Ethanol-The Primary Renewable Liquid Fuel

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International Fuel Ethanol Workshop and Expo
June 2011
Indianapolis

Perspective paper by Rathin Datta, Mark Maher, Coleman Jones, and Richard Brinker
J. Chemical Technology and Biotechnology, 2011,
86: 473-480, Society of Chemical Industry

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Primary topics

1. Renewable biomass feedstocks that are efficiently and easily available are highly oxygenated

2. Ethanol is the primary renewable liquid transportation fuel with a long history of very good performance

3. Ethanol can be produced with high yields and efficiency with some conversion technologies – particularly the "Hybrid" of gasification with bioconversion – that have developed to the commercial implementation stage

4. Longer chain alcohols, lipids or hydrocarbons cannot be derived from renewable carbon sources with equivalent yields

5. Large quantities of renewable and sustainable biomass feedstocks to produce ethanol are available in the US and many other parts of the world

- ***Thus ethanol is and should continue to be the major renewable liquid fuel.***

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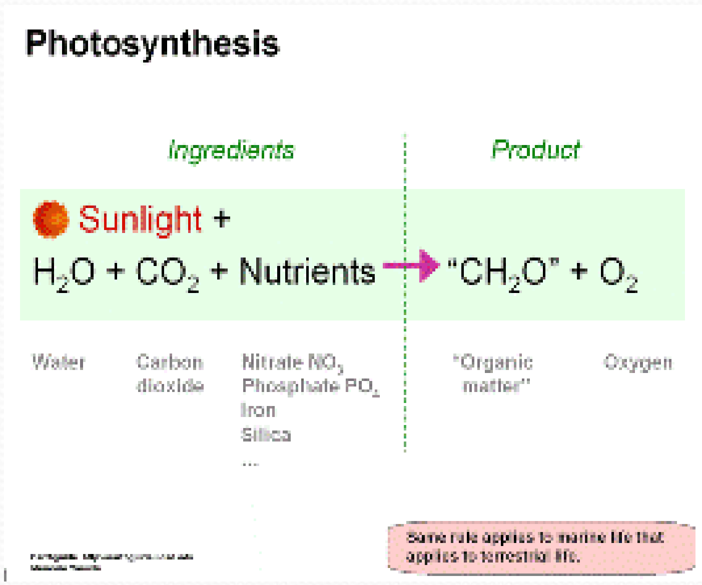
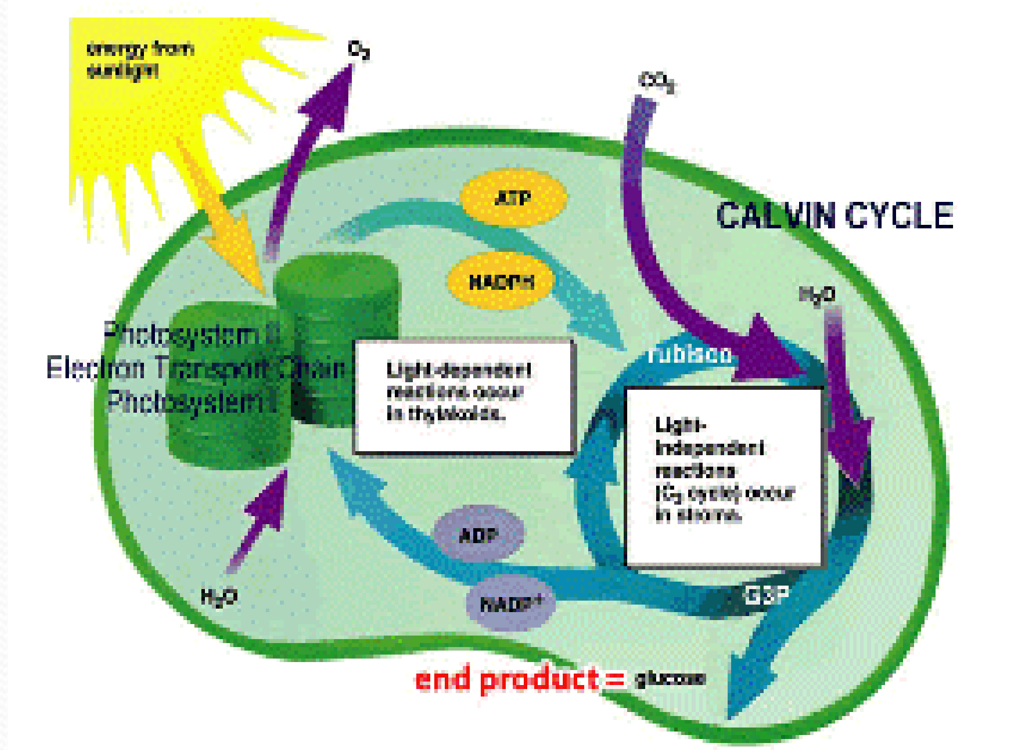
Photosynthesis and biomass composition

- CO_2 is fixed in nature in a complex but well balanced system – the primary composition of "photosynthate" – "CH_2O"





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High yielding biomass composition

- **Typical high yielding biomass composition – C $H_{1.45}$ $O_{0.65}$**
  (Biomass Feedstock Composition and Property Database – U.S. DOE, www.afdc.energy.gov/biomass/progs/search)
  - Irrespective of Species
  - Sustainable yields – 3 to 6 Tons/acre

Biomass feedstock	C (% mass)	H (% mass)	O (% mass)	Composition CHO
Hybrid Poplar	49.8	6.1	41.5	$CH_{1.47}O_{0.63}$
Black Locust	49.9	6.1	41.6	$CH_{1.47}O_{0.63}$
Eucalyptus	49.9	5.9	42.5	$CH_{1.42}O_{0.64}$
Monterey Pine	50.2	6.0	42.1	$CH_{1.44}O_{0.64}$
Corn Stover	46.7	5.5	40.6	$CH_{1.41}O_{0.65}$
Sugarcane bagasse	47.6	5.7	41.4	$CH_{1.44}O_{0.65}$
Switchgrass	48.0	5.7	40.0	$CH_{1.43}O_{0.63}$

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Production of More Reduced Feedstock - Oils, Fats, Hydrocarbons – Loss of Yield

- This is fundamental and governed by laws of electron balances and Thermodynamics
  - Independent of species or production systems – terrestrial or aquatic plants or algae
  - More "photosynthate" "CH_2O" units required per molecule –
    - e.g. 14 $CH_2O \rightarrow C_9H_{19}COOH + 4\ CO_2 + 4\ H_2O$
      - (theoretical yield 41%; actual is lower 20 -30%)

- Typical vegetable oils produced annual crops or plantations
  - 0.2 to 1 ton/acre/yr

The Winning Strategy

- Hence, based on the fundamentals of photosynthesis and laws of thermodynamics, the biomass feedstocks that are and will be efficiently available are highly oxygenated and are lignocellulosic materials.

- ***For liquid fuel or chemical production from this feedstock, the winning strategy is to produce a product that has proven and widespread use, with the highest yield using the entire feedstock***

  – and that is ethanol.

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Performance as liquid transportation fuel

- Long history of use as a liquid transportation fuel
  - Henry Ford – 1908 in the original Model T
  - Has been blended with gasoline (ranging from 3% to 85%) in many countries for decades
- Suitable for "spark ignition "Otto" cycle engines
  - 80% of the vehicles run on this type of engine
  - About 650 million worldwide
- The automobile manufacturers have successfully adapted their technology to handle ethanol gasoline blends
- In the US
  - E 10 vehicles started in the 1970s
  - In the 1990s the industry began to develop E85 (blend of 70 to 85% ethanol in gasoline)
  - Currently all vehicles are E10
  - About 9 million are E85 and that number is growing rapidly

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Ethanol's properties: Lower emissions, higher engine efficiency

Comparative properties between ethanol and gasoline

- Some of these properties lead to less emissions and increase in engine efficiency
- Numerous studies on emissions have been conducted
  - Reduction of carbon monoxide, VOC, SO_2
  - References on "Ethanol Fact Book" - Ethanol Fact Book, Clean Fuels Development Coalition, www.cleanfuelsdc.org, 60p. (2010).

Fuel	Density, gm/ml	Oxygen content m/m	Boiling Point C	Vapor pressure at 37.8C, kPa	Heat of Vaporization J/g	Water Solubility	Research Octane (RON)	Motor Octane (MON)	Conductivity µS/cm
Ethanol	0.7893	0.347	78.5	16	0.92	Miscible	108	92	6
Gasoline	0.72-0.78	0	25-225	35-110	0.36	Negligible	90-98	82-90	1E-8

Higher engine efficiency can be achieved

- Ethanol's properties
  - High octane number leads to higher compression ratios
  - High heat of vaporization also allows higher compression
  - Faster flame propagation
- High ethanol containing blends (E85) actually give higher engine efficiency
- Recent EPA certification data (2010 vehicles) with E85
  - Average 2 % increase in engine efficiency
  - For GM cars – average 3.2 % increase

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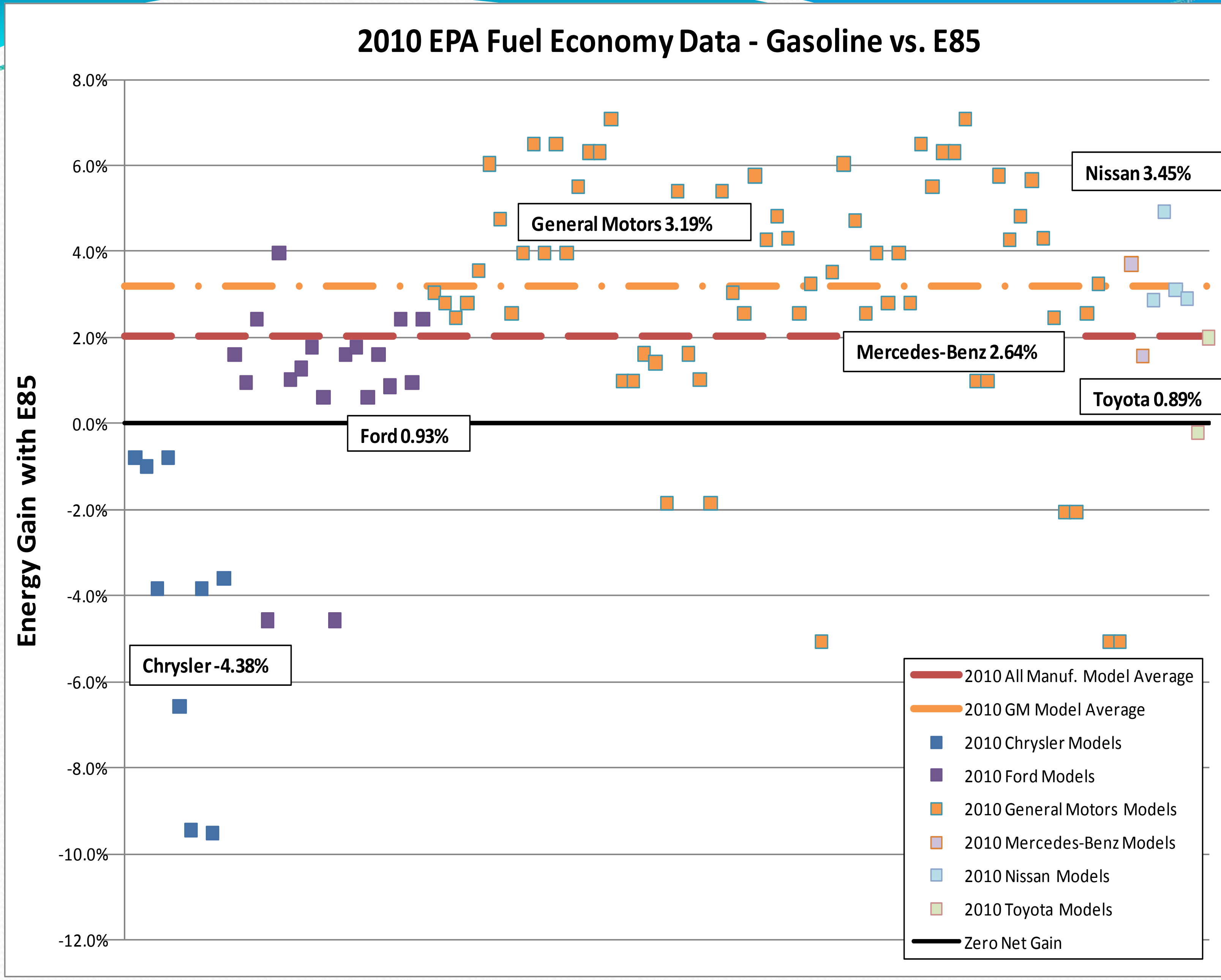
2010 EPA Fuel Economy Data - Gasoline vs. E85
Energy Gain with E85
8.0%
6.0%
4.0%
2.0%
0.0%
-2.0%
-4.0%
-6.0%
-8.0%
-10.0%
-12.0%
General Motors 3.19%
Nissan 3.45%
Mercedes-Benz 2.64%
Toyota 0.89%
Ford 0.93%
Chrysler -4.38%
2010 All Manuf. Model Average
2010 GM Model Average
2010 Chrysler Models
2010 Ford Models
2010 General Motors Models
2010 Mercedes-Benz Models
2010 Nissan Models
2010 Toyota Models
Zero Net Gain

Transition to Electricity – Ethanol fits very well

- Lot of popular interest and news on this subject
- Recent high level study and report by the National Research Council has been published to put this subject in appropriate technical, feasibility, timing and commercial context

  National Research Council, NRC report, ISBN: 0-309-14851-0, 70 p. (2010)
- The report has looked at various rates of penetration from the 'Maximum Practical' to a 'Realistic' rate considering the high cost of batteries, modest gasoline savings, limited availability of places to plug in, competition from other vehicles, consumer resistance to plugging in virtually every day and continuing government support for several decades.
- Regarding the effect on oil consumption the report concludes

  "PHEVs will have little impact on oil consumption before 2030 because there will not be enough of them in the fleet. More substantial reductions could be achieved by 2050 but will reduce oil consumption only slightly more than can be achieved by just the hybrid vehicles (HEVs)".
- Hence, liquid fuels will be required and will be the primary fuel for decades while this transition takes place.
- ***Ethanol as a renewable liquid fuel would be a very good fit***

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Key points established

- Based on the fundamentals of photosynthesis and laws of thermodynamics, the biomass feedstocks that are and will be efficiently available are highly oxygenated and are lignocellulosic materials.
- Ethanol is the primary renewable liquid transportation fuel with a long history of very good performance
- Ethanol fits very well into the future of combination of electricity and renewable liquid fuel for transportation

- ***The winning strategy is to produce ethanol, a product that has proven and widespread use, with the highest yield using the entire feedstock***

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Conversion technology, yield and efficiency

- **Ethanol, butanol, hydrocarbons – the yield issue**
  - Butanol or other reduced hydrocarbon production from biomass
  - A lot of recent discussions on these more reduced, so called "Drop In" products.
  - The yields are governed by the same laws of electron balances and thermodynamics and would thus be considerably lower than that of ethanol.
  - None of these "Drop In"s have the proven record of widespread use in automobile transportation

Comparative yields of ethanol vs. other reduced products

Product	Chemical Equation	Theoretical Yield (w%)	Typical Yields Achieved	Comments
Ethanol	3"CH_2O" → C_2H_5OH + CO_2	51%	46 to 50%	90 to 98% of theoretical yields achieved in industrial carbohydrate fermentations
n-Butanol or iso-Butanol	6"CH_2O"→ C_4H_9OH + 2 CO_2 + H_2O	41%	23 to 25%	55 to 60% of theoretical yields achieved in industrial scale ABE fermentations (11)
Octane C8-Hydrocarbon	13 "CH_2O" → C_8H_{20} + 5CO_2 + 3H_2O	29.7	N.A.	Wide ranging mix of hydrocarbons and oxygenates are produced in catalytic processes – not practiced industrially

Conversion technology paths for ethanol

1. The **Biochemical path** uses enzymes to convert pretreated lignocellulosic biomass materials into sugars which can then be fermented into ethanol.
2. The **Thermochemical path,** a biomass feedstock is gasified to produce syngas (carbon monoxide, hydrogen and carbon dioxide) which is then converted into ethanol by a chemical reaction utilizing chemical catalysis.
3. The **Hybrid path** combines both the thermochemical and biochemical elements, gasification is used to convert a biomass feedstock into syngas, microorganisms ferment the syngas into ethanol, and the ethanol is then separated from water to produce fuel grade ethanol.
   - converts all the components of the biomass feedstock to the syngas mixture of CO, H2 and CO2 with > 75% efficiency
   - specific anaerobic organisms can convert these to ethanol with >95% theoretical yield.
   - the heat generated in the gasification process provides a portion of the process energy for drying and distillation.

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Conversion technology comparison

	Biochemical (pretreat +enzyme +fermentation)	Thermochemical (gasification +catalysis)	Hybrid (Gasification +fermentation)
Ethanol synthesis technology	Enzymes and Microorganisms	Metal Catalyst	Microorganisms
Feedstock flexibility	**No**	**Yes**	**Yes**
Significant feedstock pre-treatment reqd.	**Yes**	**No**	**No**
Low pressure process	**Yes**	**No**	**Yes**
Selectively produces ethanol	**Yes**	**No**	**Yes**
Yield (gal/dry ton)	72-90*	74-86*	>100[#]

*Yield estimates from DOE's FY2007 State of Technology reports. Low end of range represents 2007 status based on NREL bench scale data and high end represents 2012 NREL targets.

Source Coskata, Inc.

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The "Hybrid" path – progress to commercialization

- **Three companies - Ineos BIO, Coskata, Lanzatech**

Moving from development to demonstration to commercial project

- **INEOS Bio** announced the commercial project in Indian River County in Florida to convert renewable biomass to ethanol using their process that follows the "Hybrid" technology path. This joint venture project between INEOS Bio and NPE Florida is targeted to produce about 30 million liters/year of ethanol
- **Coskata technology progress**
  - In the four years since its inception, Coskata has advanced the technology from the bench to the pilot scale at its Warrenville, Illinois, facility to the demonstration scale in its "Lighthouse" facility in Pennsylvania
  - The Lighthouse facility successfully started up in the third quarter of 2009 and has since generated over 2000 hours of operating data, including hundreds of hours at steady-state operations.
  - The operating results from Lighthouse is validating the base case economic forecasts for its full scale commercial plant.

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Coskata commercial project - Flagship

- **Location SE US**
  - **55 million GPY capacity**
  - **Woody biomass feedstock**

Further economic analysis has shown that this facility will produce fuel-grade ethanol at a very competitive cost point.

Project, when completed and operational ,will:

- Contribute meaningfully to the volume of cellulosic biofuel mandated by the current Renewable Fuel Standard;
- Provide cash flow sufficient to service the debt associated with the Project and allow Coskata to continue to invest in optimizing its technology platform;
- Generate an attractive return on capital employed, and therefore a sustainable return to stakeholders;
- Provide the basis for technology licensing, such that the production capacity for cellulosic ethanol can be expanded in the marketplace as rapidly as possible; and
- Validate a commercial-scale process for producing ethanol as a renewable transportation fuel that is environmentally sustainable
  - From non-food and ag crops
  - Reduces lifecycle greenhouse gas emissions
  - Vastly reduces requirements for scarce resources such as water.

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Key points established

- Based on the fundamentals of photosynthesis and laws of thermodynamics, the biomass feedstocks that are and will be efficiently available are highly oxygenated and are lignocellulosic materials.
- Ethanol is the primary renewable liquid transportation fuel with a long history of very good performance
- Other “Drop in” products will not have the yield advantages of ethanol and do not have the long history performance and usage
- Ethanol fits very well into the future of combination of electricity and renewable liquid fuel for transportation
- The “Hybrid” Technology path provides many advantages
  - Use of all the feedstock components
  - Feedstock flexibility
  - High yield
  - High process efficiency
  - Attractive economics
- This technology is moving to commercialization

Large quantities of renewable and sustainable biomass feedstocks to produce ethanol are available or can become available in the US and many other parts of the world

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Large and sustainable feedstock supply

- **The "Billion Ton Report – 2005**

  The Technical Feasibility of a Billion-Ton Annual Supply, Report of a joint study sponsored by the U.S. Department of Energy and U.S. Department of Agriculture (2005). www.osti.gov/bridge

  - **Primary conclusions**
  - U S is capable of producing a sustainable supply of biomass sufficient to displace 30 percent or more of the country's present petroleum consumption
  - Over 1.3 billion dry tons per year of biomass potential — about 368 million dry tons of sustainably removable biomass could be produced on forestlands, and about 998 million dry tons could come from agricultural lands".

- **Follow up report – Sandia National Laboratory 2009**

  West, T. et al, Feasibility, Economics and Environmental Impact of Producing 90 Billion Gallons of Ethanol per Year by 2030, Report by the Sandia National Laboratory, SAND 2009 – 3076J (2009).

- **Primary conclusions**
  - No theoretical barriers to reaching large volumes (~90 billion gallons/year) of ethanol production.
  - Practical barriers need to be overcome:
    - Sustained effort will be needed to achieve large production goals.
    - Sustained technology improvement in feedstock development and conversion technology is critical.
    - Other practical considerations, such as capital availability and cost, are also significant.
    - Sensitivity analysis - feasible for cellulosic ethanol to be cost competitive with gasoline at oil prices above approximately $90/barrel.
    - Improvements in conversion yield and significant decreases in feedstock and capital costs can make cellulosic ethanol more cost-competitive at lower oil rices

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The Southeastern Forest Industry Experience

Actual experience from the past 70 years in the southeastern US helps to further support the fact that an efficient and sustainable biomass supply can be developed and maintained to support large increased usage.

- **The forest industry evolved over the past 100 years**
  - Early to mid 1900s - Supply of solid wood – lumber and timber for construction
  - From 1920 to 2000 – development and maturation of pulp and paper industry
  - Continuous evolution and improvement of forest management practice
  - Continuous improvement in harvesting technologies
- **Some key achievements**
  - Pulpwood production quadrupled from 1953 to 2006 – from 44 to 177 million tons/yr
  - The volume of standing timber increased 80% - from 60 to 108 billion cu ft
  - The total area of forest land remained stable since the 1970s ~ 214 million acres
  - The land ownership has also remained stable – 89% privately owned
    - 22 percent by the forest industry
    - 21 percent by farmers
    - 12 percent by other corporations
    - 45 percent by other individuals

Conclusions: Ethanol-The Primary Renewable Liquid Fuel

- Based on the fundamentals of photosynthesis and laws of thermodynamics, the biomass feedstocks that are and will be efficiently available are highly oxygenated and are lignocellulosic materials.
- Ethanol is the primary renewable liquid transportation fuel with a long history of very good performance
- Other "Drop in" products will not have the yield advantages of ethanol and do not have the long history performance and usage
- Ethanol fits very well into the future of combination of electricity and renewable liquid fuel for transportation
- Among the conversion technologies:

  The "Hybrid" Technology path provides many advantages
  - **Use of all the feedstock components**
  - **Feedstock flexibility**
  - **High yield**
  - **High process efficiency**
  - **Attractive economics**

  This technology is moving to commercialization
- Large quantities of renewable and sustainable biomass feedstocks to produce ethanol are available or can become available in the US and many other parts of the world
  - Actual experience from the past 70 years in the southeastern US helps to further support the fact that an efficient and sustainable biomass supply can be developed and maintained to support large increased usage.

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