CO_2 CAPTURE AND STORAGE STRATEGIES FOR COAL AND BIOMASS TO REDUCE GHG EMISSIONS FOR SYNFUELS

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Viewgraphs for Presentation

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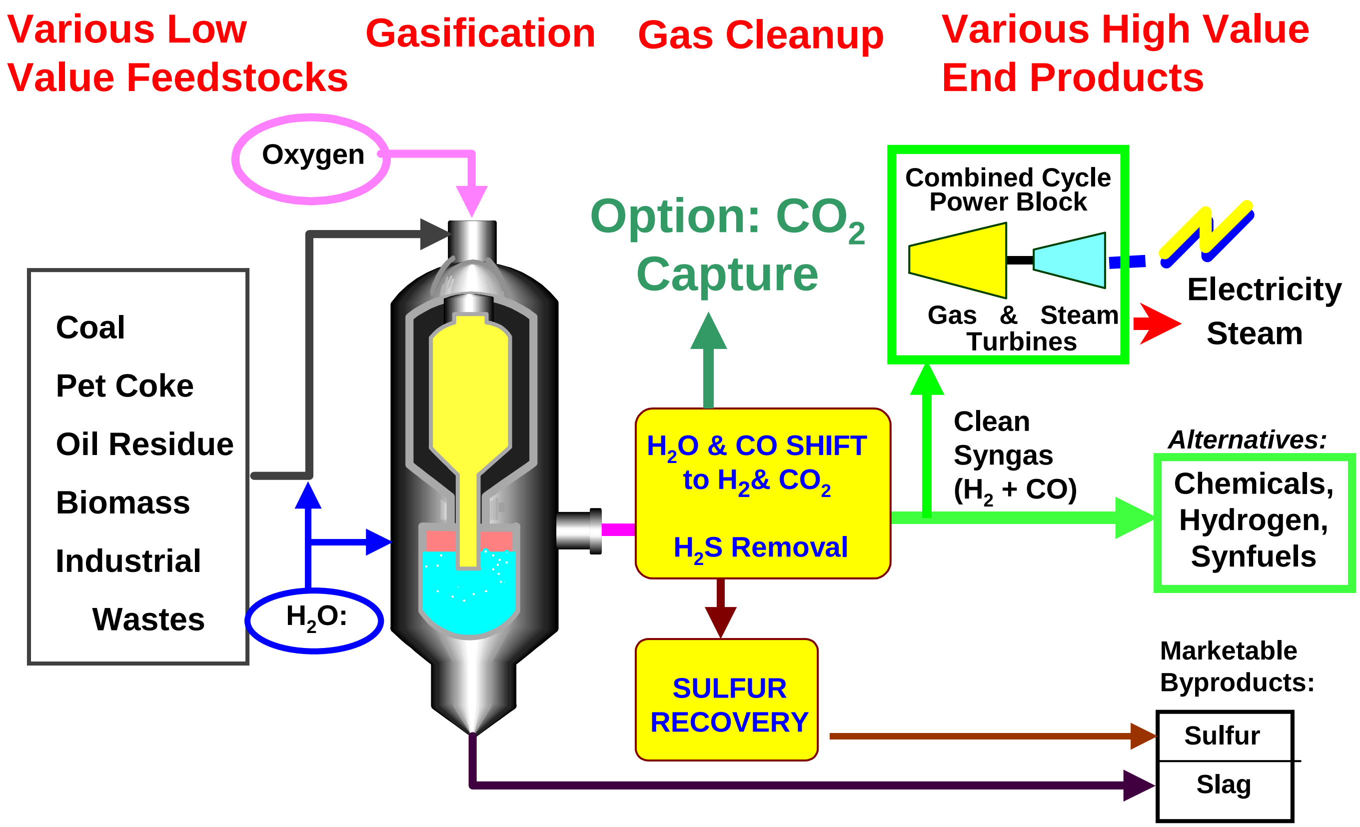
OUTSTANDING ISSUES

- Alternatives to conventional oil will be pursued aggressively because of oil supply insecurity, high oil price concerns
- GTL, tar sands, & heavy oil each represent a "Saudi Arabia" of proved reserves, competitive @ ~ $20/bbl crude
- Coal liquids will also be needed…China already pursuing
  - Potential liquid fuel supplies much greater
  - Low, stable coal prices
  - Prospective "superclean" designer fuels via indirect liquefaction
  - Breakeven crude oil prices:
    - > $40/bbl, liquid-fuel-only plants
    - < $30/bbl, "polygeneration" plants…economically interesting
- Climate change concerns: high C intensity, huge coal synfuel potential
- w/CCS can reduce GHG emissions to $\leq$ rates for oil-derived HC fuels
- Greater GHG emissions reductions needed to stabilize atmospheric CO_2 @ $\leq$ 2X pre-industrial level

OPTIONS FOR CLIMATE MITIGATION FOR FUELS USED DIRECTLY (*other than for power generation*)

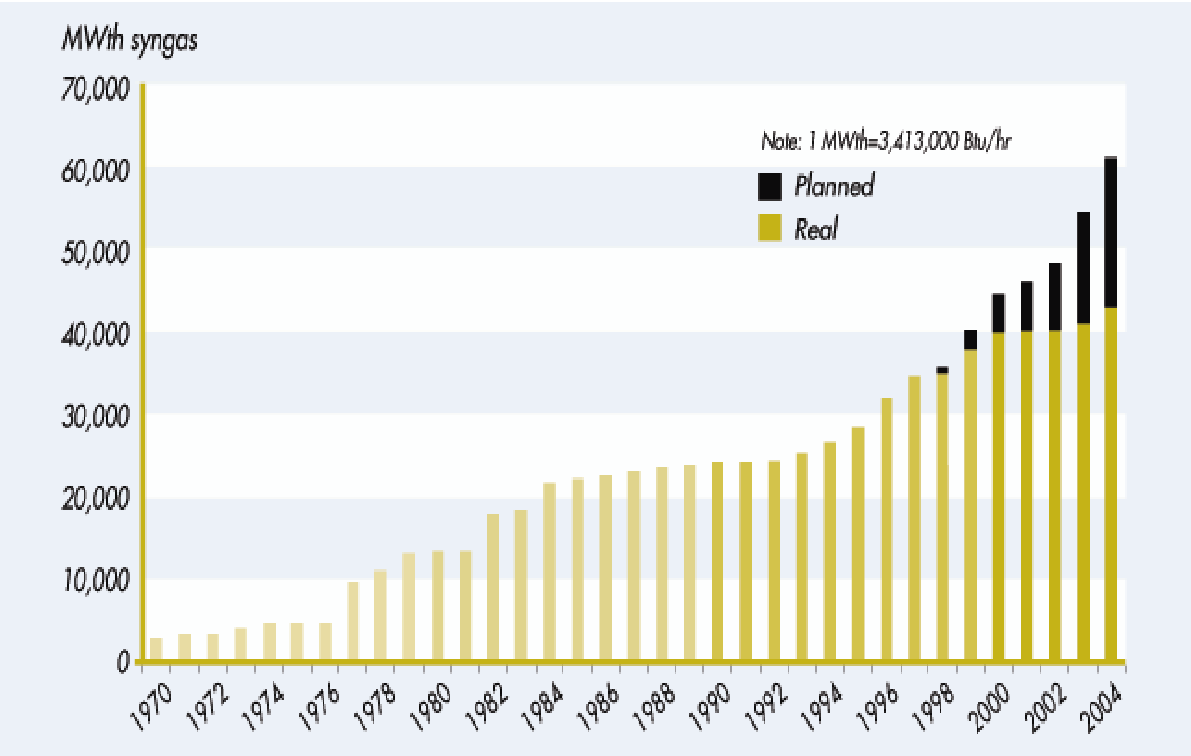
- Evolve H_2 economy:
  - Coal H_2 with CCS likely to be least-costly option for natural gas prices > $4/GJ
  - Much innovation needed to make H_2-using technologies cost-competitive
  - Huge infrastructure development costs
  - Plausible significant option for 2^{nd} Qtr this century
- Biofuels: can be introduced earlier than H_2 economy…but costs high without high supporting CMP. Also, land availability constraints ➔ biofuels *alone* can't do "whole job"
- Third option considered here: 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

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



Gasification is key to clean energy, low-cost CO_2 capture & storage (CCS), & thus coal's playing major roles in a climate-constrained world

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:

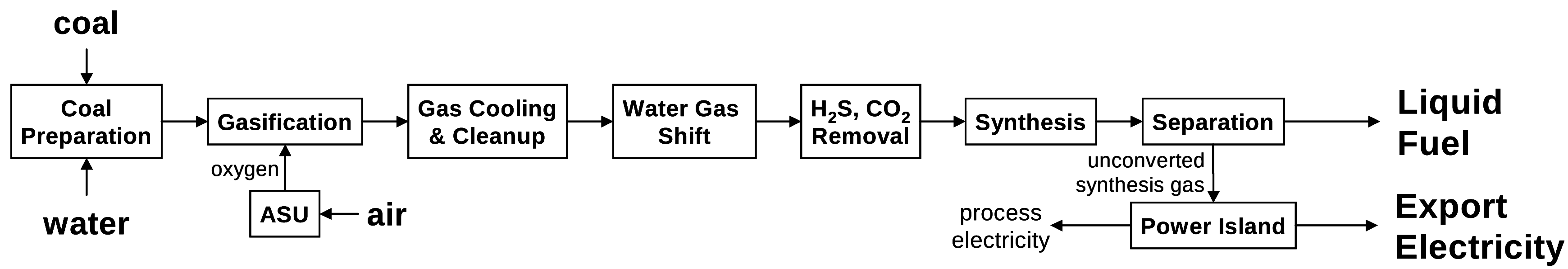
- 27 GW_{th} petroleum residuals
- 27 GW_{th} coal
- 6 GW_{th} natural gas
- 1 GW_{th} biomass

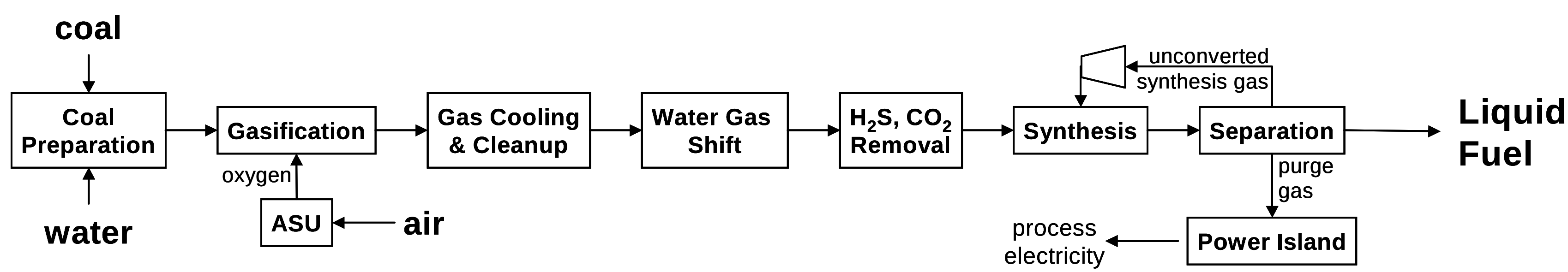
Current market dominated by polygeneration of chemicals, electricity, process heat via petroleum residuals gasification…largest potential = polygeneration of synfuels, electricity, processs heat via coal gasification

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 typical bituminous 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

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

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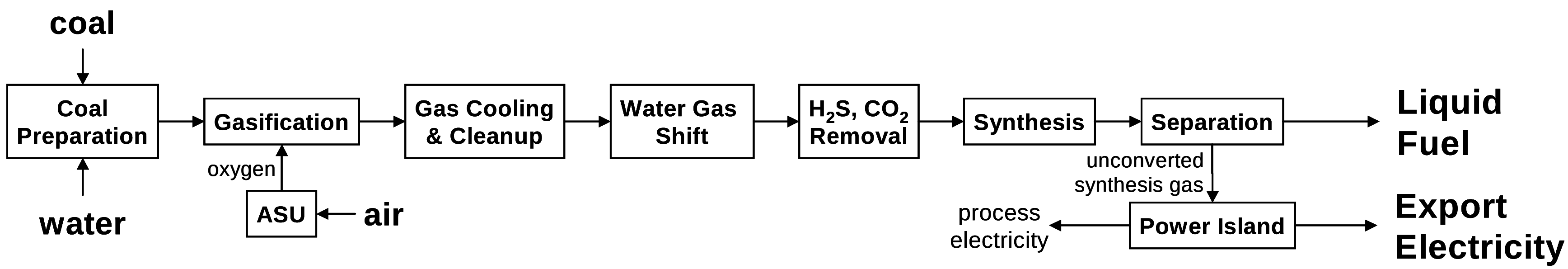

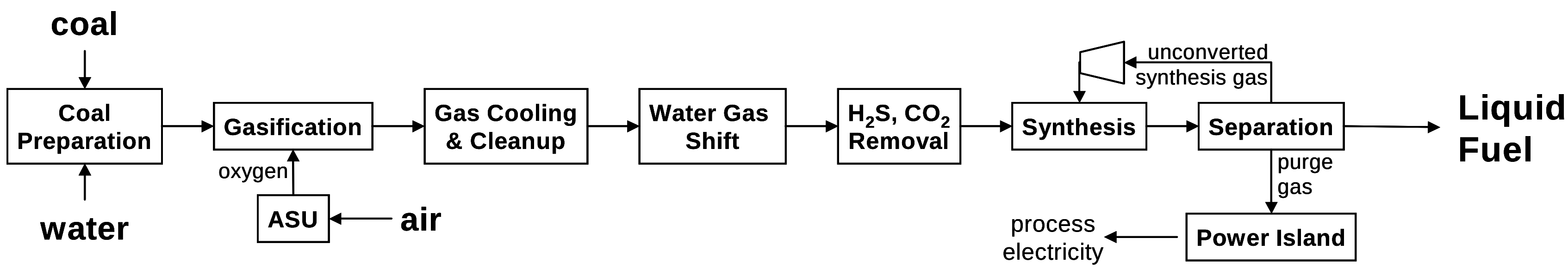

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- <u>RC option</u> (*bottom*): unconverted syngas recycled to maximize synfuel production; purge gases burned → electricity only for process; no electricity for export
- While RC systems require > $40/bbl oil to be competitive, breakeven crude oil prices < $30/bbl can be realized for OT systems

SYNFUEL OPTIONS VIA COAL GASIFICATION

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

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

DME → Use directly as fuel

F-T = Fischer-Tropsch; MeOH = methanol; DME = dimethyl ether

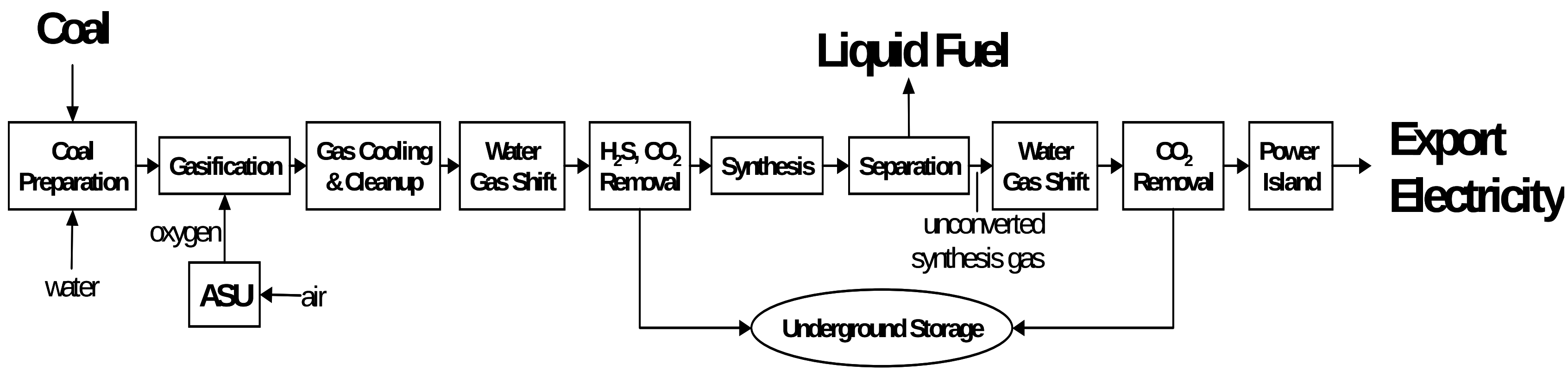
CANDIDATE DESIGNER FUEL: DME (CH_3OCH_3)

- Ozone-safe aerosol propellant and chemical feedstock
- Production ~ 150,000 t/y by MeOH dehydration (*small plants*)
- Clean cooking fuel—LPG supplement—esp. for LDCs
- Outstanding Diesel engine 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

    ➔ Can facilitate shift to super-efficient CIE or CIE/hybrid-electric vehicles
- Drawbacks:
  - Gas at atmospheric pressure—mild pressurization (*as for LPG*) needed

    ➔ new infrastructure for transport…but far more modest challenge than for H_2
  - 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*)

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

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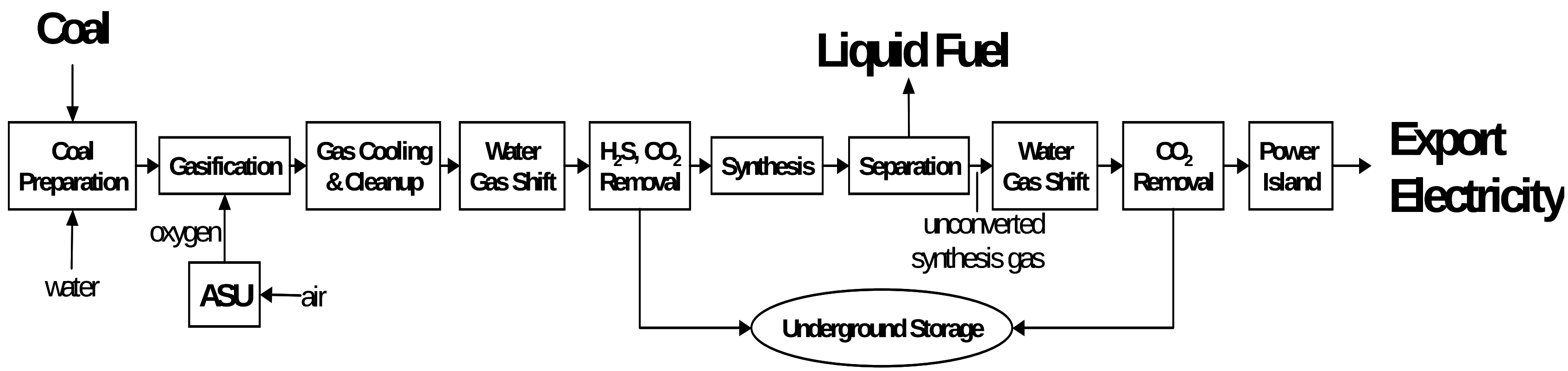
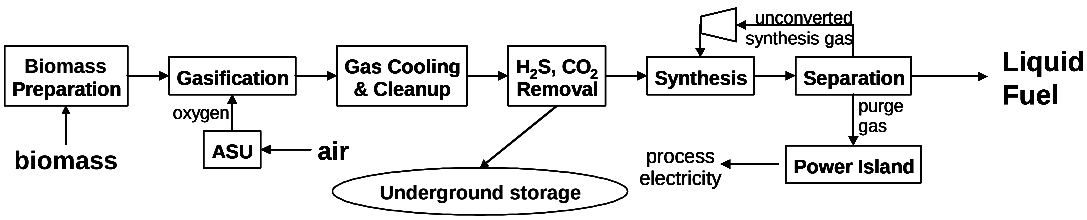


This decarbonization strategy is a necessary but not a sufficient condition for widespread use of coal synfuels for a world seeking stabilization of atmospheric CO_2 @ ≤ 2X preindustrial level

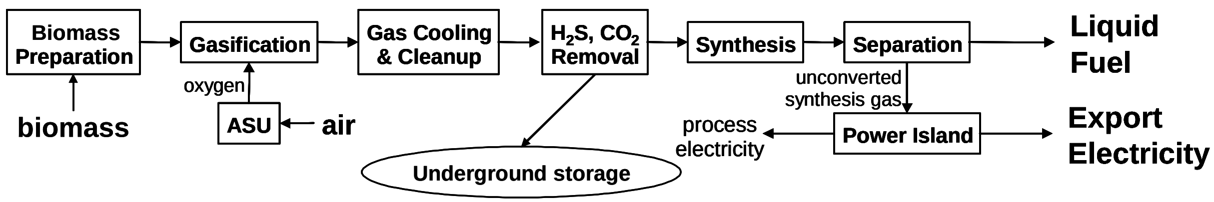
But also pursuing CCS for bioenergy can "make room in atmosphere for coal liquids"

ALTERNATIVE CONFIGURATIONS FOR MAKING LIQUID FUELS FROM BIOMASS WITH CCS

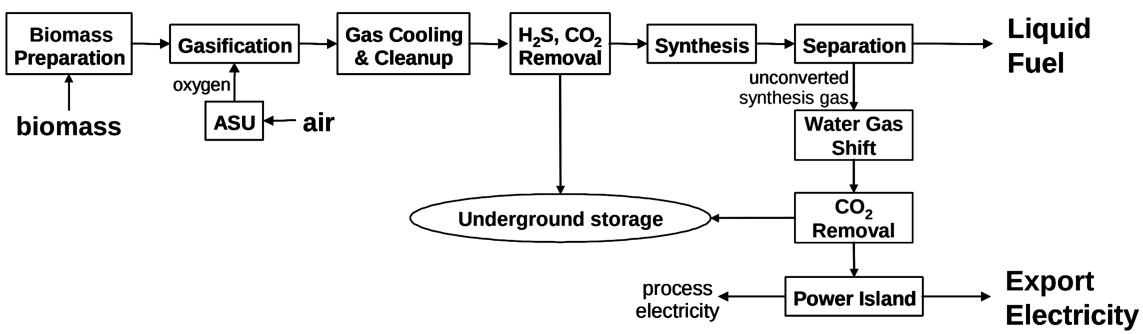
RC/UCAP (*Recycle; Up Stream Capture—50% of C stored)*



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

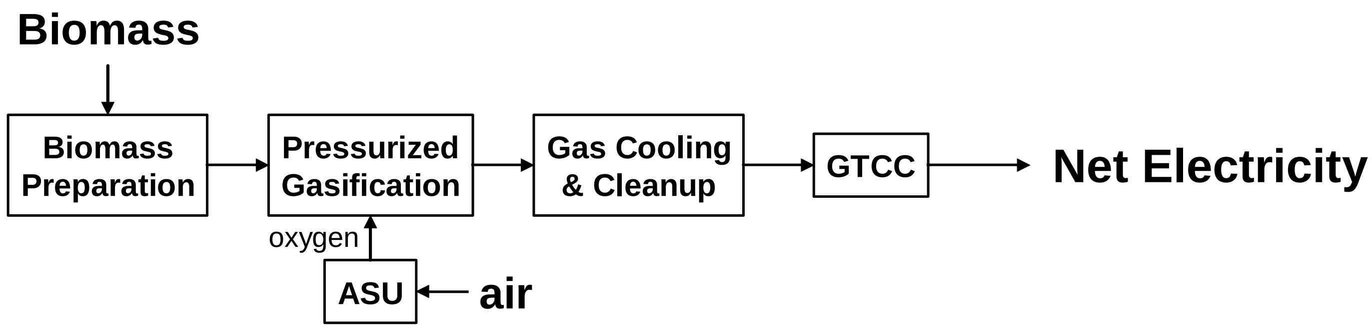


OT/DCAP (*Once-Thru; Down + Up Stream Capture—74% of C stored*)

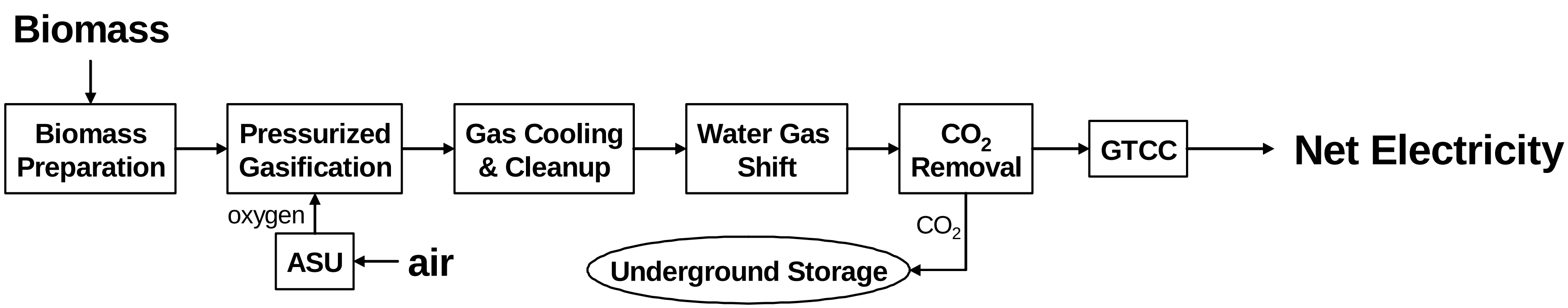


BIOMASS INTEGRATED GASIFIER COMBINED CYCLE POWER GENERATION

With CO_2 vented (*BIGCC/VENT*):



With CO_2 Captured and Stored (*BIGCC/CCS—91% of C stored*):

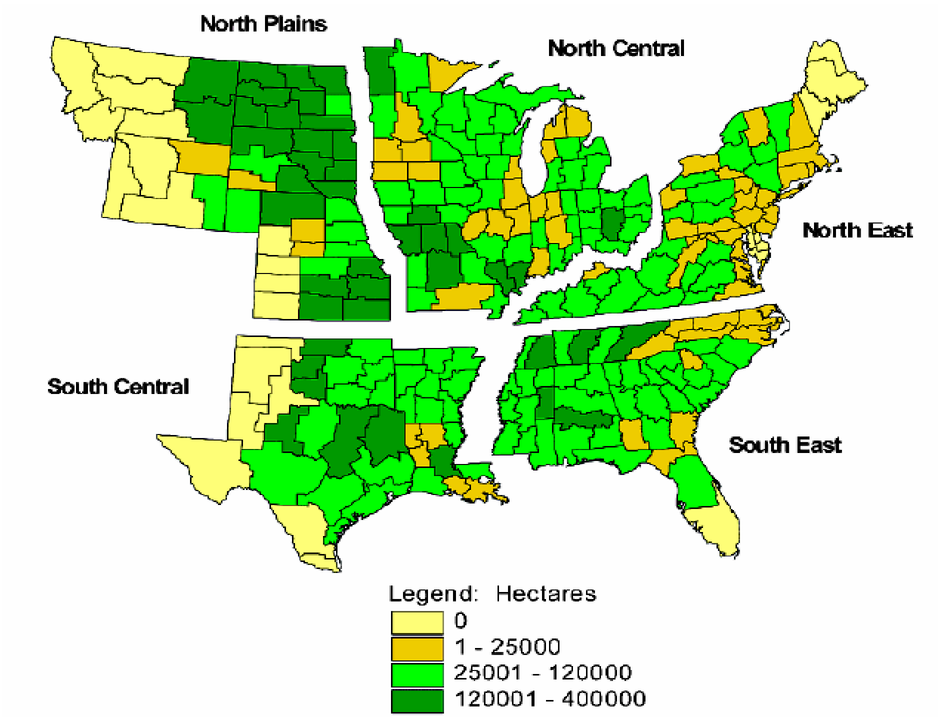


OPTIMAL BIOENERGY/CCS OPTION?

- Options:
  - RC/UCAP
  - OT/UCAP
  - OT/DCAP
  - BIGCC/CCS
- BIGCC/CCS offers:
  - Greatest GHG mitigation potential
  - Least mitigation cost
- What feedstocks might be used for bioenergy?

BIOMASS FEEDSTOCK OPTIONS

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

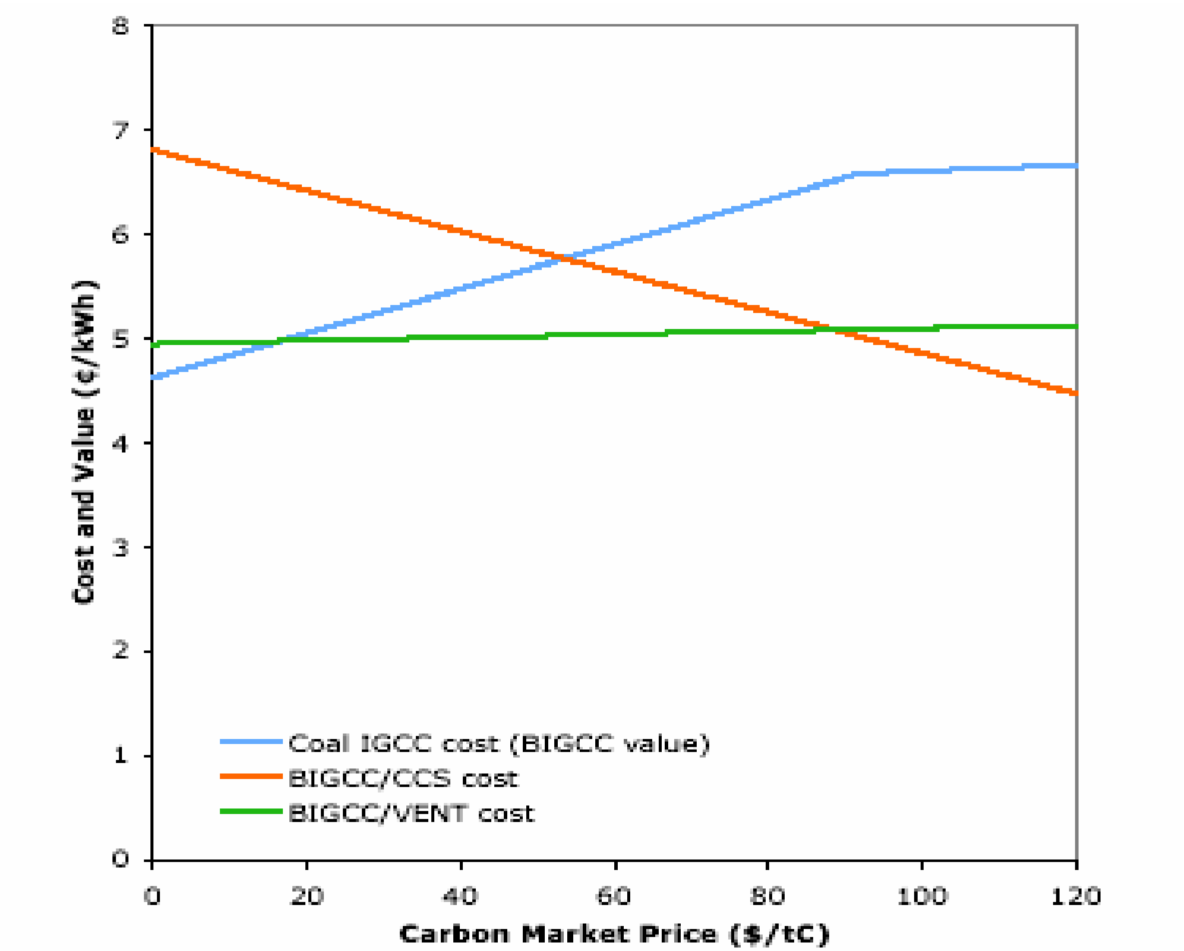


Source: McLaughlin et al., 2002: High-value renewable energy from prairie grasses, *Envir. Sci.& Tech.*, **36** (10): 2122-2129

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

Delivered cost of switchgrass is high (*current technology*):
~ $54/tonne or $3.0/GJ (*~ 2.5 X ave coal price for US power plants*)

COSTS & VALUE OF ELECTRICITY FOR SWITCHGRASS BIGCC



For mature near-commercial technology:

Switchgrass @ \$3.0/GJ,
Coal @ \$1.2/GJ (HHV)

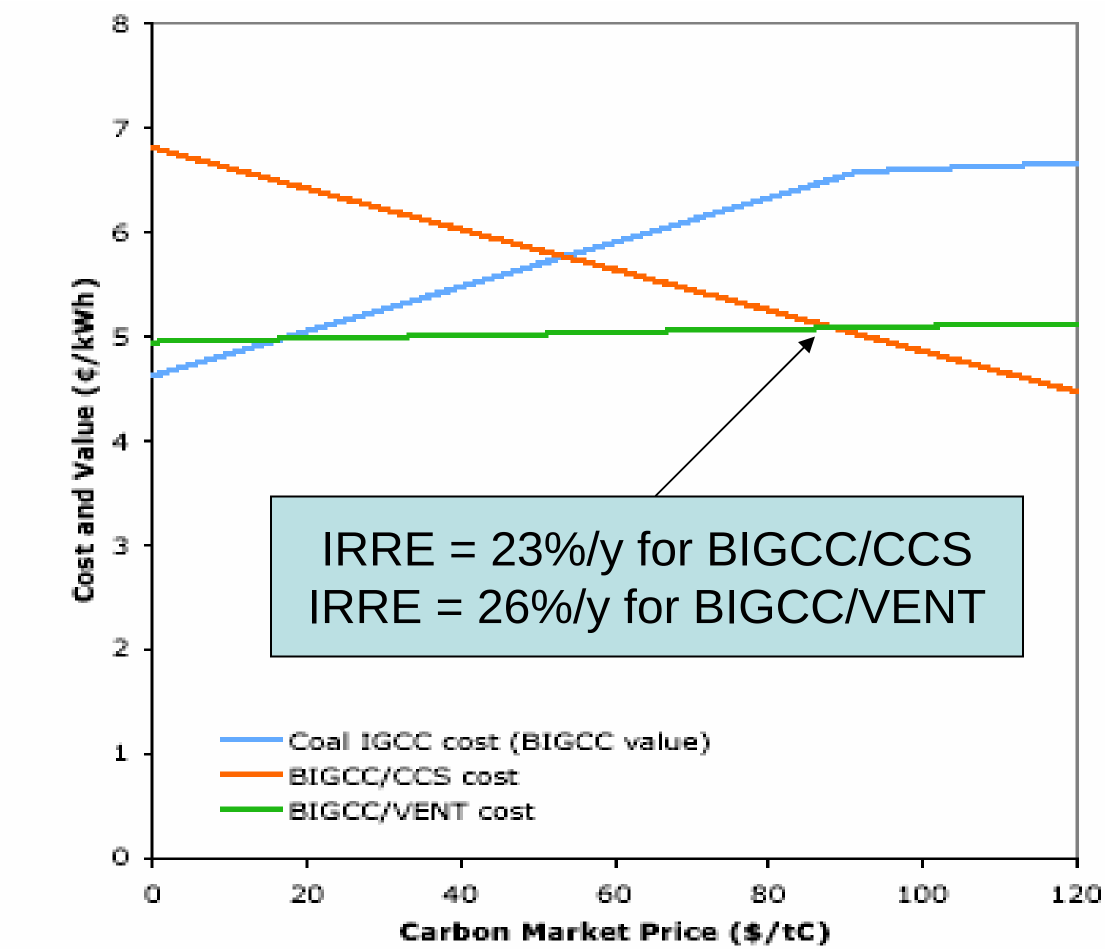
BIGCC VENT: η = 45%
442 MW_e, \$960/kW_e

BIGCC CCS: η = 38.5%
379 MW_e, \$1330/kW_e

Assumed BIGCC Value = Cost of Least-Costly Coal IGGC (VENT or CCS)

At what CMP does CCS become cost-effective for BIGCC?

COSTS AND VALUE OF SWITCHGRASS BIGCC ELECTRICITY



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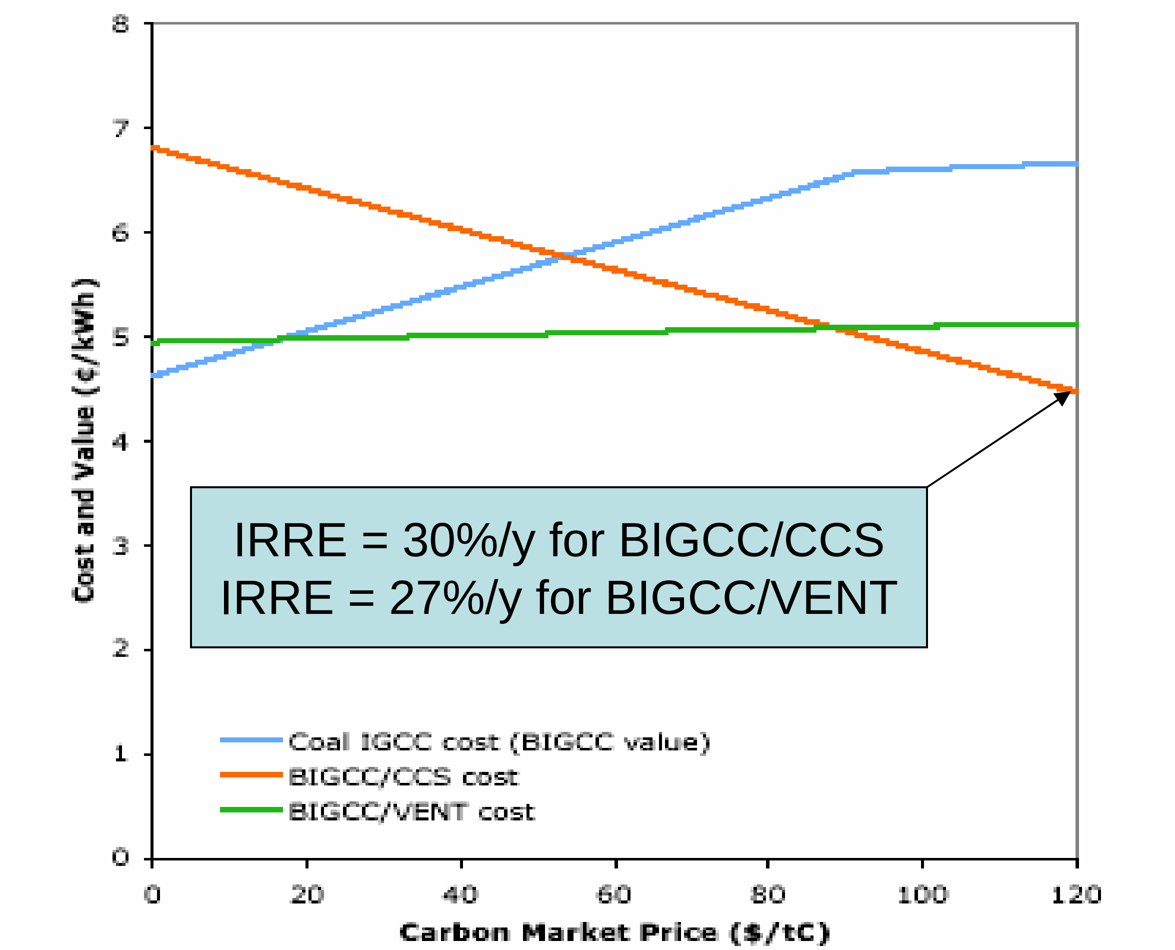

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CMP ~ \$120/tC needed to give higher IRRE for BIGCC/CCS than for BIGCC/VENT

CAN A BUSINESS CASE BE MADE FOR COORDINATED DEVELOPMENT OF COAL SYNFUELS AND BIOENERGY WITH CCS?

- Advantages:
  - Relatively modest additional investments in bioenergy by coal synfuels producer could generate significant benefits to its stockholders under climate constraint
  - Bioenergy development could be accelerated
  - Much more liquid fuels with low GHG emissions per unit of biomass than what can be realized with conventional biofuels
  - Synthetic liquid fuels costs ~ $1.0 a gge could be realized much more quickly than with conventional biofuel options (*e.g.*, *cellulosic EthOH*)…even without a climate policy in place
  - Emphasis on low-GHG-emitting synfuels could facilitate building of societal consensus to allow stream-lining of permitting process so that many large synfuels plants can be built quickly
- Downside: Requires unprecedented cooperation among coal, biomass, and oil industries

SOME POSSIBLE BIOMASS/COAL HYBRIDS FOR MAKING DME + ELECTRICITY :

Coal	Biomass
System (*% of feedstock C: captured/embodied in DME*)	
RC/UCAP (*37%/40%)*	RC/UCAP (50%/34%)
OT/UCAP (29%/20%)	OT/UCAP (46%/16%)
OT/UCAP (29%/20%)	OT/DCAP (74%/16%)
OT/DCAP (74%/20%)	OT/DCAP (74%/16%)
OT/DCAP (74%/20%)	BIGCC/CCS (91%/0%)

RC = Recycle; OT = Once Through

UCAP = CO_2 Capture Upstream of Synthesis Only

DCAP = CO_2 Capture Downstream & Upstream of Synthesis

BIGCC/CCS = Biomass Integrated Gasifier Combined Cycle w/CCS

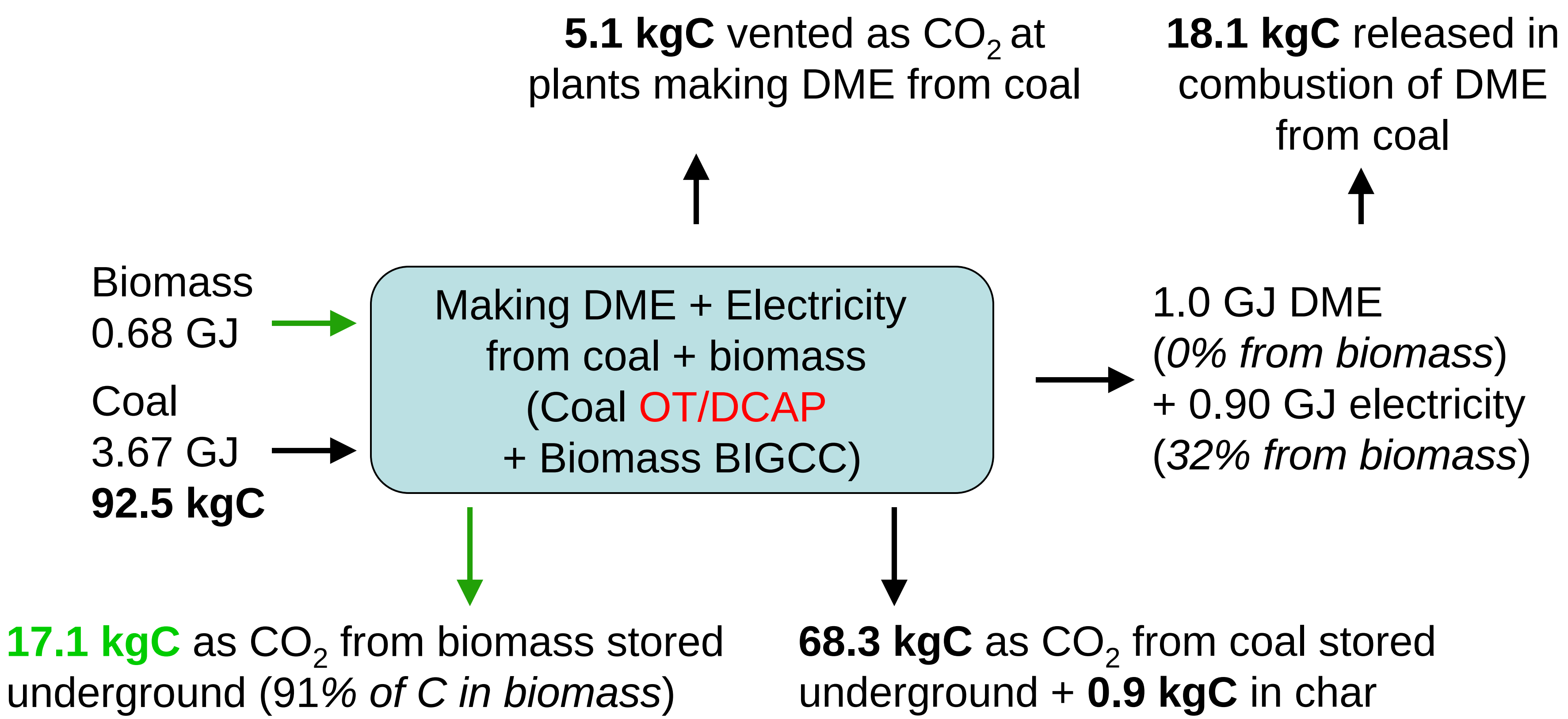
THOUGHT EXPERIMENT FOR COORDINATED DEVELOPMENT OF COAL SYNFUELS + BIOENERGY W/CCS

- Assume CCS for both coal synfuels and bioenergy

- Assume coal/biomass hybrids with just enough bioenergy to reduce fuel-cycle-wide GHG emissions rate for synfuels produced to level for H_2 from coal with CCS = *5.4 kgC$_{equiv}$/GJ* (*~ 1/5 GHG emission rate for gasoline or Diesel from crude oil*)

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

(*High C Price Configuration—full decarbonization*)

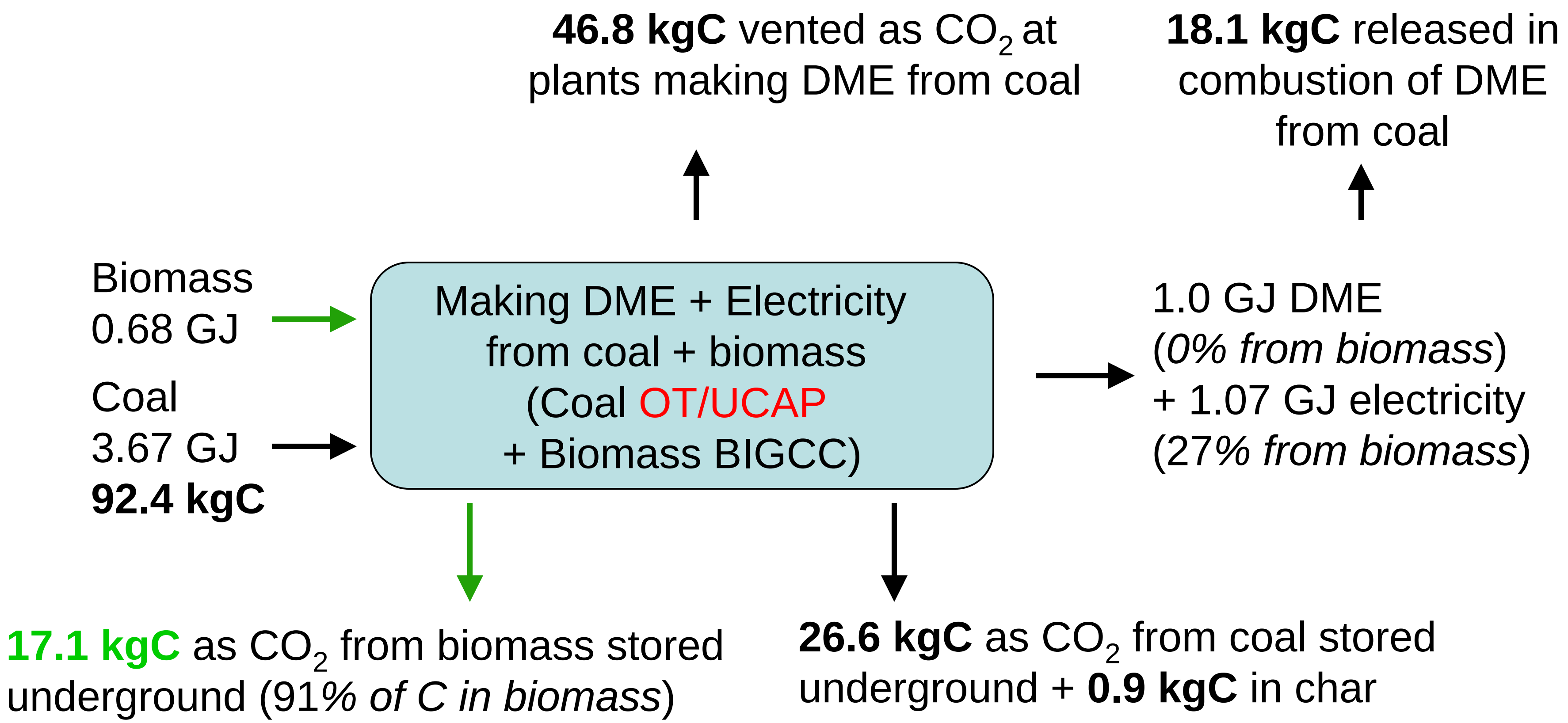


Direct net CO_2 emissions = 5.1 + 18.1 – 17.1 = 6.1 kgC per GJ DME

Total fuel cycle GHG emissions allocated to DME (*in kgCequiv per GJ DME*)
= 6.1 + [5.1 (coal/bio upstream)] + 0.5 (DME delivery) – [6.3 (coal/bio elect)] = 5.4

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

(*Low C Price Configuration—partial decarbonization*)



Direct net CO_2 emissions = 46.8 + 18.1 – 17.1 = 47.8 kgC per GJ DME

Total fuel cycle GHG emissions allocated to DME (*in kgCequiv per GJ DME*)
= 47.8 + [5.1 (coal/bio upstream)] + 0.5 (DME delivery) – [47.9 (coal/bio elect)] = 5.4

POTENTIAL FOR EFFECTIVE NEAR-ZERO GHG-EMITTING LIQUID FUEL PRODUCTION

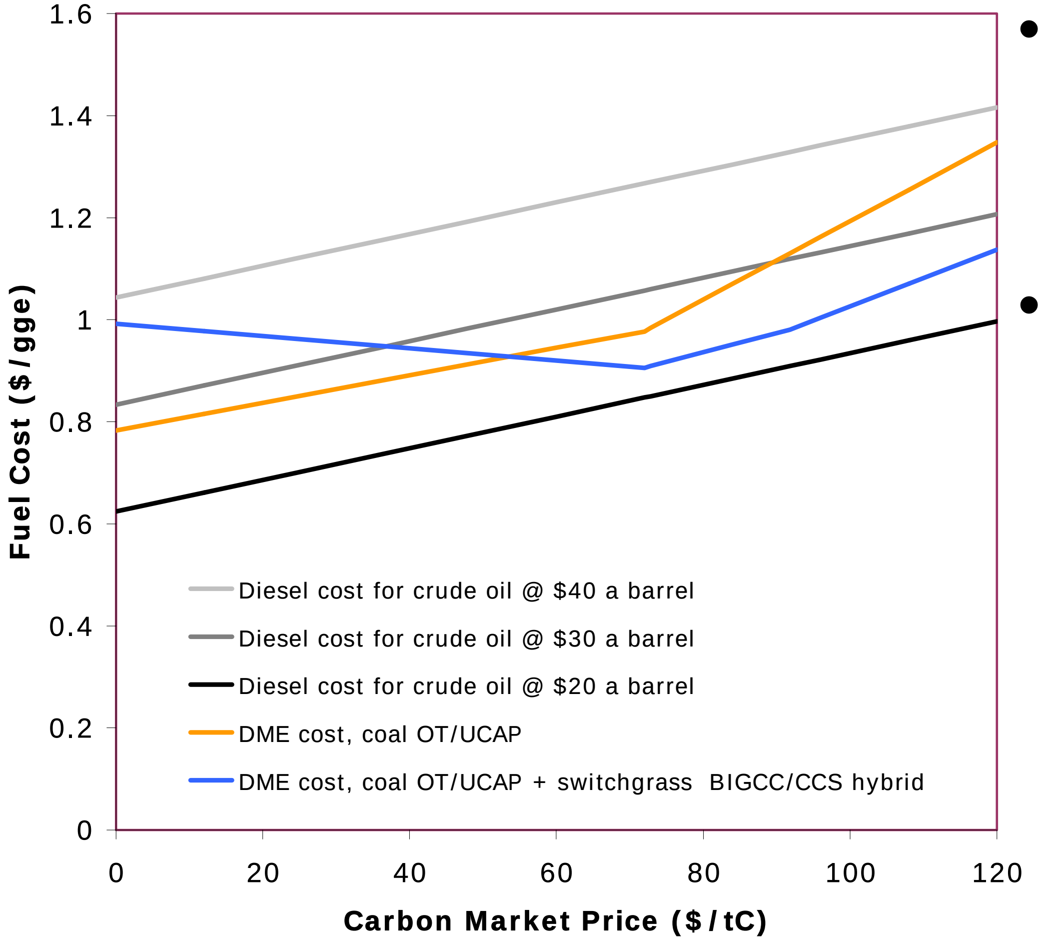
(*gallons of gasoline equivalent per dry tonne of biomass*)

Cellulosic EthOH from switchgrass* (*current technology: 50 gallons EthOH/ton, @ $2.3/gge***)	37
Cellulosic EthOH from switchgrass* (*advanced technology:105 gallons EthOH/ton, @ $1.0/gge***)	78
DME—switchgrass RC/VENT (*@ $1.5/gge***)	75
DME—coal OT/UCAP + switchgrass BIGCC/CCS hybrid (*@$1.0/gge***)	210

* N. Greene and L. Lynd, *Role of Bioenergy in America's Energy Future*, Report to the National Commission on Energy Policy, December 2004

** For all cases the assumed switchgrass price = $3.0/GJ

DME, DIESEL COST TRENDS
DURING TRANSITION TO HIGH CMP



- Investment for BIGCC/CCS hybrid = 1.2 X investment for coal OT/UCAP plant
- If DME sold at crude-derived Diesel cost,

  hybrid is more profitable at relatively modest CMPs

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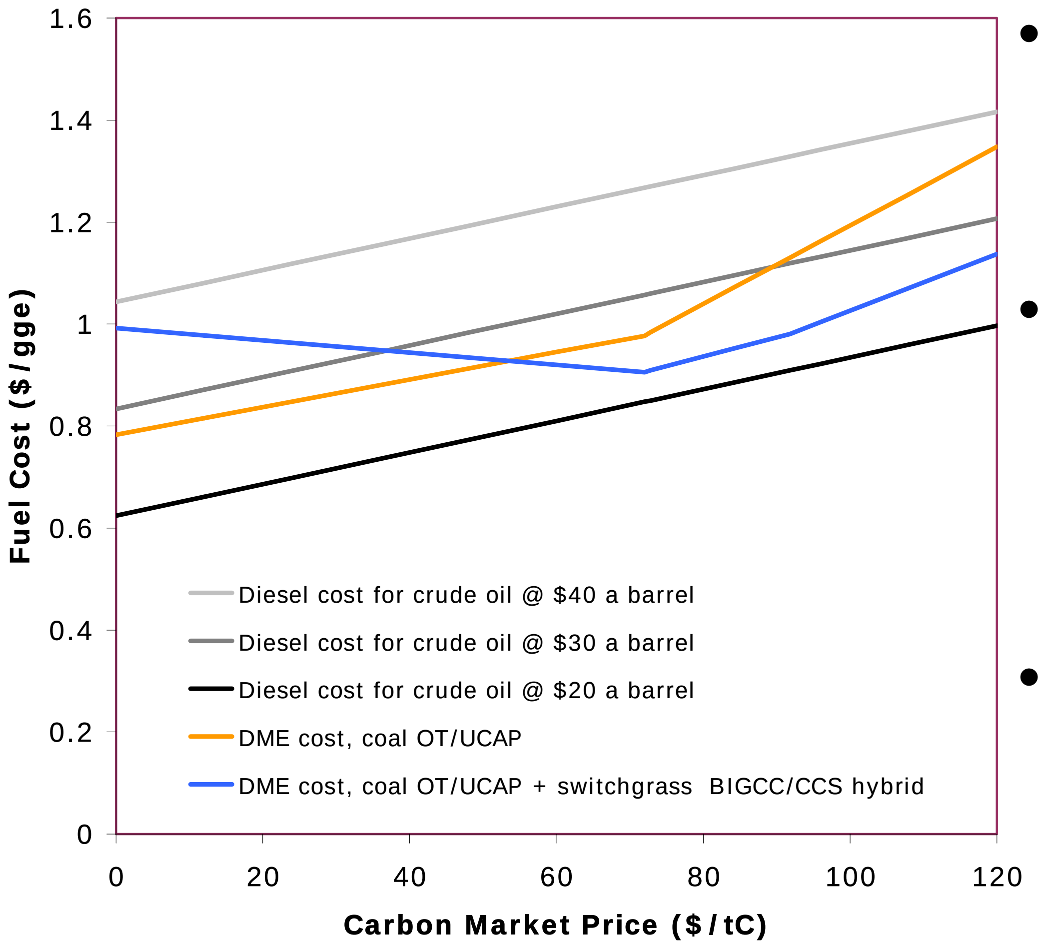

- Investment for BIGCC/CCS hybrid = 1.2 X investment for coal OT/UCAP plant
- If DME sold at crude-derived Diesel cost, hybrid is more profitable at relatively modest CMPs
- But BIGCC/VENT hybrid more profitable still up to CMP = $120/tC

SUBSIDY STRATEGY FOR LAUCHING BIGCC/CCS + COAL OT/UCAP HYBRIDS AT CMP = $0/tC?

- Consider shifting \$1.6 x 10^9/y corn EthOH subsidy to these hybrids (*subsidy currently supports 2.1 x 10^9 gge/y of corn EthOH*)
- Subidy could support:
  - 9.1 GW of BIGCC/CCS power, reducing GHG emissions 16 MtC/y if existing coal steam-electric plants are displaced
  - 6.7 x 10^9 gge/y of DME via hybrid, reducing GHG emissions 16 MtC/y displacing gasoline in LDVs (*11.4 X as much with corn EthOH*)
  - GHG emissions reduction for LDVS could be increased to 40 MtC/y if DME (as designer fuel) facilitated shift from 20 mpg LDVs to 50 mpg_{ge} hybrid-electric vehicles

[2002 GHG emissions for LDVs (coal power) = 390 (510) x 10^6 tC/y]

- CO_2 storage rates for plants involved:
  - 21.1 MtC/y for coal OT/UCAP plants (*as acid gas management strategy*)
  - 13.5 MtC/y at BIGCC/CCS plants (*supported by subsidy*)

CONCLUSIONS

- Coordinated production of designer synfuels from coal/biomass with CCS is an approach to addressing challenges posed by the automobile for which it seems feasible to make substantial contributions *in this quarter century*
  - Major technical uncertainty is "gigascale" viability of CO_2 storage—many more "megascale" CO_2 storage demos needed…soon
  - Biomass gasification technology requires some further development, demonstration, and commercialization …and bioenergy systems must be deployed at scales typical for coal…not mini-scale usually envisioned for bioenergy
  - Synfuel plants with CCS must be demonstrated…but radical new technologies not needed
  - Advanced technologies can help reduce costs of CO_2 emissions avoided
- Carbon mitigation policy needed…but a case can be made for going forward even before such a policy is put into place
- Institutional/cultural challenges:
  - Overcoming widespread ill feelings about coal synfuels—costly synfuels failures of late 1970s-early 1980s
  - Coalition-building for proposed strategy—across multiple industries


BIG
COAL
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