Fourth Annual Conference on Carbon Capture & Sequestration

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

Advanced Concepts – Biomass Offsets

Cost-Competitive, Low-GHG-Emitting Synthetic Liquid Fuels via Coordinated Energy Production with CO_2 Capture and Storage from Coal and Biomass

Robert H. Williams

May 2-5, 2005, Hilton Alexandria Mark Center, Alexandria Virginia

OUTLOOK: LIQUID FUELS FOR TRANSPORTATION

- Whatever one's concerns (*beliefs*) about oil:
  - Production peaking (*or plateauing*) sometime in this ¼ century,
  - Security risks from overdependence on Persian Gulf oil,

  emerging consensus: return of cheap (< *$30/bbl*) oil is unlikely.

- OPEC producers' efforts to keep oil prices high (*$40-$50/bbl or more*) will stimulate investments in alternative transport fuel options.

- Coal liquids will play dominant role among alternatives because of:
  - Huge reserves,
  - Low and stable coal prices,
  - Commercially ready technologies to make super-clean "designer" synfuels.

- Although coal synfuel GHG emissions > than for oil-based HC fuels:
  - CCS can reduce GHG emissions to ~ levels for crude-oil-derived HC fuels,
  - Coordinated production of coal synfuels + bioenergy with CCS for both can:
    - Reduce net GHG emissions for liquid transport fuels to near zero,
    - Provide liquid fuels at prices competitive with $30/bbl oil and create climate for coal synfuel investors that is stable over wide range of prospective carbon market prices (CMPs).

OPTIONS FOR MITIGATING CLIMATE CHANGE IN TRANSPORTATION

- <u>Evolve H_2 economy</u>:
  - Coal H_2 w/CCS likely to be least-costly option for natural gas prices > $4/GJ;
  - Much innovation needed to make H_2-using technologies cost-competitive;
  - Huge infrastructure development costs;
  - Plausible significant option…but not until 2nd quarter of this century.
- <u>Biofuels</u>: can be introduced earlier than H_2 economy…but costs high without high supporting CMPs. Also, land availability constraints ➔ biofuels *alone* can't do "whole job."
- <u>Third option considered here</u>: CCS for bioenergy (*as well as for coal synfuels*) to "make room in atmosphere for coal liquids" as a result of negative emissions when biomass-derived CO_2 is stored underground. This strategy leads to:
  - Much lower synfuel costs than costs of conventional biofuels (*by exploiting the low feedstock cost of coal*);
  - Much more low GHG-emitting liquid fuels per unit of biomass than what can be provided with conventional biofuels.

UNCONVENTIONAL LIQUID FUELS

Potential Liquid Fuel Supplies Based on Proved Reserves of Feedstock and Near-Term Conversion Technologies (*10^9 barrels*)		
Venezuelan heavy oil	60	World Energy Council (2003)
Canadian tar sands	140	Based on 174 x 10^9 barrels proved bitumen reserves. (Dunbar, 2004). Calculation assumes: 60% of recovered bitumen is processed like crude oil; 40% is gasified to make synfuel @ 50% efficiency
Gas-to-liquids	230	From 2000 TCF of stranded gas (Pat Davis, 2003), Sasol
Enhanced oil recovery	340	Constrained by available CO_2 (Beecey and Kuuskraa, 2004)
Coal-to-liquids (*CTL*)	800	Assumes 42% of 20,700 EJ of proved coal reserves (Rogner et al., 2000) converted to synfuels @ 50% efficiency

As in the case of BTL, gasification-based technologies are attractive CTL options. But while BTL technologies require high CMPs to be competitive, some CTL technologies can compete with $30/bbl oil at zero CMP.

CTL PROJECTS—HISTORICAL AND PLANNED

Fischer-Tropsch Liquids

- 150,000 B/D (*crude oil equivalent*) current productive capacity, Sasol II & III, South Africa
- 5,000 B/D DOE demo project (*WMPI*), Gilberton, PA, USA
- Two 80,000 B/D plants in China (*China/Sasol feasibility study*)
- Two prospective plants in Wyoming, USA:
  - 33,000 B/D plant (*DKRW Energy*)
  - 57,000 B/D plant (*WMPI*)

Dimethyl Ether

- 800,000 t/y (*11,000 B/D of Diesel equivalent*) plant planned, Ningxia Autonomous Region, China
- 800,000 t/y plant planned, Inner Mongolia Autonomous Region, China

STUDIES THAT PROVIDE THE BASIS FOR CTL PERFORMANCE/COSTS IN CURRENT ANALYSIS:

Celik F., E. Larson, and R. Williams, 2004: Transportation fuel from coal with low CO_2 emissions, *7th International Conf. on Greenhouse Gas Control Technologies*, Vancouver, September.

Larson, E., and T. Ren, 2003: Synthetic fuels production by indirect coal liquefaction, *Energy for Sustainable Development*, **VII**(4): 79-102.

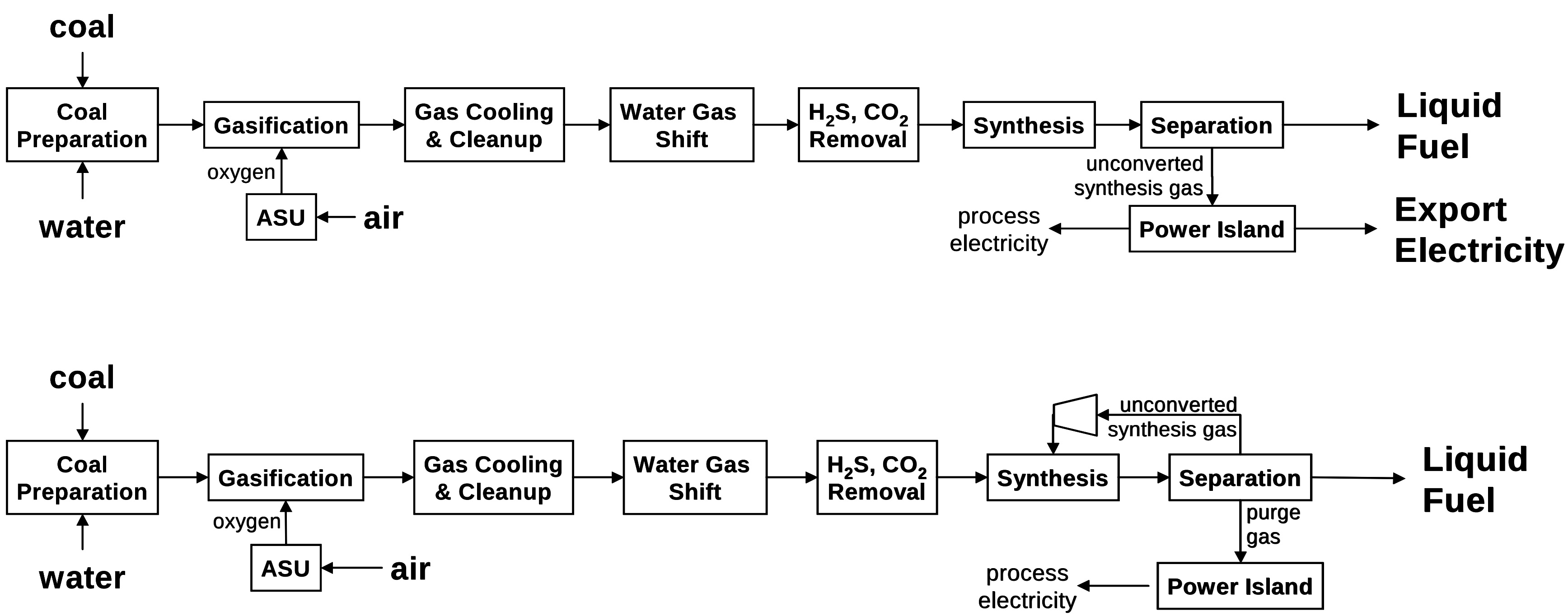
PERFORMANCE/COST ESTIMATES FOR BIOENERGY w/CCS SYSTEMS ARE BASED ON:

Larson, E., H. Jin, R. Williams, and F. Celik, 2005: Gasification-based liquid fuels and electricity from biomass with carbon capture and storage, *4th Annual Conference on Carbon Capture and Sequestration*, Alexandria, VA, 2-5 May.

PERFORMANCE/COST ESTIMATES FOR CO_2 TRANSPORT AND STORAGE ARE BASED ON:

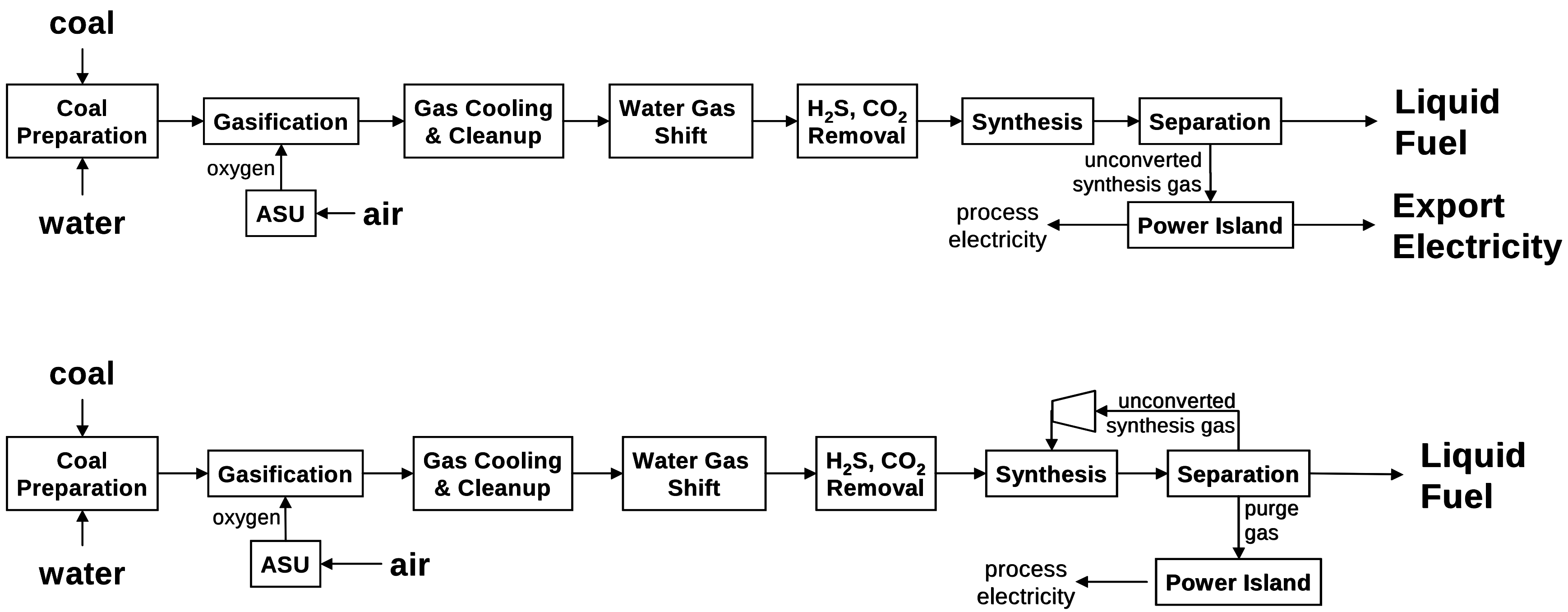
Ogden, J.M., 2002: Modeling infrastructure for a fossil hydrogen energy system with CO_2 sequestration, Paper J2-5, paper presented at the *6th International Conference on Greenhouse Gas Control Technologies*, Kyoto, Japan, September.

ONCE-THROUGH (OT), RECYLE (RC) CTL OPTIONS



- OT option (*top*): syngas passes once through synthesis reactor; un-converted syngas burned → electricity coproduct in combined cycle.
- RC option (*bottom*): unconverted syngas recycled to maximize synfuel production; purge gases burned → electricity only for process; no electricity for export.
- OT systems are often the most cost-effective using new liquid-phase synthesis reactors…if markets are available for electricity coproduct.

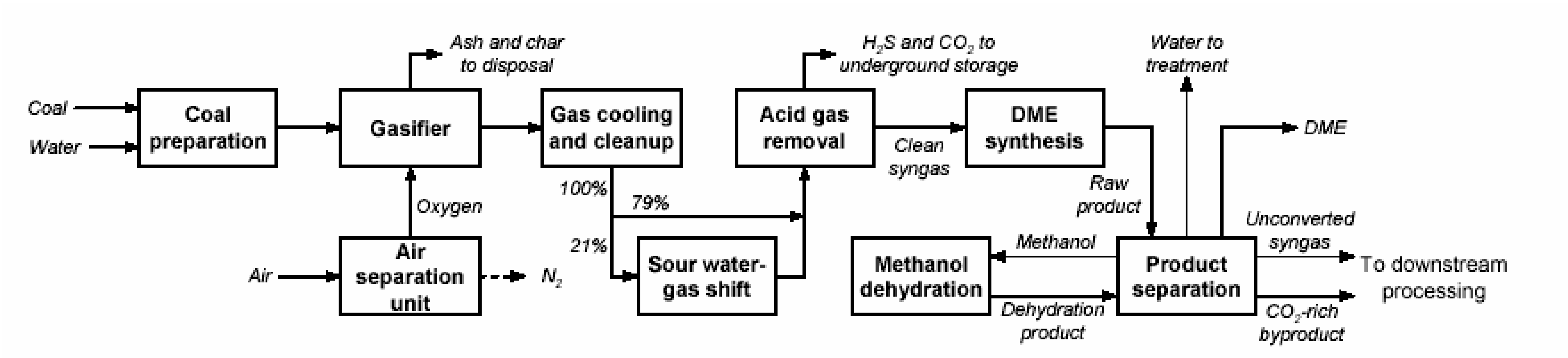
ONCE-THROUGH (OT), RECYLE (RC) CTL OPTIONS



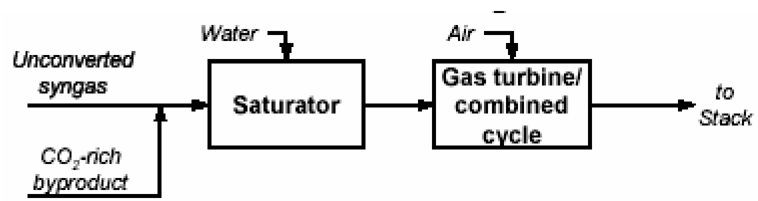
- <u>OT option</u> (*top*): syngas passes once through synthesis reactor; un-converted syngas burned → electricity coproduct in combined cycle.
- <u>RC option</u> (*bottom*): unconverted syngas recycled to maximize synfuel production; purge gases burned → electricity only for process; no electricity for export.
- While RC systems require > $40/bbl oil to be competitive, breakeven crude oil prices ~ $30/bbl can be realized for OT systems.

CCS FOR COAL DME SYSTEMS

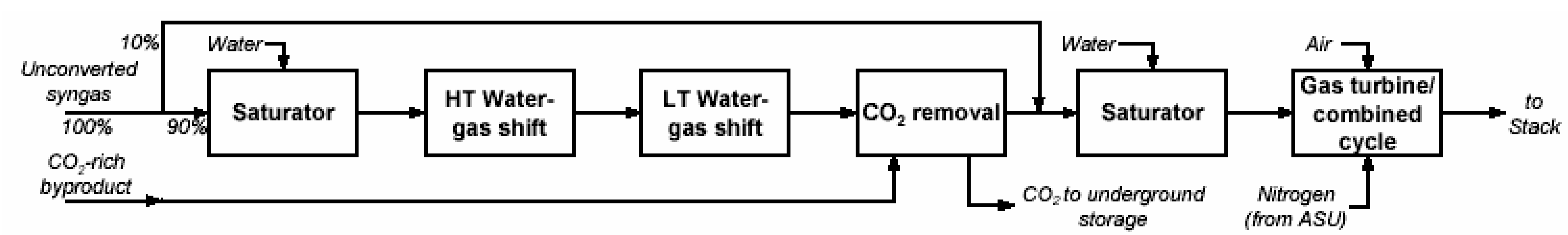
Processing through DME synthesis (*assume CO_2 + H_2S co-capture/co-storage*)



Processing downstream of synthesis for OT/UCAP

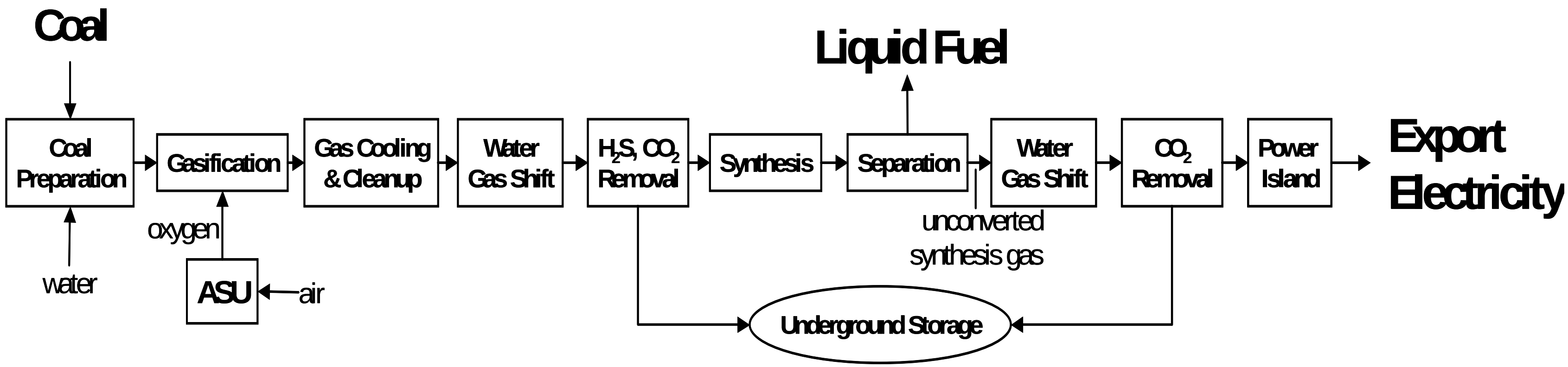


Processing downstream of synthesis for OT/DCAP



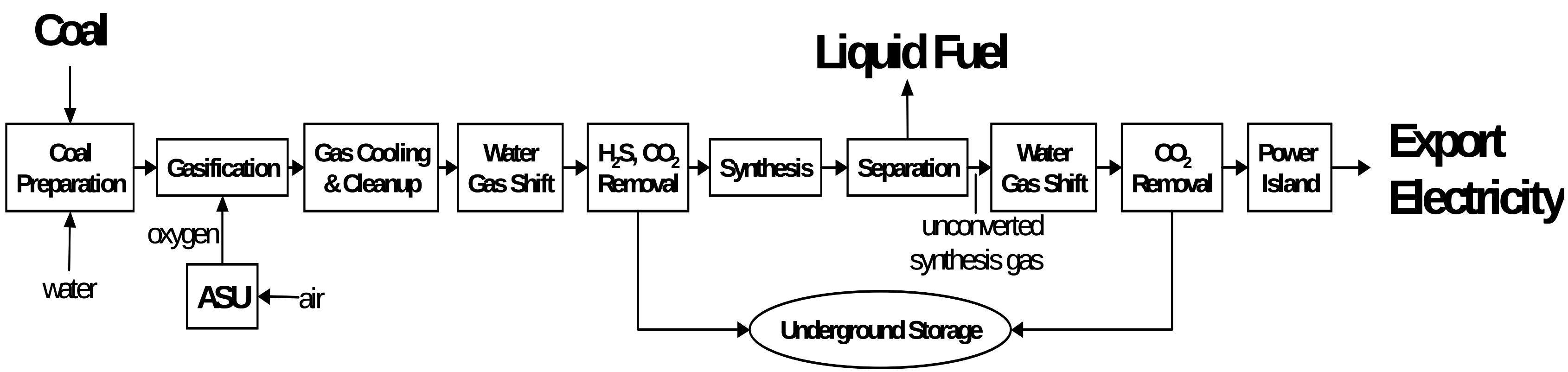
Here analysis is focused on DME…but results are likely to be similar for F-T liquids

Under Climate Constraint, Coproduce Liquid Fuel + Electricity with CO_2 Capture Upstream and Downstream of Synthesis Reactor



- Upstream CO_2 capture (UCAP) to the extent of nearly 30% of C in coal will often be cost-effective as acid gas management strategy (*co-capture and co-storage of* CO_2 + H_2S) even with CMP = $0/tC.
- With UCAP option, fuel-cycle-wide GHG emissions for coal-derived liquid fuel ~ or slightly < emissions for crude-oil-derived HC fuels.
- Carbon management policy (high CMP) needed to induce CO_2 capture downstream as well as upstream of synthesis (DCAP)—leading to decarbonization of electricity coproduct.

Under Climate Constraint, Coproduce Liquid Fuel + Electricity with CO_2 Capture Upstream and Downstream of Synthesis Reactor



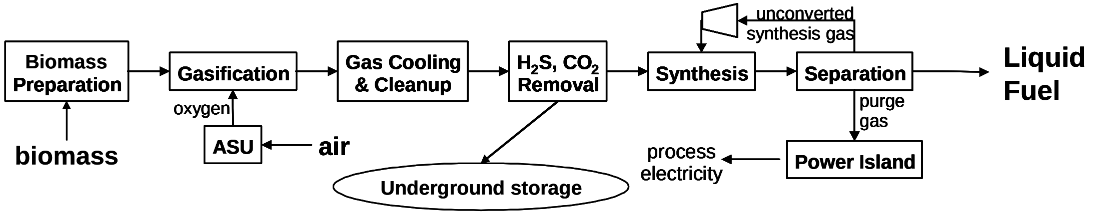
This decarbonization strategy is a necessary but not a sufficient condition for widespread use of coal synfuels for a world seeking stabilization of atmospheric CO_2 @ $\leq$ 2X preindustrial level.

But also pursuing CCS for bioenergy can "make room in atmosphere for coal liquids."

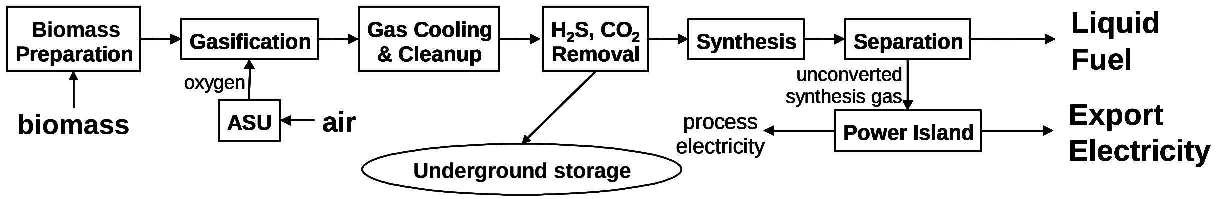
CCS can be pursued for bioenergy systems that make: (*i*) only liquid fuels, (*ii*) fuels + electricity, or (*iii*) only electricity.

ALTERNATIVE CONFIGURATIONS FOR MAKING LIQUID FUELS FROM BIOMASS WITH CCS

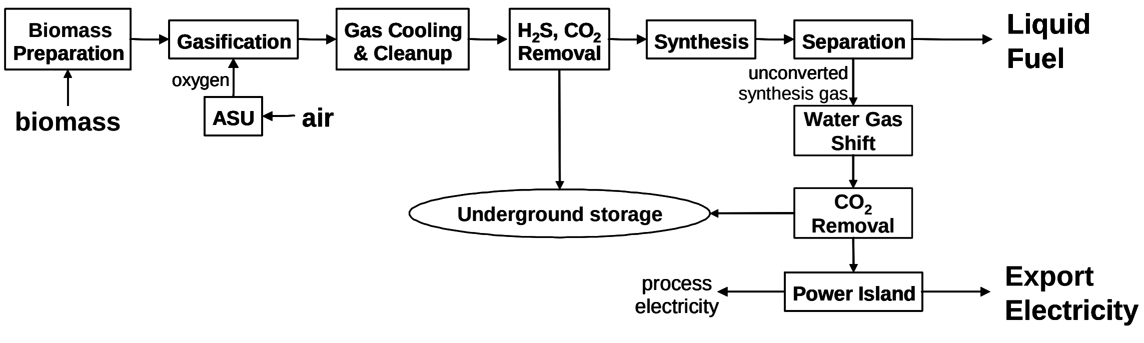
B-RC/UCAP (*Recycle; Up Stream Capture—50% of C stored)*



B-OT/UCAP (*Once-Thru; Up-Stream Capture—46% of C stored*)

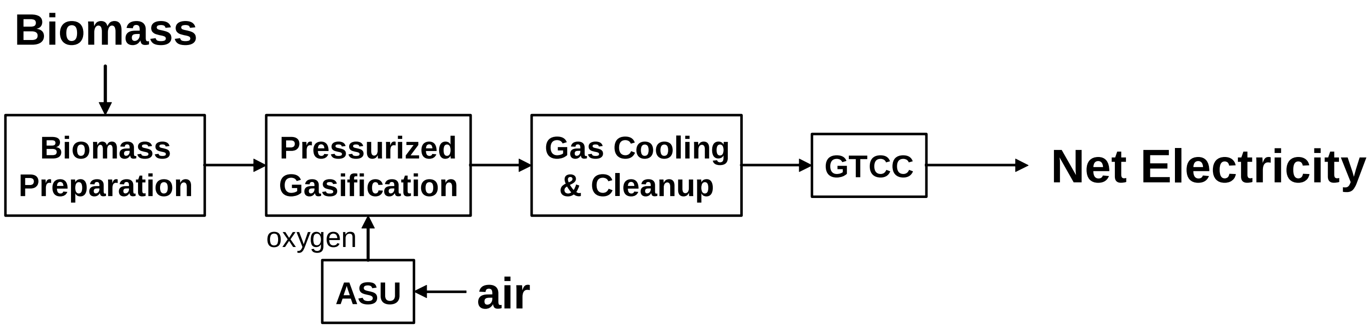


B-OT/DCAP (*Once-Thru; Down-/Up-Stream Capture—74% of C stored*)

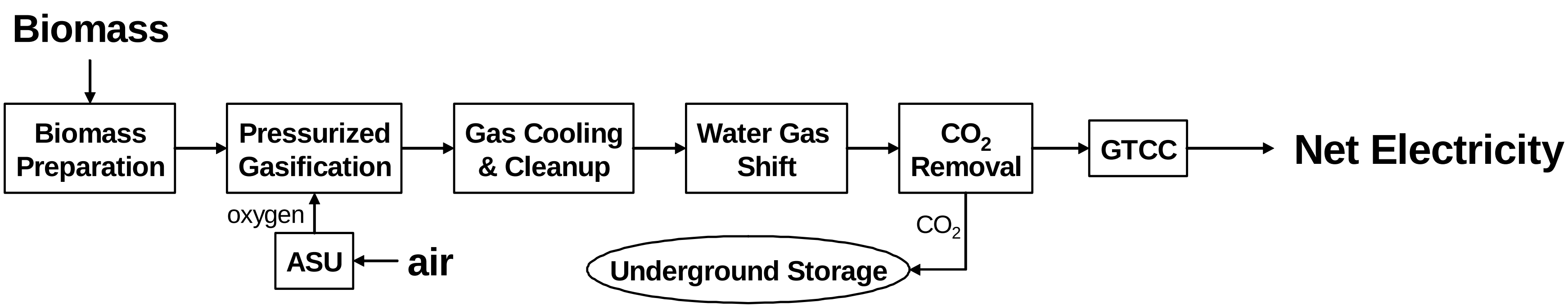


BIOMASS INTEGRATED GASIFIER COMBINED CYCLE POWER GENERATION

B-IGCC/VENT (*CO_2 vented*):



B-IGCC/CCS (*91% of C captured and stored*):



As will be shown, B-IGCC/CCS will often be the optimal bioenergy/CCS option in offsetting GHG emissions from liquid fossil fuels.

STRATEGIES FOR BIOENERGY w/CCS

- Governments will promote bioenergy w/CCS to help compensate for difficult-to-decarbonize fossil fuel energy (*e.g, in transportation*) in seeking to meet overall GHG emissions targets.

- Private firms, especially those providing difficult-to-decarbonize fossil energy products, will buy in carbon trading markets GHG emissions reduction credits from producers of bioenergy w/CCS.

- Some producers who can offer low-cost fossil synfuels today will invest in bioenergy w/CCS projects so as to be able to continue offering synfuels at low costs and thereby expand liquid fuel market share as CMP rises—here focus is on this option for CTL.

- Here assume coordinated CTL/bioenergy production, w/CCS for both, using just enough bioenergy w/CCS to reduce GHG emissions for coal liquids to "near zero"—via systems called "C-B hybrids."

- Base-case analysis: assume C-B hybrids with just enough bioenergy to reduce fuel-cycle-wide GHG emissions rate for synfuels produced to level for H_2 from coal w/CCS = $5.4\ kgC_{equiv}/GJ$ (*~ 1/5 GHG emission rate for gasoline or Diesel from crude oil*).

DESIGNING DME/ELECTRICITY SUPPLY SYSTEM WITH TARGETED DME GHG EMISSION RATE = GHG EMISSION RATE FOR H_2 FROM COAL w/CCS

GHG emission rate for H_2 from coal w/CCS = 5.4 kgC_{equiv}/GJ

w kgC vented as CO_2 at plants making DME from **coal**

x kgC released in combustion of DME from **coal**

a GJ **biomass**

u GJ **coal**
v kgC

Making DME + Electricity from **coal** (*in one region*) + **biomass** (*in another region*)

1.0 GJ DME (**b**% *from* **biomass**) + c GJ electricity (**c**% *from* **biomass**)

d kgC as CO_2 from **biomass** stored underground

y kgC as CO_2 from **coal** stored underground + **z** kgC in char

Carbon balance for **coal**: **v** = **w** + **x** + **y** + **z**

Choose **biomass** system (**a**, **b**, **c**, **d**) s.t.:

w + **x** + other FC emissions – **d** – emissions for electricity = 5.4 kgC_{equiv}/GJ

FINANCIAL PARAMETERS, ECONOMIC ANALYSES

	Levelized Cost Analyses[a]	Internal Rate of Return on Equity Analyses
Construction period (y)	4	4
Inflation rate (%/y)	2	2
Book life (y)	30	30
Tax life (y)	20	20
Depreciation (for tax purposes)	MACRS[b]	MACRS[b]
Corporate income tax rate (%)	38.2	38.2
Property taxes & insurance (%/y)	2	2
Nominal (real) return on equity (%/y)	16.3 (14.0)	Determined by market prices of products
Nominal (real) return on debt (%/y)	6.5 (4.4)	6.5 (4.4)
Equity share (%)	45	45
Debt share (%)	55	55
Real discount rate[c] (%/y)	7.8	-

[a] Based on EPRI (1993) for regulated utilities.

[b] Modified accelerated capital recovery system.

[c] After tax weighted average cost of capital.

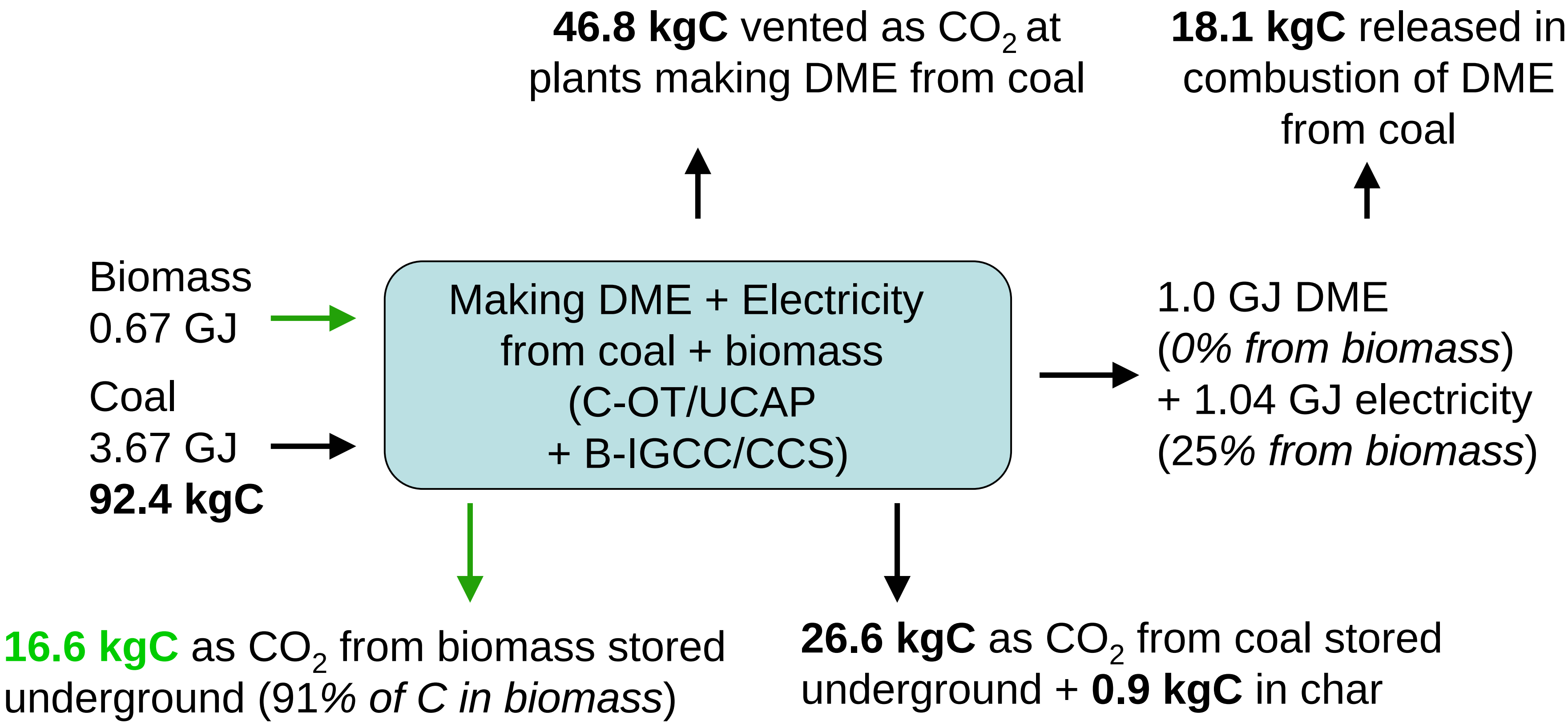
B-IGCC/CCS = PREFERRED BIOMASS OPTION FOR C-B HYBRIDS

B-energy option for coal-biomass (C-B) hybrid	Impacts per GJ of biomass input relative to B-IGCC/CCS in a C-B hybrid			**B-Energy Systems with:** • DME selling at Diesel cost ($30/barrel crude); • B-IGCC/CCS selling at minimum C-IGCC cost	
	Products		GHG emissions reduction potential	Carbon Market Price	
	DME (C + B)	Electricity (B)		$100/tC	$140/tC
				IRRE (%/y) for B-energy	
B-IGCC/CCS	1.00	1.00	1.00	19.5	23.4
B-RC/UCAP	0.93	0.19	0.64	5.8	11.0
B-OT/UCAP	0.71	0.73	0.72	15.1	18.7
B-OT/DCAP	0.99	0.65	0.86	14.1	18.9

At CMP = $140/tC, crude oil price ~ $55-$65/bbl needed to make B-liquids as profitable as B-IGCC/CCS.

E/C BALANCES FOR DME/ELECTRICITY FROM COAL/SWITCHGRASS MIX

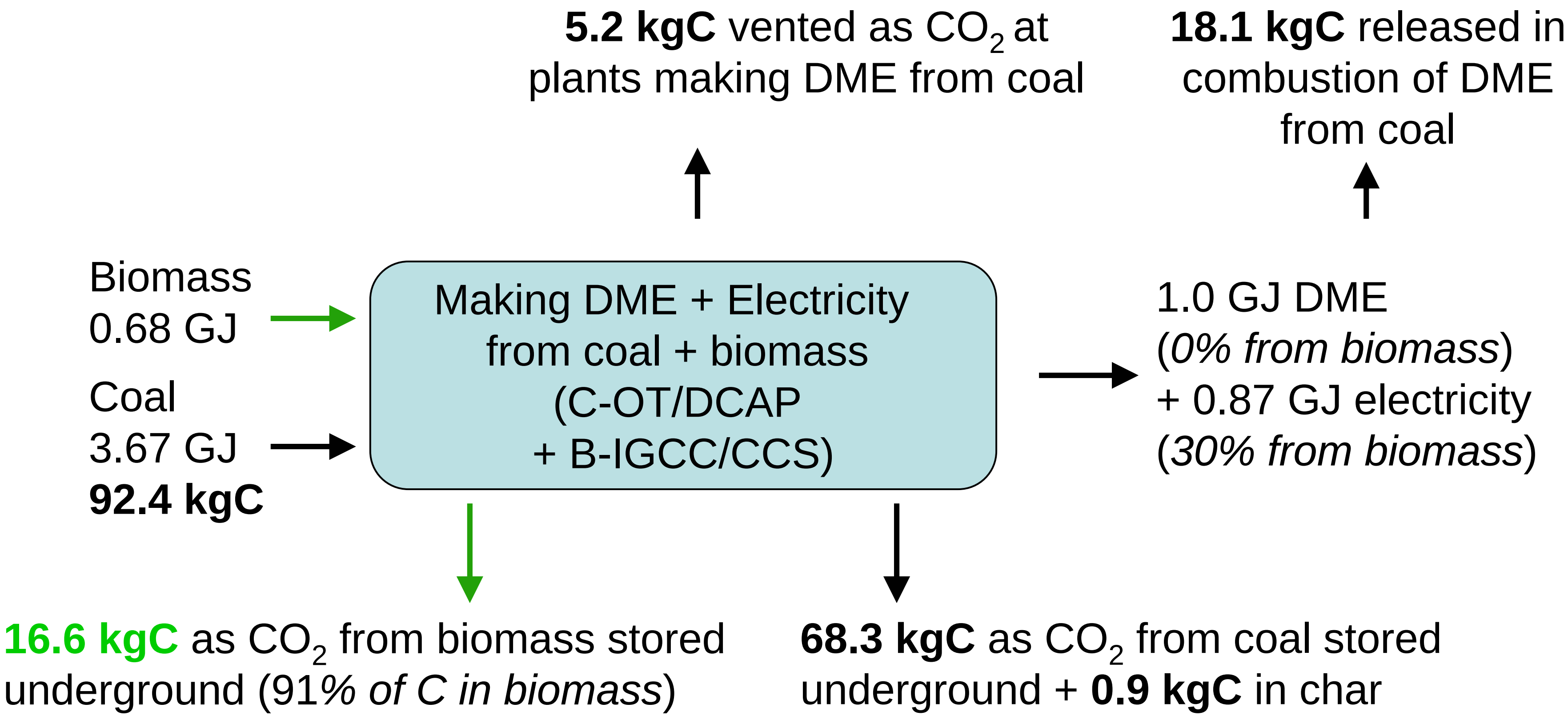
(*Low CMP Configuration—partial decarbonization*)



Direct net CO_2 emissions = 46.8 + 18.1 – 16.6 kgC = 48.3 kgC per GJ DME

E/C BALANCES FOR DME/ELECTRICITY FROM COAL/SWITCHGRASS MIX

(*High CMP Configuration—full decarbonization*)



Direct net CO_2 emissions = 5.2 + 18.1 – 16.6 kgC = 6.7 kgC per GJ DME

FUEL-CYCLE-WIDE (well-to-wheels) **GHG EMISSION RATE FOR DME C-B HYBRIDS**

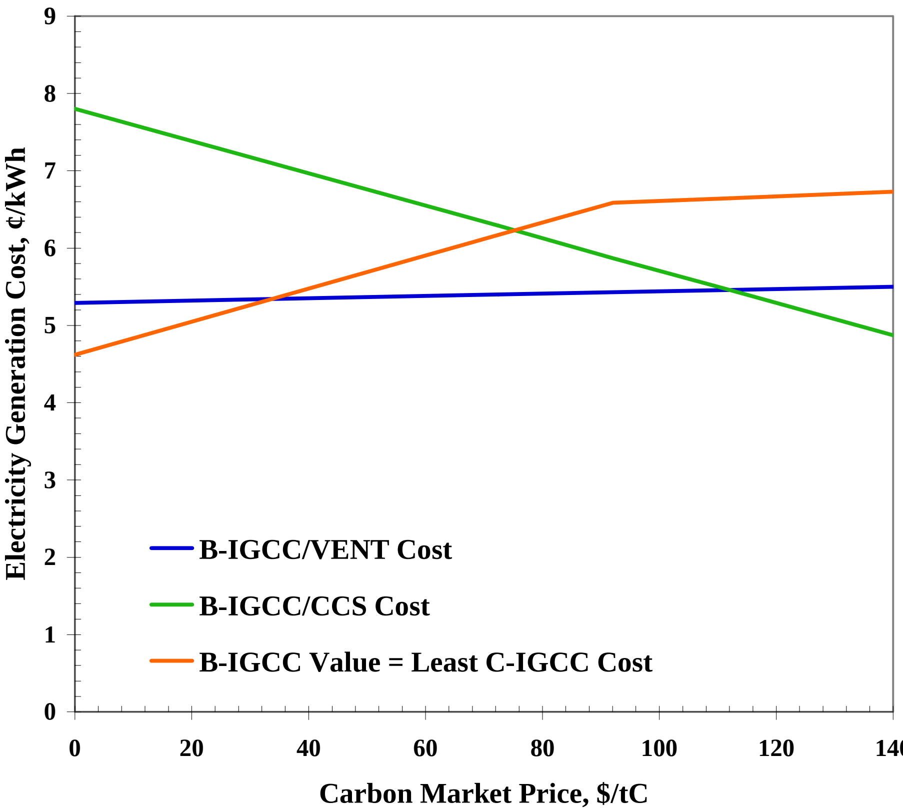
(*kgC*$_{equiv}$*/GJ of DME*)

Hybrid based on B-IGCC/CCS + coal:	OT/UCAP	OT/DCAP
Direct net CO_2 emissions	48.3	6.7
Upstream coal	3.7	3.7
Upstream biomass	1.4	1.4
Downstream DME	0.5	0.5
Assigned to C-electricity	- 46.3	- 4.7
Assigned to B-electricity	- 2.0	- 2.0
Net GHG emissions for DME	5.4	5.4

Based on fuel-cycle-wide GHG emission rates of:

- 22.7 kgC$_{equiv}$/GJ for DME (*C-OT/UCAP and C-OT/DCAP*);
- 214 gC$_{equiv}$/kWh for C-OT/UCAP electricity (= *rate for C-IGCC/VENT*);
- 28.0 gC$_{equiv}$/kWh for C-electricity, B-electricity in OT/DCAP hybrid.

AT WHAT CMP DOES CCS BECOME COST-EFFECTIVE FOR B-IGCC?



Levelized costs (LCs) in graph, assuming:

- LACCR = 15%/y, CF = 80%, IDCF = 1.123;
- Biomass @ $3.0/GJ, coal @ $1.2/GJ (HHV);
- B-IGCC/VENT: 442 MW_e, $967/$kW_e$ (OCC),. η= 45.0% (HHV), + 14.9 gC_{equiv}/kWh;
- B-IGCC/CCS: 352 MW_e, $1430/$kW_e$ (OCC), η= 35.8% (HHV), - 209 gC_{equiv}/kWh;

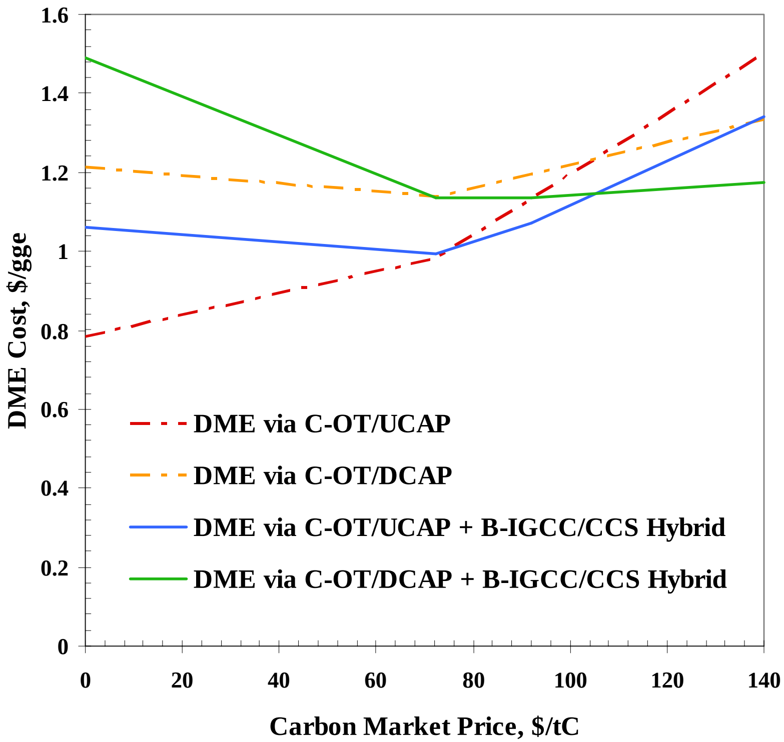
But if electricity selling price is set by least-costly C-IGCC option at any CMP, an internal rate of return on equity (IRRE) analysis is needed to determine CMP at which shift from VENT to CCS takes place.

Although B-IGCC/CCS LC < C-IGCC/VENT LC for CMP > $75/tC & < B-IGCC/VENT LC for CMP > $112/tC, IRRE analysis shows that if coal power sets electricity price:

shift to CCS requires CMP ≥ $140/tC.

CMP ($/tC)	112	140
IRRE (%/year)		
BIGCC/VENT	22.9	23.2
BIGCC/CCS	20.2	23.4

DME COSTS VS CARBON MARKET PRICE



B-IGCC/CCS: 352 MW_e, OCC = $0.50 x 10^9;

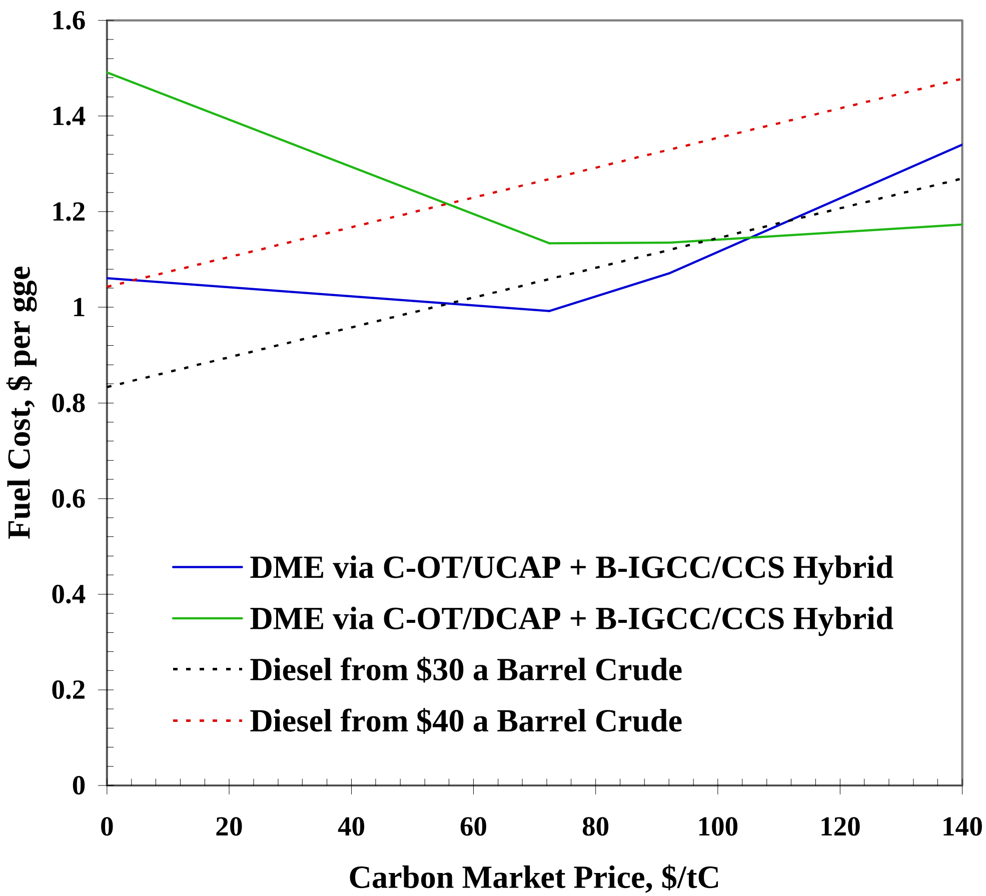
C-OT/UCAP: 600 MW DME + 470 MW_e, OCC = $0.92 x 10^9;

C-OT/DCAP: 600 MW DME + 365 MW_e, OCC = $1.00 x 10^9;

1 Hybrid = B-IGCC/CCS + 2.2 x (*C-OT/UCAP or C-OT/DCAP*).

- Investment for C-B hybrid ~ 1 ¼ X investment for coal-only plant;
- Assumed biomass price: $3.0 per GJ;
- Assumed coal price for making DME: $0.5 per GJ (*minemouth plants*);
- Assumed electricity price = least costly C-IGCC generation cost;
- LACCR = 15%/y, CF = 80%, IDCF = 1.123.

HYBRID DME & DIESEL COSTS VS CARBON MARKET PRICE



- Hybrid DME competes with Diesel from $30/barrel crude for CMP > $50/tC.
- Hybrid DME cost ~$1/gge over wide range of CMP.
- Significance:
  - US refinery-gate gasoline price = $1.0/gallon in 2003 when crude oil price = $29/barrel;
  - ~ $1/gge = long-term cost goal for cellulosic EthOH.

Low net GHG emission rate and stable low production cost over wide range of CMPs ➔ good prospects for expanding liquid fuel market share under climate constraint…as long as oil price does not collapse.

UNDER WHAT CONDITIONS IS TARGETED GHG EMISSION RATE FOR DME "OPTIMAL"?

- GHG emissions target for hybrid-derived DME selected arbitrarily.
- But, for $35/barrel oil, target ~ "optimal" for DME producer seeking stable IRRE for investors over wide range of prospective CMPs.
- At this oil price, selected target ➔ same IRRE for hybrid at CMP = $140/tC as for coal-only system at CMP = $0/tC.

IRRE analysis for alternative systems when crude oil is $35 a barrel		
System configuration:	CMP ($/tC)	
	0	140
	IRRE (%/y)	
Making DME with coal-only systems:		
Coal OT/UCAP	16.4	12.0
Coal OT/DCAP	9.8	14.7
Making DME via hybrids, BIGCC/CCS +:		
Coal OT/UCAP	12.5	14.5
Coal OT/DCAP	6.8	16.4

IMPLICATIONS OF ALTERNATIVE GHG EMISSIONS TARGETS FOR DME FROM COAL/BIOMASS HYBRIDS

- Total system GHG emissions reduction per GJ of biomass input invariant across alternative DME emission targets;
- The lower the GHG emissions target for DME, the greater the GHG emissions reduction per kgC stored as CO_2;
- The higher the GHG emissions target, the more DME is produced per GJ of biomass;
- Higher GHG emissions targets require lower breakeven oil prices to realize the same system IRRE at $0/tC and $140/tC.

Targeted DME GHG emission rate (kgC_{equiv}/GJ)	(DME out) /(biomass in)	GHG emissions reduction (*exc. from decarbonizing coal elect*.) kgC_{equiv} per:		Equal IRRE point for C-OT/UCAP ($0/tC) & C-B OT/DCAP hybrid ($140/tC)	
		GJ biomass	kgC stored as CO_2	Crude oil price ($/barrel)	IRRE (%/y)
2.7	1.3	46	0.78	38	17.3
5.4	1.5	46	0.71	35	16.4
10.8	2.2	46	0.56	28	14.1

COMPARING BIOMASS LIQUID FUEL SYSTEMS

System characteristic	Cellulosic EthOH[a]		DME	
	Current	Advanced	RC/VENT	Hybrid
Liquid fuel (*% of biomass energy input*)	25	53	51	144
GHG emissions (kgC_{equiv}/GJ *liquid fuel*)	2.0	0.96	3.2	5.4
GHG emissions reduction in displacing gasoline (*% of biomass C*)	22	49	42	109
Biomass electricity (*% of biomass energy input*)	5.0	5.0	8.8	39
GHG emissions (gC_{equiv}/kWh *biomass electricity*)	15	15	15	28
GHG emissions reduction in displacing C-IGCC/VENT electricity (*% of biomass C*)	10	10	18	76
Total GHG emissions reduction (*% of biomass C*)	33	59	61	186
Liquid fuel cost[b] (*$ per gge*)	2.35	1.0[c]	1.75	1.06[d]

[a] EthOH @ 50 (105) gallons per short ton of biomass for current (advanced) technology

[b] All costs are for switchgrass @ $3.0 per GJ (HHV)

[c] Long-term cost goal for cellulosic EthOH

[d] Cost for B-IGCC/CCS + C-OT/UCAP hybrid

Should B-IGCC/CCS Technology Be Subsized?

- Market launch for CTL technology expected soon (*China*, *maybe US*).
- But large B-IGCC/CCS plants require CMP ~ \$140/tC (*years away*).
- Rationale for subsidy: (*i*) create industry/infrastructure for supporting large B-IGCC technology, and (*ii*) gain early experience with CCS for this technology, in preparation for eventual climate mitigation regime with high CMPs.
- <u>Suggestion</u>: consider shifting current US corn EthOH subsidy (*\$1.6 x 10^{9}/y*) to low GHG-emitting synfuels generated via C-B hybrids.
- Corn EthOH subsidy: 51¢/g EthOH for 3.1 x 10^9 g ➔ \$1.6 x 10^9/y.
- 3.2¢/kWh subsidy needed to make B-IGCC/CCS competitive with C-IGCC/VENT @ CMP = \$0/tC.
- 7.8 GW_e of B-IGCC/CCS can be supported @ \$1.6 x 10^9/y subsidy.
- What are relative merits of current subsidy vs subsidy shift to low GHG-emitting synfuels generated via C-B hybrids?

IMPLICATIONS OF SUBSIDY SHIFT

	Corn EthOH	C-B Hybrid DME
Unit subsidy per unit of liquid fuel, ¢/gge	76	28
Supportable liquid fuel production, 10^9 gge/y	2.1	5.7
GHG emission rate (kgC_{equiv}/GJ) relative to gasoline, %	72	21
GHG emissions reduction via displacing gasoline with synthetic fuel, 10^6 tC/y	1.8	13.7
GHG emissions reduction via displacing C-IGCC/VENT with B-IGCC, 10^6 tC/y	-	9.2
Total GHG emissions reduction, 10^6 tC/y	1.8	22.9
Public cost for GHG emissions avoided, $/tC	900	70

"Winner-picking" concerns could be avoided by specifying not technology but performance required to qualify for subsidy.

CONCLUSIONS

- Bioenergy w/CCS = attractive option for generating offsets for difficult-to-decarbonize energy-using sectors (*e.g.*, *transportation*).

- B-IGCC/CCS technology = favored bioenergy/CCS option for maximizing both total GHG emissions reduction & low GHG-emitting liquid fuel production.

- Fossil synfuel producers who can offer low-cost synfuels at CMP = $0/tC can sustain low production costs as CMP rises by investing modestly in B-IGCC/CCS for C-B hybrids—thereby enhancing prospects for sustaining liquid fuel market share growth as public policy-generated climate mitigation constraints tighten.

- Vastness and low cost of coal resource ➔ coal synfuel producers will be well positioned to exploit this opportunity.

CONCLUSIONS (*continued*)

- C-B hybrids can be designed to offer the same degree of GHG emissions reduction in transportation as a shift to coal-derived H_2 w/CCS, but these climate mitigation benefits, as well as the crude oil displacement benefits, can be realized much earlier with the liquid fuels offered by C-B hybrids than with a shift to H_2.
- Consideration should be given to subsidizing B-IGCC/CCS to gain early experience with the technologies, to begin building the needed infrastructures, and to launch the new industries involved, before the high CMPs needed to motivate the technologies via market forces are put into place.
- There are opportunities for providing the needed subsidies without new government expenditures—via shifts of existing subsidies.

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