AMERICA'S ENERGY FUTURE

Liquid Transportation Fuels from Coal and Biomass

Technological Status, Costs, and Environmental Impacts

Panel on Alternative Liquid Transportation Fuels

DOE LDV Workshop 7-26-10

Mike Ramage and Jim Katzer

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CHARGE TO THE ALTF PANEL

- Evaluate technologies for converting biomass and coal to liquid fuels that are deployable by 2020.
  - Current and projected costs, and CO_2 emissions.
  - Key R&D and demonstration needs.
  - Technically feasible supply of liquid fuels
- Estimate the potential supply curve for liquid fuels produced from coal or biomass.
- Evaluate environmental, economic, policy, and social factors that would enhance or impede development and deployment.
- Review other alternative fuels that would compete with coal-based and biomass-based fuels over the next 15 yr.
- No policy recommendations.

PANEL ON ALTERNATIVE LIQUID TRANSPORTATION FUELS

MICHAEL RAMAGE, Chair	ExxonMobil R&E Co (retired)
G. DAVID TILMAN, Vice Chair	U.of Minnesota,
DAVID GRAY	Noblis, Inc.
ROBERT HALL	Amoco Corporation (retired)
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DOUGLAS KARLEN	USDA / Iowa State U.
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HAROLD SCHOBERT	Pennsylvania State University
CHRISTOPHER SOMERVILLE	Energy BioSciences Institute
GREGORY STEPHANOPOULOS	MIT
JAMES L. SWEENEY	Stanford University

As Detailed in the Following Slides, the Panel's Analyses Showed That

1. About 500 million tons/year of biomass can be sustainably produced in the US without incurring significant direct or indirect greenhouse gas emissions

2. Liquid transportation fuels from coal and biomass have potential to supply 2-3 MBPD of oil equivalent fuels with significantly reduced CO_2 emissions by 2035

3. Timely commercial deployment may hinge on adoption of fuel mandates and a carbon price, and on accelerated federal investment in essential technologies

BIOMASS SUPPLY—Key Assumptions

- No indirect land use change and minimum competition with food.
- Corn stover—Adequate corn stover be left in the field to protect and maintain soil resources.
- Dedicated fuel crops—Biomass feedstock be produced on 24 million acres of CRP land in 2020.
- Woody biomass—Estimates based on reports by Milbrandt (2005) and Perlack et al. (2005).
- Hay and wheat straws—Yield increase over time = historic increase.

Estimated Lignocellulosic Feedstock That Could Potentially Be Produced for Biofuel

Feedstock Type	Current	2020
	Millions of dry tons	
Corn stover	76	112
Wheat and grass straw	15	18
Hay	15	18
Dedicated fuel crops	104	164
Woody residues[a]	110	124
Animal manure	6	12
Municipal solid waste	90	100
TOTAL	**416**	**548**

[a]Woody residues currently used for electricity generation are not included in this estimate.

BIOMASS COSTS

Biomass costs include costs of:

- Nutrient replacement.
- Harvesting and maintenance.
- Transportation and storage.
- Seeding.
- Opportunity costs (for example, cropland rental costs).

The panel reviewed the literature and determined a low cost, a baseline cost, and a high cost. See Appendix H for list of references used.

BIOMASS COSTS

	Dollars per dry ton	
Biomass	**Estimated in 2008[a]**	**Projected in 2020**
Corn stover	110	86
Switchgrass	151	118
Miscanthus	123	101
Prairie grasses	127	101
Woody biomass	85	72
Wheat straw	70	55

[a]2008 costs = baseline costs

BIOCHEMICAL CONVERSION STATUS

- Technology Ready for Deployment by 2020
  - Cellulosic biomass converted to sugars then ethanol
  - Key challenges freeing sugars from biomass structure
  - Conversion of cellulosic biomass to ethanol in early commercial scale-up
- Technologies Ready for Deployment After 2020
  - Catalytic conversion biomass sugars to biobutanol or hydrocarbon fuels – active development
  - Bacteria/based direct routes to fuels- active research
  - Algal biofuels -How and where to grow algae?

THERMOCHEMICAL CONVERSION STATUS

- Technology Ready for Deployment by 2020
  - Indirect Liquefaction
    - Gasification, followed by Fischer-Tropsch, or Methanol-to-Gasoline– commercially deployable now
    - Integrated Gasification, Fischer-Tropsch, or Methanol-to-Gasoline with CCS needs commercial demonstration now
  - Direct Liquefaction looks like a poor choice for the U.S.
  - Geologic Storage of CO_2 must be demonstrated by 2015, for 2020 deployment
- Feedstocks

  Coal, Biomass, and Coal + Biomass

BIOCHEMICAL[a] AND THERMOCHEMICAL[b] CONVERSION—KEY ASSUMPTIONS

The panel assumes in its analyses that

- Conversion plants that use biomass consume 4000 dry tons of biomass per day.
- Coal and biomass are combined at a ratio of 60:40 on an energy basis.
- Conversion plants that use coal only have a production capacity of 50,000 bbl/day of gasoline equivalent.
- Coal cost = $42/ton, and biomass cost = $101/dry ton.
- Capital costs were updated to 2007 dollars.

[a]Modeling done with SuperPro Designer and estimates of a corn-grain ethanol plant cross-checked with literature values.
[b]Modeling done with AspenPlus.

COMPARISON OF LIFE-CYCLE COSTS—Effect of a $50/tonne CO_2 price

Fuel Product	Cost without CO_2 Equivalent price ($/bbl of gasoline equivalent)	Cost with CO_2 Equivalent price of $50/tonne ($/bbl of gasoline equivalent)
Gasoline at crude-oil price of $60/bbl	75	95
Gasoline at crude-oil price of $100/bbl	115	135
Cellulosic ethanol	115	110
Biomass-to-liquid fuels without carbon capture and storage	140	130
Biomass-to-liquid fuels with carbon capture and storage	150	115
Coal-to-liquid fuels without carbon capture and storage	65	120
Coal-to-liquid fuels with carbon capture and storage	70	90
Coal-and-biomass-to-liquid fuels without carbon capture and storage	95	120
Coal-and-biomass-to-liquid fuels with carbon capture and storage	110	100

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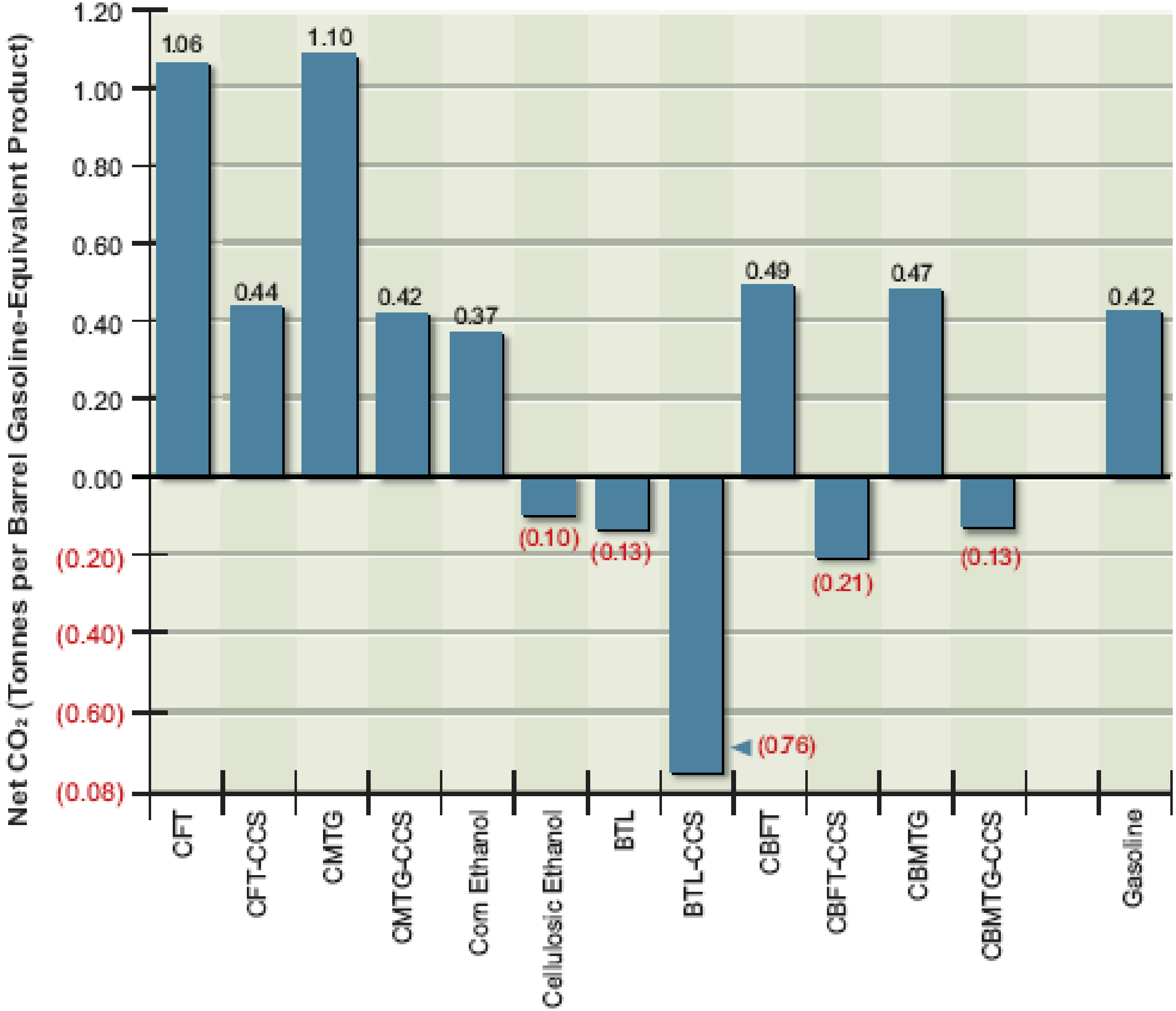
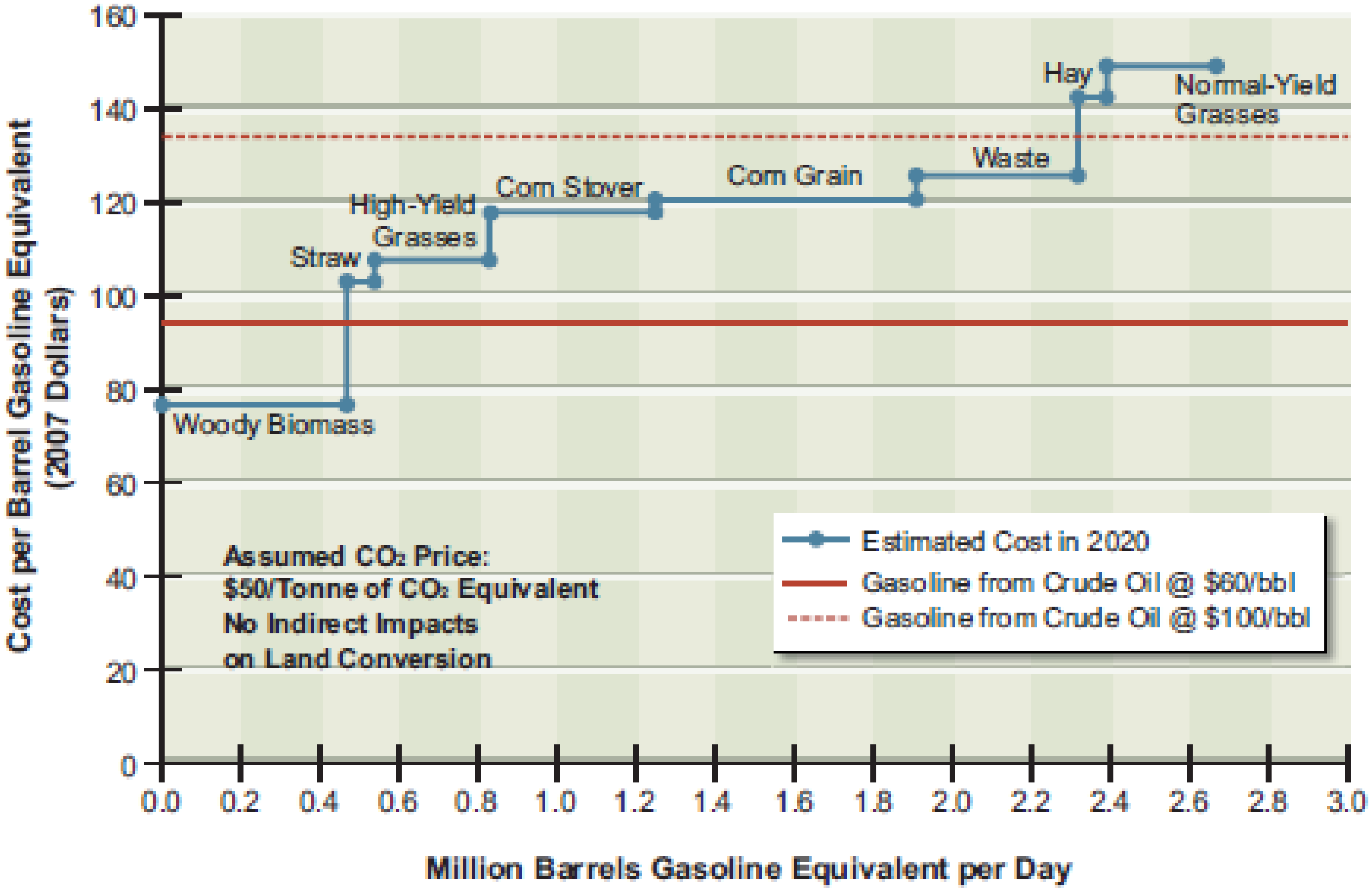
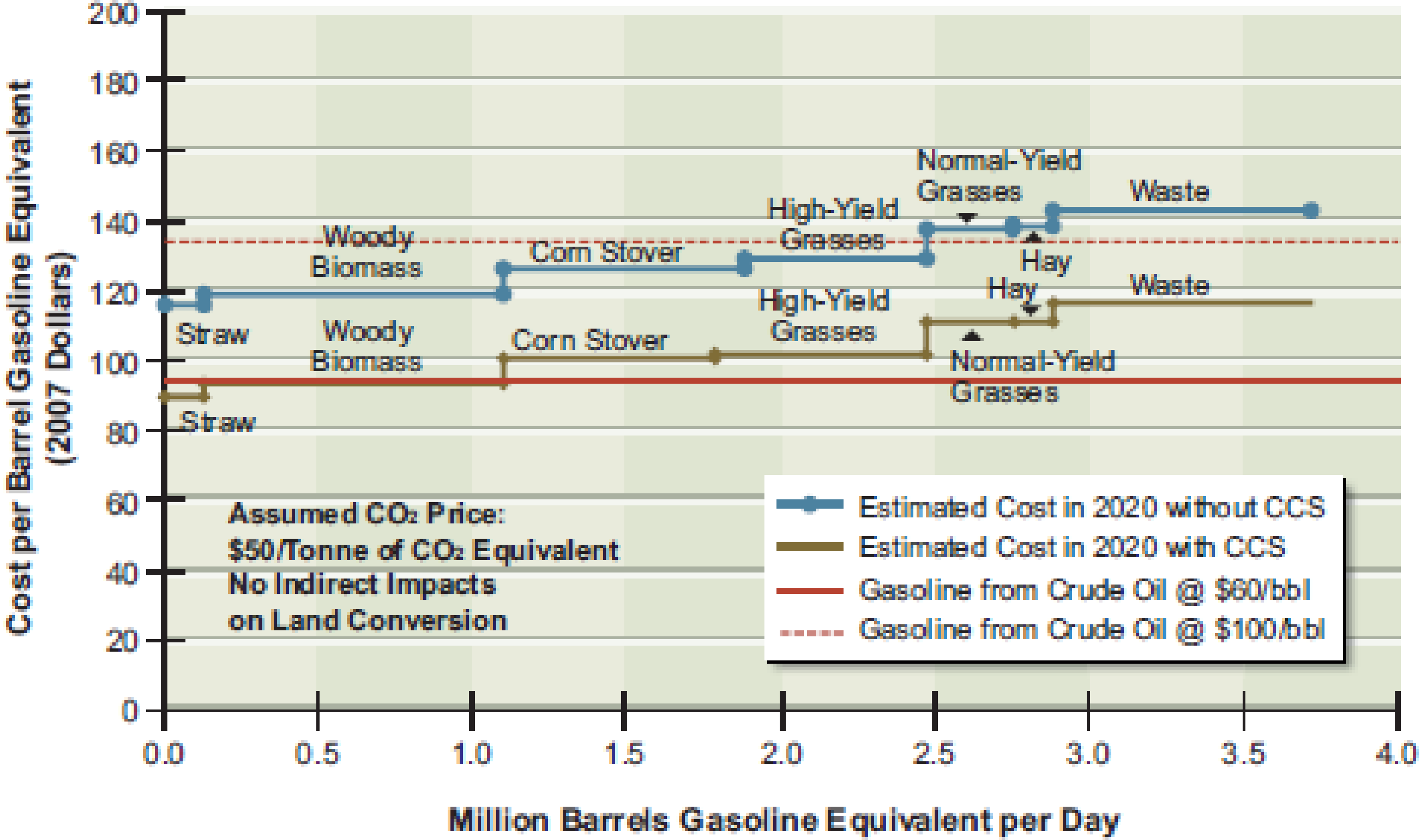
COMPARISON OF CO_2 LIFE-CYCLE EMISSION



SUPPLY OF CELLULOSIC ETHANOL—TECHNICALLY FEASIBLE



SUPPLY OF COAL-AND-BIOMASS-TO-LIQUID—TECHNICALLY FEASIBLE



SUPPLY OF ALTERNATIVE LIQUID FUELS—COMMERCIAL DEPLOYMENT

Cellulosic Ethanol

- 0.5 million bbl of gasoline eq./day by 2020,
- Then 1.7 million bbl of gasoline eq./day by 2035.
- CO_2 emissions close to zero

Coal-and-Biomass-to-Liquid (CBTL) Fuels

- CBTL fuels could reach 2.5 million barrels of gasoline eq./day by 2035.
- CO_2 emissions close to zero with CCS

Coal-to-Liquid (CTL) Fuels

- Then CTL fuels can reach 3 million bbl of gasoline eq./day by 2035, with a 50 percent increase in US coal production.
- If CCS used, CO_2 emission equivalent to petroleum fuels

BARRIERS TO DEPLOYMENT

- Developing a well-organized and sustainable cellulosic biofuel industry
- Implementing commercial demonstrations of conversion processes ASAP
- Completing megatonne geologic storage demonstrations ASAP
- Developing more efficient, economical pretreatment and improving enzymes to free up sugars
- Permitting and constructing tens to hundreds of conversion plants
- Approaches that recognize commodity prices, especially oil prices, vary widely.

CONCLUSION

Liquid transportation fuels from coal and biomass have potential to supply 2-3 MBPD of oil equivalent fuels with significantly reduced CO_2 emissions by 2035

- And thus play an important role in addressing issues of energy security, supply diversification, and CO_2 emissions

- But their commercial deployment by 2020 will require aggressive large-scale demonstration in the next few years.

- Investor confidence will most likely require a carbon price or fuel mandates with specified reductions in GHG emissions

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- BP America
- Dow Chemical Company Foundation
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- General Motors Corporation
- Intel Corporation
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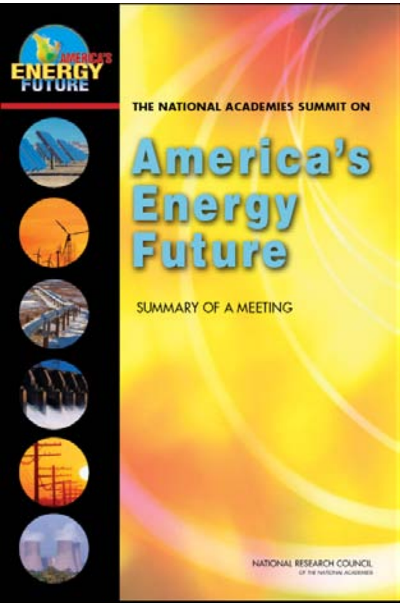
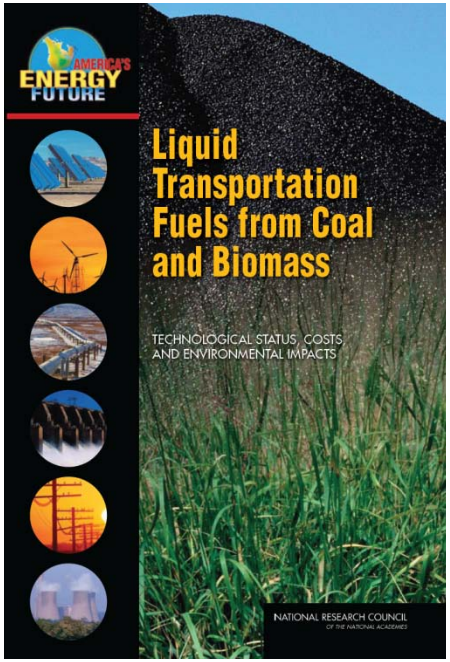
Backup Slides

Additional Information on the America's Energy Future Effort

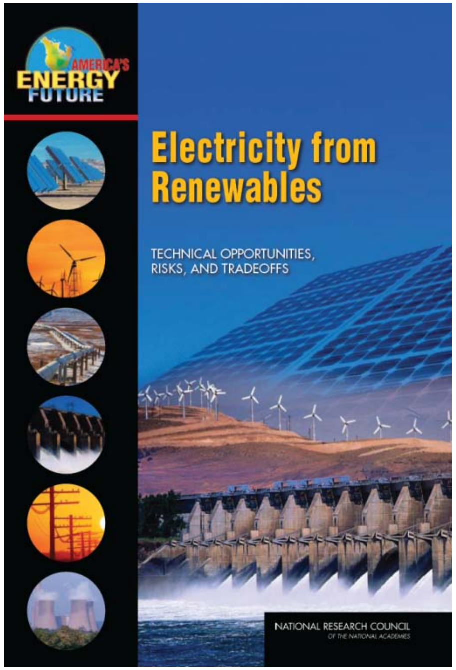
www.nationalacademies.org/energy



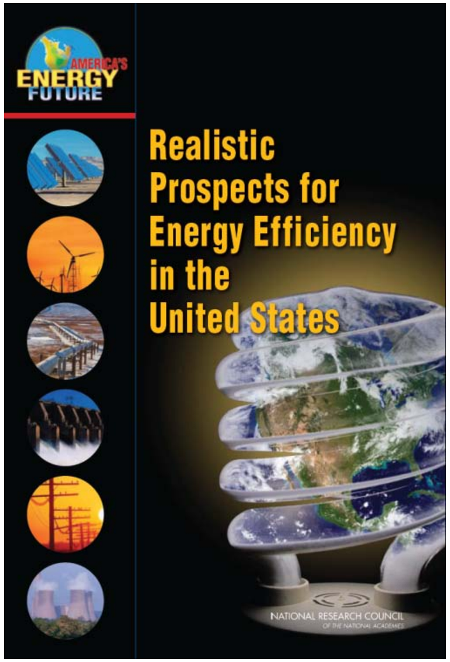
October 2008



May 20, 2009



June 15, 2009



December 9, 2009

Final Report, July 28, 2009

America's Energy Future: Technology and Transformation

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PANEL'S APPROACH

- Biomass Supply
  - Estimated supply and costs of different cellulosic feedstocks.
- Biochemical and Thermochemical Conversion
  - Estimated costs and performance of the conversion processes.
  - Estimated CO_2 emissions from the conversion processes and the burning of the fuel.

Biochemical feedstock : biomass.
Thermochemical feedstock : coal, biomass, or coal + biomass.

PANEL'S APPROACH (cont)

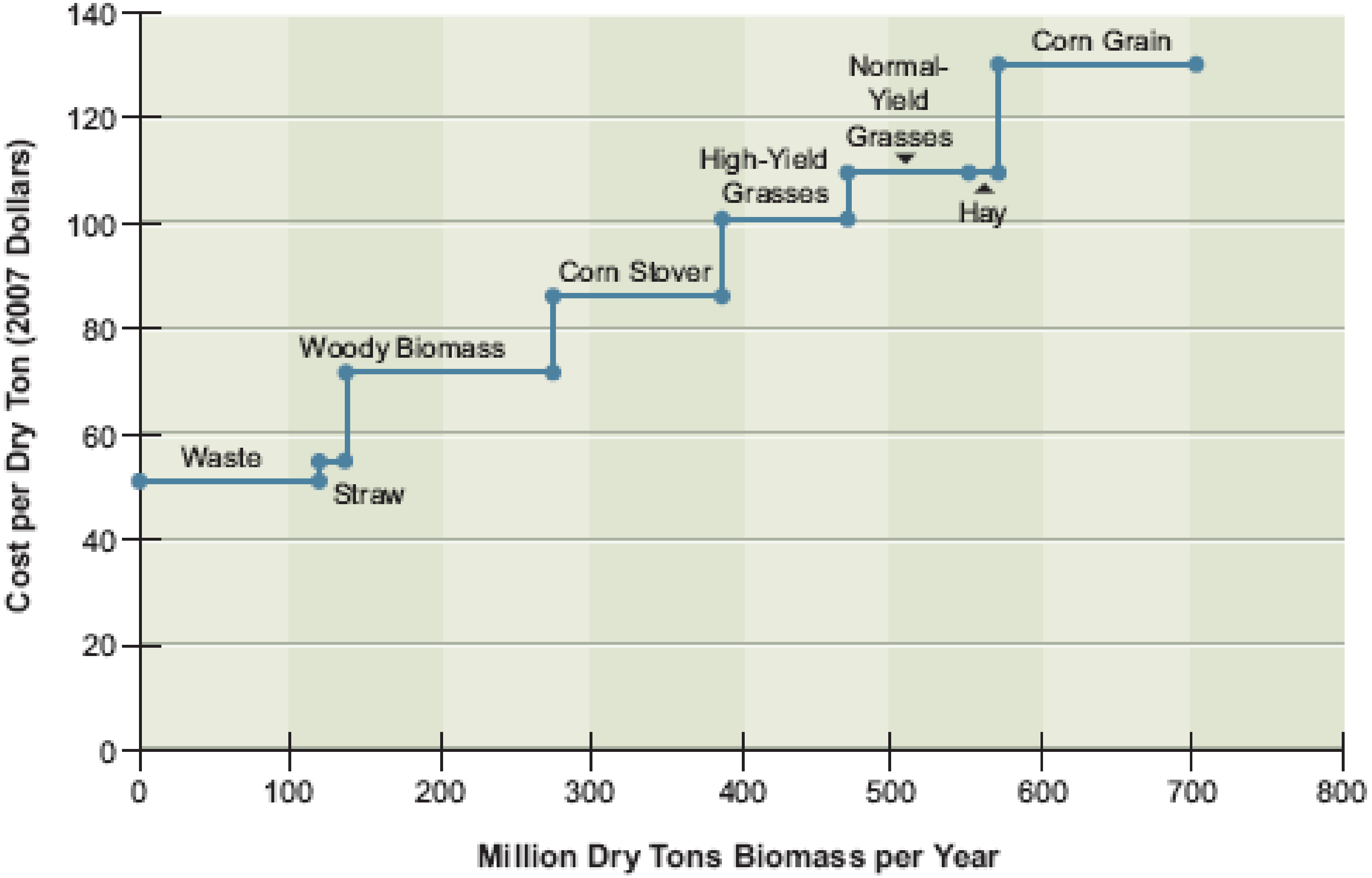
- Compared life-cycle costs and CO_2 emissions of biofuels, coal-to-liquid fuels, and coal+biomass-to-liquid fuels on a consistent basis.

- Estimated amount of fuels that is technically feasible to deploy by 2020.

- Estimated market penetration of fuels in 2020 and 2035.

The panel's analyses include input from Princeton University, University of Minnesota, Massachusetts Institute of Technology, Purdue University, Iowa State University, USDA and others who presented to the panel.

Supply function for biomass feedstocks in 2020



BIOCHEMICAL CONVERSION OF POPLAR TO ETHANOL—KEY ASSUMPTIONS AND COSTS

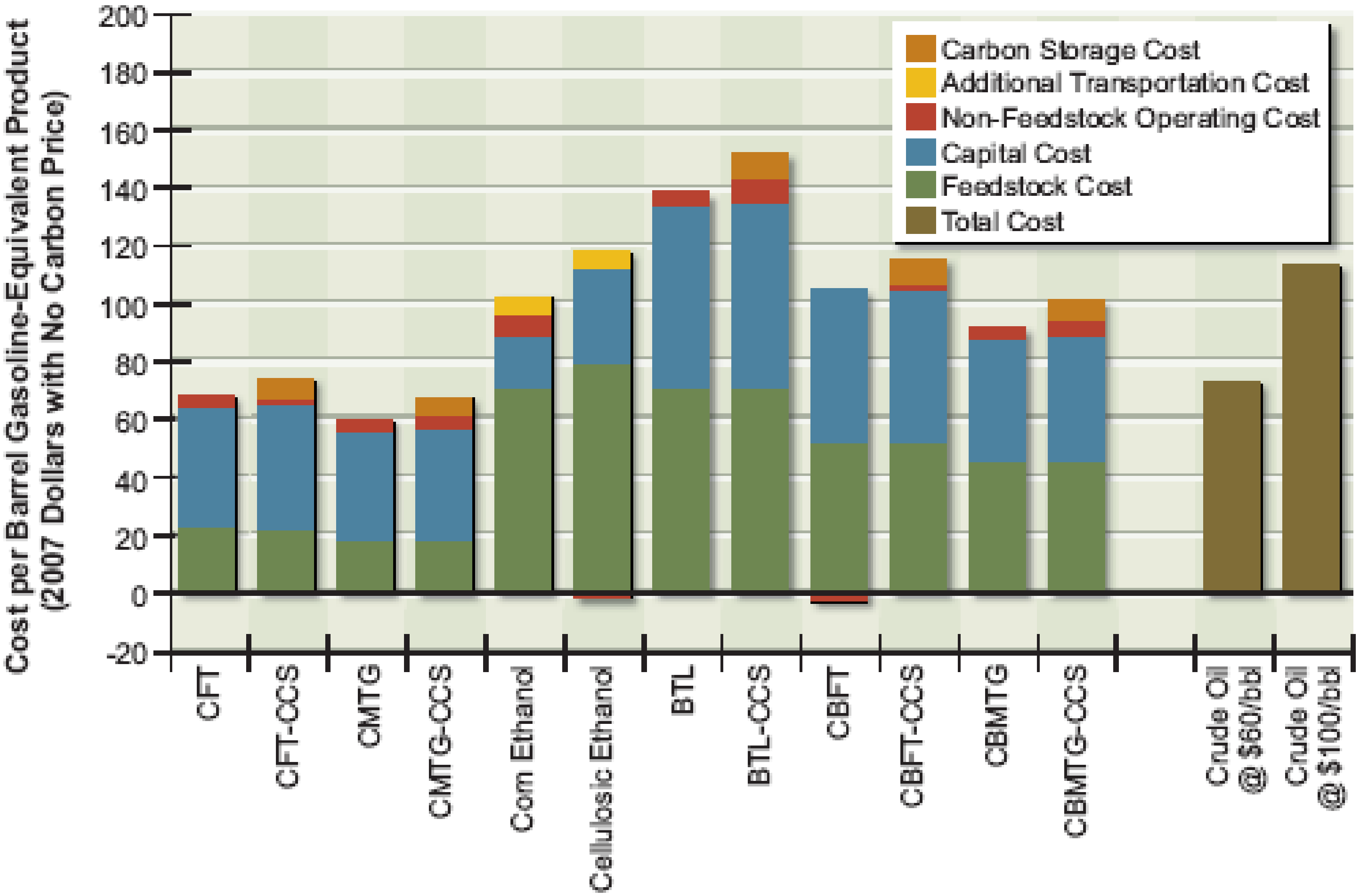
Deployable year	**Current**	**2020**	**2020**
Plant Capacity gal/yr	40 M	40 M	100 M
Feedstock rate dt/d	1.5k	1.5k	4 k
Pretreatment yield	80%	85%	85%
Cellulase cost $/gal	$0.40	$0.25	$0.25
Ethanol yield, gal/dt	67	78	78
Ethanol production cost ($/gal, gasoline equil)	4.00	3.00	2.70

- SuperPro Designer Modelling – Grain Ethanol Validated

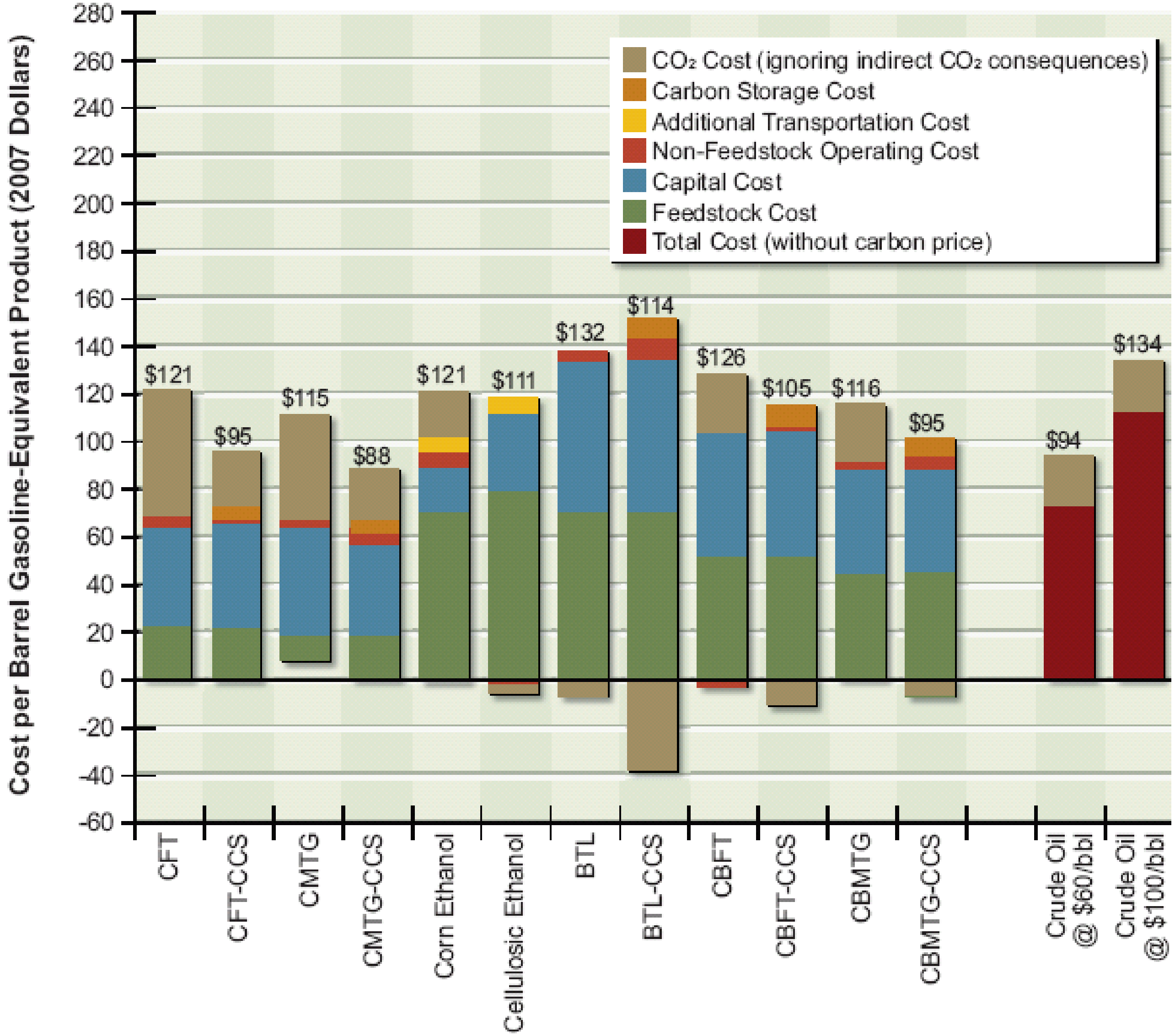
THERMOCHEMICAL CONVERSION OF COAL, BIOMASS OR COMBINED BIOMASS—KEY ASSUMPTIONS, OUTPUTS, AND COSTS

	CTL FT With CCS	CBTL FT With CCS	BTL FT With CCS
Coal, tons/day	26,700	3,030	0
Biomass, tons/day	0	3,950	3,950
Total liquid fuels, bbl/d	50,000	10,000	4,410
Specific total plant cost, $/bbl per day	98,900	134,000	147,000
Total liquid fuels cost, $/gal gasoline equivalent	1.64	2.52	3.32
Breakeven oil price, $/bbl	68	103	139
FT liquids per petroleum-derived diesel emissions	1	0	-1.4

COMPARISON OF LIFE-CYCLE COSTS



Cost of alternative liquid fuels produced from coal, biomass, or coal and biomass with a CO_2 equivalent price of $50/tonne.



EFFECT OF LIFE-CYCLE GREENHOUSE GAS PRICE ON FUEL COST – for $0 and $50/tonne CO_{2eq} price

Fuel Product	Cost without CO_2 Equivalent Price ($/bbl gasoline equivalent)	Cost with CO_2 Equivalent Price of $50/tonne ($/bbl gasoline equivalent)
Gasoline at crude-oil price of $60 and $100/bbl	75, 115	95, 135
Cellulosic ethanol	115	110
BTL without CCS	140	130
CTL with CCS	70	90
CBTL without CCS	95	120
CBTL with CCS	110	100

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BARRIERS TO DEPLOYMENT—Conversion

Thermochemical Conversion

- Implementing commercial demonstration of conversion processes integrated with geologic storage ASAP
- Completing Megatonne geologic storage demonstrations to resolve siting, operating, monitoring and regulatory issues, and to establish safety and efficacy

Biochemical Conversion

- Implementing commercial demonstration
- Developing more efficient, economical pretreatment to free up sugars from celluloses and hemicelluloses.
- Discovering better enzymes that are not subject to end-product inhibition.

BARRIERS TO DEPLOYMENT—Market Penetration

- Approaches that recognize commodity prices, especially oil prices, vary widely.

- Permitting and constructing tens to hundreds of conversion plants and the associated, water requirements, fuel transport and delivery infrastructure

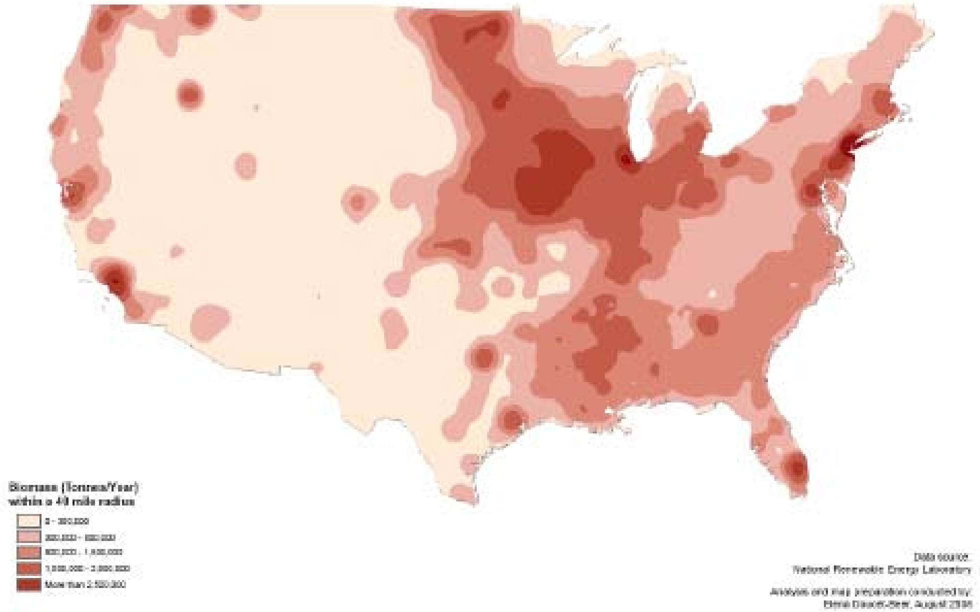
EFFECT OF LIFE-CYCLE GREENHOUSE GAS PRICE ON FUEL COST – for $0 and $50/tonne CO_{2eq} price

Fuel Product	Cost without CO_2 Equivalent Price ($/bbl gasoline equivalent)	Cost with CO_2 Equivalent Price of $50/tonne ($/bbl gasoline equivalent)
Gasoline at crude-oil price of $60 and $100/bbl	75, 115	95, 135
Cellulosic ethanol	115	110
BTL without CCS	140	130
CTL with CCS	70	90
CBTL without CCS	95	120
CBTL with CCS	110	100

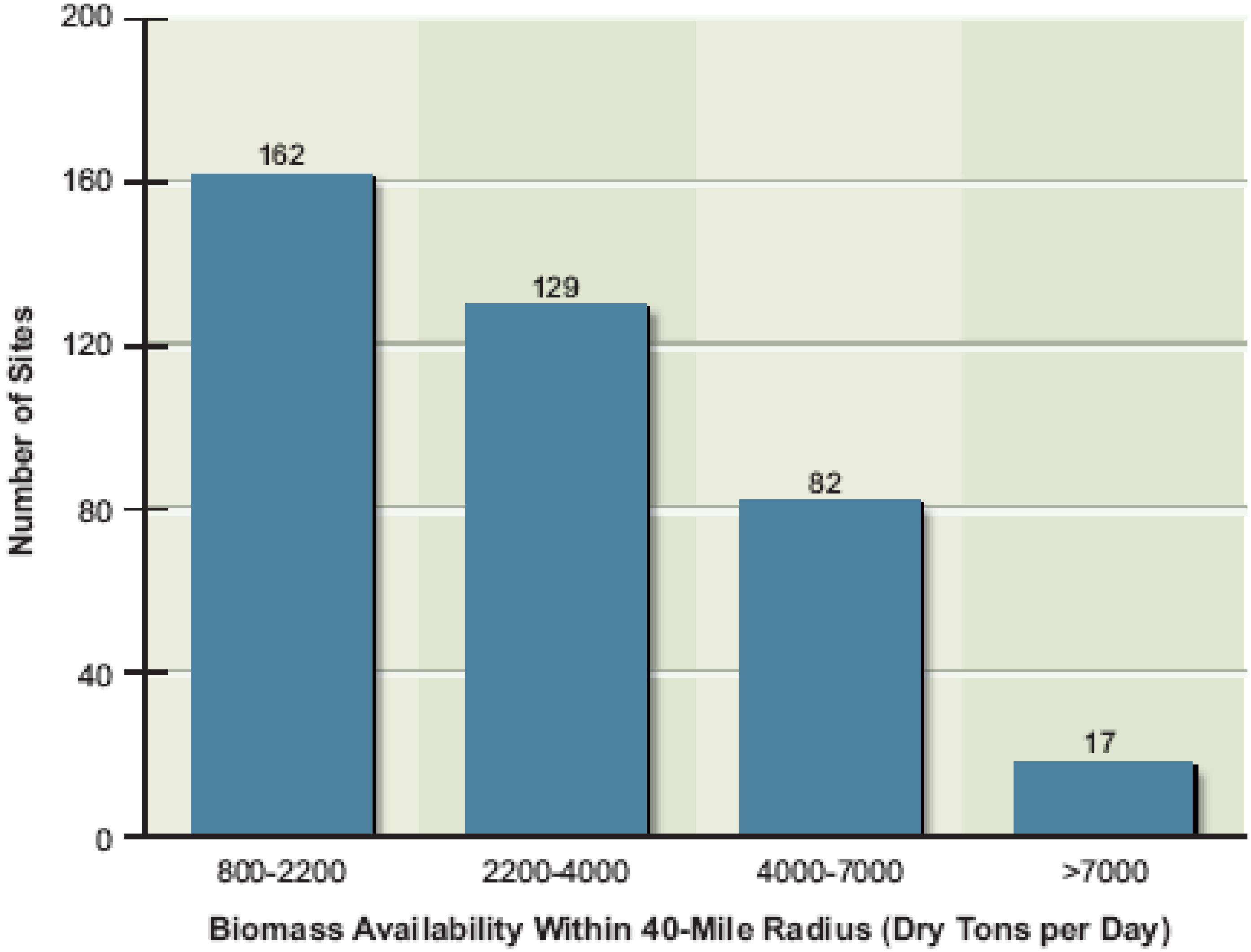
BIOMASS COSTS

Willingness-To-Accept Price per Dry Ton ($)					
Biomass	**Low Cost**	**50% Low (2020)**	**Baseline (2008)**	**50% High**	**High Cost**
Corn stover	65	**86**	**110**	140	175
Switchgrass	93	**118**	**151**	199	286
Miscanthus	82	**101**	**123**	150	186
Prairie grasses	79	**101**	**127**	179	273
Woody biomass	59	**72**	**85**	104	124
Wheat straw	40	**55**	**70**	97	123

Geographic distribution of potential biomass supply for biofuel production. Shading shows the annual supply of all potential biomass feedstocks within a 40-mile radius of any point in the lower 48 states.



Number of sites in the United States with a potential to supply indicated daily amounts of biomass within a 40-mile radius.



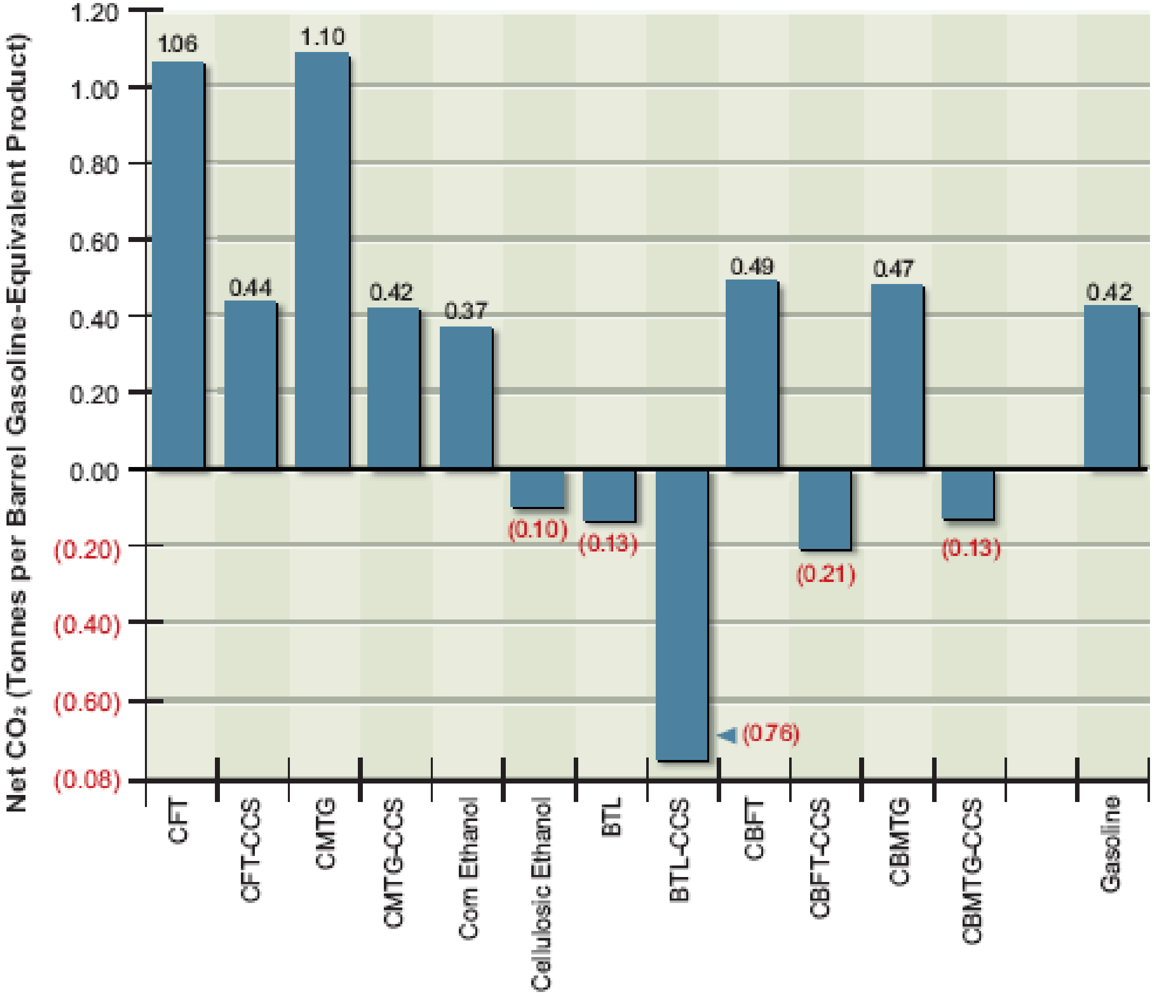
BIOCHEMICAL CONVERSION OF POPLAR TO ETHANOL—KEY ASSUMPTIONS AND COSTS

Variable Deployable	Low Current	Medium 2020	High 2020+
Size of conversion plant	40 M gal/yr	40 M gal/yr	40 M gal/yr
Solids loading	18%	21%	25%
Pretreatment yield	80%	85%	95%
Cellulase cost	$0.40/gal	$0.25/gal	$0.10/gal
Ethanol yield, gal/dt	67	78	87
Total capital ($ millions)	$223 M	$194 M	$174 M
Ethanol production cost ($/gal, gasoline equil)	4.00	3.00	2.30

- SuperPro Designer Modelling – Grain Ethanol Validated

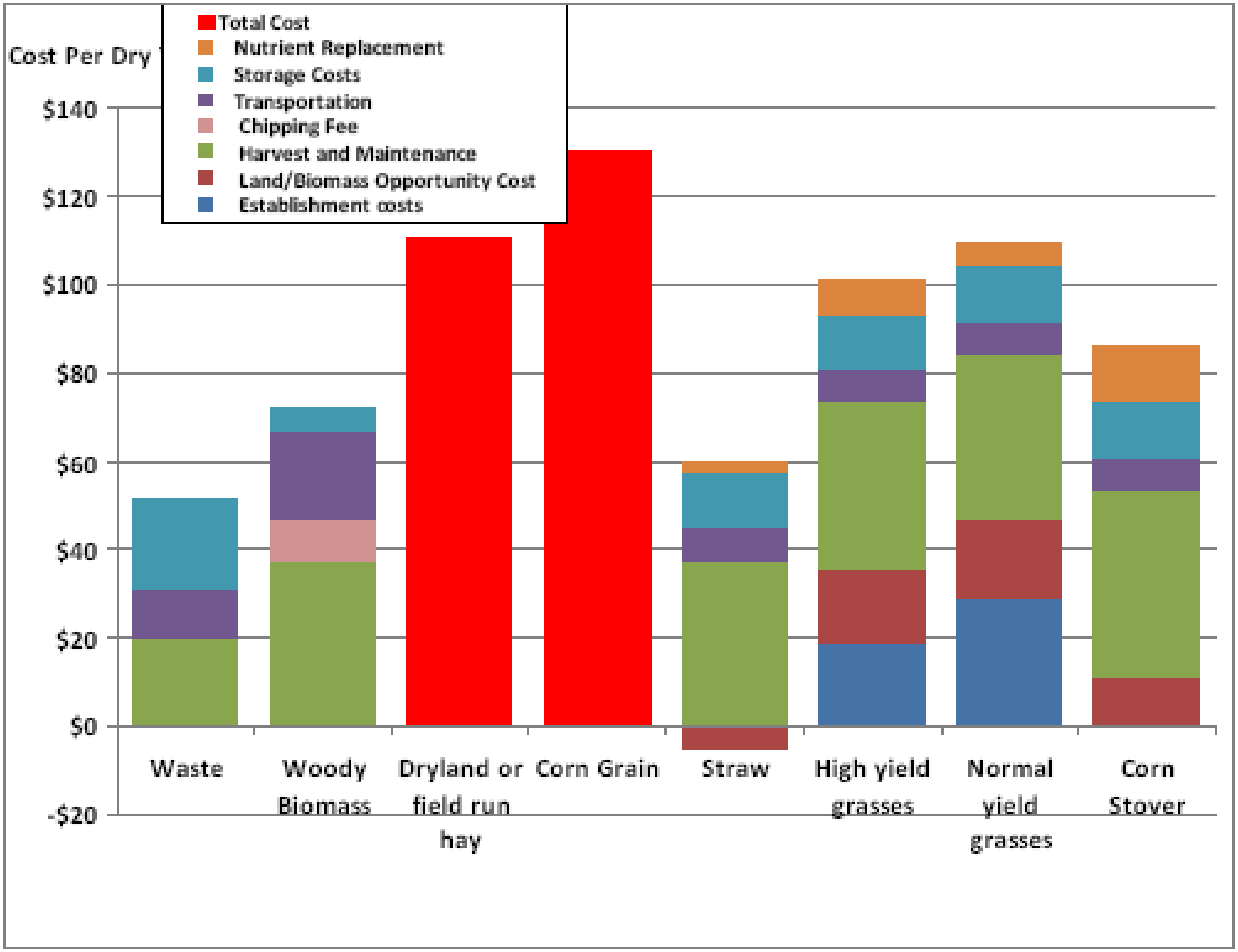
- Biomass feed rate = 1,500,000 DT/Day

COMPARISON OF CO_2 LIFE-CYCLE EMISSION

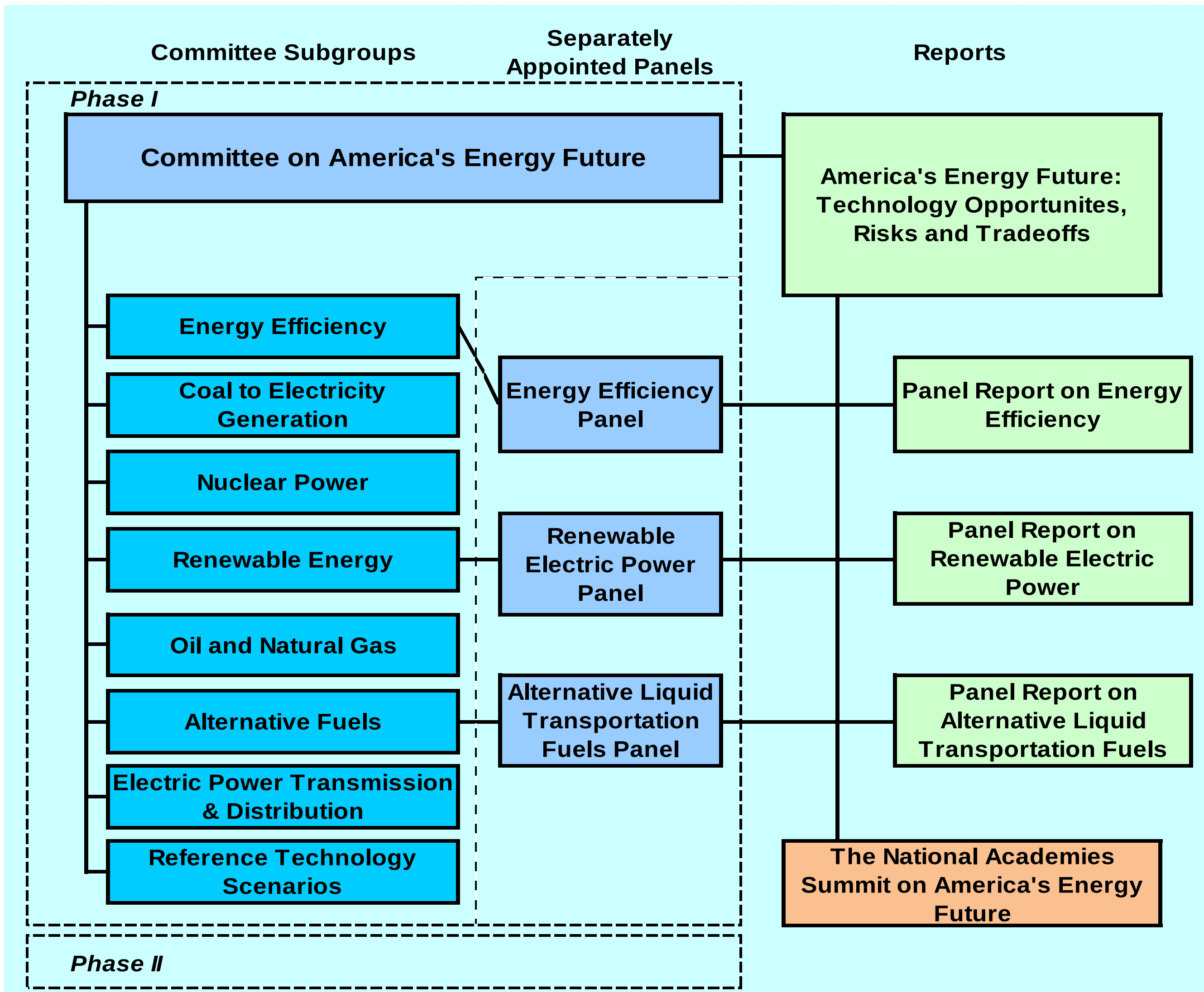


Analysis assumes that conversion plants sell net electricity to the grid. Electricity-related CO_2 emissions are dependent on the case: IGCC venting CO_2 for vent cases, and IGCC-CCS(90%) for CO_2 storage cases.

Estimated Biomass Input Costs in 2020



America's Energy Future: *Technology Opportunities, Risks and Tradeoffs*



SUPPLY OF ALTERNATIVE LIQUID FUELS— COMMERCIAL DEPLOYMENT

Cellulosic Ethanol

- If commercial demonstration successful,
- Commercial deployment begins in 2015,
- Capacity growth = 50 percent each year,
- Then 0.5 million bbl of gasoline eq./day by 2020,
- Or 1.7 million bbl of gasoline eq./day by 2035.

Coal-and-Biomass-to-Liquid (CBTL) Fuels

- If commercial demonstration of CBTL with carbon capture and storage (CCS) is successful,
- First commercial plants start up in 2020,
- Capacity growth = 20 percent each year,
- Then CBTL fuels could reach 2.5 million barrels of gasoline eq./day by 2035.

SUPPLY OF ALTERNATIVE LIQUID FUELS—COMMERCIAL DEPLOYMENT

Coal-to-Liquid (CTL) Fuels

- If commercial demonstration of CTL plants with CCS is successful,
- First commercial plants start up in 2020,
- Growth capacity = 2-3 plants each year,
- Then CTL fuels can reach 3 million bbl of gasoline eq./day by 2035,
- U.S. coal production will increase by 50 percent.