SYNTHETIC LIQUID FUELS FROM COAL + BIOMASS WITH NEAR-ZERO GHG EMISSIONS

Robert H. Williams
Princeton Environmental Institute
Princeton University

Viewgraphs for Presentation

Deep Dive on Fuels
CMI Annual Meeting
Princeton University
12 January 2005

MAJOR CHALLENGES POSED BY OIL AND CARS

- Supply insecurity
- Oil price (*prospective peaking of global production*)
- Health impacts of air pollution (*especially for Diesel vehicles*)
- Climate change (*need to decarbonize energy for cars*)

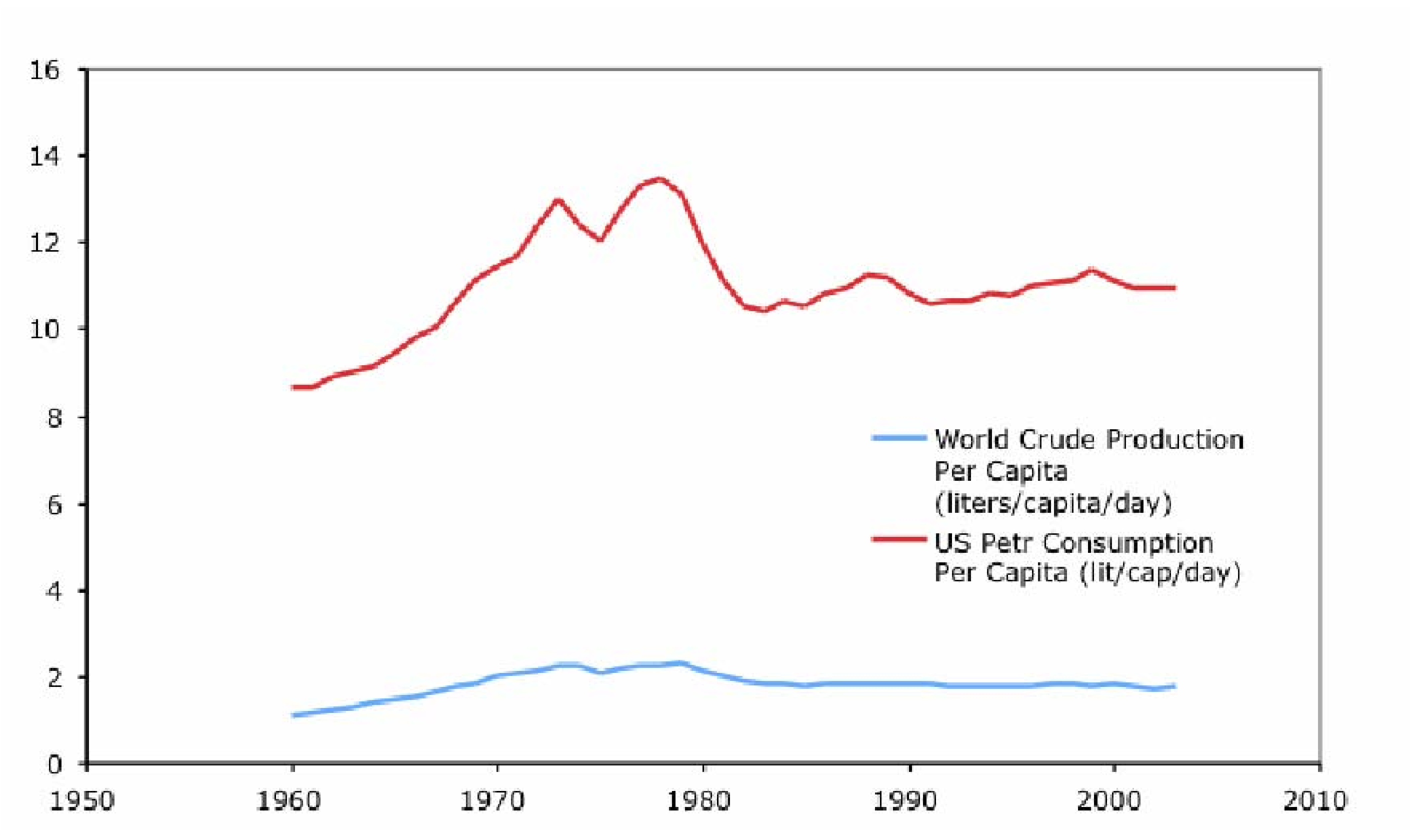
THE CAR'S CONTRIBUTION TO OIL, CLIMATE CHALLENGES

Year	2000	2030
Number of light-duty vehicles worldwide, 10^6	690	1270
Average fuel economy (mpg_{ge})	*24.4*	*28.0*
Crude oil consumed, 10^6 barrels/day (% of Persian Gulf production, 2000)	16.7 (*89*)	27.1 (*136*)
Fuel cycle-wide GHG emissions, GtC/year (% of global total, 2000)	0.74 (*11.6*)	1.20 (*18.8*)

Source: World Business Council for Sustainable Development, *Mobility 2030: Meeting the Challenges of Sustainability*, The Sustainable Mobility Project, 2004

HIGH FUEL ECONOMY/SYNFUELS IMPERATIVE

World Oil Production/Capita Peaked before 1980 at Fraction of US Oil Consumption Rate



Distribution of Global CO_2 Emissions from FFs (%)

Year	2000	2020	2050
Electricity generation	36	25-38	22-43
Industry	32	28-32	24-37
Transportation	21	21-25	18-33
Residential/commercial	12	12-20	11-19

Must decarbonize fuels used directly (FUD) as well as electricity

IEA data for 2000. Projections are for A1B-AIM, AIT-Message, A2-Image, B1-Image, B2-Message scenarios of IPCC's *Special Report on Emissions Scenarios* (IPCC, 2000)

OUTLOOK FOR AUTO FUEL ECONOMY

	Current technology	Advanced technology *(~ 2020)*	
Engine (E) type:	SIE	SIE/HE	CIE/HE
Power/weight (*kW/t*)	75	75	75
Fuel economy (mpg_{ge})	30	69	80
Weight (t) (*w/136 kg payload*)	1.46	1.16	1.19
Drag coefficient	0.33	0.22	0.22
Frontal area (m^2)	2.0	1.8	1.8
Rolling resistance	0.009	0.006	0.006
Auxiliary power (*kW*)	0.7	1.0	1.0

Source: M.A. Weiss, J.B. Heywood, A. Schafer, and V.K. Natarajan, *Comparative Assessment of Fuel Cell Cars*, MIT LFEE 2003-001 RP, February 2003

By 2020, new CIE/HE cars could be (80/30) = 2.7 X as fuel-efficient as today's world-average gasoline car without performance loss ➔ 65 mpg_{ge} …or 50-55 mpg_{ge} for US

"Designer" synfuels could facilitate transition to CIE/HE cars.

SIE/CIE = spark-ignition engine/compression-ignition engine; HE = hybrid-electric

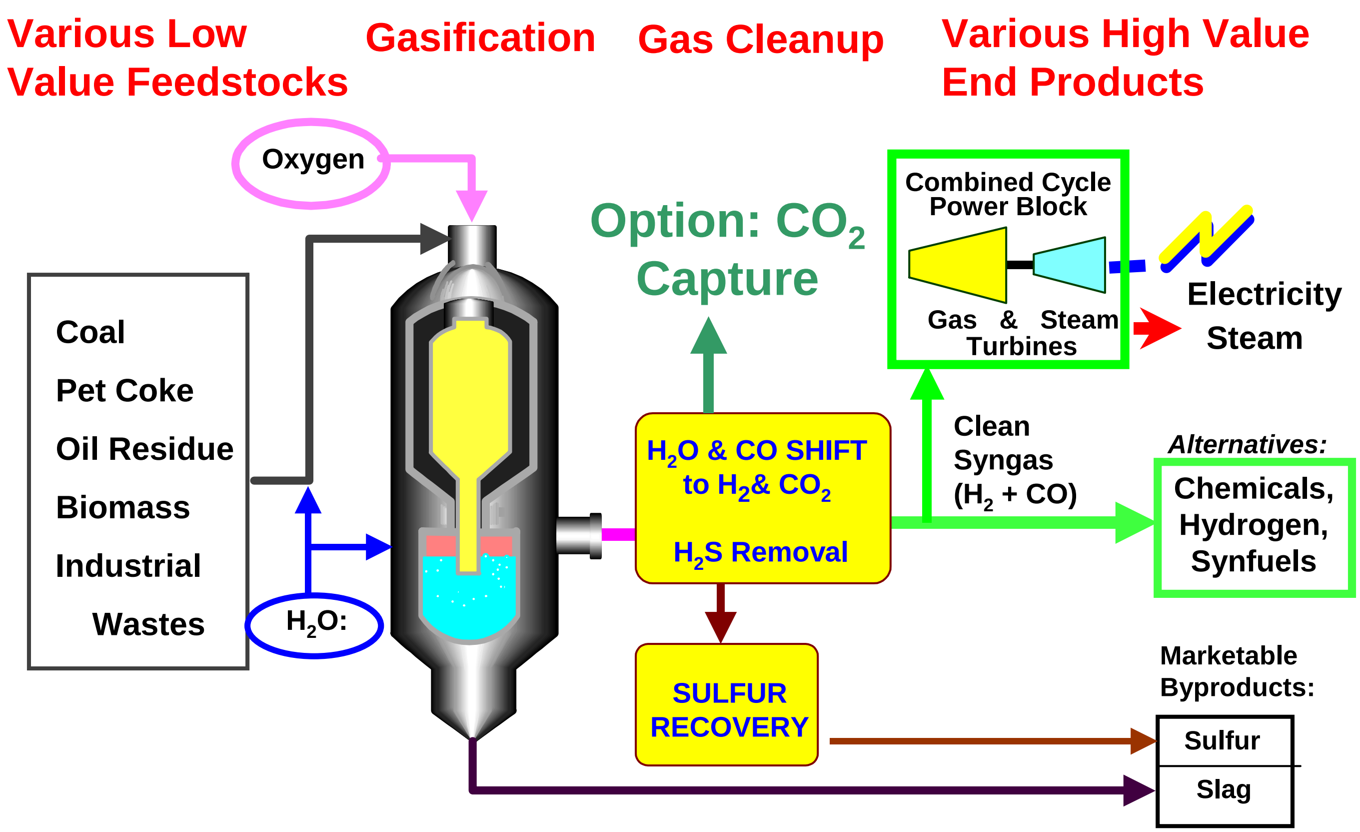
COAL: CHALLENGE…AND OPPORTUNITY

- Coal = <u>main</u> challenge for energy w/r to climate change
- Also severe air pollution problems, mining hazards
- Coal not likely to be abandoned because of:
  - Coal abundance
  - Low, non-volatile coal prices
- Can coal be made environmentally acceptable? Gasification is key:
  - Gasification can make coal electricity as clean as NGCC power
  - Coal synfuels (*via gasification*) can be cleaner that crude oil-derived HC fuels
  - Pre-combustion CCS via gasification: least costly way to decarbonize coal
  - Coal synfuels made with CCS ➔ slightly less GHG emissions than for crude oil-derived HC fuels…not good enough for CO_2 stabilization at 500 ppmv
  - Synfuels from biomass/coal with CCS: promising route to low GHG emissions
  - Residual environmental, health, safety problems of coal mining

WHY SYNFUELS FROM COAL AND BIOMASS?

- Constraints on conventional oil, most other unconventional oil sources
- Gasification-based coal synfuels are nearly commercially ready...and competitive at oil prices of $30 per barrel
- China is intent on pursuing coal-derived liquid fuels
- Fuels from biomass and coal with CO_2 capture and storage (CCS) makes it feasible to address climate challenge for fuels used directly
- Alternative options for decarbonizing fuels used directly have limited potential for addressing challenges in this Qtr century:
  - H_2, fuel cell vehicles (*focus of Administration*, *many automakers*) cannot make major contributions before 2nd Qtr of 21st century
  - Land-use constraints ➔ biofuels *alone* cannot do the job
- Foci of talk:
  - Synfuels from coal and biomass with CCS (*underground*)
  - "Designer" synfuels to facilitate shift to super-energy-efficient hybrid-electric cars

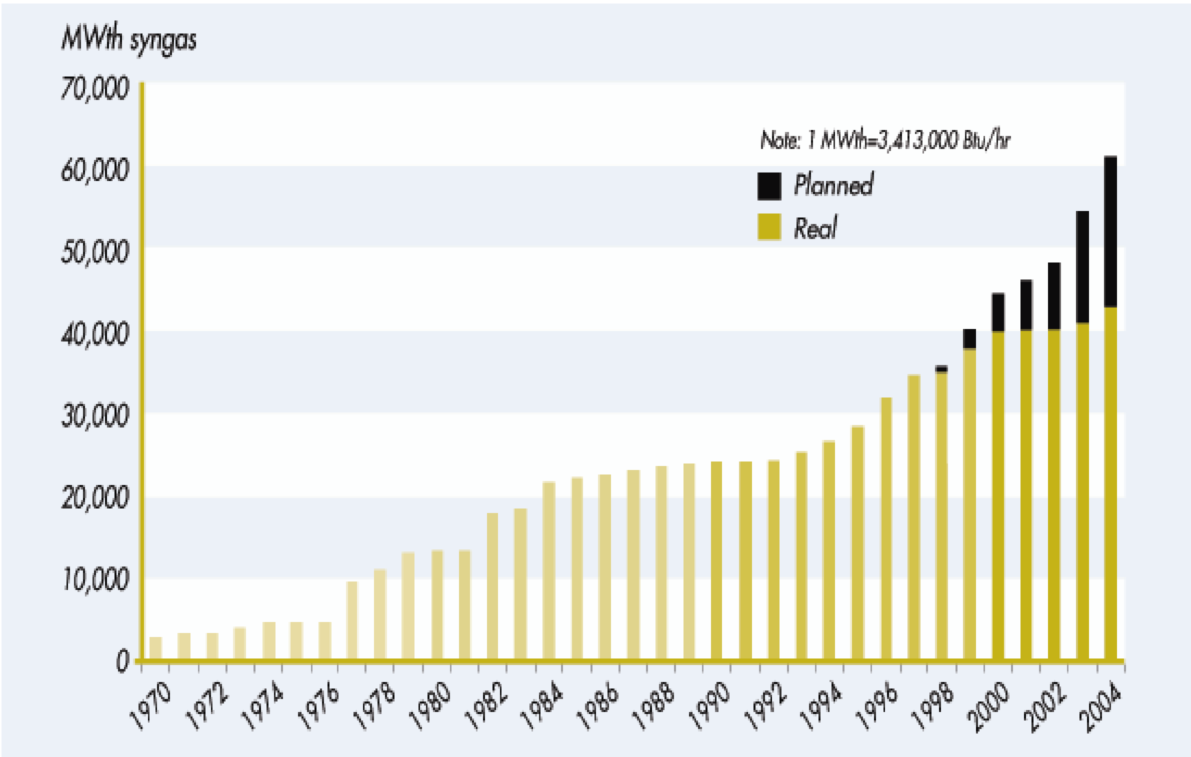
GASIFICATION TO CONVERT LOW-VALUE FEEDSTOCKS INTO HIGH-VALUE PRODUCTS



WGS ($CO + H_2O \rightarrow H_2 + CO_2$) is key both to creation of high-value products and to decarbonization for climate-change mitigation

Coal must be focus of CO_2 capture and storage effort

GASIFICATION IS BOOMING GLOBAL ACTIVITY



Worldwide gasification capacity is increasing by 3 GW_{th} per year and will reach 61 GW_{th} in 2004

- **In 2004**
- By activity:
- 24 GW_{th} chemicals
- 23 GW_{th} power
- 14 GW_{th} synfuels
- By region:
- 9 GW_{th} China
- 10 GW_{th} N America
- 19 GW_{th} W Europe
- 23 GW_{th} Rest of world

By feedstock:

- 27 GW_{th} petroleum residuals
- 27 GW_{th} coal
- 6 GW_{th} natural gas
- 1 GW_{th} biomass

Current market dominated by polygeneration of chemicals, electricity, process heat via petroleum residuals gasification…largest potential = polygeneration of synfuels, electricity, processs heat via coal gasification

MAKING LIQUID FUELS FROM COAL

- Gasify coal in O_2/H_2O to produce "syngas" (*mostly* CO, H_2)
- <u>Challenge</u>: increase H/C ratio to ~ 2 to 4 (*H/C ~ 0.8 for coal*)
- Increase H/C ratio via water gas shift reaction ($CO + H_2O \rightarrow H_2 + CO_2$) to maximize conversion in synthesis reactor
- Remove acid gases (H_2S *and* CO_2), other impurities from syngas
- Convert syngas to liquid fuel in "synthesis" reactor

SYNFUEL OPTIONS VIA COAL GASIFICATION

F-T liquids → Blend with crude oil-derived liquids
F-T liquids → Use as substitute for crude oil-derived liquids

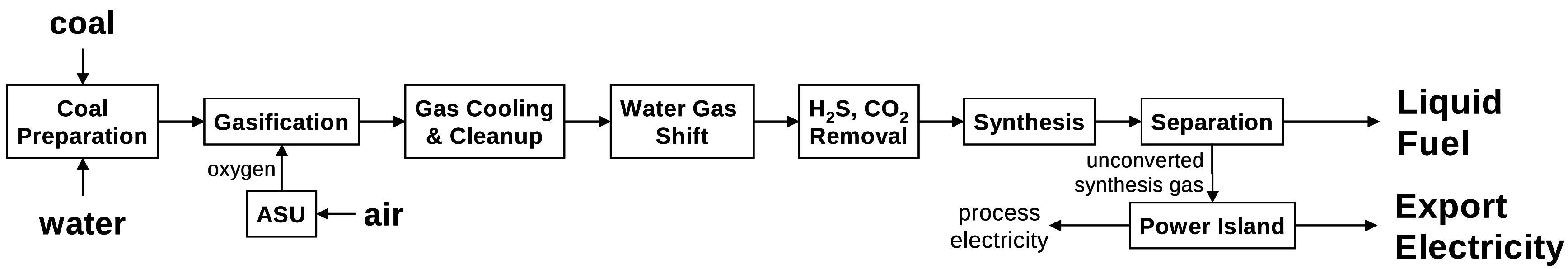
MeOH → Convert to gasoline (*Mobil process*)
MeOH → Use directly as fuel
MeOH → Convert to DME via dehydration

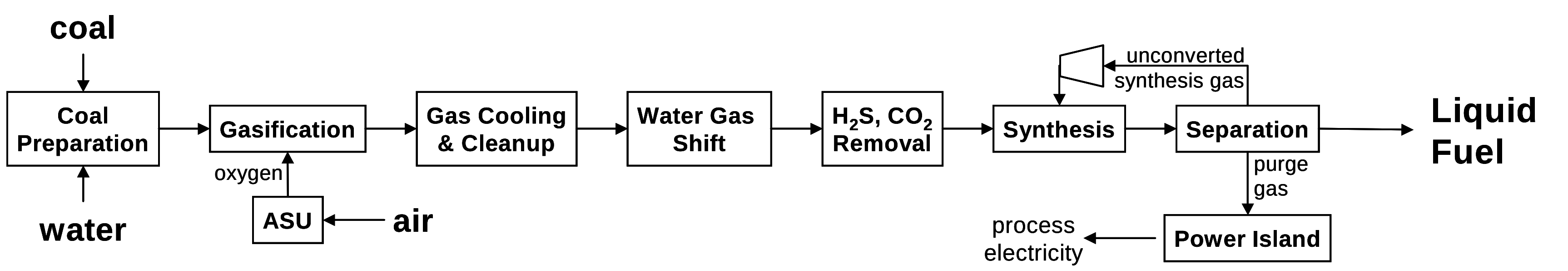
DME → Use directly as fuel

CANDIDATE DESIGNER FUEL: DME (CH_3OCH_3)

- Ozone-safe aerosol propellant and chemical feedstock
- Production ~ 150,000 t/y by MeOH dehydration (*small plants*)
- Prospective clean cooking fuel—LPG supplement—esp. for LDCs
- Prospectively outstanding compression-ignition engine (*CIE*) fuel:
  - high cetane #
  - no sulfur, virtually no soot formation ➔ no PM/NO_x tradeoff in quest for low emissions, so low NO_x emission rate readily achievable
- Drawbacks:
  - Gas at atmospheric pressure—mild pressurization (*as for LPG*) needed ➔ need new infrastructure for transport applications
  - Further engine developments needed before DME is ready for transport markets
- Production plans (*targeting domestic fuel applications*):
  - NG → DME: 110,000 t/y (*Sichuan, China, 2005*); 800,000 t/y (*Iran, 2006*)
  - Coal → DME (*800,000 t/y project approved, Ningxia, China*)

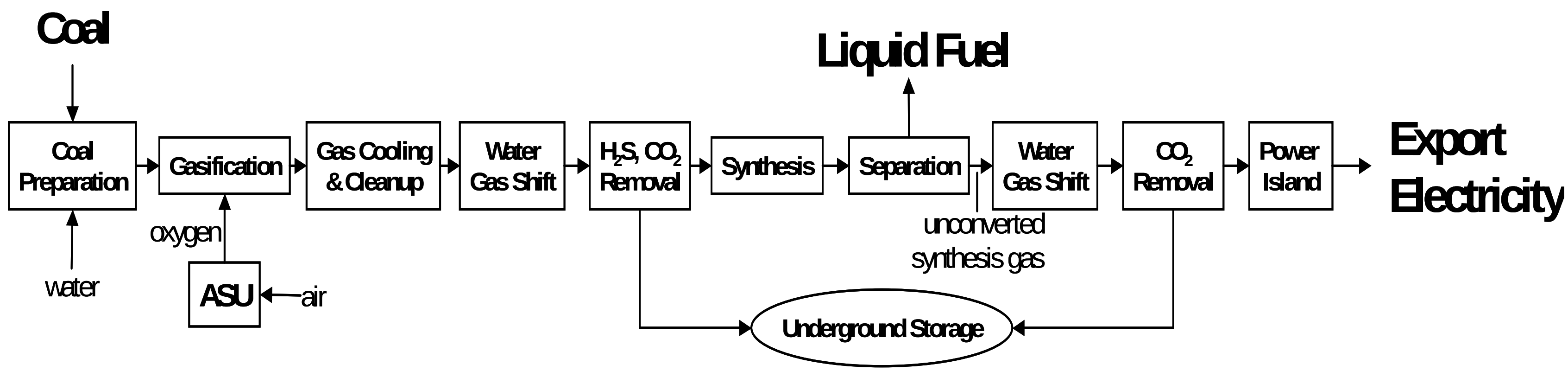
ONCE-THROUGH (OT) vs RECYLE (RC) OPTIONS





- <u>OT option</u> (*top*): syngas passes once through synthesis reactor; unconverted 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
- OT systems are often the most cost-effective using new liquid-phase synthesis reactors…if markets are available for electricity coproduct

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



Fuel-cycle-wide GHG emissions for coal-derived liquid fuels can be 80-90% of emissions for crude-oil-derived hydrocarbon fuels with CCS…but must do much better under C constraint.

Can do much better with coordinated development of synfuels from coal and biomass…with CCS in both instances

NEGATIVE EMISSIONS WITH BIO-SYNFUELS

- Making liquid fuels from biomass involves removing stream of nearly pure CO_2 (~ *45-50% of C in biomass*) upstream of synthesis[a]. Consider gasification of switchgrass:

  $CH_{1.34}O_{0.66} + 0.26\ O_2 + 0.23\ H_2O \rightarrow 0.71\ H_2 + 0.41\ CO + 0.50\ CO_2 + 0.094\ CH_4$

  ➔ low-cost CO_2 capture.

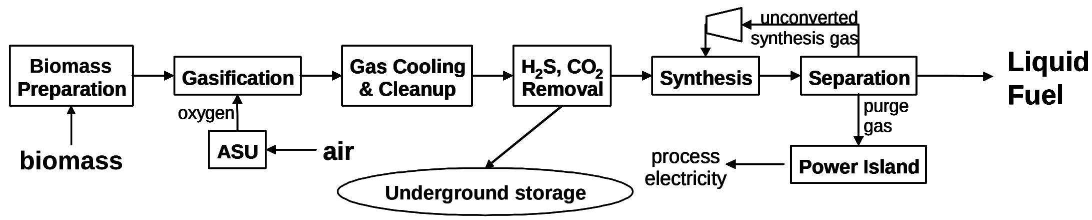
- Major C-trading opportunity for biomass-rich countries
- Coal synfuel-producing regions could meet climate mitigation obligation by promoting biomass synfuels production with CCS in biomass-rich regions

---

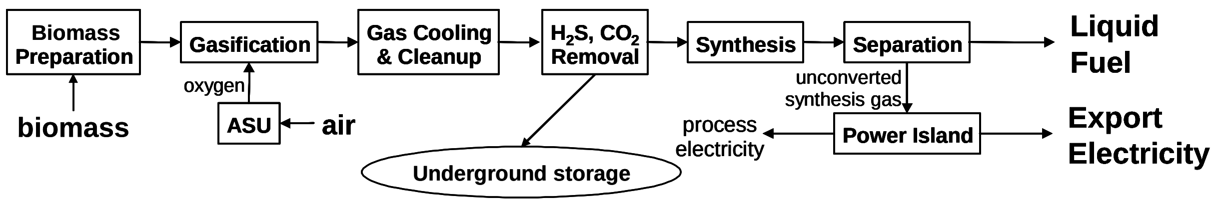
[a] E. Larson, H. Jin, and F. Celik, "Thermochemical Fuels Production from Switchgrass," Princeton Environmental Institute, draft manuscript, 15 October 2004

ALTERNATIVE CONFIGURATIONS FOR MAKING LIQUID FUELS FROM BIOMASS WITH CCS

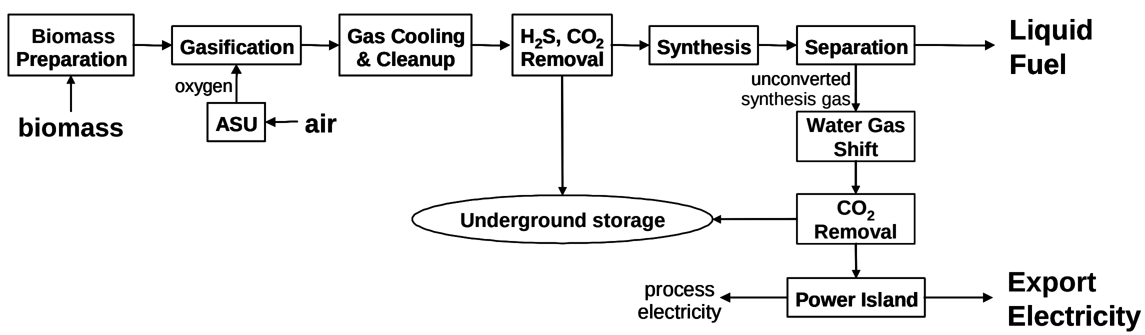
RC/UCAP (*Recycle; Upstream CO_2 Capture*)



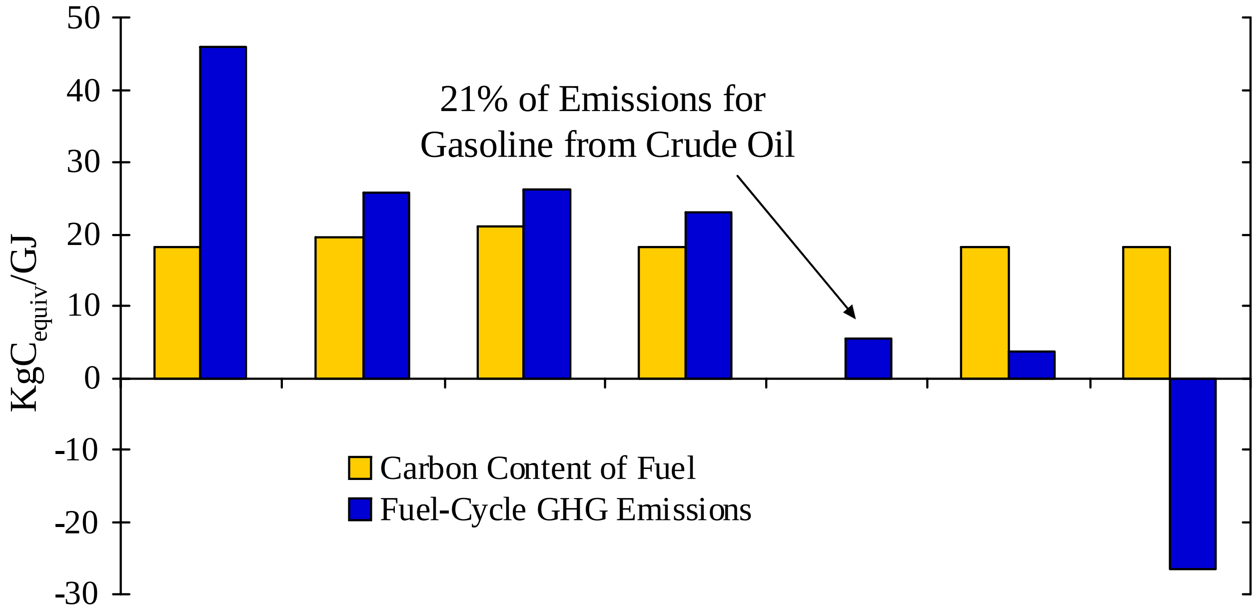
OT/UCAP (*Once-Through; Upstream CO_2 Capture*)



OT/DCAP (*Once-Through; Downstream + Upstream CO_2 Capture*)



FUEL CARBON CONTENT, FUEL CYCLE GHG EMISSIONS FOR ALTERNATIVE FUELS/PRIMARY ENERGY SOURCES

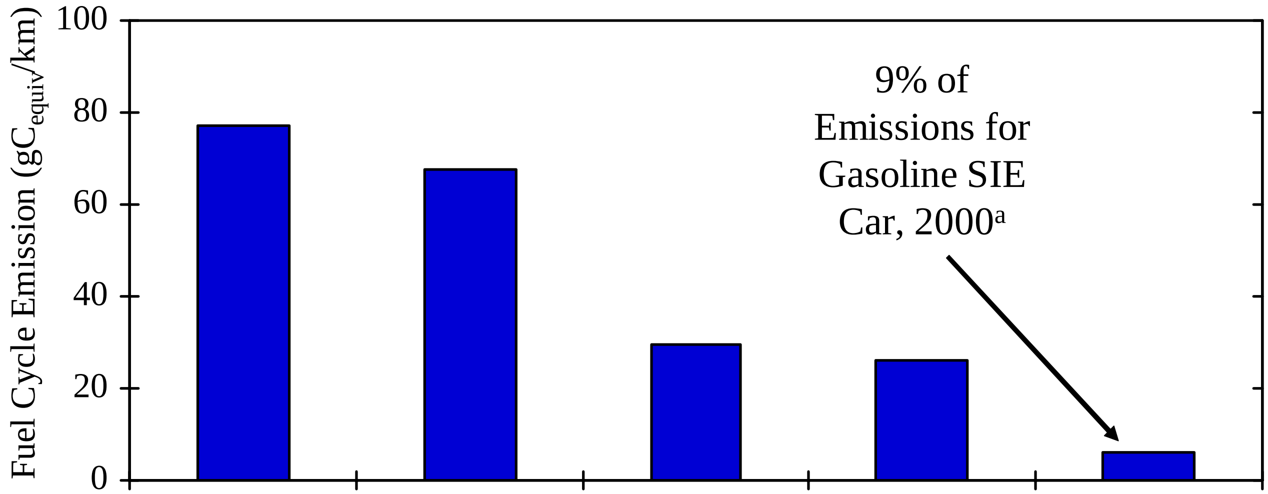


Energy Carrier	DME	Gasoline	Diesel	DME	Hydrogen	DME	DME
Primary Energy Source	Coal	Crude Oil	Crude Oil	Coal	Coal	Biomass	Biomass
CO_2 Capture and Storage?	No	No	No	Yes	Yes	No	Yes

Consider coordinated production of DME from coal and biomass with CCS (*not necessarily at same site*) such that GHG emission rate = that for H_2 from coal with CCS

The coal DME with CCS option is for the OT/DCAP configuration. The biomass DME with CCS option is for the RC/UCAP configuration.

FUEL CYCLE GHG EMISSIONS FOR ALTERNATIVE FUELS/PRIMARY ENERGY SOURCES/ENGINES



Engine	SIE	SIE	CIE/HE	CIE/HE	CIE/HE
Fuel	Gasoline	Gasoline	Diesel	DME	DME
Primary Energy	Crude Oil	Crude Oil	Crude Oil	Coal	Coal/Biomass
Fuel Economy (mpg_{ge})	24.4[a]	28.0[b]	65.2	65.2	65.2
CO_2 Capture and Storage?	No	No	No	Yes	Yes

[a] World Average, 2000
[b] World Average Projected for 2030, Sustainability Mobility Project

Key
CIE = Compression Ignition Engine
HE = Hybrid Electric
mpg_{ge} = Miles per Gallon, Gasoline Equivalent
SIE = Spark Ignition Engine

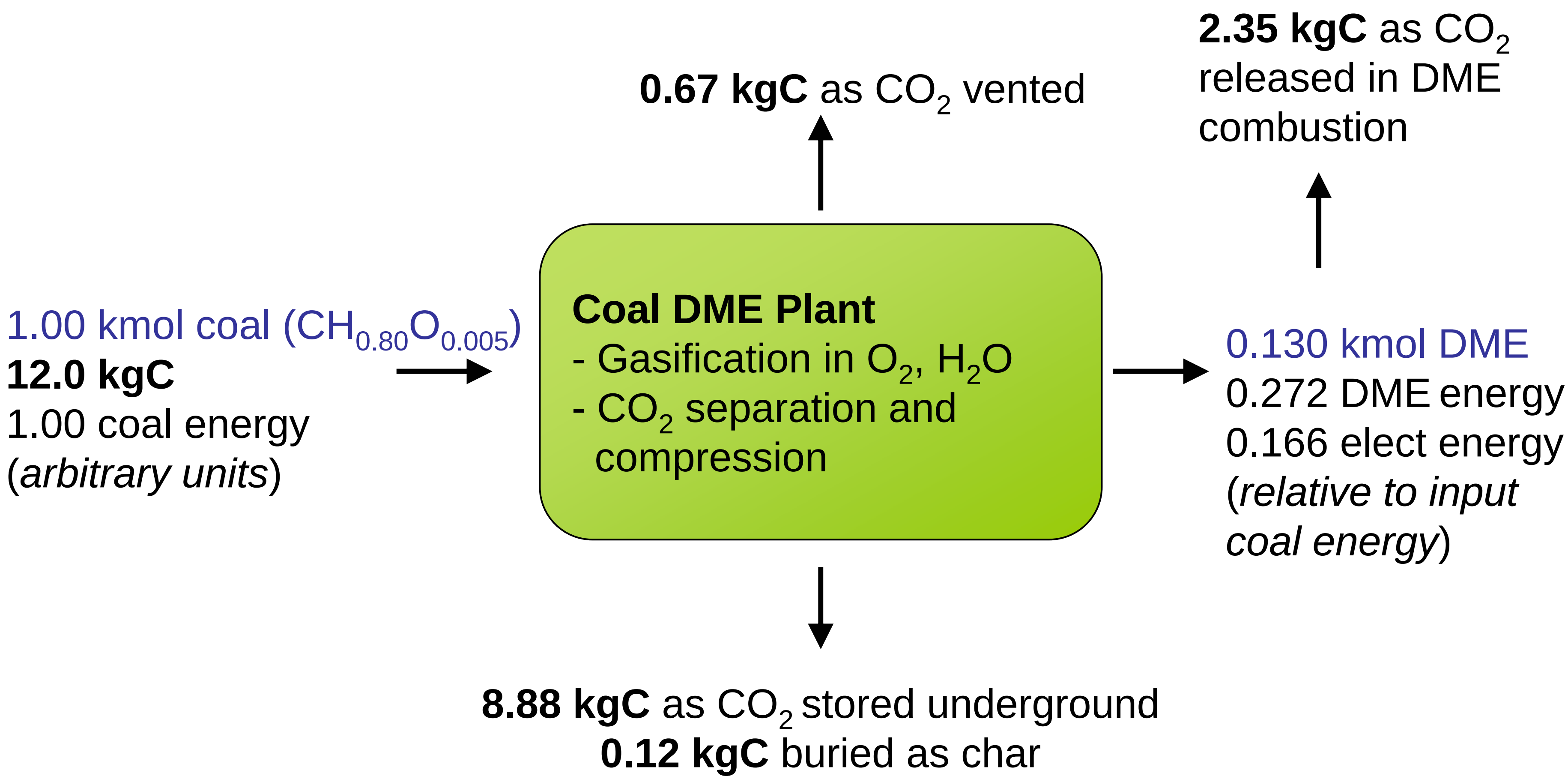
MANY POSSIBLE BIOMASS/COAL HYBRID CONFIGURATIONS FOR MAKING LIQUID FUELS, E.G:

Coal	Biomass
RC/UCAP	RC/UCAP
OT/UCAP	OT/UCAP
OT/UCAP	OT/DCAP
OT/DCAP	OT/DCAP

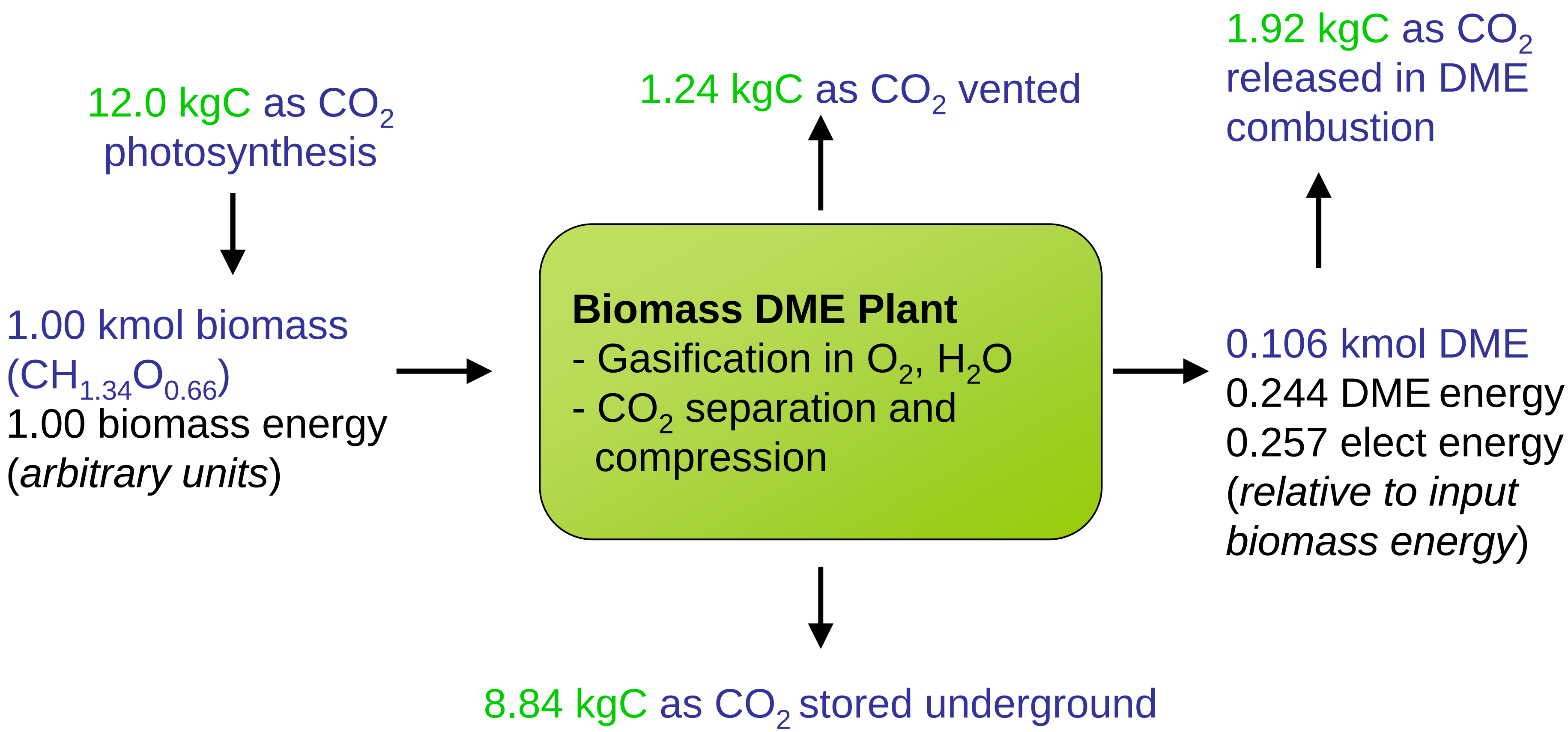
RC = Recycle; OT = Once Through
UCAP = CO_2 Capture Upstream of Synthesis Only
DCAP = CO_2 Capture Downstream & Upstream of Synthesis

CARBON BALANCE FOR MAKING DME + ELECTRICITY FROM COAL WITH CSS

(*OT/DCAP OPTION*)



POTENTIAL FOR NEGATIVE CO_2 EMISSIONS IN MAKING DME + ELECTRICITY FROM BIOMASS WITH CSS (*OT/DCAP OPTION*)



Manufacture of liquid fuel from biomass w/CCS can "make room in atmosphere" for coal liquids w/CCS

ENERGY/CARBON BALANCES FOR DME FROM COAL/BIOMASS HYBRID WITH MIX SUCH THAT: GHG EMISSION RATE = RATE FOR COAL H_2 w/CCS

4.2 kgC vented as CO_2 at plants making DME from coal

14.9 kgC released in combustion of DME from coal

Biomass
0.73 GJ

Coal
3.01 GJ
75.8 kgC

Global system making DME from biomass and coal (OT/DCAP for both)

1.0 GJ DME
(*0.18 GJ from biomass*)
+ 0.69 GJ elect
(*0.19 GJ from biomass*)

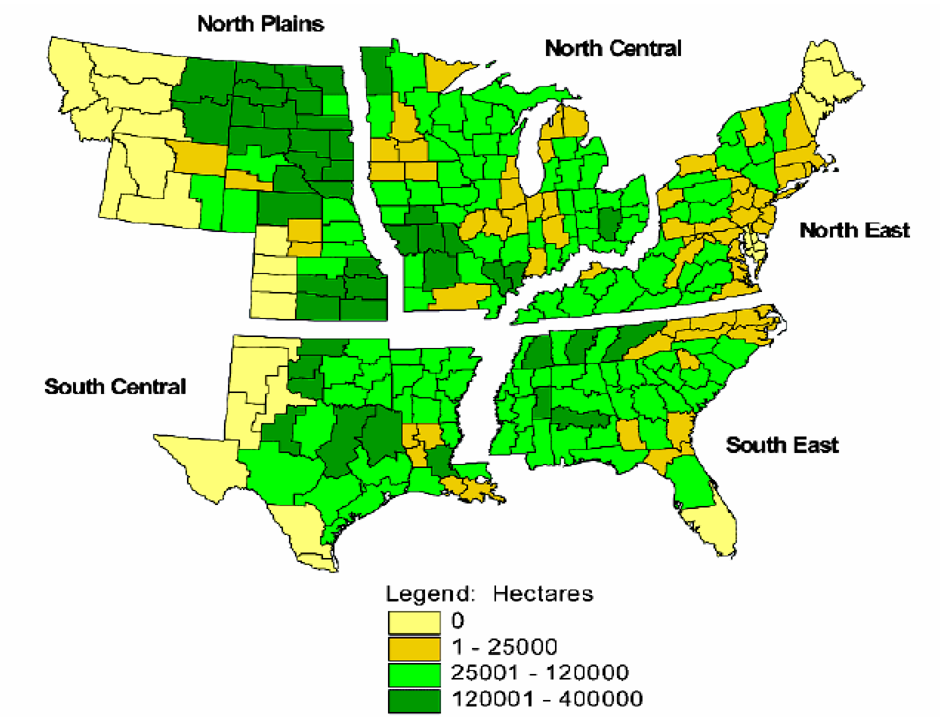
14.9 kgC as CO_2 from biomass stored underground (*74% of C in biomass*)

56.0 kgC as CO_2 from coal stored underground + **0.8 kgC** in char

Total direct CO_2 emissions from coal = 4.2 + 14.9 – 14.9 = 4.2 kgC per GJ DME
Direct CO_2 emissions allocated to DME = 4.2 – 1.7 = 2.5 kgC per GJ DME
Total fuel cycle GHG emissions allocated to DME = 5.4 kgC_{equiv} per GJ DME

BIOMASS FEEDSTOCK OPTIONS

- Agricultural/forest product industry residues in near term
  - DME from pulp and paper residues (*Sweden*)
  - Sugar cane in developing countries (*esp. Brazil*)
- Energy crops—e.g., switchgrass in Great Plains—for longer-term

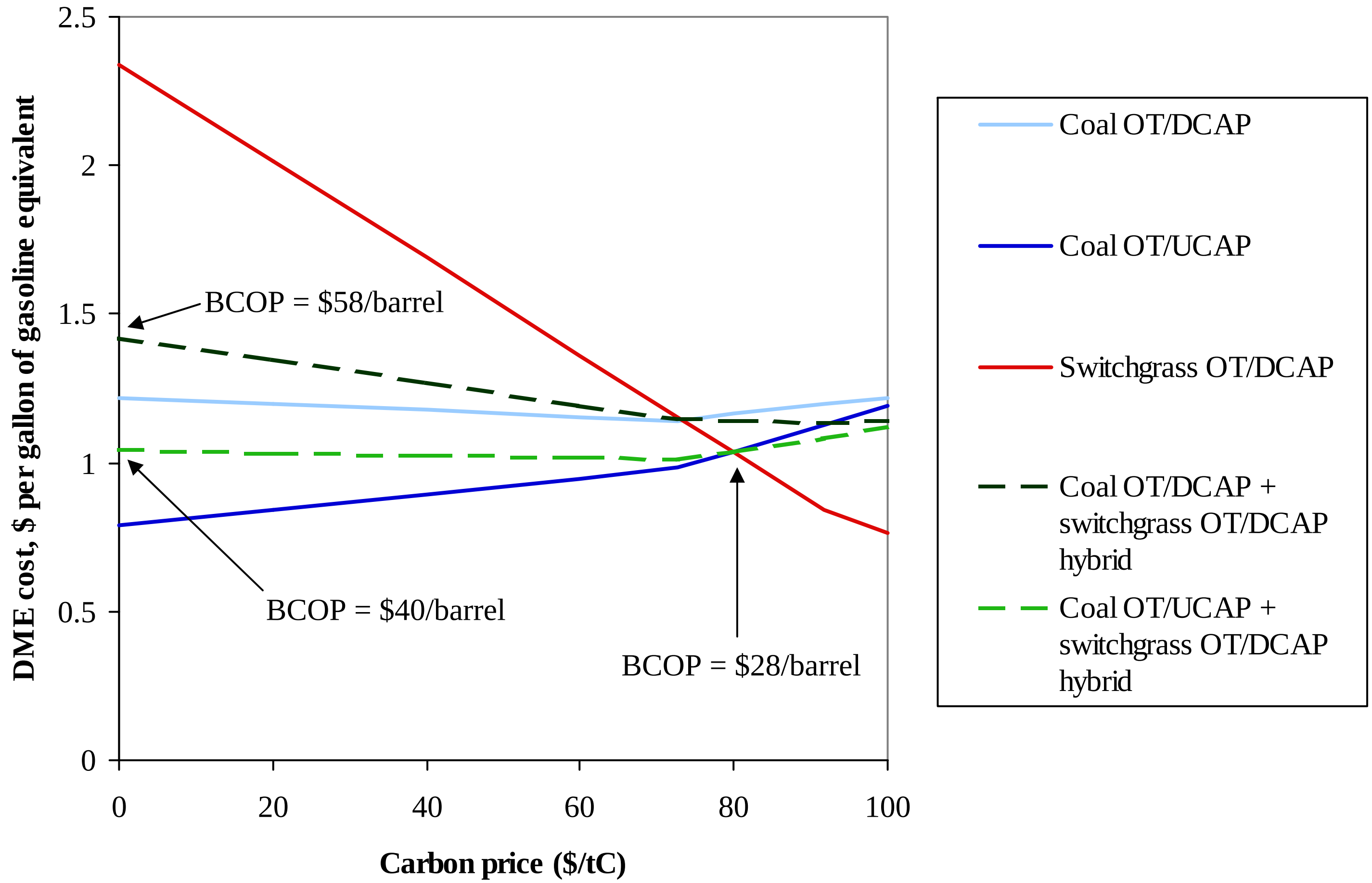


Source: McLaughlin et al., 2002: High-value renewable energy from prairie grasses, *Envir. Sci.& Tech.*, **36** (10): 2122-2129

This study projects that if the market valued switchgrass at current average farm-gate cost ($44/t), 17 million hectares would be converted to switchgrass.

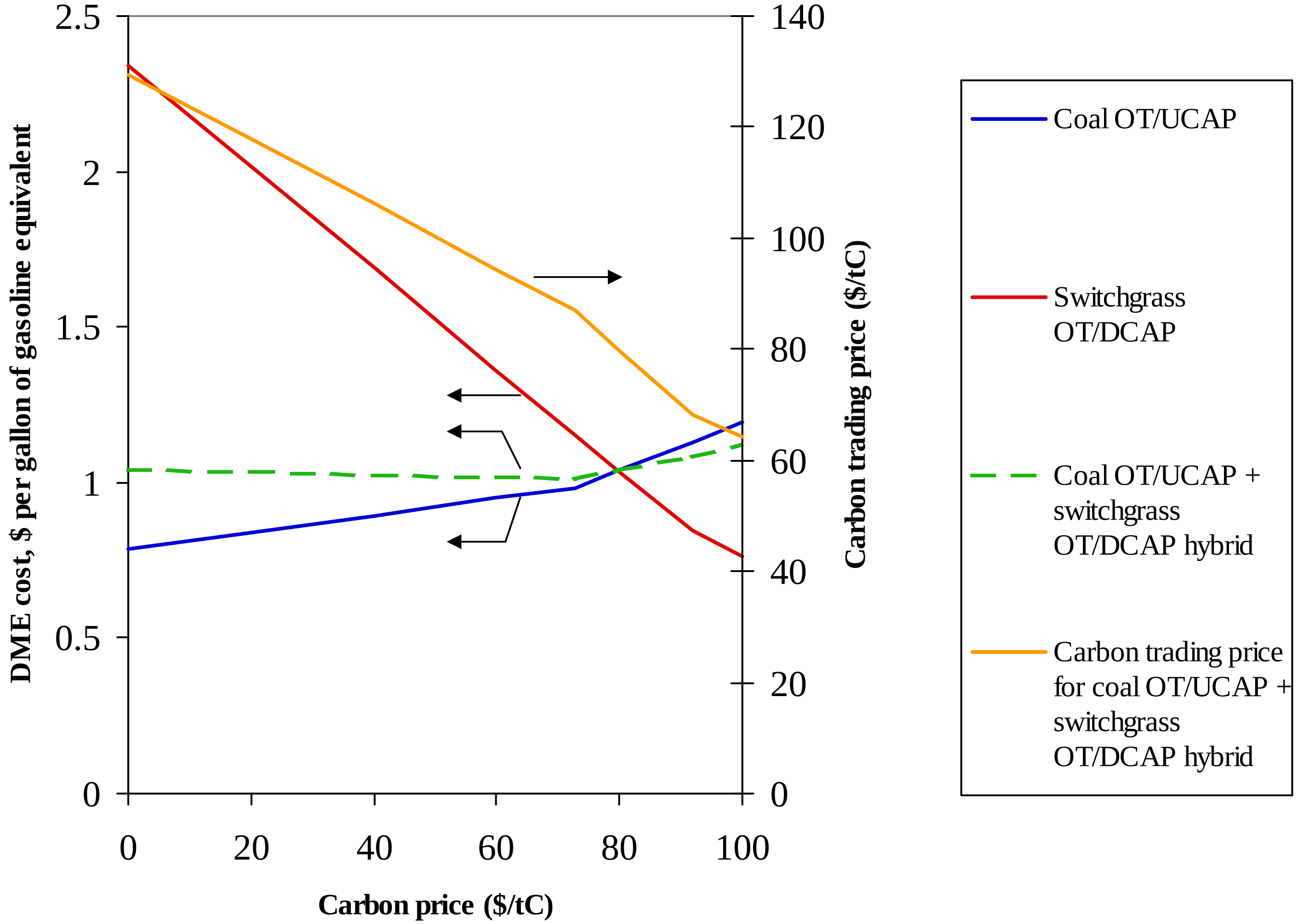
With 17 Mha, switchgrass OT/DCAP + coal OT/DCAP DME hybrid could support > 60% of US LDVs if shifted to 50-55 mpg$_{ge}$ HEVs

EVEN WITH TODAY'S COSTLY SWITCHGRASS ($3.3/GJ) & LOW C PRICES, COSTS FOR COAL OT/UCAP + SWITCH-GRASS OT/DCAP HYBRID ARE ALMOST INTERESTING



BCOP = Breakeven Crude Oil Price (*at which DME cost = Diesel cost*)

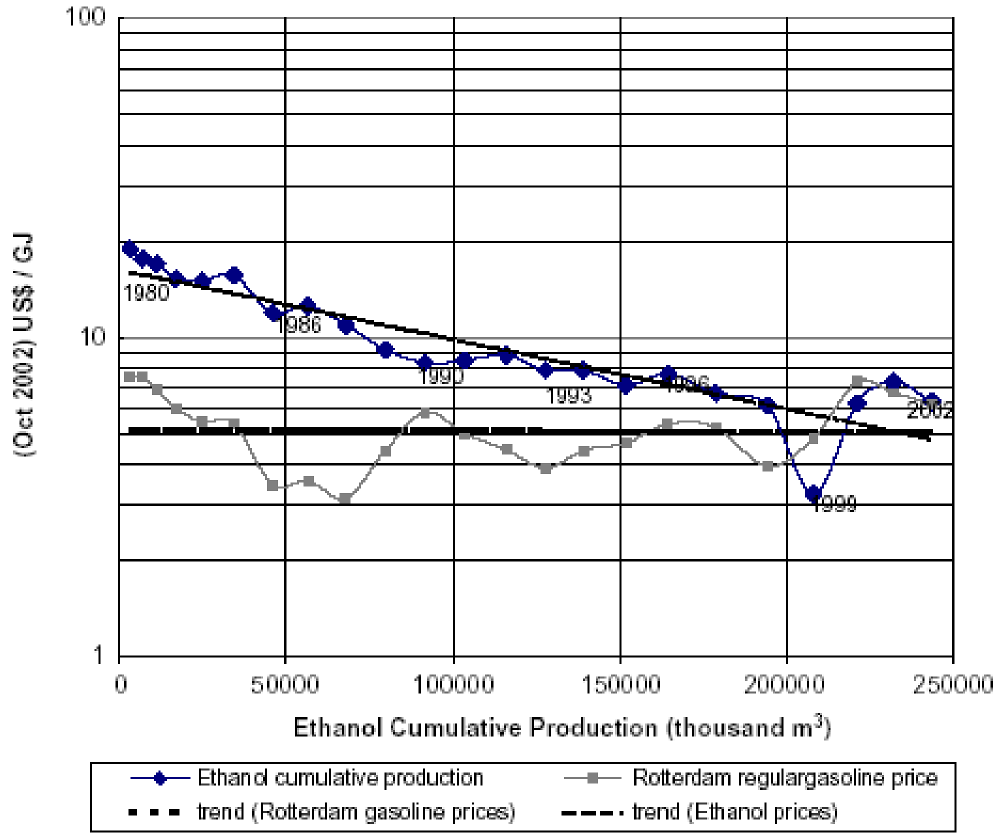
CARBON TRADING PRICE FOR COAL OT/UCAP + SWITCHGRASS OT/DCAP HYBRID



WHY SUGAR CANE?

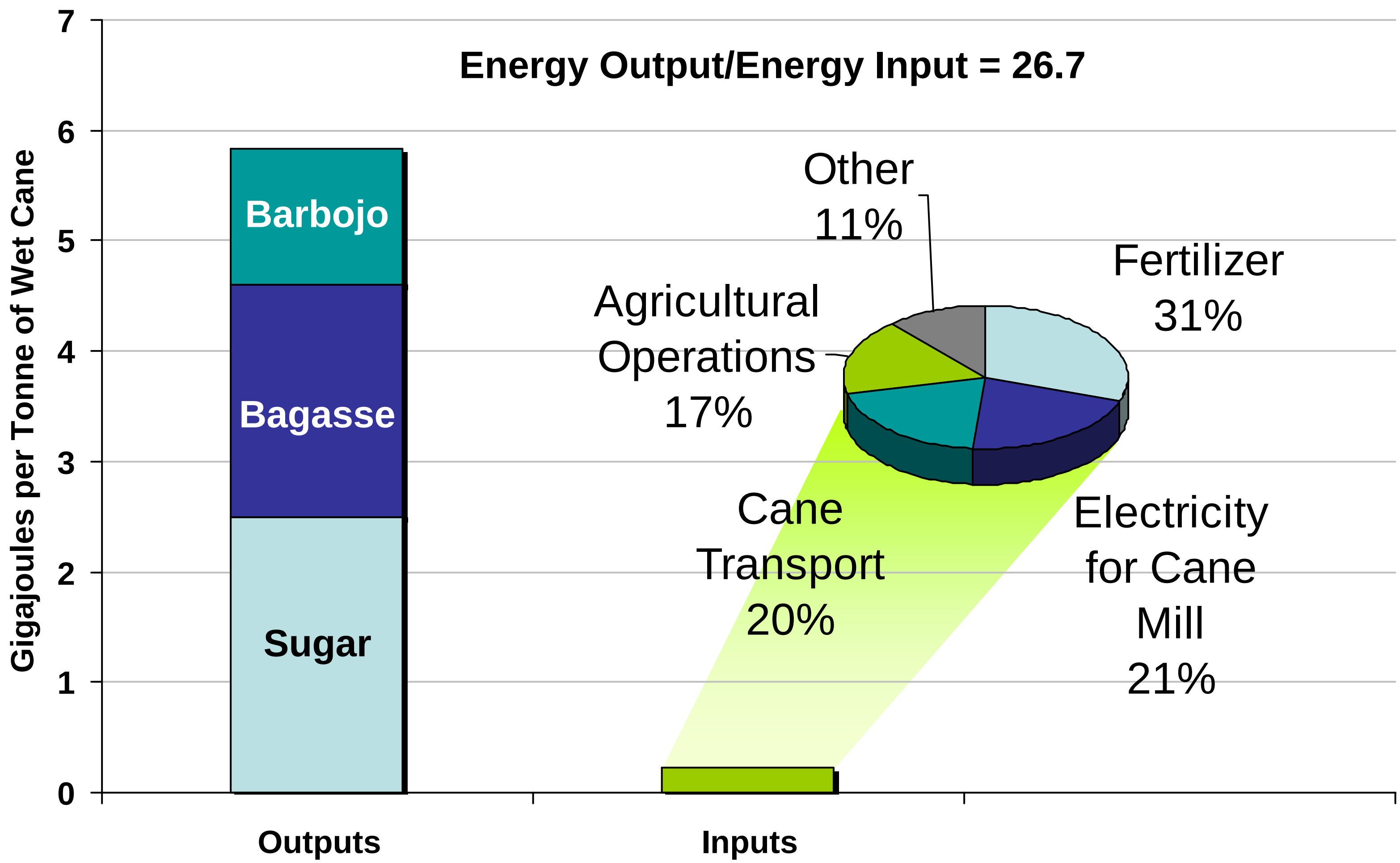
- Well-established industry~ 20 million hectares established worldwide (*cane production growing 2%/y worldwide*)
- High photosynthetic efficiency: average recoverable dry plant matter:
  - 10.1 t/ha/y sugar (*bagasse-equivalent*)
  - 13.6 t/ha/y recoverable residues [*bagasse + 60% of "barbojo"* (*tops/leaves*)]
- In Brazil, EthOH from sugar cane produced, without subsidy, at price competitive with crude oil-derived gasoline at 2002 world oil price (*$24/barrel*)
- Sugar in cane is converted efficiently (η ~ *75%*) to EthOH…but sugar is only ~ 40% of energy content of recoverable cane
- Recoverable residues are poorly utilized at present:
  - Bagasse is converted to electricity via inefficient steam turbines
  - Barbojo is typically not recovered (*burned off in fields before harvest*)
- Opportunity for large-scale bio-synfuels with CCS in this Qtr century

BRAZIL HAS SHOWN THAT ETHANOL CAN COMPETE WITH GASOLINE FROM CRUDE OIL



Source: J. Goldemberg, J., S.T. Coelho, P.M. Nastari, and O. Lucon, "Ethanol learning curve—the Brazilian experience," *Biomass and Bioenergy*, **26**: 301-304, 2004.

ENERGY BALANCE FOR CANE PRODUCTION



THOUGHT EXPERIMENT FOR CANE, COAL, & CARS

- Suppose that for all sugar cane currently produced on 20 million ha:
  - Cane residues are gasified to make DME with CO_2 capture and storage (CCS)
  - Elsewhere in the world DME is made from coal with CCS
  - DME produced via Coal OT/UCAP + cane residue OT/DCAP hybrid
  - DME is used in fuel-efficient hybrid-electric cars (*65 mpg_{ge}*)
- Global implications:
  - DME would support 390 x 10^6 light-duty vehicles (*> ½ world's cars*)
  - Crude oil displaced = 9.5 x 10^6 barrels/day
    (*Saudi Arabia's production = 8.4 x 10^6 barrels/day in 2000*)
  - GHG emissions/km for DME CIE/HE cars ~ 1/10 rate for today's gasoline cars
  - Global CO_2 emissions reduction for LDVs ~ 0.39 GtC/y
  - Global CO_2 storage rate ~ 225 x 10^6 tC/y (*38% from biomass-derived DME*)
  - 1400 TWh/y coproduct electricity (*31% of elect, developing countries, 2000*)
  - 20% increase in global coal production required

CONCLUSIONS

- It seems feasible to make a major contribution in addressing challenges posed by the automobile—in this quarter century—via production and use of designer synfuels from coal/biomass with CCS
    - Major technical uncertainty is "gigascale" viability of CO_2 storage—many more "megascale" CO_2 storage demos needed…soon
    - Biomass synfuel production technology must be brought to commercial readiness (*commercial gasifier needed*) and demonstrated…new Swedish biomass synfuel test facility at former BIGCC demo site
    - Also demos needed for synfuels plants with CCS…but radical new technologies not needed
- Carbon mitigation policy needed
- Institutional/cultural challenges:
    - Overcoming widespread ill feelings about coal synfuels—costly synfuels failures of late 1970s-early 1980s
    - Political will to enact ambitious automotive efficiency improvement policy
    - Coalition-building for proposed strategy—across multiple industries and involving international collaborations (*e.g., among Australia, Brazil, China, US*)


BIG
COAL
GRO
MOR
CARS
R
US
BIG
OIL