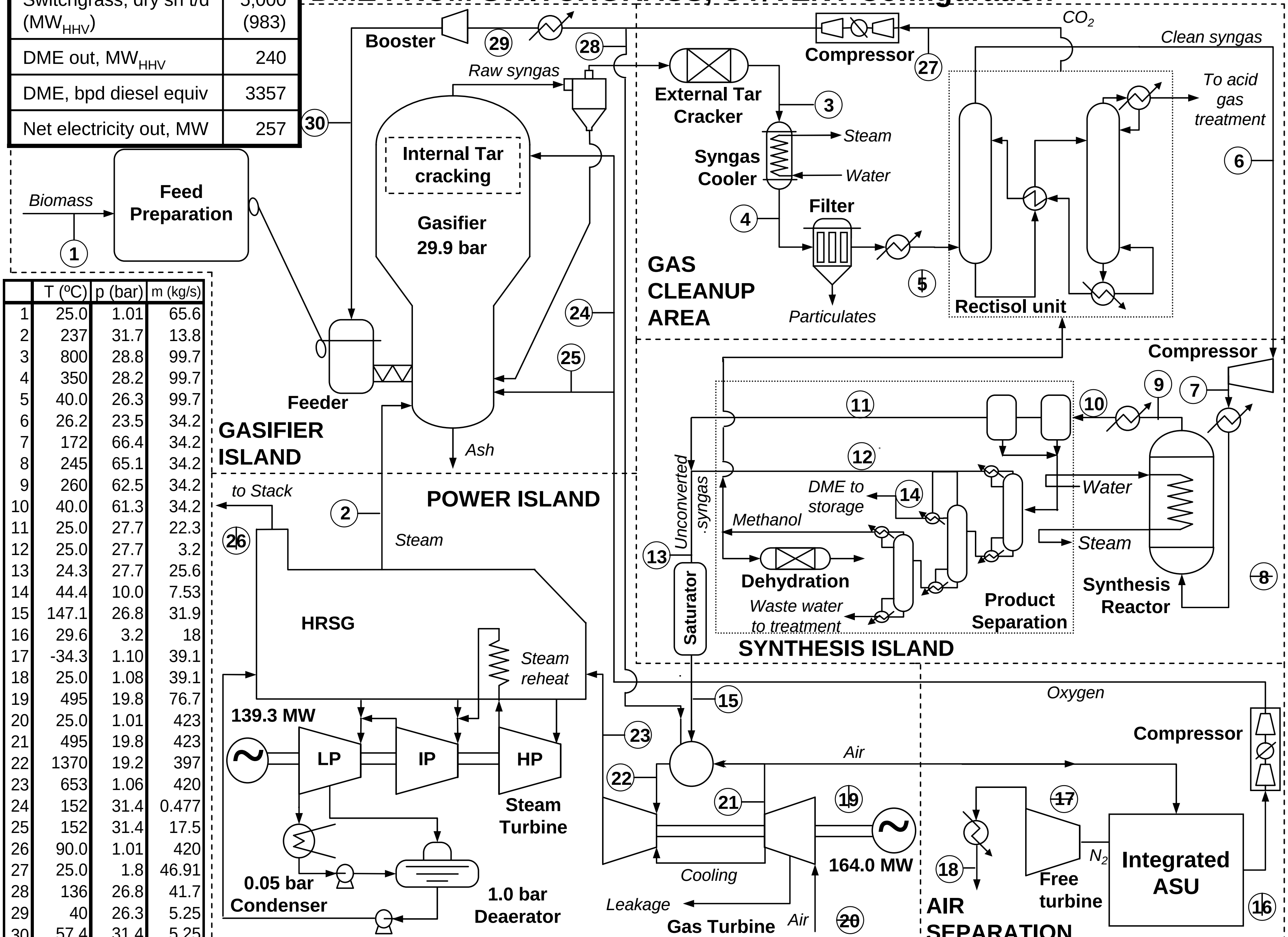


Liquid Phase Reactor

DME FROM SWITCHGRASS, OT/VENT Configuration

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



Energy and carbon flows

	DME + Electricity					FT+Elec		Electricity Only	
	OT/ VENT	OT/ UCAP	OT/ DCAP	RC/ VENT	RC/ UCAP	OT/ VENT	OT/ UCAP	BIGCC/ VENT	BIGCC/ CCS
Switchgrass input (20% moisture), MW_{th} (HHV)	983	983	983	983	983	983	983	983	983
Switchgrass input (20% moisture), MW_{th} (LHV)	893	893	893	893	893	893	893	893	893
Switchgrass carbon input, tC/hr	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9
ENERGY FLOWS									
Total internal power use, MW_e	25.4	46.7	58.8	65.0	79.5	21.0	44.0	15.3	54.0
Gas turbine gross output, MW_e	150.7	164.0	156.6	53.3	56.4	86.69	99.40	267.5	241.6
Steam turbine gross output, MW_e	144.2	139.3	131.4	90.5	90.5	140.90	135.44	190.3	164.0
Net power output, MW_e	269.6	256.6	229.2	78.8	67.3	206.6	190.8	442.4	351.6
F-T Gasoline output, MW (LHV)						116.9	117.2		
F-T Diesel output, MW (LHV)						188.1	188.6		
DME output, MW_{th} (LHV)	217.2	217.9	217.9	467.5	469.3				
Liquid output, barrels diesel-equivalent per day	3357	3368	3368	7226	7253	4630	4641		
Electric efficiency, % of switchgrass LHV	30.2%	28.7%	25.7%	8.8%	7.5%	23.1%	21.4%	49.5%	39.4%
Fuels efficiency, fuel LHV as % of switchgrass LHV	24.3%	24.4%	24.4%	52.3%	52.5%	34.1%	34.2%		
CARBON FLOWS									
Total captured CO2, tCO2/h	0	150	240	0	162	0	162	0	295
Total captured C02, tC/h	0	41	66	0	44	0	44	0	80
Captured at upstream AGR, % of switchgrass C	0%	46%	46%	0%	50%	0%	50%		
Captured downstream of synthesis, % of switchgrass C	0%	0%	28%	0%	0%	0%	0%		90%
Vented to atmosphere, % of switchgrass C	84%	38%	10%	66%	16%	75%	26%	100%	10%
Carried in fuel product, % of switchgrass C	16%	16%	16%	34%	34%	25%	25%		
Total carbon captured, % of switchgrass C	0%	46%	74%	0%	50%	0%	50%	0%	90%

Approximate amount of switchgrass carbon captured for storage:

- 50% for OT/UCAP and RC/UCAP configurations.
- 75% for OT/DCAP configuration.
- 90% for BIGCC/CCS.

Cost estimates

- Based on our earlier coal-related work* plus analysis of additional literature and discussions with industry experts, we developed detailed and consistent set of capital costs by major equipment area – adjustments made to balance-of-plant and indirect costs to ensure consistency between different sources.
- Financial parameters assumptions
  - Year-2003 dollars (GDP deflator used to adjust if necessary)
  - Interest during 4-year construction = 12.3% (7.8% avg. cost of capital)
  - Capacity factor = 80% (2 x 50% gasifier/gas cleanup, no spares)
  - Capital charge rate = 15% per year
- Other cost assumptions
  - Non-fuel O&M = 4% of overnight installed capital cost
  - CO_2 transportation and storage = $5/t$CO_2$
  - Plant-gate switchgrass price: $3.0/GJ (HHV), or $56/dry metric ton
- Baseline plant capacity = 5,681 metric tons/day input of 20% moisture content as-received switchgrass (5,000 short t/day dry matter).

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* Chiesa, Consonni, Kreutz & Williams, "Co-Production of Hydrogen, Electricity and CO_2 from Coal with Commercially Ready Technology. Part A: Performance and Emissions" and "Part B: Economic Analysis" (Kreutz, Williams, Consonni & Chiesa), *International Journal of Hydrogen Energy*, 2005, forthcoming.

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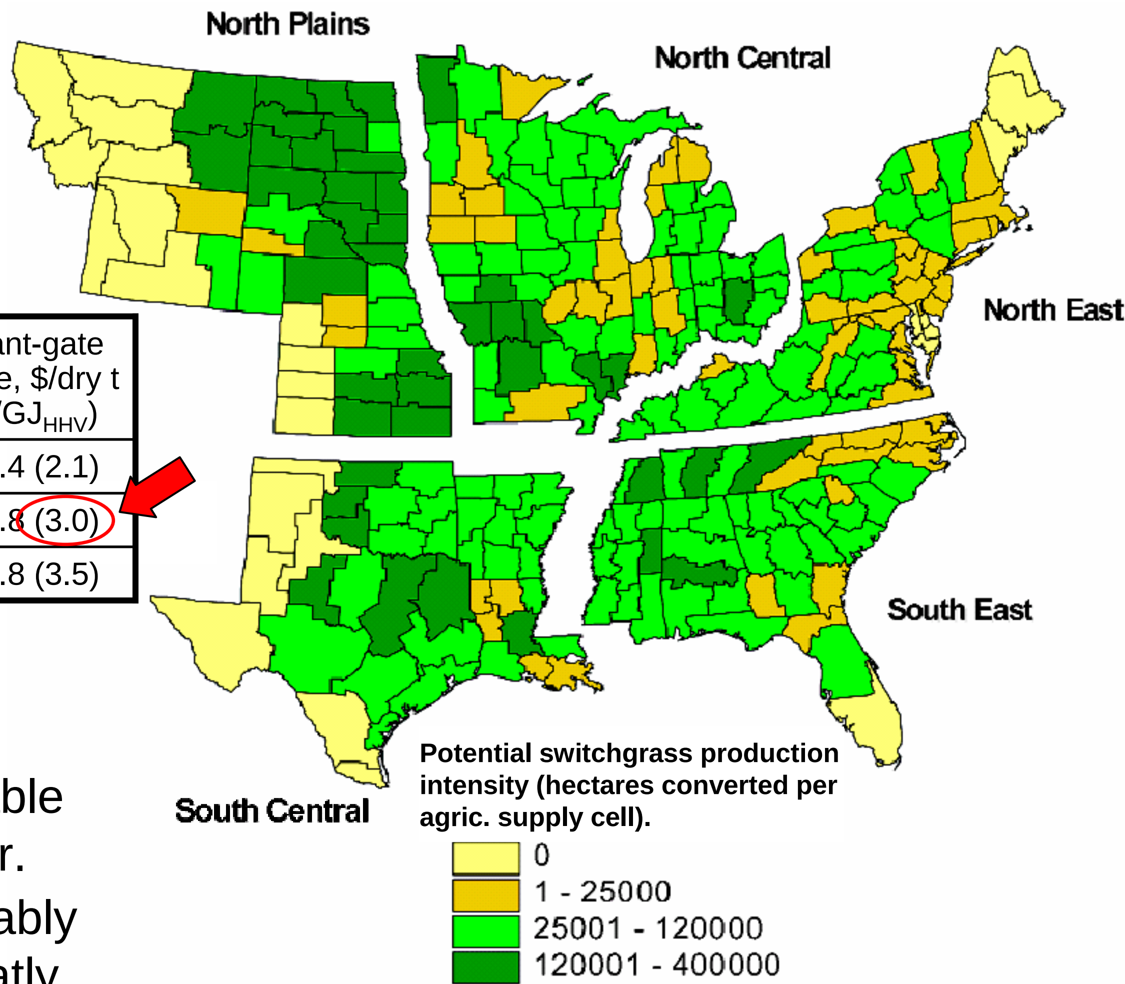
Switchgrass production potential in U.S.A.

- Detailed agriculture model (POLYSIS) used to predict potential U.S. land conversion to switchgrass.* With currently-achievable yields:

Paid to farmer, \$/dry tonne (2003 \$)	Land that would be planted with swg., million ha	Avg. yield, Dry t/ha/yr (EJ_{HHV}/yr))	Plant-gate price, \$/dry t (\$/GJ_{HHV})
32.0	3.1	11.1 (0.64)	39.4 (2.1)
46.5	16.8	9.4 (2.95)	56.8 (3.0)
55.4	21.3	9.0 (3.58)	65.8 (3.5)

For comparison with ^^^^^
2003 US coal used for electricity, EJ: (21.8)
2003 US diesel for transportation, EJ: (5.7)
2003 US gasoline for transportation, EJ: (17.5)



- Projected 2025 average sustainable field-scale yields:15-22 dry t/ha/yr.
- Such yield levels would considerably reduce production costs and greatly expand acreage planted in switchgrass.

* McLaughlin, de la Torre Ugarte, Garten, Lynd, Sanderson, Tolbert, and Wolf, 2002, “High-value renewable energy from prairie grasses,” *Environmental Science and Technology*, **36**(10): 2122-2129.

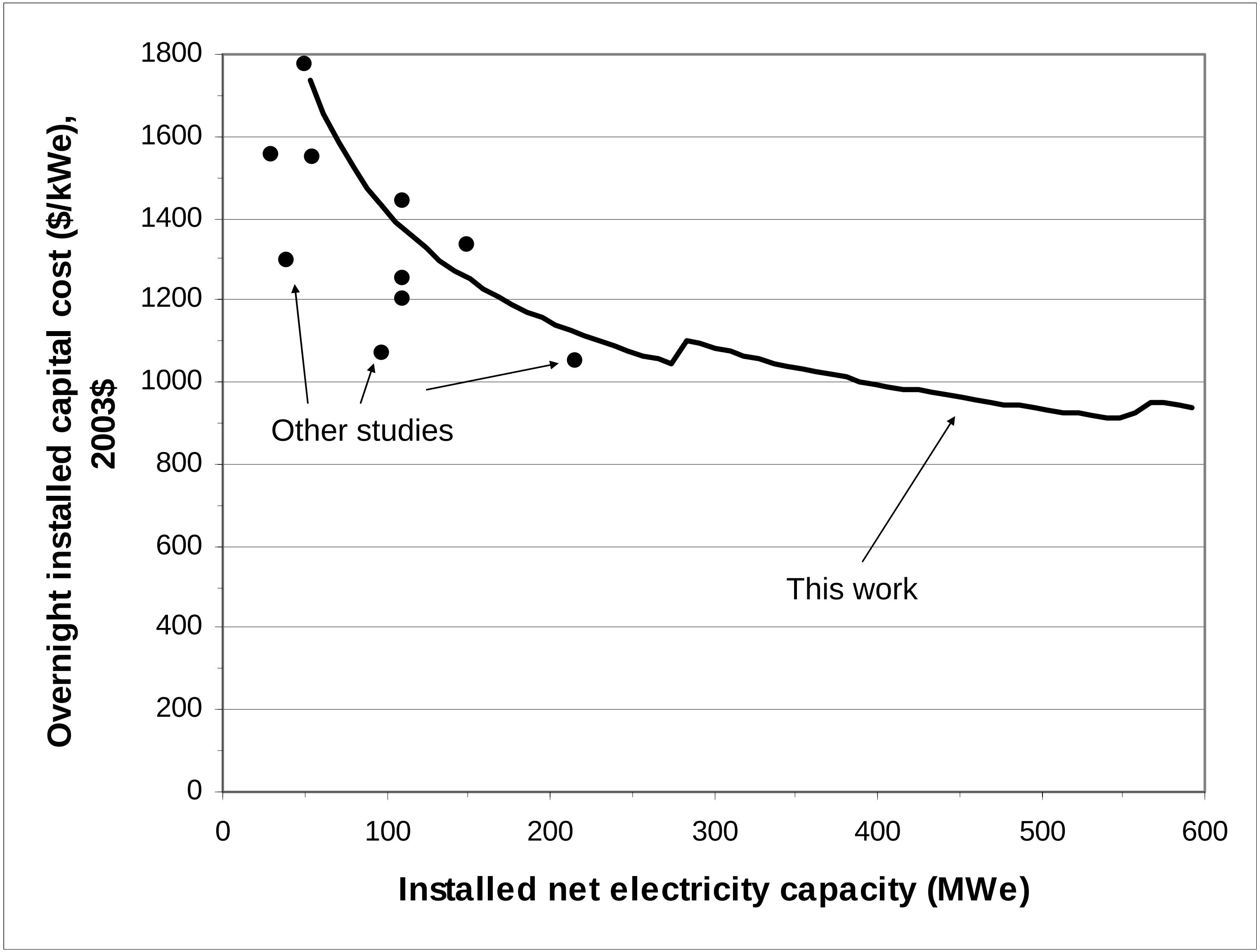
Capital cost basis for gasification and power

		Capacities (in indicated units)			Cost (in million 2003 $)	
		Base	Max. unit	Unit of Capacity	Base	Scaling exponent
Plant Area	Sub-Unit	S_o	S_{max}		C_o	f
Gasifier Island	Feed preparation	64.6	n.a.	wet tonne/hr biomass	9.84	0.77
	Gasifier	41.7	120	dry tonne/hr biomass	6.41	0.7
	Ash Cyclone	68.7	180	actual m^3/s gas feed	0.91	0.7
Gas Cleanup	External tar cracker[b]	47.1	52	actual m^3/s gas feed	0.732	0.7
	Syngas cooler	77	n.a.	MW_{th} heat duty	25.4	0.60
	Ceramic filter	14.4	n.a.	actual m^3/s gas feed	18.6	0.65
Carbon Capture Island	Saturator[c]	20.9	n.a.	actual m^3/s gas feed	0.30	0.70
	WGS reactors[d]	1377	n.a.	MW_{LHV} biomass input	30.6	0.67
	Rectisol AGR[e]	0.20	n.a.	million Nm^3/hr gas feed	20	0.65
	AGR compressor[f]	10	n.a.	MW compressor power	4.83	0.67
	CO_2 compressor[g]	10	n.a.	MW compressor power	4.75	0.67
	Supercritical CO_2 comp.[h]	13	n.a.	MW compressor power	7.28	0.67
Air Separation Unit	ASU	76.6	n.a.	tonne/hr pure O_2	22.7	0.5
	O_2 compressor	10	n.a.	MW compressor power	5.54	0.67
	N_2 compressor	10	n.a.	MW compressor power	4.14	0.67
Power Island	Gas turbine	266	334	GT MW_e	56.0	0.75
	HRSG + heat exchangers	355	n.a.	MW_{th} heat duty	41.2	1
	Steam cycle (turbine + cond.)	136	n.a.	ST gross MW_e	45.5	0.67

Capital cost basis for fuels production

Plant Area[xx]	Sub-Unit	Capacities (in indicated units)			Cost (in million 2003 $)	
		Base	Max. unit	Unit of Capacity	Base	Scaling exp.
		S_o	S_{max}		C_o[a]	*f*
FT Synthesis, Fuel Upgrading and Refinery	Slurry phase F-T reactor[d]	2.52	n.a.	million scf/hr feed gas	10.5	0.72
	Hydrocarbon recovery unit[e]	14.44	200	thousand lbs/hr feed	0.56	0.7
	H_2 recovery unit[f]	0.033	0.1	million scf/hr H_2 prod	0.65	0.7
	Wax hydrocracker[g]	8.984	575	thousand lbs/hr feed	7.21	0.7
	Distillate hydrotreater[h]	2.871	650	thousand lbs/hr feed	1.93	0.7
	Naphtha hydrotreater[i]	2.05	650	thousand lbs/hr feed	0.58	0.7
	Naphtha reformer[j]	3.43	750	thousand lbs/hr feed	4.02	0.7
	C_5/C_6 isomerization[k]	1.158	250	thousand lbs/hr feed	0.74	0.7
	CO shift reactor[l]	0.040	0.080	million scf/hr feed gas	0.79	0.7
	Fuel gas compressor[m]	10	n.a.	MW compressor power	4.83	0.67
DME Synthesis and Separation	Once-through LP synthesis[n]	2.91	n.a.	kmol/sec feed gas	15.8	0.65
	Recycle LP synthesis[o]	8.68	n.a.	kmol/sec total feed gas	88.8	0.65
	DME distillation plant[p]	6.75	n.a.	kg/s DME product	21.3	0.65
	MeOH dehydration[q]	2.91	n.a.	kmol/s MeOH feed	15.8	0.65
	Syngas expander[r]	10	n.a.	MW_e generated	2.41	0.67
	Syngas compressor[m]	10	n.a.	MW compressor power	4.83	0.67

Literature comparison of overnight installed capital costs for BIGCC/VENT

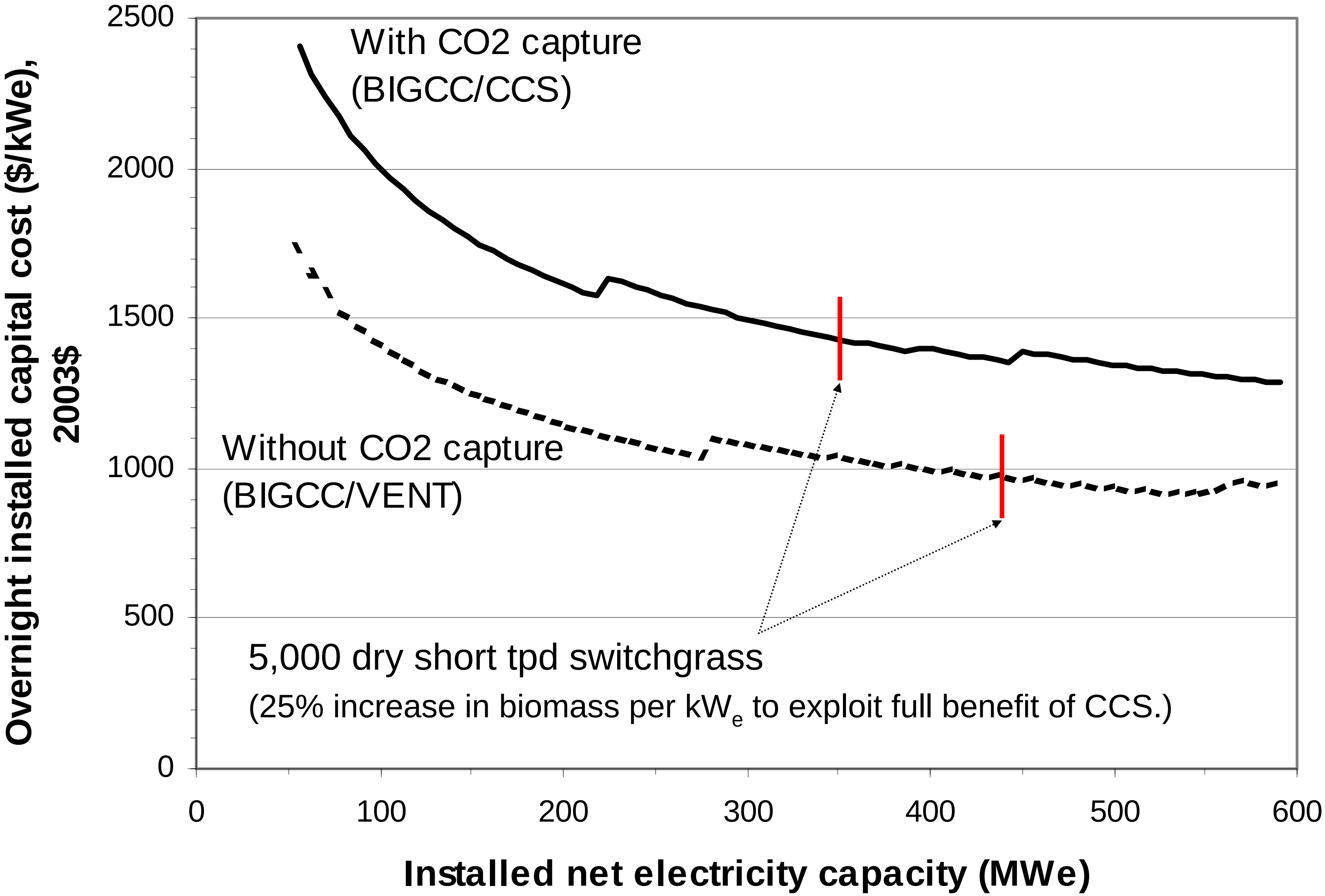


Coal-Biomass capital cost comparison

390 MW_e Net Production		Coal IGCC*		Biomass IGCC
Feed preparation, handling		36.0		42.5
Gasifier (coal case includes gas cooling/cleaning)	(70 bar)	76.3	(30 bar)	31.7
Syngas cooler, ceramic filter cleanup		n.a.		83.3
Air separation unit		47.0		24.2
Oxygen compressor		9.0		4.2
Nitrogen compressor		10.7		5.1
Sulfur control		41.5		n.a.
Sulfur recovery		28.2		n.a.
Gas turbine		74.0		64.9
HRSG and heat exchangers		72.4		68.4
Syngas expander		3.0		--
Steam cycle (turbine + condenser)		72.2		66.5
Overnight installed (million 2003$)		**470**		**391**
Unit cost (2003 $/kW)		**1205**		**1000**

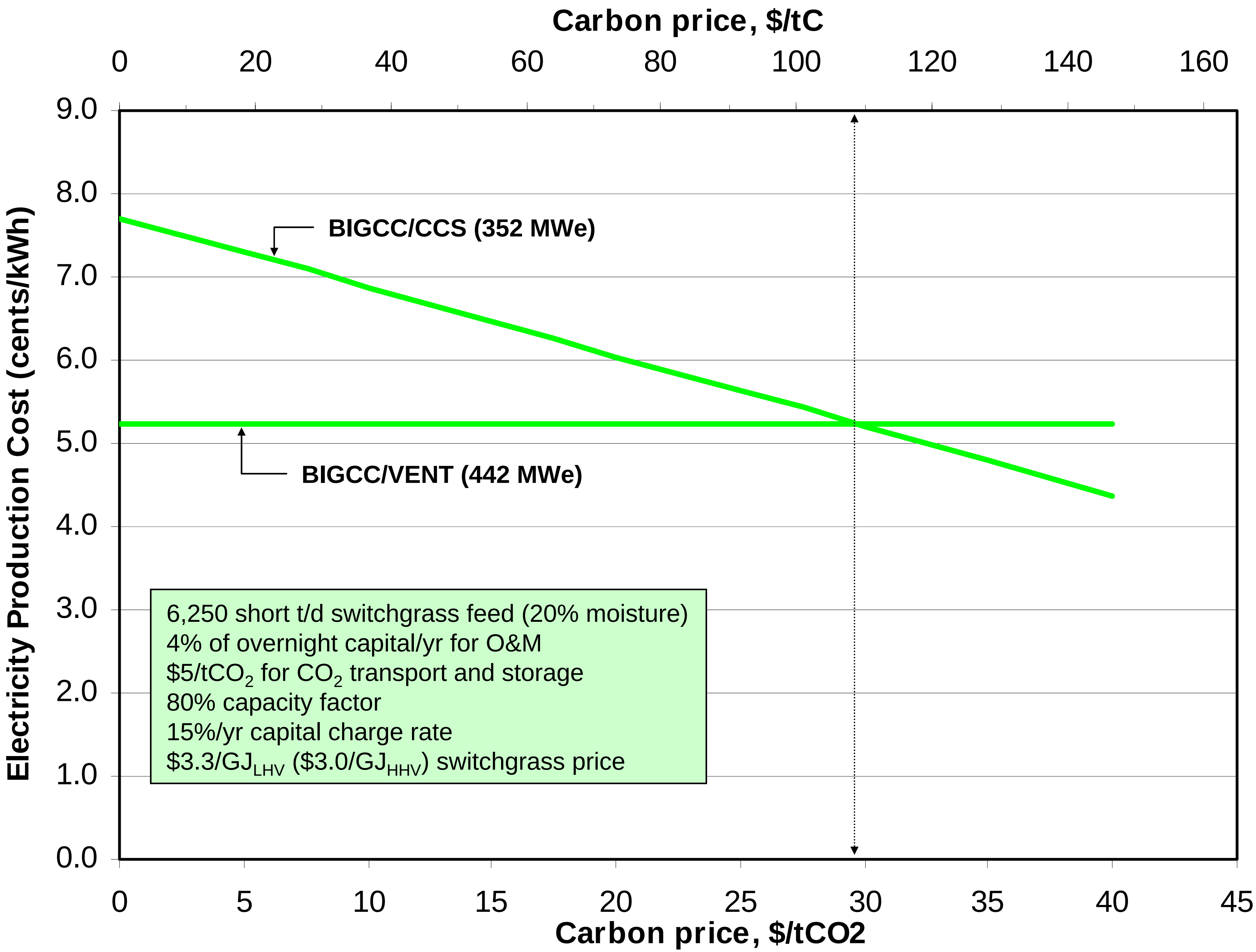
* Source: Kreutz, Williams, Consonni & Chiesa, "Co-Production of Hydrogen, Electricity and CO_2 from Coal with Commercially Ready Technology. Part B: Economic Analysis", *Int'l. J. Hydrogen Energy*, 2005, forthcoming.

Overnight installed capital costs for electricity without and with CCS

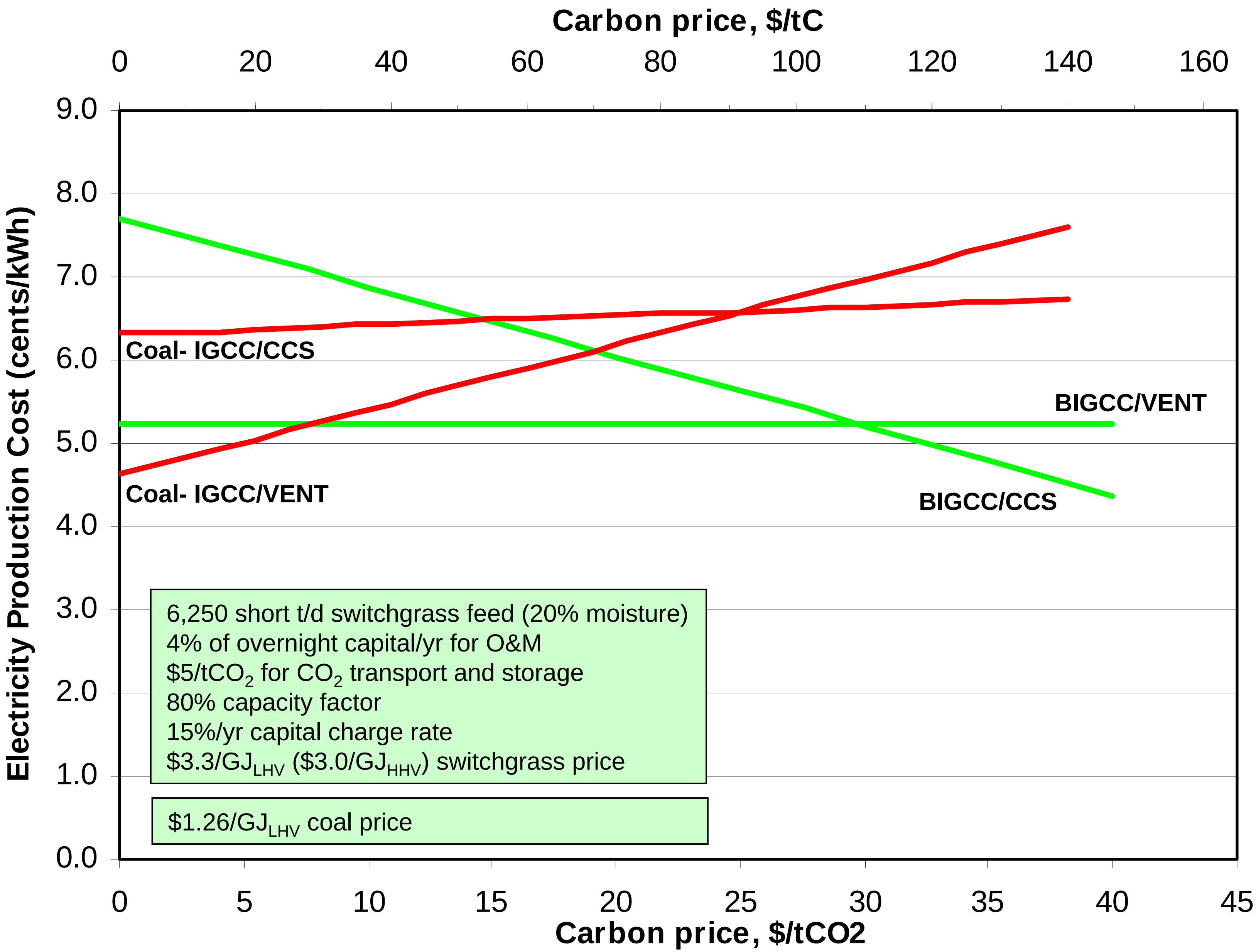


Note: Two gasifier/gas cleanup trains at 50% capacity each. No spares.

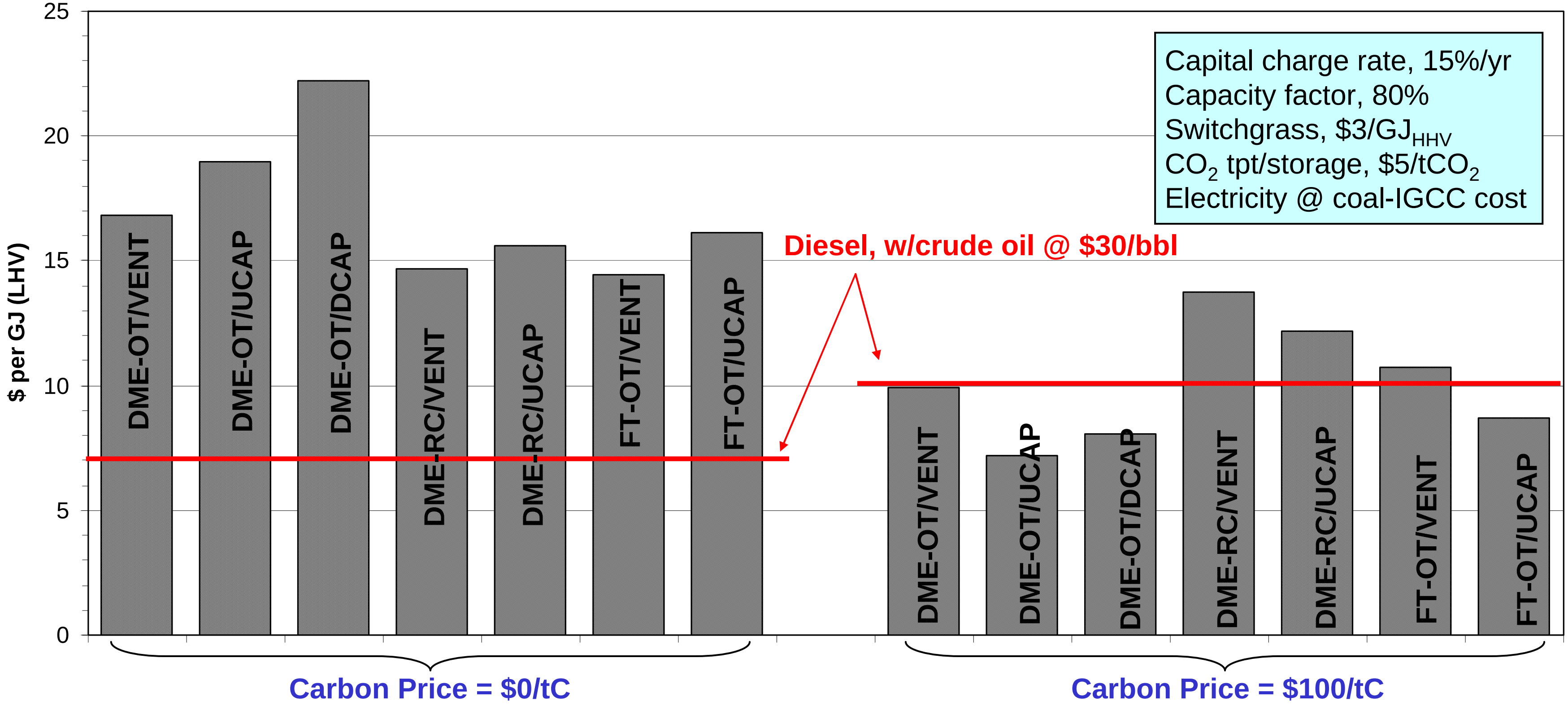
Biomass electricity production costs



Biomass and coal electricity costs



Net plant-gate cost of fuel from switchgrass, including sale of co-product electricity

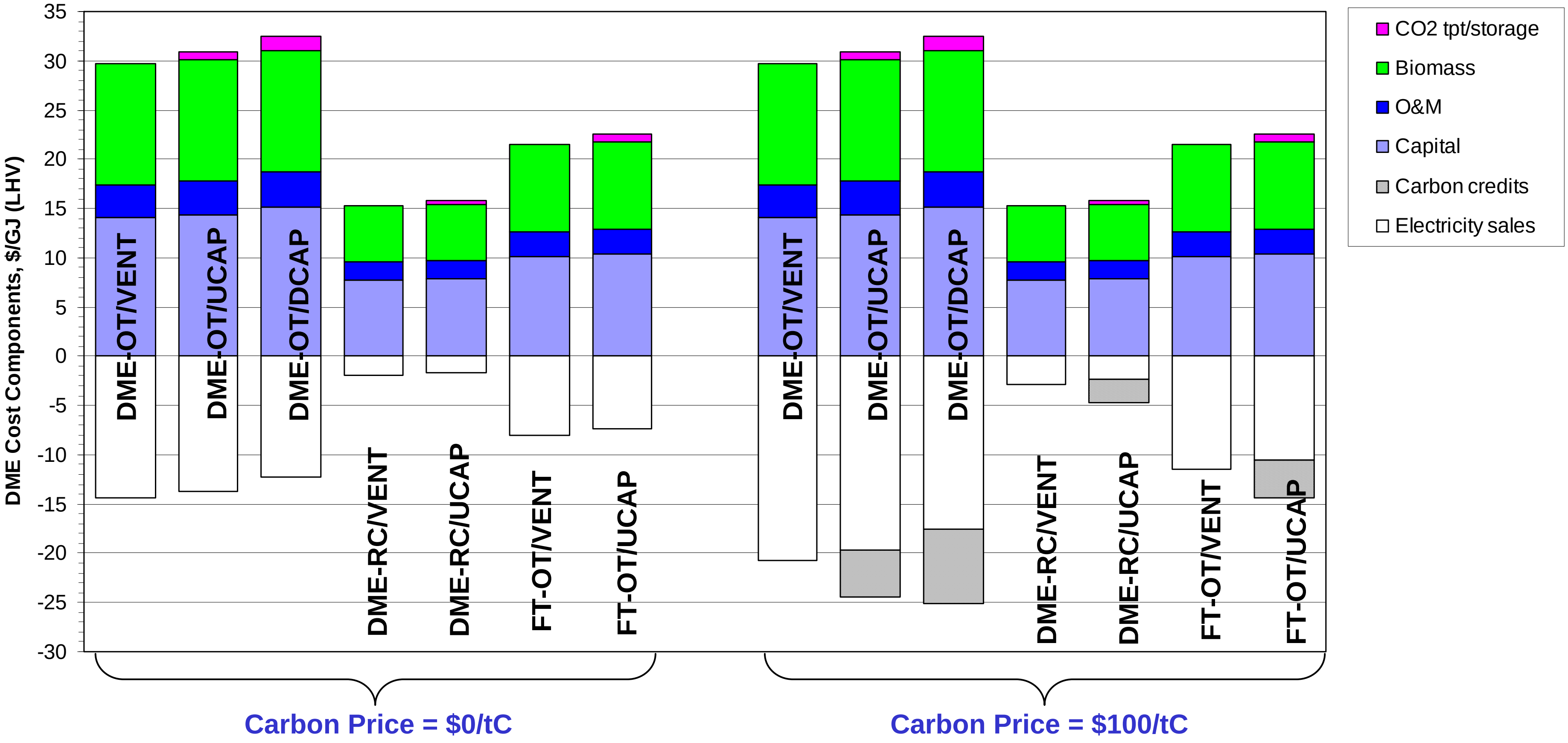


- Synfuels are not competitive with petroleum diesel when crude oil is $30/bbl and carbon price is zero.
- Synfuels can be competitive when carbon price is $100/tC.
- Value of the electricity co-product is increasingly important as carbon price increases
  ➔ OT designs can compete at $100/tC, but RC designs cannot.

Notes

- Other's analysis suggests cost of DME delivery and refueling ≈ diesel vehicle avoided pollution control costs.
- For F-T above cost is average for synthetic diesel (62% of liquids output) and high-octane gasoline blendstock (38%).

Cost breakdown for fuels production



Capital charge rate, 15%/yr

Capacity factor, 80%

Switchgrass, $3/GJ$_{HHV}$

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

Electricity @ coal-IGCC value

Summary/Conclusions

- Large-scale conversion of biomass with CCS would produce negative-CO_2 electricity or fuels.
- Significant U.S. potential for switchgrass as energy crop.
- Carbon policy needed for competitive economics.
- Electricity:
  - BIGCC/VENT competitive with coal for carbon price (CP) ~$30/tC.
  - BIGCC/CCS competitive with coal for CP ~$70/tC
  - BIGCC/CCS competitive with BIGCC/VENT for CP ~$110/tC
- Liquid Fuels:
  - With CP = 0, synfuels do not compete with diesel from $30/bbl oil.
  - With CP = $100/tC, synfuels compete well with diesel from $30/bbl oil in OT process configurations (but not in RC configurations).