Fifth Annual Conference on Carbon Capture & Sequestration

Steps Toward Deployment

Session title: CCS with Biomass and Landfill Gas

Hydrogen and Electricity from Biomass with and without CCS*

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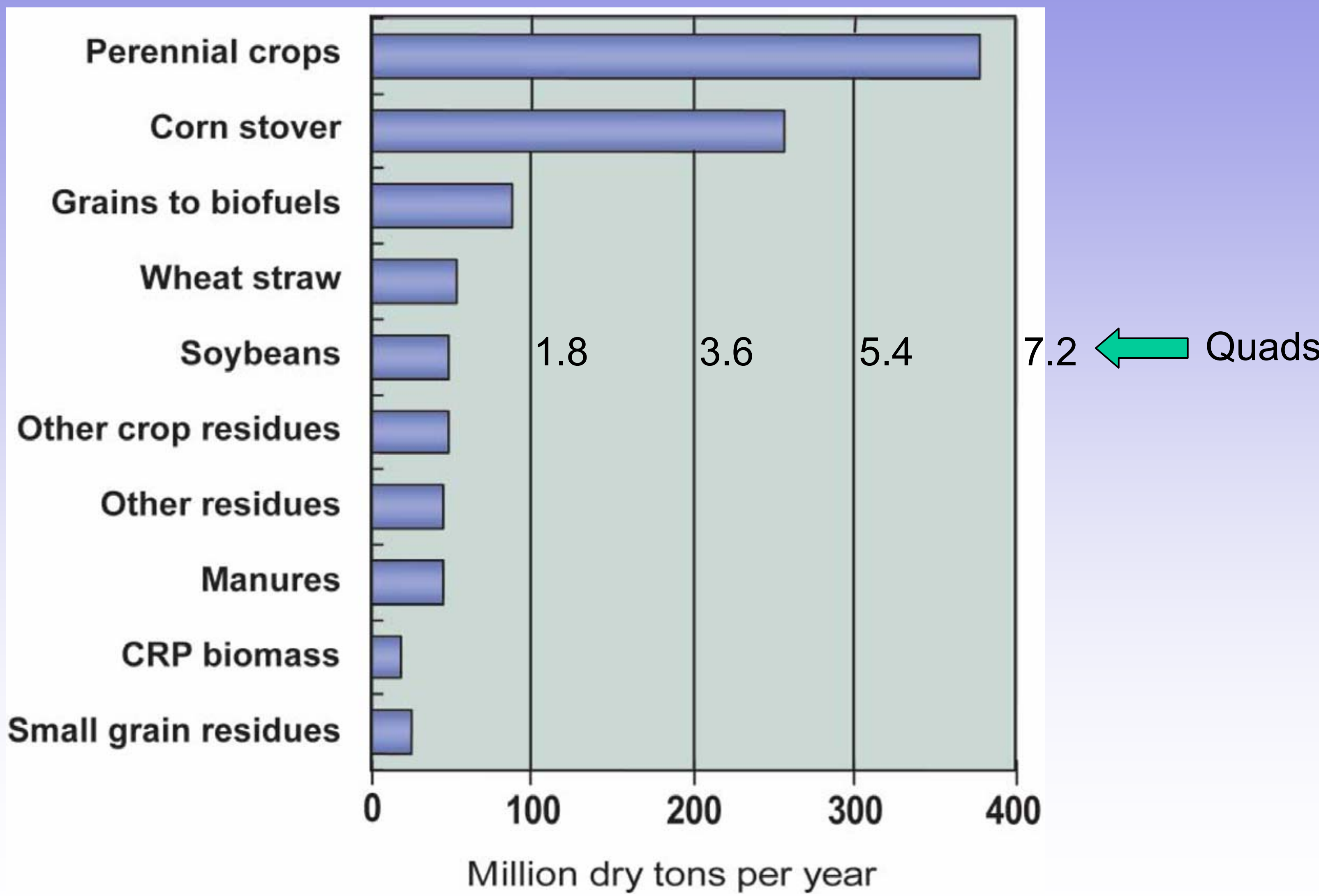
* See Larson, Jin, and Celik, 2005. *Gasification-Based Fuels and Electricity Production from Biomass, without and with Carbon Capture and Storage*, Princeton Environmental Institute, Princeton University, Princeton, NJ, October, 77 pages.

Motivation for this Work

- H_2 may be important energy carrier in long term.
- Least costly renewable way known today for making H_2 is from biomass.
- Biomass converted to H_2 ➔ ~zero CO_2 emissions.
- With CCS ➔ negative CO_2 emissions, which may be important to meet CO_2 stabilization targets.
- There is a significant potential for renewable biomass energy production in the US.

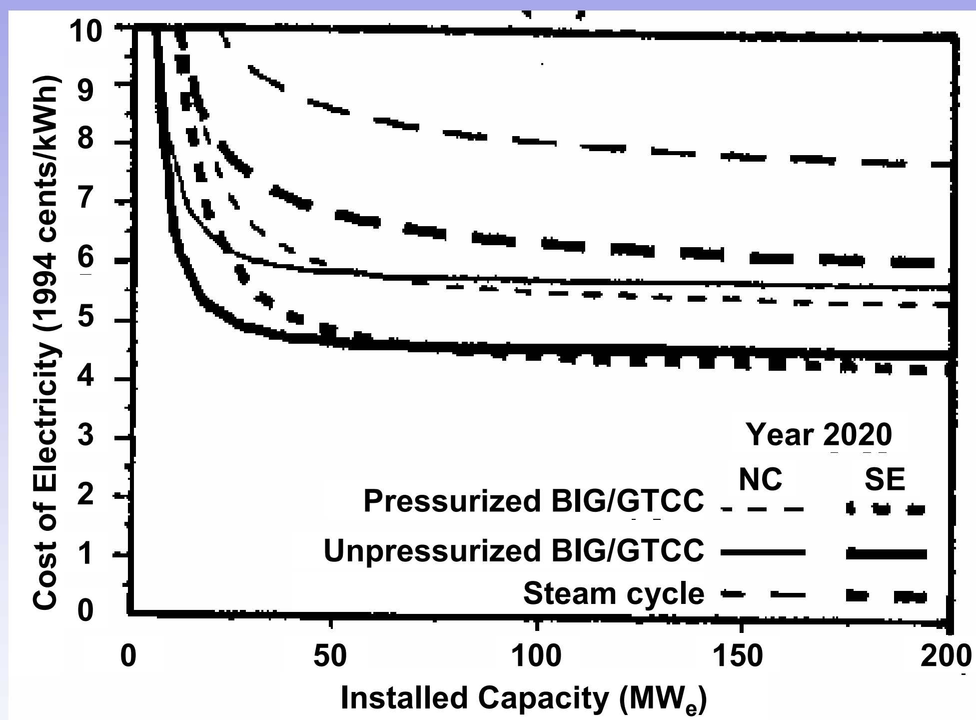
Potential US Biomass Energy Resources, 2030



Source: RD Perlack, LL Wright, A Turhollow, RL Graham, B Stokes, and DC Erbach, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, US Departments of Energy and Agriculture, Wash DC, April 2005.

Scale Economics of Biomass

- Technologies for biomass conversion to H_2 (with and without CCS) are similar to those for coal-H_2.*
- As for coal, economics for biomass improve with scale.
- For farmed energy crop, scale-economy benefits of larger conversion plants outweigh added feedstock transport costs up to relatively large plant sizes.



Source: C.I. Marrison and E.D. 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.

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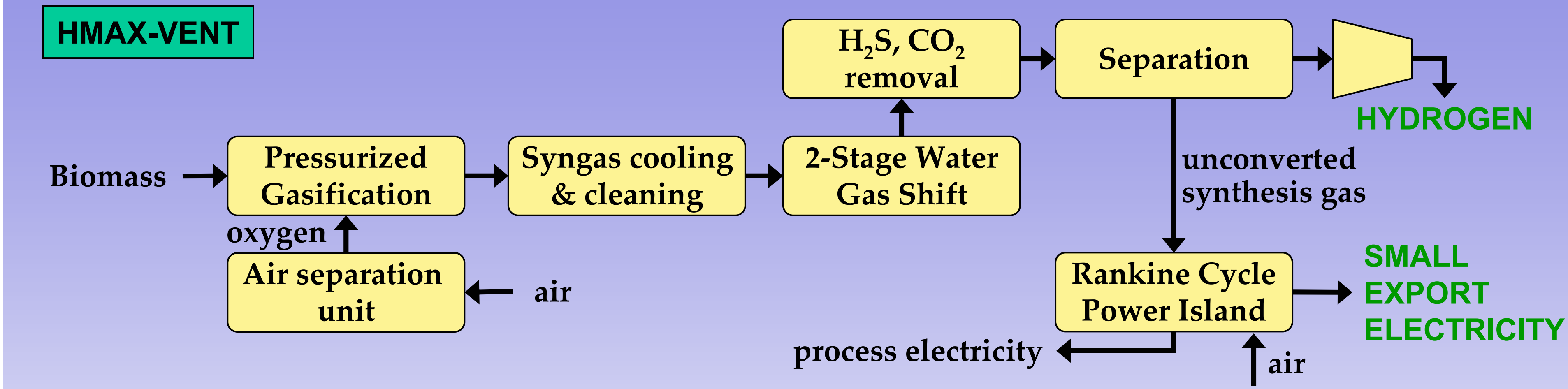
* Chiesa, P., Consonni, S., Kreutz, T. and Williams, R. 2005. "Co-Production of Hydrogen, Electricity and CO_2 from Coal with Commercially Ready Technology. Part A: Performance and Emissions," International Journal of Hydrogen Energy, 30: 747-767.

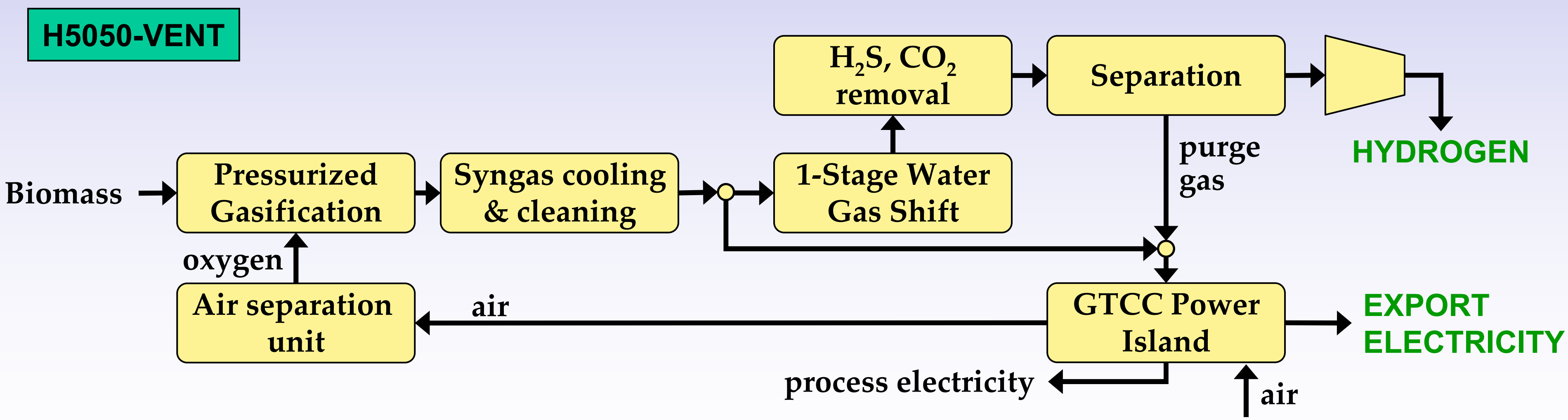
Kreutz, T., Williams, R., Consonni, S. and Chiesa, P. 2005. "Co-Production of Hydrogen, Electricity, and CO_2 from Coal with Commercially Ready Technology. Part B: Economic Analysis," International Journal of Hydrogen Energy, 30: 769-784.

Analysis Approach

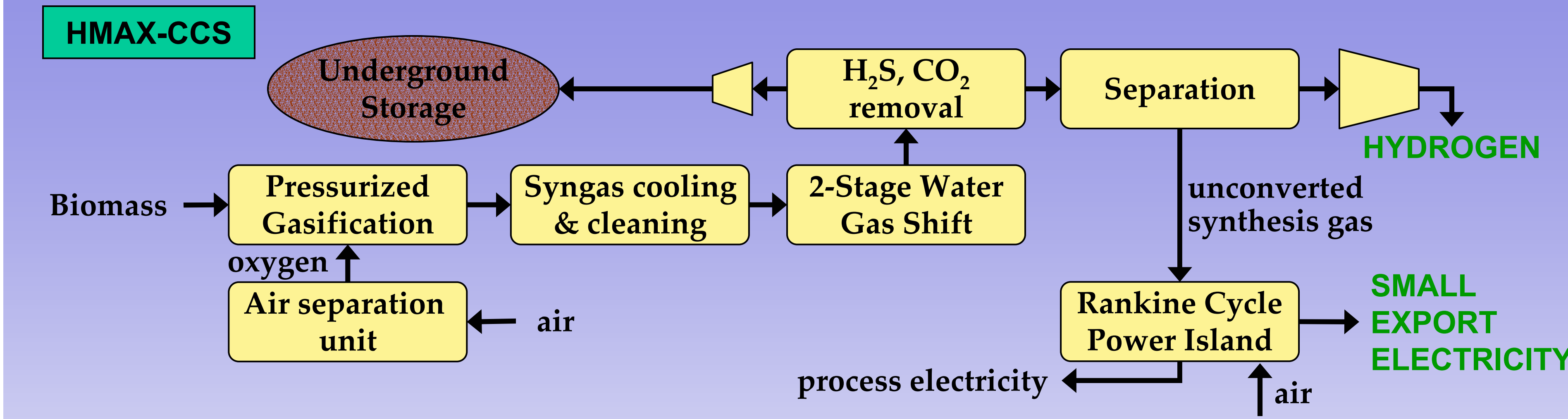
- Design H_2 production from switchgrass, with & without CCS.
- Assume commercially-mature Nth-plant technologies with design capacity of 5000 dry short tons per day (893 MW_{LHV})
- Hurdles solvable in 2010/2015 timeframe:
  - Efficient and high reliability feeding & operation of large-scale pressurized (~30 bar), fluidized-bed O_2 gasifier.
  - Gas cleanup, including tar cracking and contaminant removal.
  - Gas turbine performance on low heating value gases like state-of-the-art gas turbines firing natural gas.
  - Good process heat integration and process control.
  - Large-scale switchgrass production and delivery
- Heat/mass balances using Aspen$^+$ and Pinch; inputs based on extensive literature review and discussion with experts.
- Capital costs estimated ($\pm$ 30%) using calibrated cost database developed at Princeton. Nth plant estimates, but no “leap of faith” cost reductions assumed.

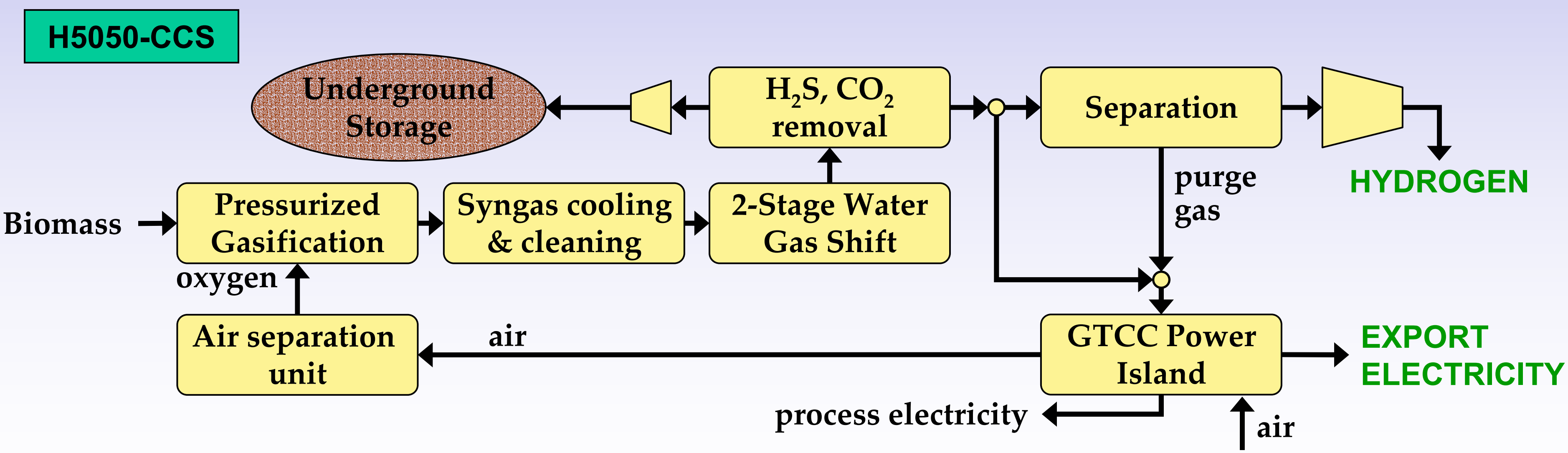
Process Configurations – no CCS





Process Configurations – with CCS





Energy and Carbon Balances

	Electricity Only		Hydrogen + Electricity Co-Product			
	BIGCC/ VENT	BIGCC/ CCS	H5050-VENT	HMAX-VENT	H5050-CCS	HMAX-CCS
Switchgrass input (20% moisture), MW_{th} (HHV)	983	983	983	983	983	983
Switchgrass input (20% moisture), MW_{th} (LHV)	893	893	893	893	893	893
Switchgrass carbon input, tC/hr	88.9	88.9	88.9	88.9	88.9	88.9
ENERGY FLOWS						
Total internal power use, MW_e	15.3	54.0	16.4	57.3	44.5	88.1
Gas turbine gross output, MW_e	267.5	241.6	166.6	0	138.9	0
Steam turbine gross output, MW_e	190.3	164.0	131.1	98.56	123.3	97.73
Net power output, MW_e	442.4	351.6	281.3	41.3	217.7	9.6
H2 output, MW (HHV)			283.5	621.9	294.0	623.9
H2 output, MW (LHV)			239.9	526.2	248.7	527.8
Electric efficiency, % of switchgrass LHV	49.5%	39.4%	31.5%	4.6%	24.4%	1.1%
Fuels efficiency, fuel LHV as % of switchgrass LHV			26.8%	58.9%	27.8%	59.1%
Total efficiency, % of biomass LHV	49.5%	39.4%	58.3%	63.5%	52.2%	60.2%
Fuels effective efficiency (LHV basis)*			73.7%	65.0%	54.8%	60.4%
CARBON FLOWS						
Total captured CO2, tCO2/h	0	295	0	0	293	293
Total captured C02, tC/h	0	80	0	0	80	80
Captured at upstream AGR, % of switchgrass C			0%	0%	0%	0%
Captured downstream of synthesis, % of switchgrass C		90%	0%	0%	90%	90%
Vented to atmosphere, % of switchgrass C	100%	10%	100%	100%	10%	10%
Carried in fuel product, % of switchgrass C			0%	0%	0%	0%
Total carbon captured, % of switchgrass C	0%	90%	0%	0%	90%	90%

* Effective efficiency is the ratio of the hydrogen produced divided by the effective amount of biomass consumed. The latter is the actual biomass consumed less an amount of biomass that would be consumed in producing the same amount of electricity as in a stand-alone biomass IGCC power plant.

90% of carbon in switchgrass is captured and stored

Basis for Capital Cost Estimates

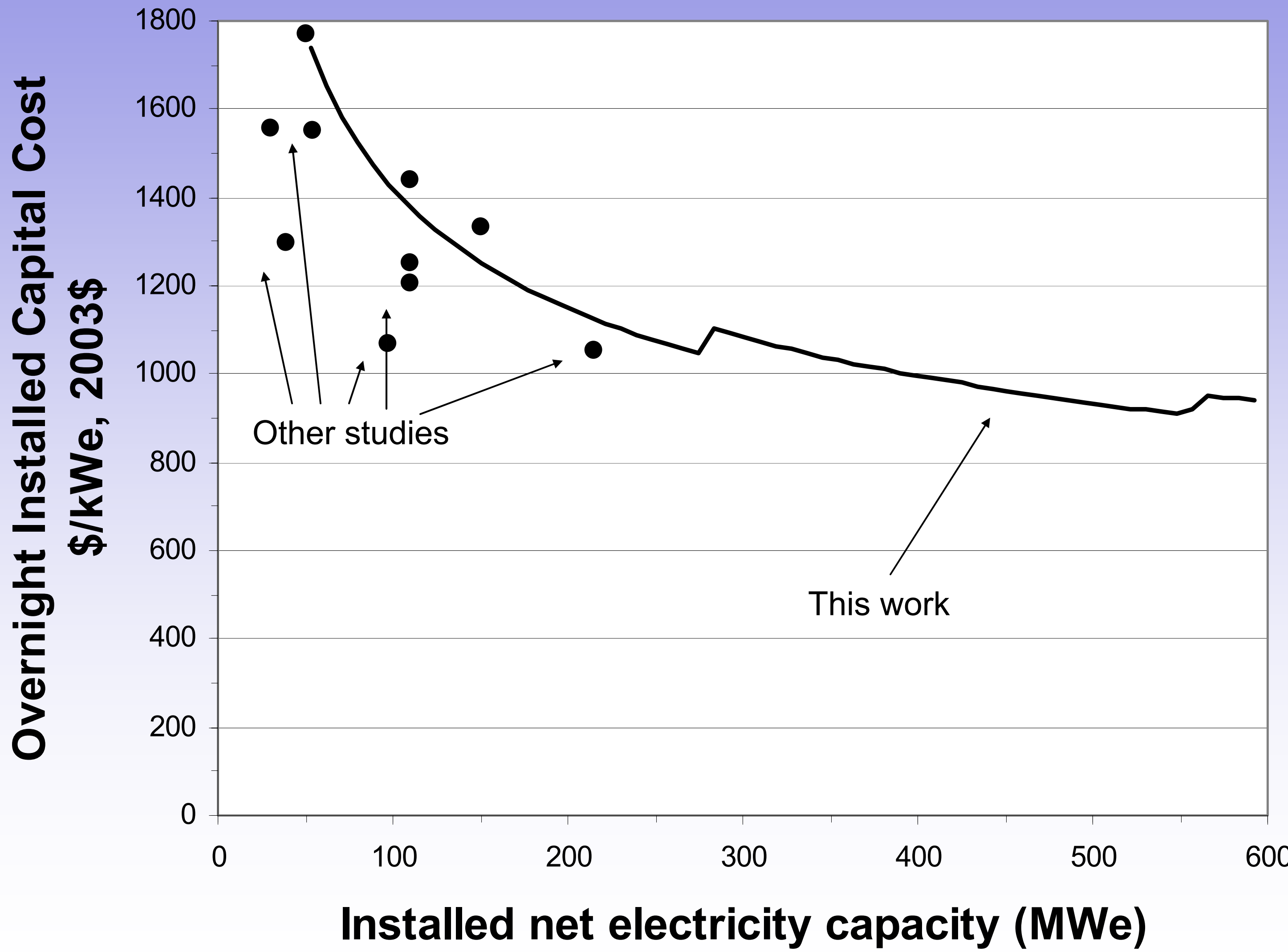
Plant Area	Sub-Unit	Capacities (in indicated units)			Cost (in million 2003 $)	
		Base	Max. unit	Unit of Capacity	Base	Scaling exp.
		S_o	S_{max}		C_o[a]	f
Gasifier Island	Feed preparation[a]	64.6	n.a.	wet tonne/hr biomass	3.17	0.77
	GTI Gasifier[a]	41.7	120	dry tonne/hr biomass	6.41	0.7
	Ash Cyclone[a]	68.7	180	actual m^3/s gas feed	0.91	0.7
Gas Cleanup and carbon capture	External tar cracker[b]	47.1	52	Actual m^3/s gas feed	0.732	0.7
	Syngas cooler[a]	77	n.a.	MW_{th} heat duty	25.4	0.6
	Ceramic filter[a]	14.4	n.a.	actual m^3/s gas feed	18.60	0.65
	Rectisol AGR[b,c]	200000	n.a.	Nm^3/hr gas feed	20.00	0.65
	AGR compressor[b]	10	n.a.	MW_e consumed	4.83	0.67
	CO_2 compression[b]	10	n.a.	MW_e consumed	4.75	0.67
	CO_2 drying/compression[b]	13	n.a.	MW compressor power	7.28	0.67
Hydrogen production	Water Gas Shift[s]	1377	n.a.	MW_{LHV} biomass input	30.6	0.67
	PSA[t]	0.294	n.a.	kmol/s purge gas flow	5.46	0.74
	PSA purge gas compressor[u]	10	n.a.	MW_e compressor power	4.83	0.67
	H_2-rich gas compressor[v]	10	n.a.	MW_e compressor power	4.83	0.67
Air Separation Area	ASU, if stand-alone[w]	76.6	n.a.	tonne/hr pure O_2	35.6	0.50
	ASU, if integrated[a]	76.6	n.a.	tonne/hr pure O_2	22.7	0.50
	O_2 compressor[a]	10	n.a.	MW_e consumed	5.54	0.67
	N_2 compressor[a]	10	n.a.	MW_e consumed	4.14	0.67
	N_2 expander[r]	10	n.a.	MW_e generated	2.41	0.67
Power Island	Saturator[b]	20.9	n.a.	actual m^3/s gas feed	0.30	0.70
	Gas turbine[a]	266	334	GT MW_e	56.0	0.75
	HRSG + heat exchangers[a]	355	n.a.	MW_{th} heat duty[a]	41.2	1
	Steam cycle (turbine + cond.)[a]	136	n.a.	ST gross MW_e	45.5	0.67

For table notes, see Table 13 of Larson, Jin, and Celik, 2005. *Gasification-Based Fuels and Electricity Production from Biomass, without and with Carbon Capture and Storage*, Princeton Environmental Institute, Princeton University, Princeton, NJ, October.

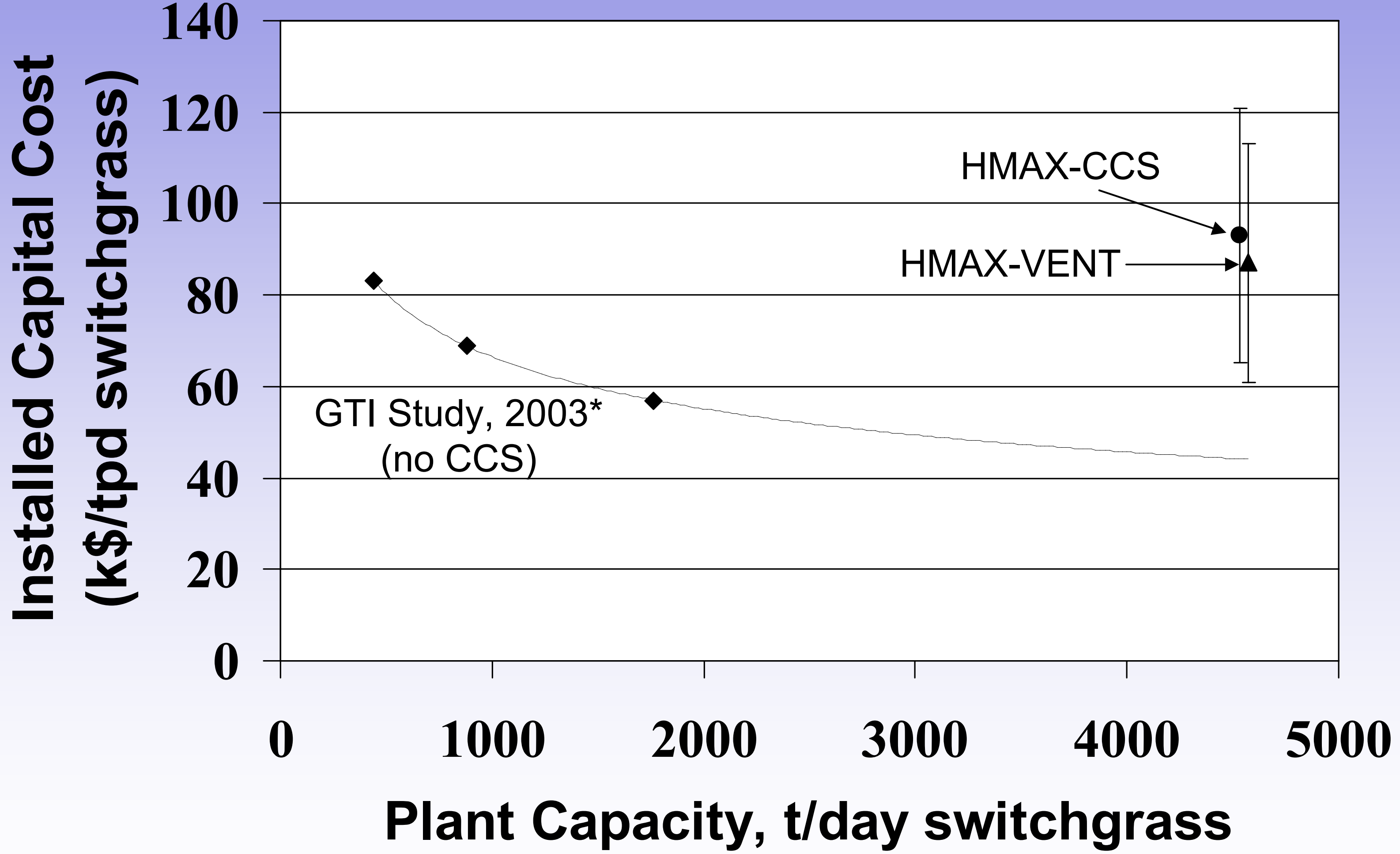
Installed Capital Cost Estimates

	B-IGCC VENT	B-IGCC CCS	H-5050 VENT	H-MAX VENT	H-5050 CCS	H-MAX CCS
Energy capacities						
Switchgrass input, MW LHV	893	893	893	893	893	893
Hydrogen production, MW LHV			240	526	249	528
Electricity output, MW	442	352	281	41	218	10
Physical capacities						
Switchgrass input, dry metric tons/day	4545	4545	4545	4545	4545	4545
CO2 captured, million tCO2/yr	0	2.57	0	0	2.56	2.57
Annual Quantities (80% capacity factor)						
Switchgrass, PJ/yr (HHV)	24.81	24.81	24.81	24.81	24.81	24.81
CO2 for storage, million tCO2/yr	0.00	2.06	0.00	0.00	2.05	2.05
Hydrogen, PJ/yr (HHV)			7.15	15.69	7.42	15.74
Electricity, TWh/yr	3.10	2.46	1.97	0.29	1.53	0.07
Overnight Installed Capital Costs (million 2003 $)						
Biomass preparation & handling	46.6	46.6	46.6	46.6	46.6	46.6
Gasifier and ash cyclone	34.5	34.5	34.5	34.5	34.5	34.5
Syngas cooler	65.4	51.4	51.6	51.6	51.6	51.6
Gas cleaning (tar cracker + ceramic filter)	24.2	26.9	26.8	26.8	26.8	26.8
Upstream water gas shift	--	29.5	7.73	30.3	30.3	30.3
Rectisol (upstream +downstream)	--	47.1	29.5	46.7	46.8	46.7
Rectisol recovery compressor	--	0.19	0.12	0.19	0.18	0.19
CO2 compression	--	11.06	4.97	1.69	11.03	11.04
Supercritical CO2 compressor	--	7.51	--	--	7.50	7.50
PSA	--	--	7.85	18.20	6.14	18.15
PSA purge gas compressor	--	--	3.09	5.15	2.82	5.13
Hydrogen compressor	--	--	3.69	6.26	3.78	6.27
ASU	25.74	25.89	25.75	40.41	25.75	40.41
O2 compressor	4.61	4.64	4.68	5.68	4.68	5.68
N2 expander	--	--	1.23	--	1.23	--
N2 compressor	6.07	5.57	--	--	--	--
Saturator	--	--	0.18	--	0.12	--
Gas Turbine	71.35	66.11	50.03	--	43.64	--
HRSG + heat exchangers	77.18	80.55	56.41	35.87	60.61	43.60
Steam cycle (ST + condenser)	72.37	65.50	56.39	46.57	54.10	46.31
Total overnight capital cost	428	503	411	397	458	421
Overnight cost, k$/tpd switchgrass	94	111	90	87	101	93

Comparison of Biomass-IGCC Capital Costs (no CCS)



Comparison of H_2 Capital Costs (no CCS)



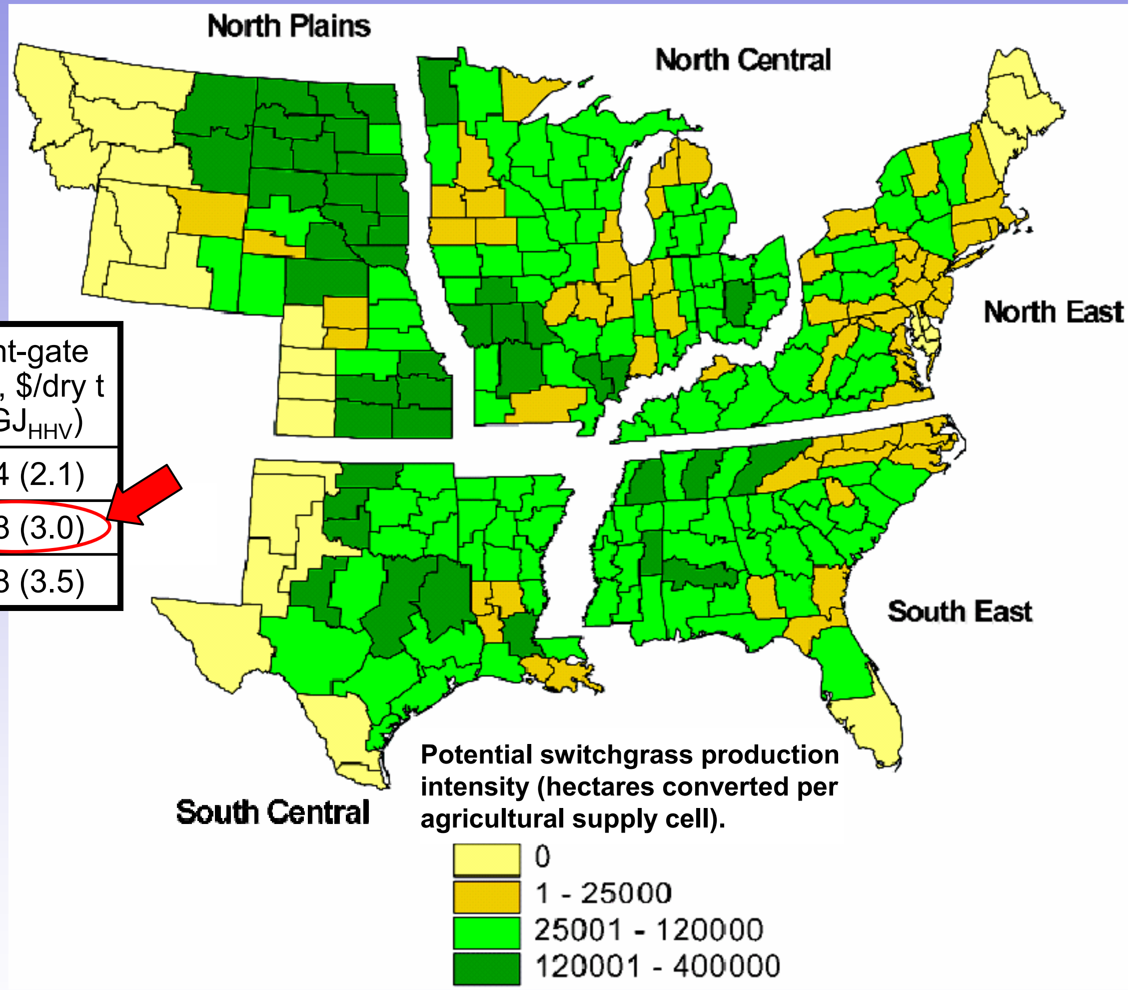
* Lau, F.S., Bowen, D.A., Dihu, R., Doong, S., Hughes, E.E., Remick, R., Slimane, R., Turn, S.Q., and Zabransky, R. 2003. "Techno-economic analysis of hydrogen production by gasification of biomass," final technical report for the period 15 Sept 2001 – 14 Sept 2002, contract DE-FC36-01GO11089 for US Dept. of Energy, Gas Technology Inst., Des Plaines, IL, June (rev.), 145 pp.

Switchgrass Cost

- Based on detailed ag sector model (POLYSIS), the potential land conversion to switchgrass, assuming currently-achievable yields, would be:*

Paid to farmer, (2003$/dry mt)	Land converted to switchgrass (million ha)	Average yield (dry t/ha/y)	Plant-gate price, $/dry t ($/GJ_{HHV})
32.0	3.1	11.1	39.4 (2.1)
46.5	16.8	9.4	56.8 (3.0)
55.4	21.3	9.0	65.8 (3.5)

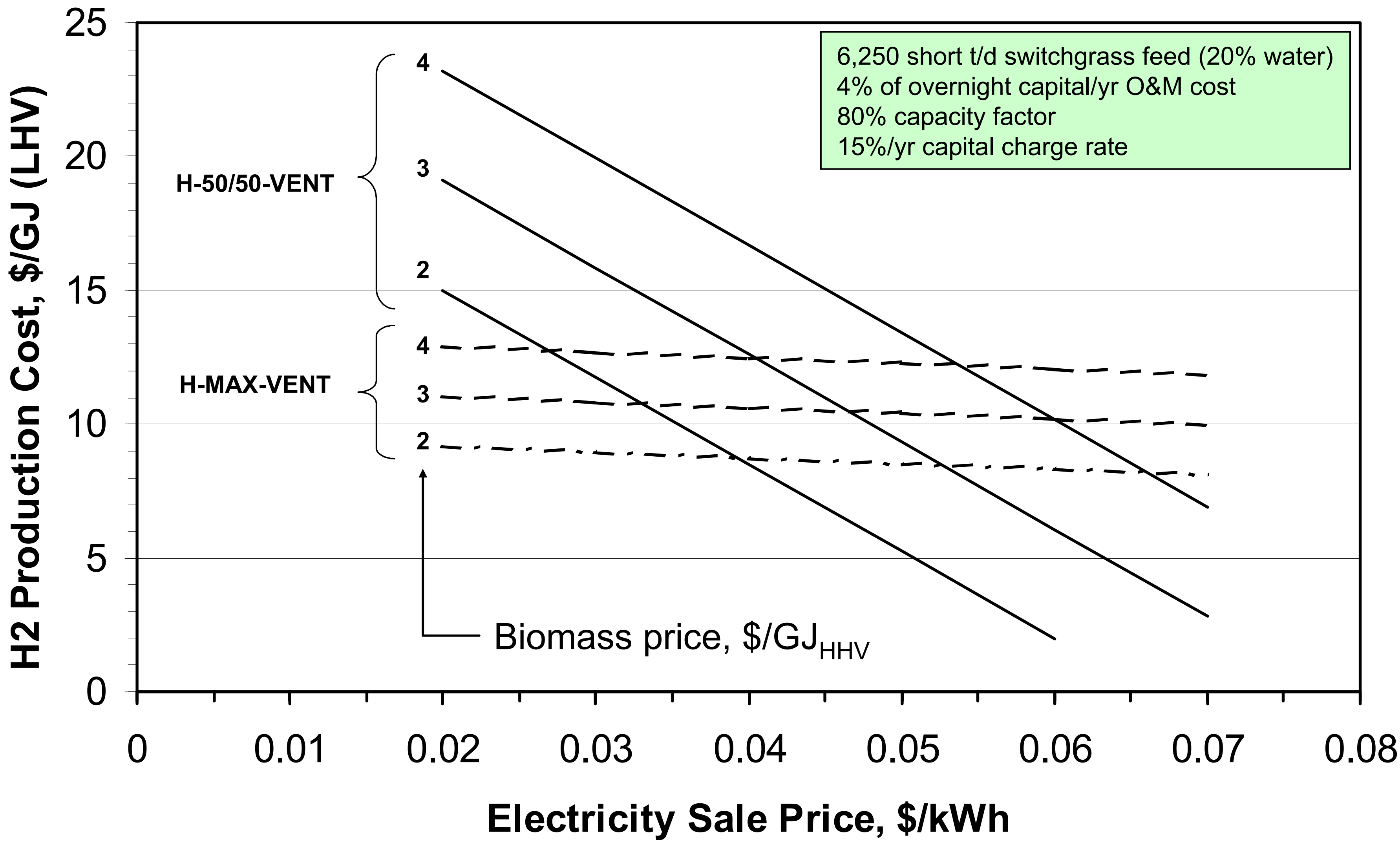
- Projected average sustainable field-scale yields in 2025 are 15 to 22 dry t/ha/yr.**
  - Such yields would expand acreage converted to switchgrass reduce costs.



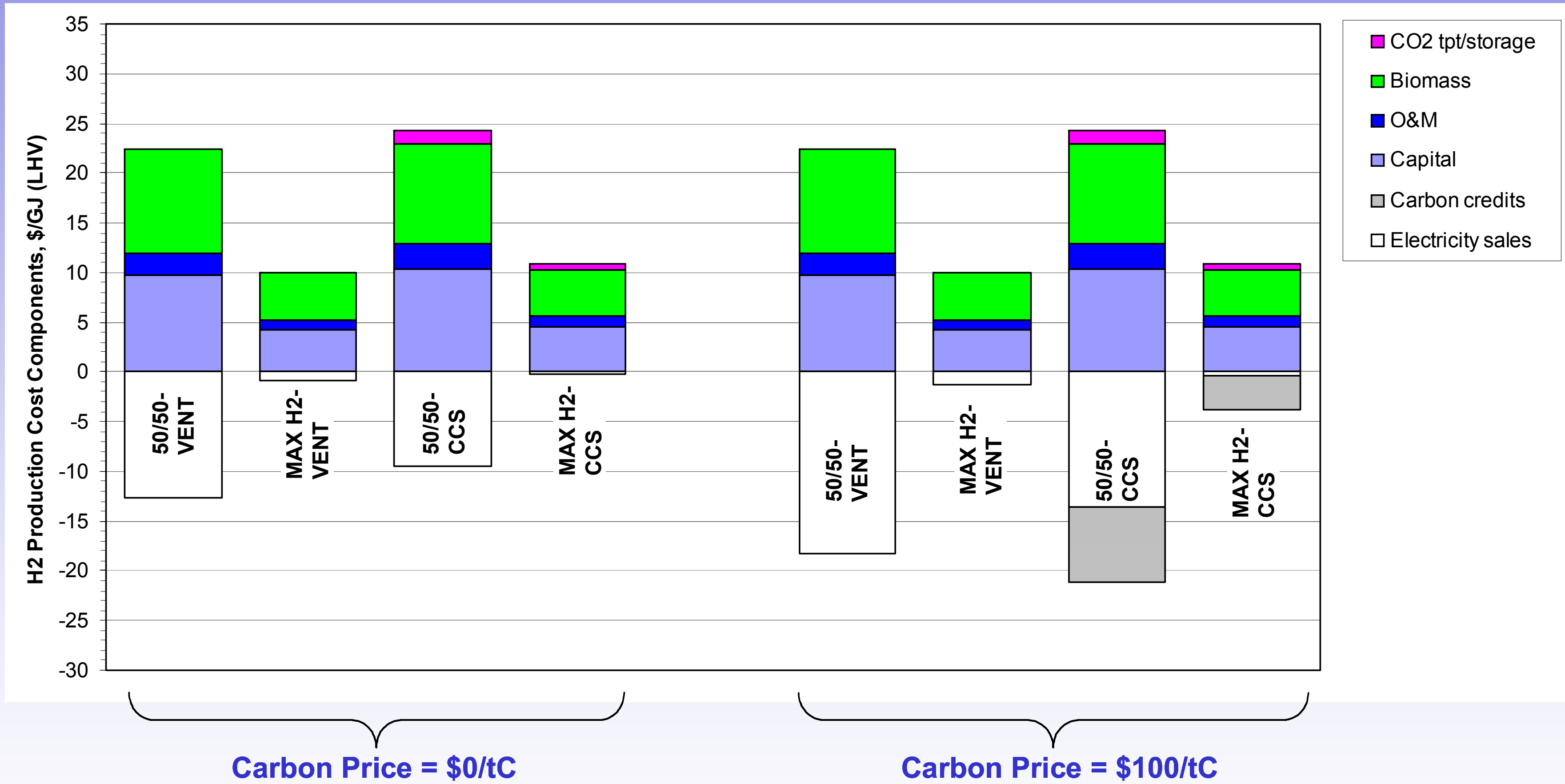
* McLaughlin, de la Torre Ugarte, Garten, Lynd, Sanderson, Tolbert, and Wolf, 2002, "High-value renewable energy from prairie grasses," *Environmental Science and Technology*, **36**(10): 2122-2129.

** Greene N (principal author), Celik FE, Dale B, Jackson M, Jayawardhana K, Jin H, Larson ED, Laser M, Lynd L, MacKenzie D, Mark J, McBride J, McLaughlin S, Sacardi D, 2004. *Growing energy: how biofuels can help end America's oil dependence*. New York: Natural Resources Defense Council, 2004.

H_2 Cost Variation with Biomass and Electricity Prices (no CCS)



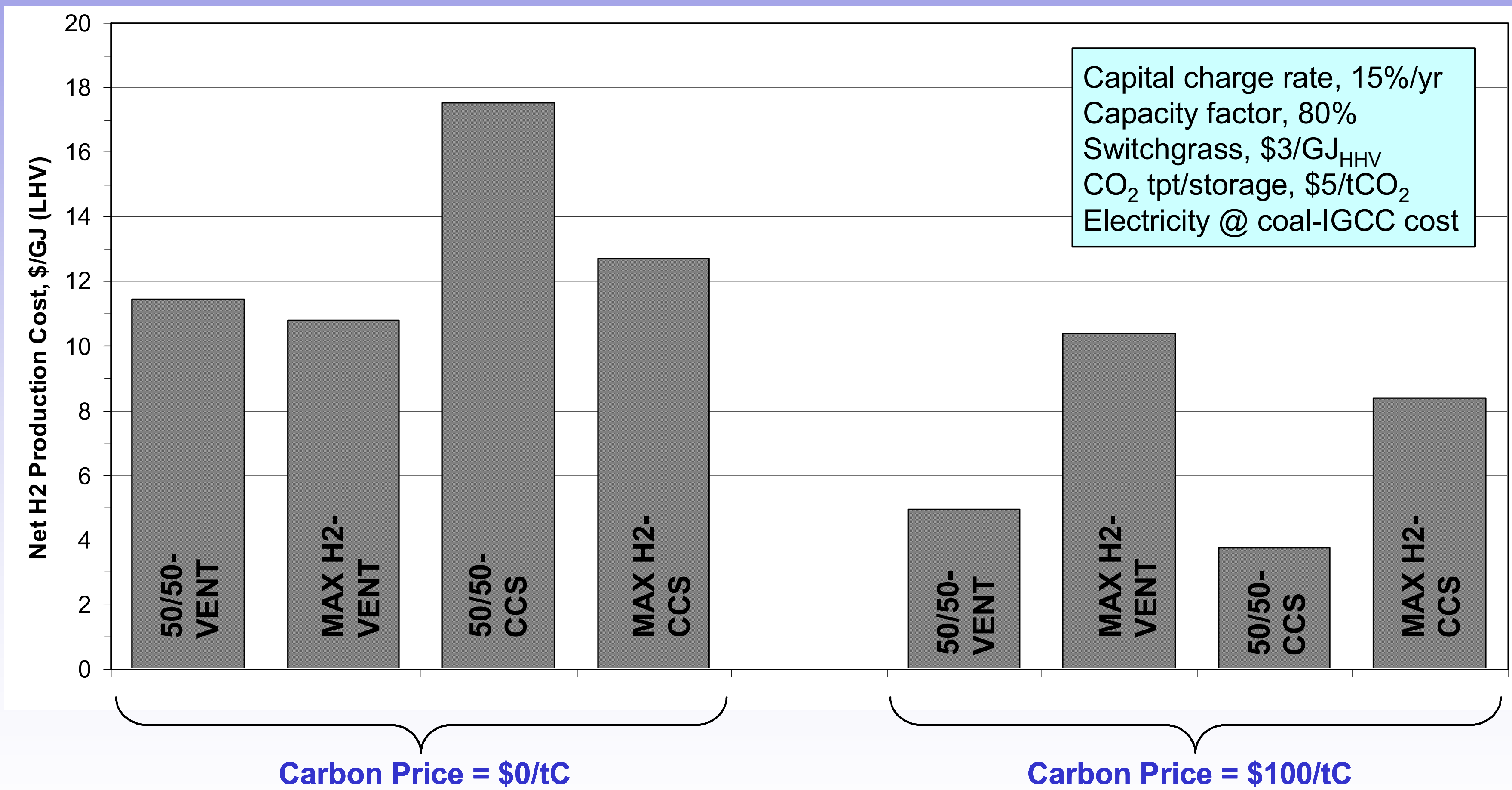
H_2 Cost with and without CCS and with and without Carbon Tax



6,250 short t/d switchgrass feed (20% moisture)
4% of overnight capital/yr for O&M
$5/t$CO_2$ for CO_2 transport and storage
80% capacity factor
15%/yr capital charge rate

Switchgrass = $3.3/$GJ_{LHV}$ ($3.0/$GJ_{HHV}$)
Electricity price = cost of least costly new coal IGCC

H_2 Cost With and Without CCS & With and Without Carbon Tax



Summary

- Biomass converted to H_2 with CCS gives negative CO_2 emissions. (~CO_2-neutral without CCS.)
- There is significant potential in the U.S. for large-scale switchgrass as an energy crop.
- With no carbon policy in place, H_2 with CCS is costlier (to much costlier) than H_2 without CCS.
- With a carbon policy in place H_2 with CCS is less costly than H_2 without CCS and the value of co-product electricity makes process designs that co-produce electricity more attractive than those that maximize H_2 production.