TOWARD TRANSPORTATION FUELS WITH ZERO GHG EMISSIONS

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ACKNOWLEDGMENTS

- Findings based on collaboration involving:
  - Eric Larson/Robert Williams—Princeton University
  - Haiming Jin—SNC Lavalin (*Houston, Texas*)
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  - Carbon Mitigation Initiative at Princeton University (*10-year project supported by BP/Ford*)
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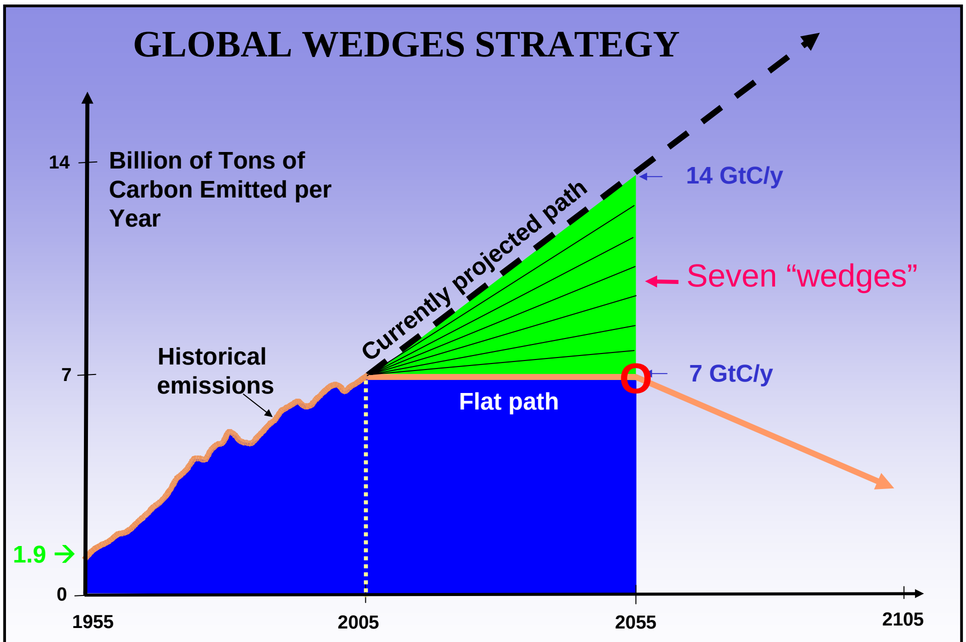
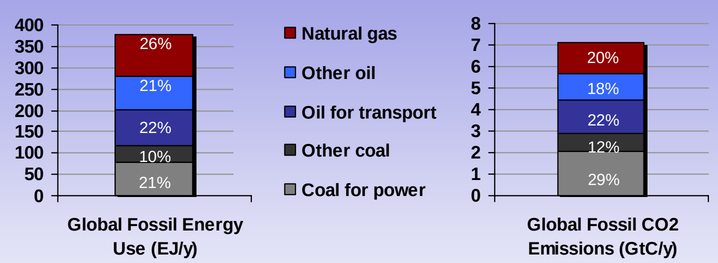
GLOBAL WEDGES STRATEGY



After Pacala and Socolow (2004)…**Stable emissions needed until 2050**

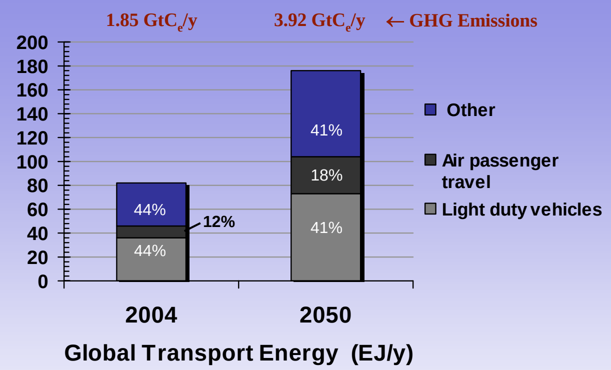
GLOBAL FOSSIL FUEL USE & CO_2 EMISSION, 2004



Source: International Energy Agency, *World Energy Outlook 2006*

Oil and coal each account for ~ 40% of CO_2 emissions from fossil fuel burning

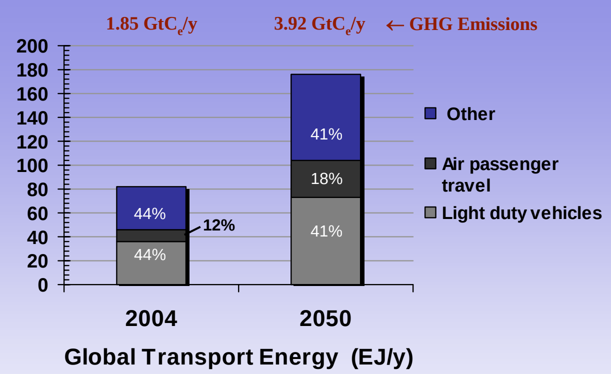
SMP GLOBAL TRANSPORT ENERGY SCENARIO



World Business Council for Sustainable Development (2004), *Mobility 2030: Meeting the Challenges to Sustainability* [Sustainable Mobility Project (*SMP*)] projected, 2004-2050:

- Population: 6.3 billion → 9.3 billion,
- GWP grows 2.8%/y (*GWP per capita up 2.4X*),
- Number of light-duty vehicles (*LDVs*): 0.7 billion → 2.0 billion,
- Average LDV fuel economy: 10.4 → 8.5 liters gasoline equivalent/100 km,
- Air travel grows 4.3 X (*2.9 X per capita*)

SMP GLOBAL TRANSPORT ENERGY SCENARIO



Two "wedges" are needed to stabilize global GHG emissions for transportation during 2004-2050. Will show this is plausibly achievable using near-commercial energy technology, without significant changes in transportation fuel infrastructure, and at competitive cost under a carbon policy…if CO_2 storage proves to be viable as a "gigascale" carbon mitigation option.

CHALLENGES/OPTIONS FOR LIQUID FUELS

- Challenges: climate change/high oil prices/oil supply insecurity
- Alternative options:
  - H_2 economy—at best a long-term option
  - Biofuels
    - Ethanol (EthOH)
      - Sugar cane EthOH—attractive option but only for tropical regions with adequate rainfall
      - Grain EthOH—marginal C mitigation benefits, adverse impacts on food prices
      - Cellulosic EthOH—good C mitigation benefits but slow in coming
    - Biodiesel—also based on food biomass, with adverse impacts on food prices
  - Coal to liquids (CTL)
    - Commercially proven—based on coal gasification + F-T synthesis
    - Cost-competitive for crude oil prices of $55 - $60 a barrel
    - Ultra-low air pollutant emissions at CTL plants
    - F-T liquids would have ultra-low sulfur, aromatics contents
    - F-T liquids can be used in existing transport fuel infrastructures
    - But F-T liquids are not helpful in mitigating climate change:
      - GHG emission rate ~ 2 X rate for crude oil-derived products with CO_2 vented
      - GHG emission rate ~ 1 X rate for crude oil-derived products with CCS

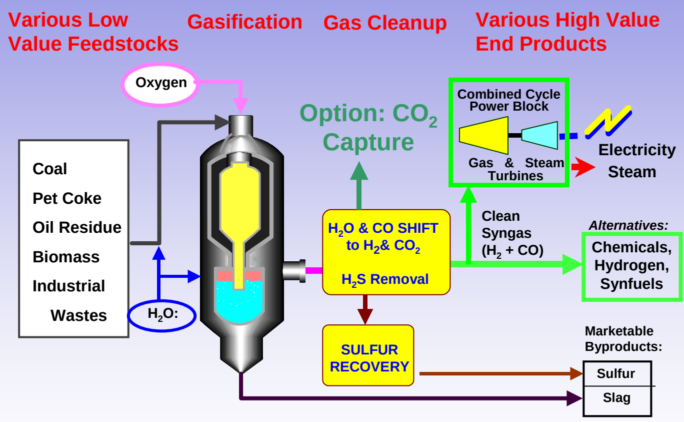
URGENCY OF SHIFTING FROM FOOD BIOMASS TO LIGNO-CELLULOSIC BIOMASS

- Potential biomass supplies involve mainly ligno-cellulosic biomass
  - Most supplies would be crop/forest residues, municipal solid wastes
  - Ligno-cellulosic energy crops (*e.g. short rotation woody crops, switchgrass, mixed prairie grasses*) can be grown on marginal lands as well as on croplands
- Shift from grain to cellulosic EthOH would help shift biomass supplies off cropland—but transition will be slow:

  "Producing cellulosic ethanol is clearly more difficult than we thought in the 1990s." Dan Reicher, former DOE Asst. Secretary for EE/RE (*NYT, 17 April 2007*)

- Alternative, *potentially faster*, route to ligno-cellulosic biomass: Synthetic diesel/gasoline via gasification + F-T synthesis
  - Route to liquid fuels that can "piggy-back" on F-T liquids from coal (*CTL*)
  - But this "thermochemical" conversion route has been neglected in biofuels R&D programs in favor of "biochemical" conversion route (*e.g, cellulosic EthOH*)

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



Gasification in O_2/steam of coal, biomass, other carbonaceous materials: key enabling technology for making clean energy (*liquid fuels and electricity*) and for low-cost CO_2 capture & storage (*CCS*)

CATALYTIC SYNTHESIS OF FUELS FROM SYNGAS

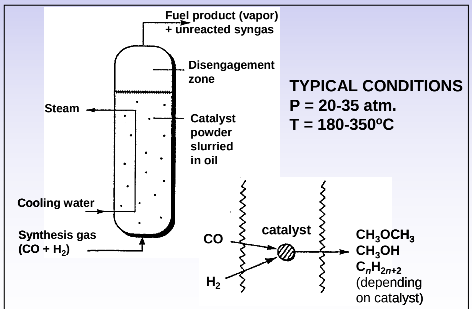
- **Basic overall reactions**:

$$CO + 2H_2 \Leftrightarrow -CH_2- + H_2O \qquad \text{Fischer-Tropsch liquids (FTL)}$$

$$3CO + 3H_2 \Leftrightarrow CH_3OCH_3 + CO_2 \qquad \text{Dimethyl ether (DME)}$$

$$CO + 2H_2 \Leftrightarrow CH_3OH \qquad \text{Methanol (MeOH)}$$

- **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* (*LP*)]: much higher single-pass conversion (*e.g., for F-T liquids, 80% with LP vs. 40% with gas phase*)
    - LP-F-T liquids reactors are commercial
    - LP-MeOH commercially demonstrated
    - LP-DME near commercial
  - Focus here on
    - LP synthesis
    - F-T liquids

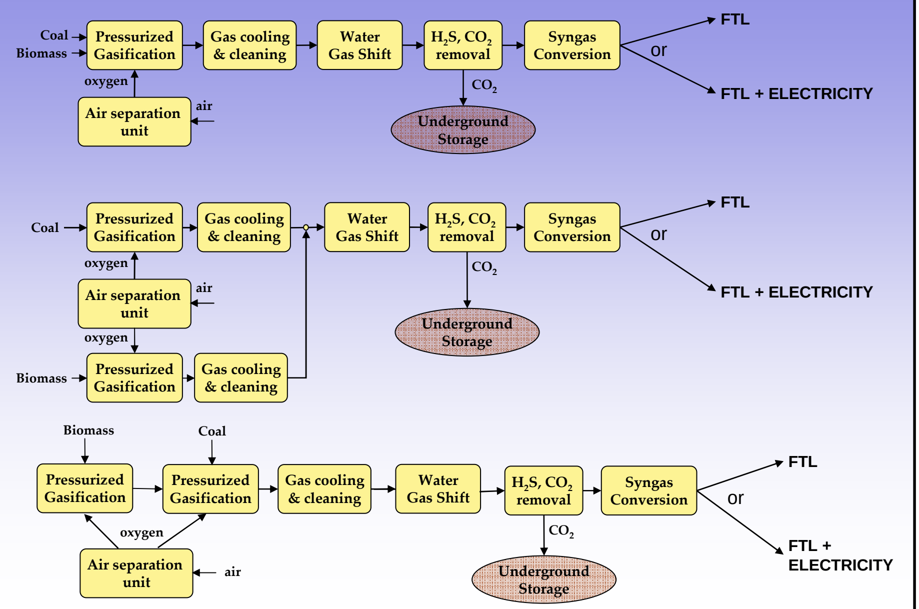


Liquid Phase Reactor

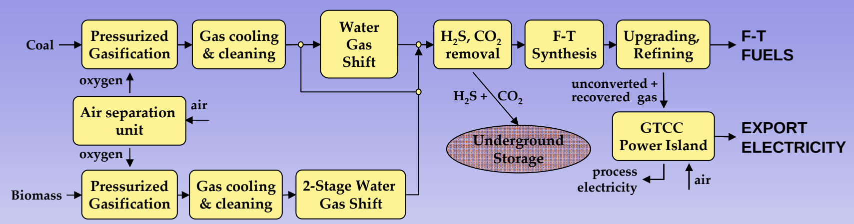
ALTERNATIVE OPTIONS FOR MAKING F-T LIQUIDS USING BIOMASS

- F-T liquids from biomass (*BTL*) with CO_2 vented
- F-T liquids from biomass with CCS (*BTL with CCS*)
  - F-T process generates pure CO_2 stream accounting for ~ ½ C in feedstock
  - Low incremental cost for CCS
  - Transforms biomass from C-neutral → C-negative via photosynthetic CO_2 storage ➔ expanded role for biomass in carbon mitigation
  - Coal has no significant future w/o CCS in C-constrained world
  - If CCS works for coal, it should also be considered for biomass
- F-T liquids from biomass + coal with CCS (*CBTL with CCS*) offers same benefits as BTL with CCS and in addition:
  - Opportunity to exploit scale economies of coal energy conversion
  - Average feedstock cost would be much less than for BTL
  - Opportunity to exploit coal for making liquid fuels in climate-friendly manner
  - Much less biomass needed to realize zero net GHG emissions than with conventional biofuels
  - Higher market price for biomass provider than with conventional biofuels
- Henceforth focus on CBTL with CCS technologies

ALTERNATIVE CBTL PLANT CONFIGURATIONS

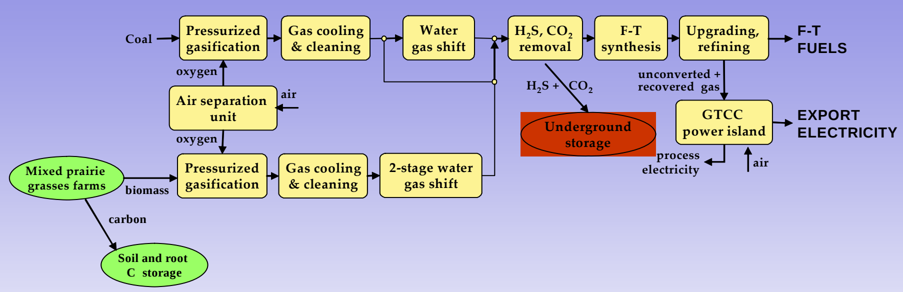


CBTL WITH CCS—SEPARATE PARALLEL GASIFIERS



- In this configuration, hydrogen (H_2) is made from biomass via gasification to compensate for the H_2 deficit in coal-derived synthesis gas used to make FTL.
- The photosynthetic CO_2 coproduct (~ *90% of the C in harvested biomass*) is stored along with coal-derived CO_2 in deep geological formations.

CBTL FOR COAL + MIXED PRAIRIE GRASSES AND TWO C-STORAGE MECHANISMS



Because biomass is a scarce resource it is desirable to pursue strategies that reduce the amount of biomass needed to realize low or zero net GHG emissions for the production and consumption of FTL.

In this option, photosynthetic carbon storage is increased relative to that realizable with the previous option by complementing storage of photosynthetic CO_2 + coal-derived CO_2 in deep underground formations with soil + root C storage arising from the growing of mixed prairie grasses (*MPGs*) on C-depleted soils.

MAJOR FINDINGS OF TILMAN GROUP'S RESEARCH ON MIXED PRAIRIE GRASSES GROWN ON CARBON-DEPLETED SOILS

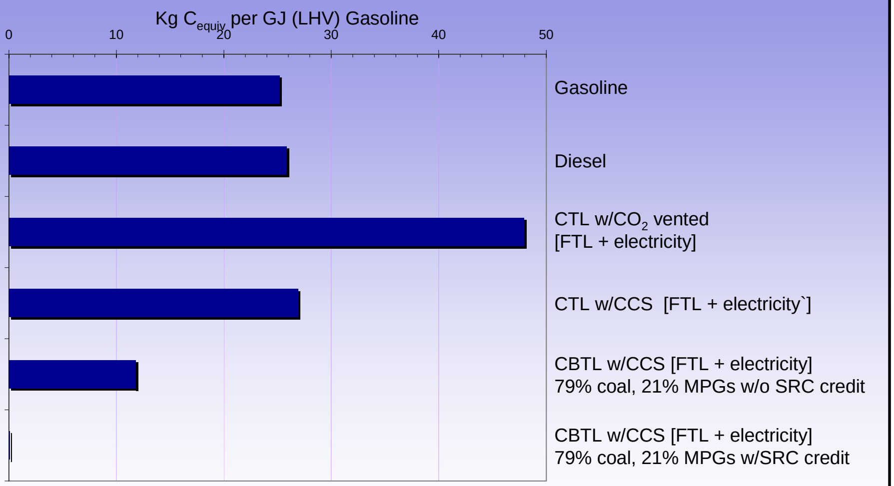
- Sustainable grass yield increases monotonically with # of species
- Soil/root C build-up increases monotonically with # of species
- Soil C build-up continues for ~ century or more
- Over 30 y, soil/root C buildup rate can average ~ 0.6 tC per tC in harvested biomass…with 16 species
- Once mixed prairie grasses (*MPGs*) have been established, only modest additional inputs (*e.g., gasifier ash*) are needed with annual harvesting
- Local biodiversity gain vs. net biodiversity loss for monocultures

Source: D. Tilman et al., *Science*, **314**: 1598-1600, 8 December 2006

SCOPE OF ANALYSIS

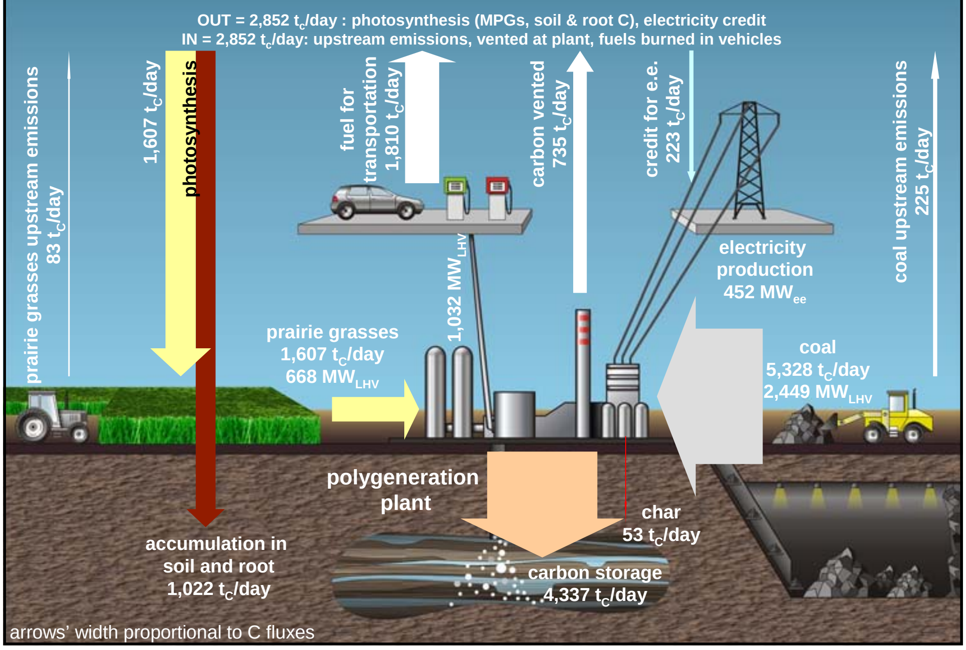
- F-T liquids production via solids gasification:
  - Once-through liquid-phase reactor for F-T synthesis
  - Unconverted syngas used to make coproduct electricity in combined cycle
- Alternative polygeneration plants sited in S. Illinois:
  - Coal-fueled plant with CO_2 vented (*GE entrained-flow quench gasifier*)
  - Coal-fueled plant with CCS (*GE entrained-flow quench gasifier*)
  - Coal/MPG-fueled plant with CCS (*GE gasifier for coal; GTI fluidized bed gasifier for biomass*) using just enough MPGs to reduce net F-T liquids GHG emissions to zero
- Minemouth plants using:
  - High S bituminous coal
  - MPGs grown on lands now growing corn
- E & C balances estimated—assigning to electricity the GHG emission rate of coal IGCC w/CCS
- For assumed (*i*) \$100/tC GHG emissions value & (*ii*) electricity credit = generation cost for coal IGCC w/CCS, economic analysis carried out from perspectives of:
  - Synfuels producer
  - Farmers growing MPGs

GHG EMISSION RATES FOR FUEL PRODUCTION AND USE

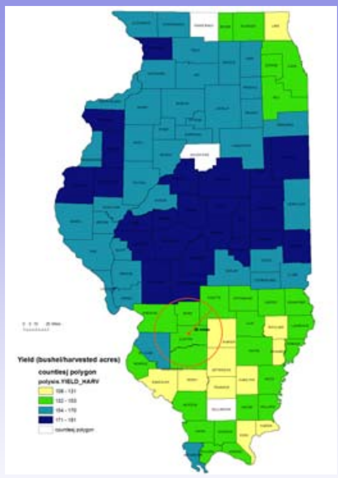


The last option shown is for a system making FTL + electricity from coal + MPGs (*16 grasses*) with CCS and with just enough MPGs (*21% of the input on an energy basis*) to realize zero net GHG emissions. For the penultimate option it is assumed for the MPG case that there is zero credit for soil + root carbon buildup**.**

C$_{equiv}$ BALANCES TO ATMOSPHERE FOR FTL IN MAKING FTL + ELECTRICITY FROM COAL + MPGS WITH CCS



SITE FOR COAL/MPGs CBTL PLANT



MPGs logistics analysis

10^6 dt/y of MPGs needed at CBTL plant

Assume MPGs are grown on land currently planted in corn, conventional tillage

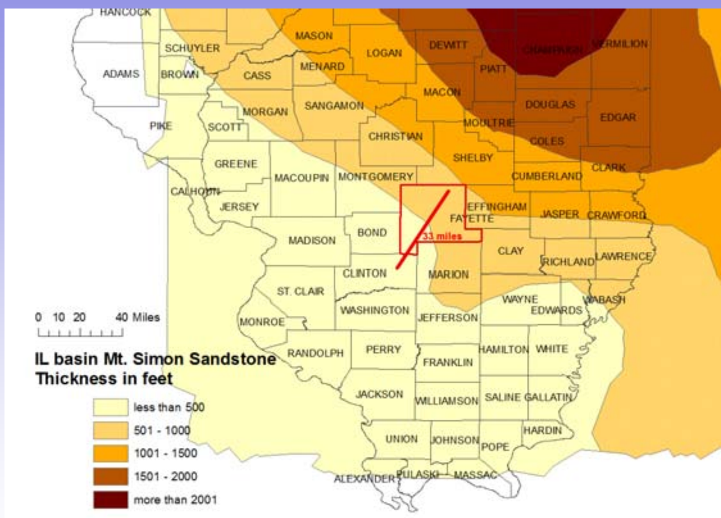
Estimated MPG yield = 10.4 dt/ha/y[a]

Assuming MPGs are grown on 15% of land around CBTL plant

Ave transport distance for MPGs = 27 miles

[a] Clarence Lehman, U. of Minnesota (*private communication, April 2007*), estimates that MPG yield on average cropland would be approximately 1.5 X hay yield on lower-grade local land growing hay, based on correlation of actual hays and general productivity models…here assumed yield = 1.5 X hay yield.

POSSIBLE AQUIFER STORAGE SITE



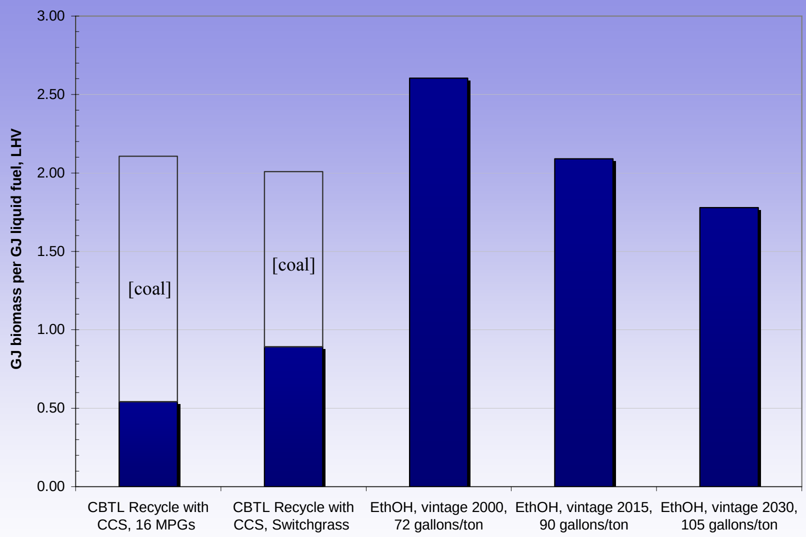
Suggested region for aquifer CO_2 storage near proposed CBTL plant offered by Hannes Leetaru, and map of Mt Simon Sandstone features provided by Chris Korose—both of the Illinois State Geological Survey, private communication April 2007

ESTIMATING VALUE OF STRATEGY TO FARMER

- Consider first coal F-T polygeneration plant with CCS
  - Site: Southern Illinois (*coal and corn country*)
  - CO_2 storage: Mt. Simon aquifer (*33 miles from FTL plant*)
  - Feedstock: high-S bituminous coal—minemouth plant @ \$1.2/GJ (*HHV*)
  - GHG emissions price: \$100/tC
  - Assume electricity sold for same price as for coal IGCC with CCS
  - Estimate levelized FTL production cost & breakeven crude oil price
- Next consider coal/MPG F-T polygen plant with just enough MPGs input to reduce net GHG emisison rate to zero for FTL & assume:
  - Estimated MPGs yields for lands now growing corn there
  - Same outputs/product prices as for coal-only plant with CCS

  ➔ determines "willingness" of synfuel producer to pay for MPGs
- Willingness to pay = 4.5 X coal price at plant gate & 2.7 X coal price at farm gate ➔ farm income ~ income from growing corn
- With 0 credit for soil/root carbon buildup, wiilngness to pay farmer drops by half—but other biomass options may still be economic

Biomass Required to Make 1 GJ of Liquid Fuel



Net FTL GHG emission rate = 0: 1st option involves soil/root C storage; 2nd does not

Biomass requirement in blue; Energy balances for cellulosic EthOH are based on NREL studies

STATUS OF TECHNOLOGIES

- Coal gasification technology is commercial
- FTL technology is commercial
- CO_2 capture technologies are commercially ready
- CO_2 EOR technology is commercial
- CO_2 storage in deep saline formations ready for megascale projects
  - 10-12 "megascale" projects (*alternative geologies*) needed worldwide to prove "gigascale" viability of CO_2 storage—need to get projects underway ASAP
  - CTL/CBTL projects good candidates for such projects (*low CO_2 capture cost*)
- Technology status for biomass gasification
  - Large O_2-blown gasifiers are not yet commercial
  - Could become commercial by ~ 2015
  - But co-gasification variant of CBTL option is commercially ready…at Buggenum in The Netherlands a commercial coal IGCC plant has been fired routinely with 30% biomass (*weight basis*) since 2006

BAARD ENERGY's OHIO CBTL PROJECT

- 50,000 B/D CBTL plant planned at Wellsville, Ohio—targeted start-up: 2011-2012
- Builds on Buggenum experience:
  - 30% biomass co-feed (*weight basis*) planned
  - CCS planned…CO_2 for EOR (*nearby oil field*) or stored in saline formation
- How "real" is project?
  - Ongoing \$50 x 10^6 FEED study…to be completed mid-2008
  - Some long-term biomass supply contracts already secured
  - Seeking federal incentives…but intent is to proceed even without
  - Ohio Air Quality Development Authority has authorized raising state tax-exempt bonds for debt financing

EXPLORE CARBON MITIGATION POTENTIAL VIA VARIANTS OF SMP SCENARIO FOR 2050

- Thought Experiment #1:
  - Keep transportation energy demand at same level as in SMP Scenario
  - Back out 100% of oil for transportation in 2050
  - Choose mix of (CBTL with CCS) & (BTL with CO_2 vented) such that 100% of prospective biomass supplies are consumed:
    - Biomass required for CBTL with CCS = 0.93 x (CBTL use)
    - Biomass required for BTL with CO_2 vented = 2.27 x (BTL use)

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- Thought Experiment #2:
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  - Keep same CBTL/BTL ratio as for Thought Experiment #1
  - Set GHG emission rate for 2050 = emission rate for 2004 (*Wedges strategy*)

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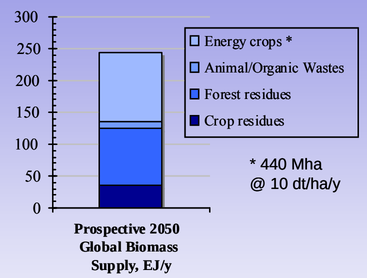
  - Keep same CBTL/BTL ratio as for Thought Experiment #1
  - Set GHG emission rate for 2050 = emission rate for 2004 (*Wedges strategy*)
- Thought Experiment #3:
  - 23% lower transportation energy demand in 2050 via improved efficiency (TECH Plus Strategy of IEA, *Energy Technology Perspectives 2006: Scenarios & Strategies to 2050,* Paris, 2006…includes average fuel economies in 2050 of 4.7 & 4.0 liters gasoline equivalent per 100 km for gasoline and diesel LDVs)
  - Keep same CBTL/BTL ratio as for Thought Experiments #1 and #2
  - Set GHG emission rate for 2050 = emission rate for 2004 (*Wedges strategy*)

PROSPECTIVE GLOBAL BIOMASS SUPPLY IN 2050



Source: R. Doornbosch and R. Steenblik, *Biofuels: Is the Cure Worse than the Disease*, report prepared for the Roundtable on Sustainable Development at the OECD, Paris, 11-12 September 2007

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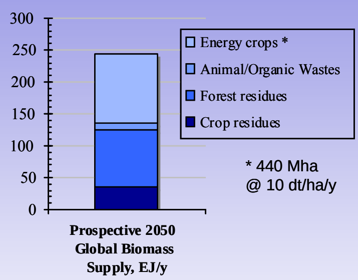
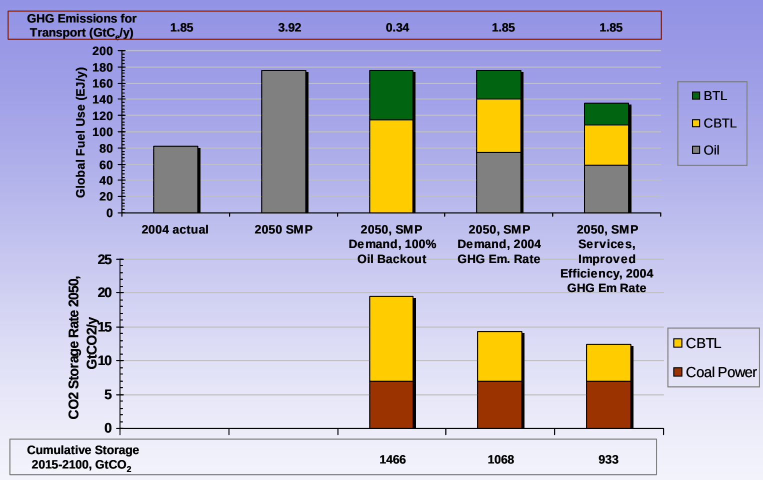


Source: R. Doornbosch and R. Steenblik, *Biofuels: Is the Cure Worse than the Disease*, report prepared for the Roundtable on Sustainable Development at the OECD, Paris, 11-12 September 2007

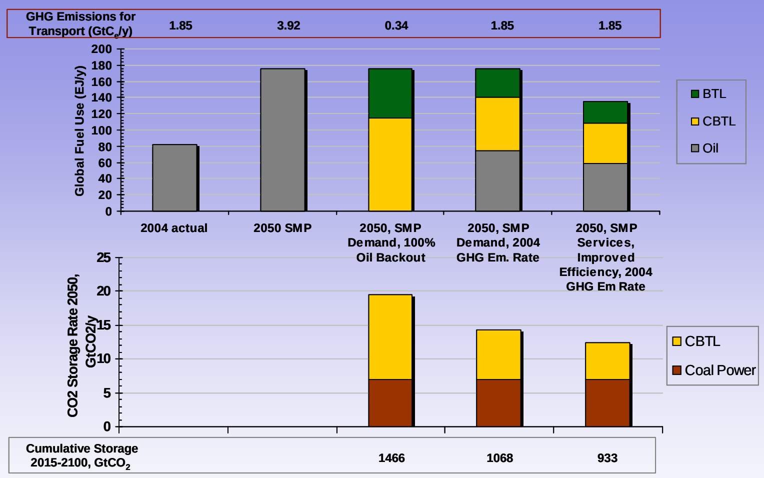
This estimate is consistent with other major global assessments—e.g, *World Energy Assessment*, 2000 (UNDP, UNDSEA, WEC) estimates that the long term potential for biomass primary energy is 100-300 EJ per year

VARIANTS OF SMP TRANSPORT SCENARIO—2050



Lower graph shows CO_2 storage for CBTL along with storage for coal power in High CO_2 Emissions Price Scenario of MIT *Future of Coal* study (2007)

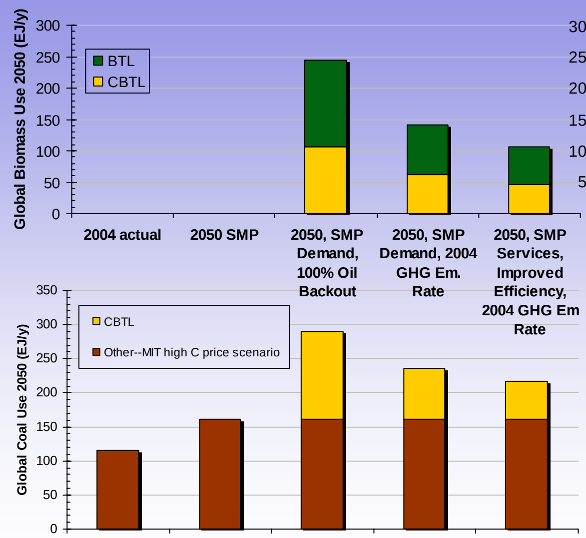
VARIANTS OF SMP TRANSPORT SCENARIO—2050

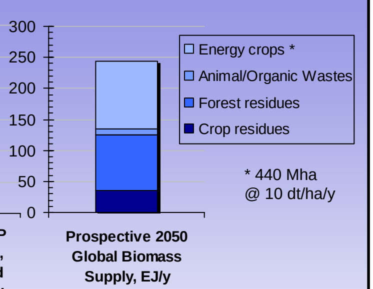


Lower graph shows CO_2 storage for CBTL along with storage for coal power in High CO_2 Emissions Price Scenario of MIT *Future of Coal* study (2007)

According to IPCC *Special Report on CCS* (2005): "…worldwide, it is likely that there is at least about 2000 Gt CO_2 of geological storage capacity…"

BIOMASS & COAL NEEDED FOR VARIANTS OF SMP SCENARIO IN 2050





There is likely to be enough biomass to address completely the climate challenge posed by transportation if CBTL w/CCS option can be exploited

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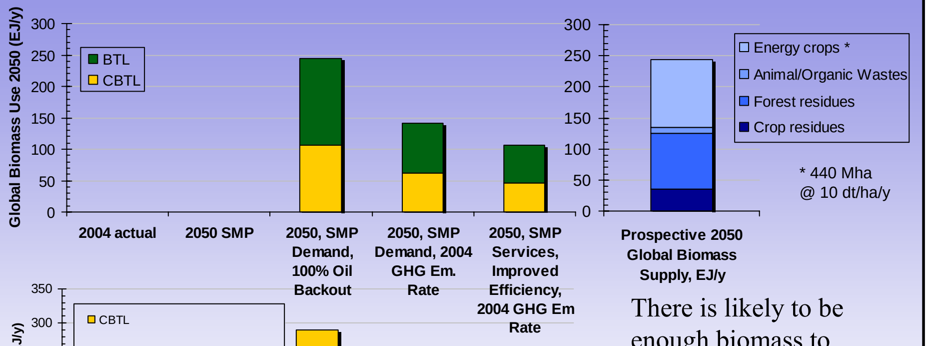

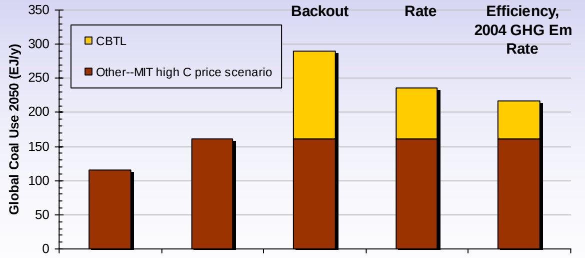

There is likely to be enough biomass to address completely the climate challenge posed by transportation if CBTL w/CCS option can be exploited

Biomass residues alone could plausibly provide “two wedges”

EXTRA SLIDES

ESTIMATING VALUE OF STRATEGY TO FARMER

- Consider first coal F-T polygeneration plant with CCS
  - Site: Southern Illinois (*coal and corn country*)
  - CO_2 storage: 7500 ft underground, Mt. Simon aquifer (*33 miles from FTL plant*)
  - Feedstock: high-S bituminous coal—minemouth plant @ \$1.2/GJ (*HHV*)
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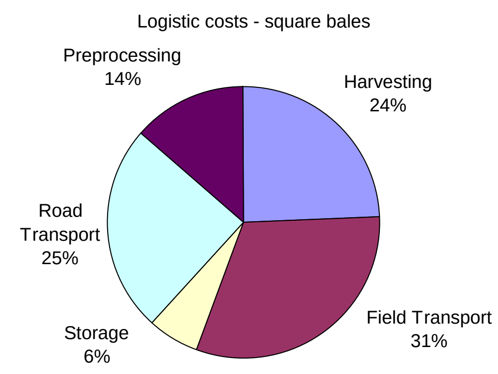
  - Estimated MPGs yields for lands now growing corn there
  - Same outputs/product prices as for coal-only plant with CCS

  ➔ determines "willingness" of synfuel producer to pay for MPGs
- Huge recent construction cost escalations make absolute capital costs highly uncertain—but:
  - Relative capital costs for alternative configurations are probably about the same as before escalations
  - Willingness to pay for MPGs is likely to be insensitive to absolute capital cost levels
- **Farmer income if MPGs displace corn compared to income from corn?**

LOGISTICS COSTS FOR MPGs



Logistics costs ($/dt) yield 10.4 dt/ha/y	
Establishment	3.6
Harvesting	8.4
In-Field Transport	10.7
Storage (*tarping*)	2.2
Road Transport	8.4
Preprocessing (*grinding*)	4.7
Total	**38**

Dry matter loss with tarping is 7% (Duffy, 2003)

ECONOMICS OF SHIFTING ILLINOIS CORN TO MPGs FOR MAKING FTL WITH COAL

Assumed carbon price, $ per tonne of C	100
Assumed MPGs yield, dt/ha/y (*1.5 X local hay yield on lower-grade land*)	10.4
MPGs price, $ per dry tonne	
Willingness to pay for MPGs at FTL plant (~ *4.5 X coal price*)	96
Logistics costs for MPGs	-38
Income to farmer (*$/tonne*)	**58**
Income to farmer (*$/ha/y*) for Bond, Clinton, Madison, and Marion counties	
For sale of grasses to FTL plant	**567**
Corn returns (*acreages, yields = 2001-2004 averages, 2007 farm prices*)	**601**

Farmer's income from growing MPGs ~ income from growing corn

Corn data from Chad Hellwinckel & Daniel de la Ugarte, U. of Tennessee, private communication, April 2007

ECONOMICS OF SHIFTING CORN TO MPGs FOR MAKING FTL—IF SOIL/ROOT C CREDIT = 0

Assumed carbon price, $ per tonne of C	100
Assumed MPGs yield, dt/ha/y (*1.5 X local hay yield on lower-grade land*)	10.4
MPGs price, $ per dry tonne	
Willingness to pay for MPGs at FTL plant (*3.1 X coal price*)	67
Cost of harvesting, grinding, storing MPGs	-38
Income to farmer *($/tonne*)	**29**
Income to farmer (*$/ha/y*) for Bond, Clinton, Madison, and Marion counties	
For sale of grasses to FTL plant	**279**
Corn returns (*acreages, yields = 2001-2004 averages, 2007 farm prices*)	**601**

Farmer's income would fall by ½ without credit for soil/root C storage

Corn data from Chad Hellwinckel & Daniel de la Ugarte, U. of Tennessee, private communication, April 2007

ECONOMICS OF SHIFTING CORN TO MPGs FOR MAKING FTL—IF SOIL/ROOT C CREDIT = 0

Assumed carbon price, $ per tonne of C	100
Assumed MPGs yield, dt/ha/y (*1.5 X local hay yield on lower-grade land*)	10.4
MPGs price, $ per dry tonne	
Willingness to pay for MPGs at FTL plant (*3.1 X coal price*)	67
Cost of harvesting, grinding, storing MPGs	-38
Income to farmer *($/tonne*)	**29**
Income to farmer (*$/ha/y*) for Bond, Clinton, Madison, and Marion counties	
For sale of grasses to FTL plant	**279**
Corn returns (*acreages, yields = 2001-2004 averages, 2007 farm prices*)	**601**

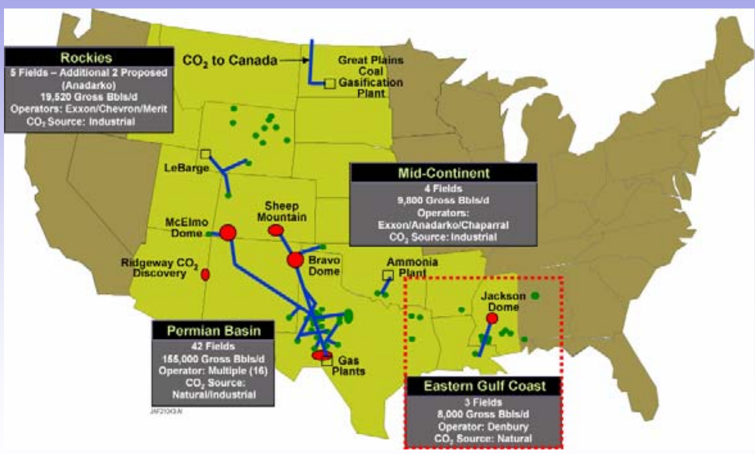
But there are likely to be alternative strategies whereby CBTL with CCS option would be competitive at these delivered biomass prices.

Corn data from Chad Hellwinckel & Daniel de la Ugarte, U. of Tennessee, private communication, April 2007

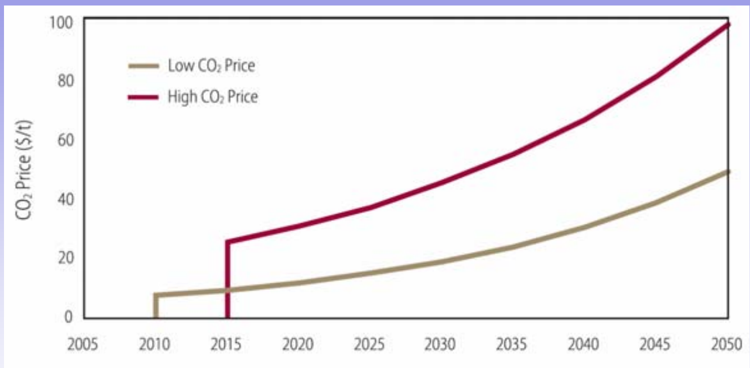
OPTIONS FOR CO_2 STORAGE

- Goal: store 100s to 1000s of Gt CO_2 for 100s to 1000s of years
- Major options, disposal in:
  - Deep ocean (*concerns about storage effectiveness, environmental impacts, legal issues, difficult access*)
  - Carbonate rocks [*100% safe, costly (huge rock volumes), embryonic*]
  - Disposal in geological media (*focus of current interest*)
    - Enhanced oil recovery
    - Depleted oil and gas fields (*geographically limited*)
    - Deep saline formations
      - Huge potential, ubiquitous (*at least 800 m down*)
      - Such formations underly land area ≡ ½ area of inhabited continents (*2/3 onshore, 1/3 offshore*)
  - Already some experience [*e.g.,* Sleipner (*saline formation under North Sea*)*;* In Salah, Algeria (*water leg of natural gas field*) and CO_2-EOR (*30 million tonnes CO_2/y—4% of US oil production*)]

EXTENSIVE US EXPERIENCE WITH CO_2 TRANSPORT FOR ENHANCED OIL RECOVERY …SOME CO_2 IS ANTHROPOGENIC



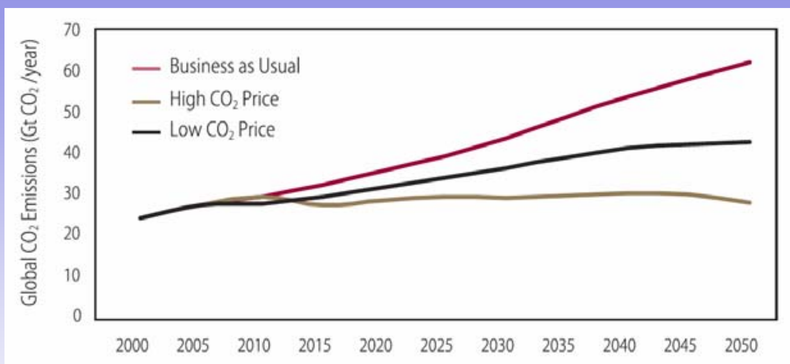
MODELING OF WORLD ENERGY IN MIT *FUTURE OF COAL* STUDY



Modeling exercise explored impacts of:

- Low price trajectory (*NCEP consensus*)
- High price trajectory (*needed to induce CCS for coal power*)

RESULTS OF MIT COAL STUDY MODELING



Stabilization of global CO_2 emissions through mid-century (*goal of Wedges Strategy*) is feasible with high CO_2 price trajectory but not with low CO_2 price trajectory