OPPORTUNITIES AND OBSTACLES IN LARGE-SCALE BIOMASS UTILIZATION

The Role of the Chemical Sciences and Engineering Communities

A WORKSHOP SUMMARY

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Chemical Sciences Roundtable

Board on Chemical Sciences and Technology

Division on Earth and Life Studies

Workshop held in 2012
Report published in 2013

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Report: http://www.nap.edu/catalog.php?record_id=14683
Slides and recordings: http://dels.nas.edu/global/bcst/biomass

April 2012

NATIONAL BIOECONOMY BLUEPRINT

Strategic imperatives:

- Support R&D investments that will provide the foundation for the future bioeconomy.
- Facilitate the transition of bioinventions from research lab to market, including an increased focus on translational and regulatory sciences.
- Develop and reform regulations to reduce barriers, increase the speed and predictability of regulatory processes, and reduce costs while protecting human and environmental health.
- Update training programs and align academic institution incentives with student training for national workforce needs.
- Identify and support opportunities for the development of public-private partnerships and precompetitive collaborations—where competitors pool resources, knowledge, and expertise to learn from successes and failures.

http://www.whitehouse.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf

Outline of Biomass Utilization Report

1. The challenge
2. Feedstocks and conversion technologies
3. Fuels and chemicals from biomass via biological routes
4. Fuels and chemicals from biomass via thermochemical routes
5. Heat and power production from biomass
6. Final thoughts

Opportunities

Environmental benefits: cleaner air, reduced GHG emissions

Political benefits: energy self-reliance and diversity of energy supply; positive balance of trade

Economic/social benefits: 300 - 500 biorefineries, each of which could produce 50-75 new direct jobs and 3,000 indirect jobs that cannot be outsourced (esp. in rural areas)

- Biomass can provide liquid fuels, a premium product unmatched in energy density and convenience, which is uniquely suited to our lifestyle
- US airline industry will have to meet European sustainability and biofuels requirements (the emissions trading scheme, EU ETS, requires all domestic and international flights that arrive at or depart from an airport in Europe to pay for the CO_2 they emit or adopt lower carbon advanced biofuels)
- Support/expand US leadership and innovation in chemistry/chemical engineering

Conundrum*

"Biofuels will have to perform all the miracles of sustainability, and still be priced lower than oil."

– Brian Duff, DOE Office of Biomass Program

*co·nun·drum
/kəˈnəndrəm/

Noun

1. a riddle whose answer is or involves a pun
2a. a question or problem having only a conjectural answer
2b. An intricate and difficult problem

Weak links in the biomass supply chain

Supply limits

- All large-scale processes for making fuels from lipid biomass have been shut down because of high feedstock cost
- Current global carbohydrate production (14 million barrels oil equiv./day) is very small compared to crude oil production (85 million barrels oil/day)
- 1.0 – 1.6 billion tons of lignocellulose could be available in U.S. to meet the demand (DOE Billion-Ton study)

"Tyranny of distance"

- Challenges in feedstock harvesting, collection, transportation and seasonal storage: biomass has low energy density, high water content, perishability
- DOE Uniform Feedstock Format: pre-processing depots with 5-20 mile radius to produce a high density pelletized biomass

Process scale

- World's largest ethanol plant produces 175 million gallons/year (12,000 barrels oil equiv./day)
- Large petroleum refinery processes 1 million barrels oil/day
- Smallest economically efficient oil refinery handles 200,000 barrels/day

U.S. BILLION-TON UPDATE

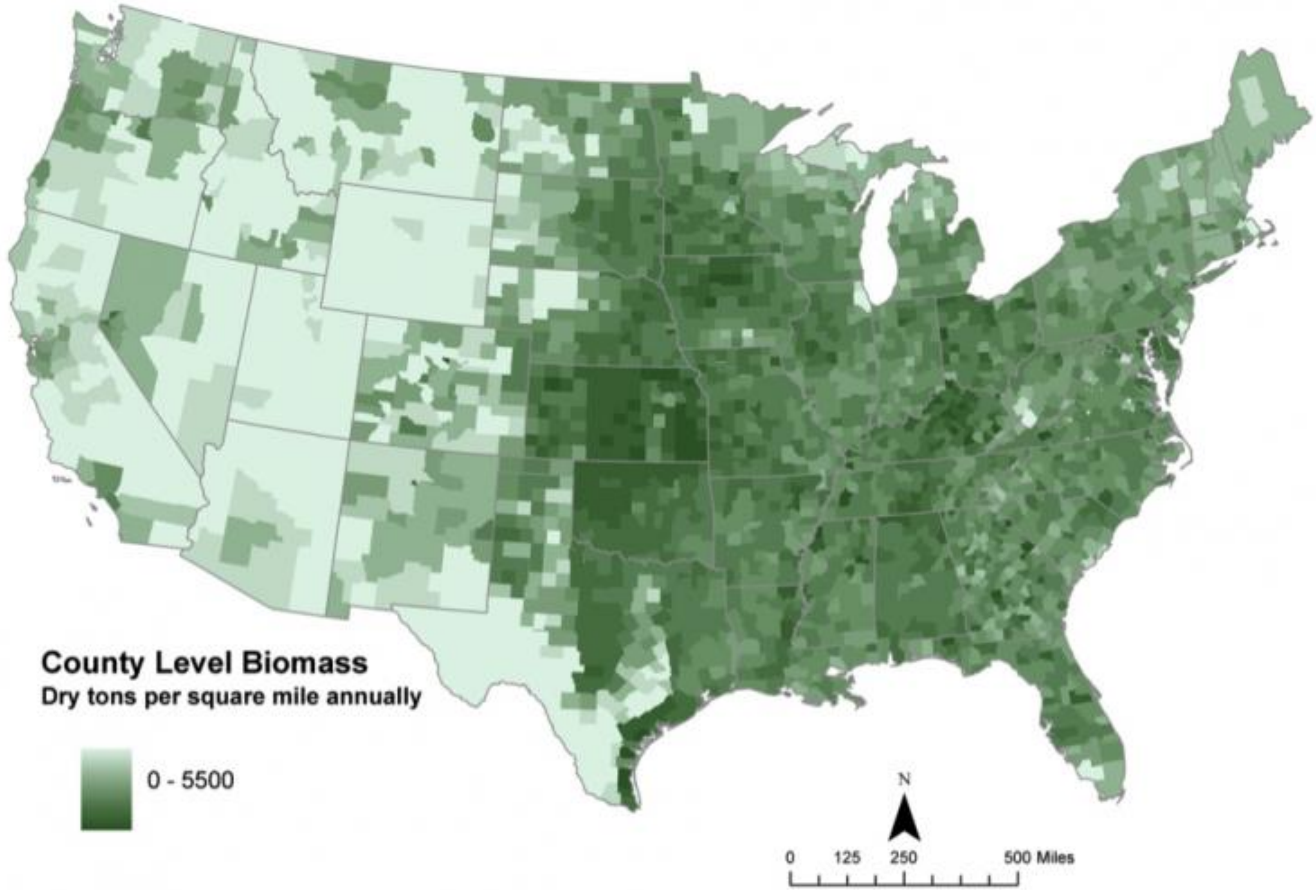
U.S. DEPARTMENT OF **ENERGY**

Biomass Supply for a Bioenergy and Bioproducts Industry

August 2011

Goal: Produce one billion tons of renewable biomass for energy uses by 2030, without impacting US farm and forest products.
Price target: $60/ton or less, without irrigation and with minimum tillage including transportation costs
Outcome: displace up to 30 % of petroleum consumption or produce up to 5 % of electricity used in US – *not a huge fraction of our energy requirements*.

Total potential biomass resources by county in the contiguous U.S.



The baseline scenario shows that biomass resources could be increased from a current 473 million dry tons annually to nearly 1.1 billion dry tons by 2030, even with conservative assumptions about future increases in crop yield.

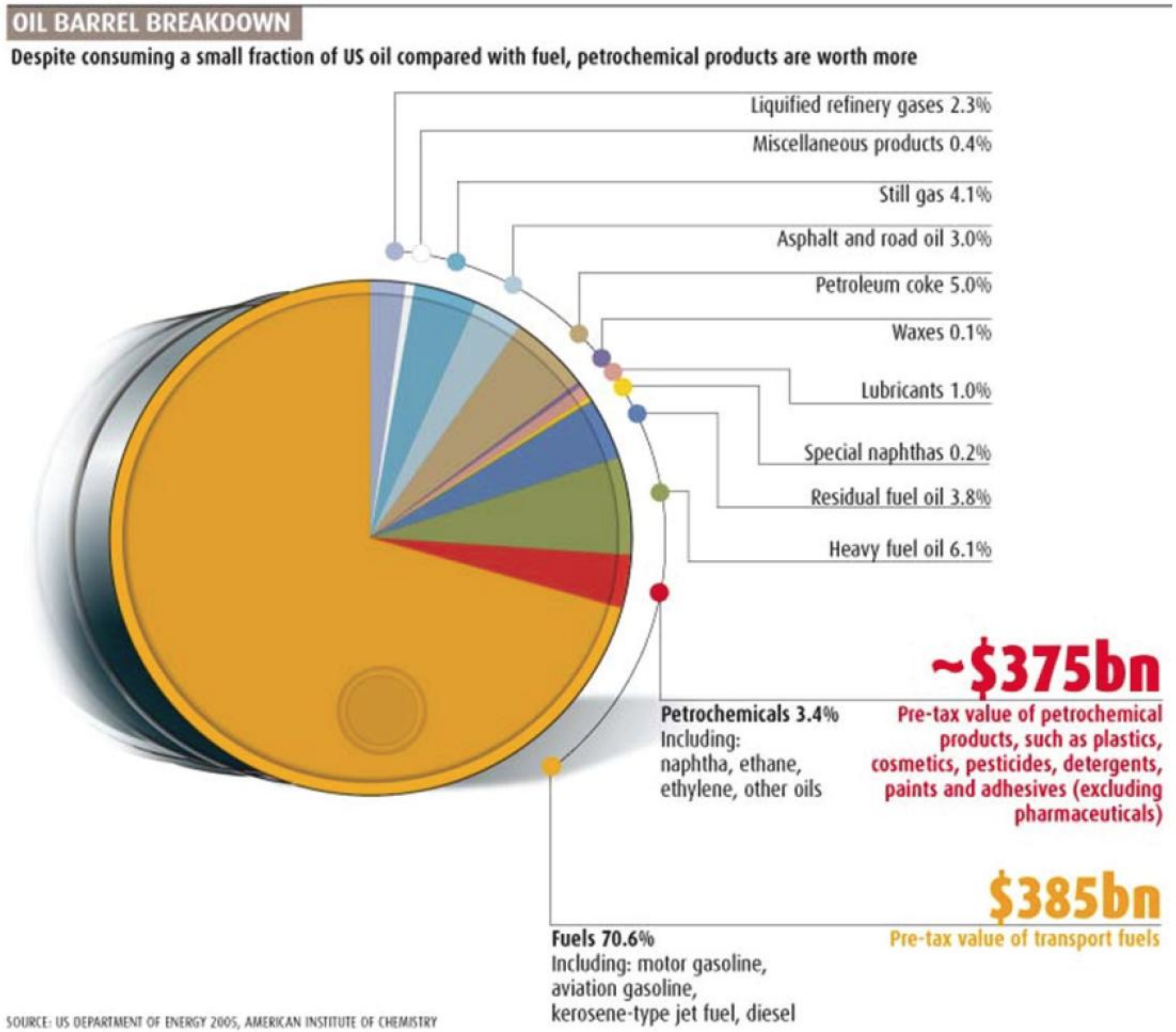
www1.eere.energy.gov/biomass/pdfs/**billion_ton_update**.pdf

Value considerations

"If you have a ton of biomass, the best way to avoid GHG emissions is to burn it, and displace coal or even natural gas. You get the biggest bang for your buck."
David Stern, ExxonMobil

Petrochemicals and specialty chemicals are high value-added products and would require very little of the available biomass.

Brazil has started to use bioethanol for higher value products, such as polyethylene.



Process considerations

- Move away from current batch processing systems towards continuous flow processing
  - Needed to compete on scale and cost with conventional fuels
  - Producing 20 billion gallons ethanol by batch fermentation is economically untenable: it would require 525 40-million-gallon plants at $40M each
- Need for new separation and purification technologies
  - Remove inorganics generated in thermochemical processing, to avoid contaminating subsequent processing steps
    - Unlike petroleum, biomass contains larger amounts of S, N, P, K, and especially O
  - Handle mixtures of products (ok for fuels, problematic for chemicals)
    - Re-explore “old” chemistries
- Need for new catalysts that resist contamination and have improved selectivity
- Co-generation (Co-gen)
  - Use biomass to generate electricity and heat in the same facility that processes biomass for fuels/chemicals

Biochemical conversion technologies

- Classic
  - Pretreatment with enzymes or mineral acids to release sugars, followed by
  - Fermentation of sugars
- Anaerobic digestion
  - Complete digestion produces methane
  - Incomplete digestion produces carboxylic acids
    - Decarboxylation leads to diesel/jet fuel
- Electrofuels process
  - Geoautotrophic bacteria metabolize minerals and produce fuel molecules
  - Can adapt to use electricity as energy source instead

Costs of bioconversion

- Operating costs (total $2.15/gallon ethanol)
  - Feedstock cost (incl. handling): $0.74/gallon
  - Pretreatment/conditioning/enzymes: $0.83/gallon
  - All operations batch:
    - Generates dilute product that must be concentrated
    - Generates large amount of wastewater
    - New enzymes required for each batch
    - Down-time between batches
- Capital costs (total $1/gallon ethanol)
  - Boilers for drying lignin, and equipment for wastewater treatment, comprise over half of capital costs
  - 50-million gallon plant could produce 1 billion gallons wastewater containing 2% solids
- Since energy density of ethanol is 2/3 that of gasoline, this is not economically viable

Towards Continuous Processing

- Separation of lignin from polysaccharides
  - Acid pretreatment (e.g., 40 % HCl) removes valuable hemicellulose as well as lignin, requires durable process equipment, and causes downstream inhibition
  - Ionic solvents too expensive and require extremely high recycling efficiencies (99.999 %)
  - Use of supercritical water is an engineering challenge
  - Need for high efficiency, affordable, recyclable enzymatic or chemical catalysts to partially depolymerize lignin
    - Enzymes from cow rumen that operate at high temperature (hard to scale manufacturing)

- Removal of fermentation products
  - Liquid-liquid extraction
  - Ethanol-selective membrane

- Development of enzymes capable of performing (or at least compatible with) multiple processing steps
  - Higher activity, less expensive
  - Not inhibited by lignin/acid/ionic solvents/pressure

- New training and research
  - Process engineering, separations technology, biofuels, surface chemistry

Thermochemical conversion technologies

Gasification: rapid heating to very high T in the presence of a limited amount of O_2

- major desired product is syn gas (CO/H_2)
- major undesired product is CO_2 (lowers carbon efficiency)
- minor products are tar, char

• does not require separation of lignin from cellulose/hemicellulose

• only works economically at large scale (to reduce capital costs), but then problem with transportation costs…

• each contaminant requires its own separation process

• major competitor is steam reforming

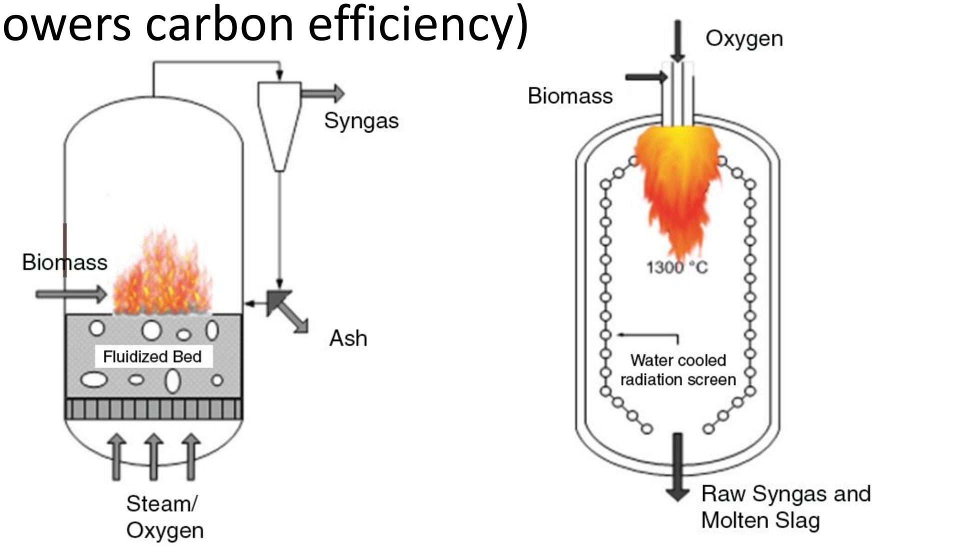


FIGURE 4-2 Gasification can be done in either a low-temperature fluidized bed system (left) or a high-temperature entrained-flow gasifier (right).
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.

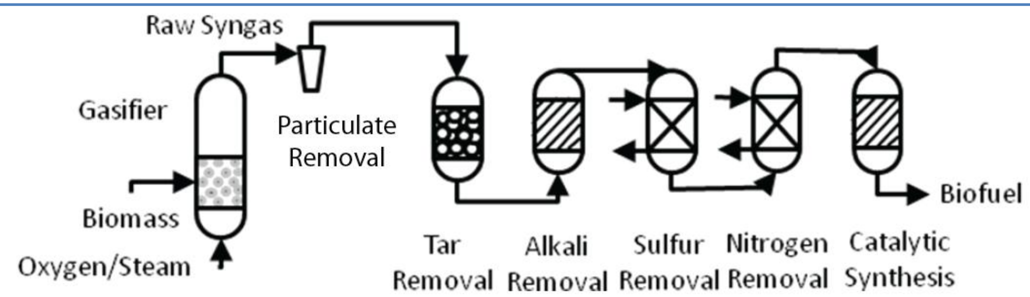


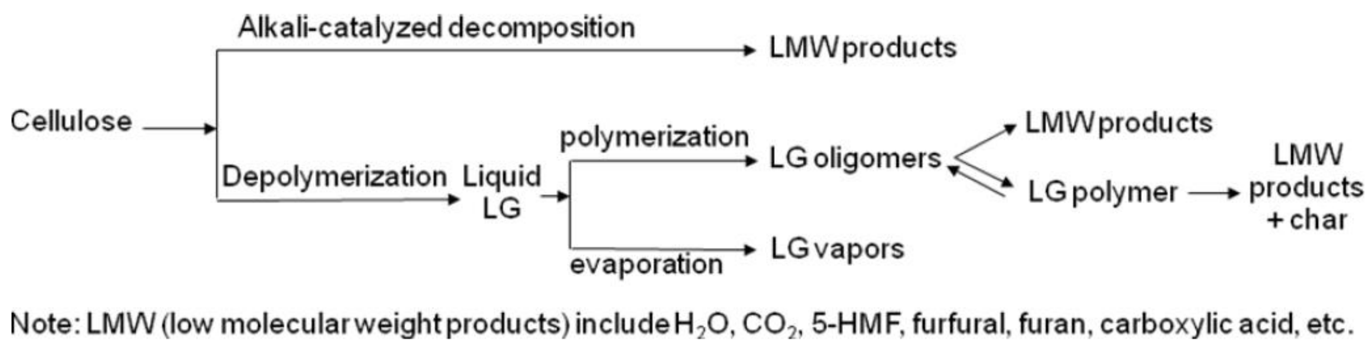
FIGURE 4-3 Removing impurities from biomass-generated syngas is a major challenge.
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.

Thermochemical conversion technologies

Fast pyrolysis: heating to moderate T (400-500 °C) in the absence of O_2

- also does not require separation of lignin from cellulose/hemicellulose
- major product (60 – 70 %) is bio-oil (unstable, corrosive mixture of oxygenated products including aromatics, ketones, carboxylic acids) that requires upgrading (removal of corrosive components and oxygen)
- also generates char (13 – 15 %) and syn gas (13 – 25 %)
- lowest cost biomass conversion process; could operate economically on 200-ton per day scale
- chemistry is poorly understood, but alkali components are thought to catalyze formation of undesired light oxygenates

Alternatives: catalytic pyrolysis (generates stable, more reduced bio-oil but catalysts coke rapidly)
solvolysis (pyrolysis in a solvent, either direct liquefaction or hydrothermal)



Heat and power production

Does not require large-scale facilities.
Could be economically viable at community-scale or even home-scale.

Education/training needs

Need for interdisciplinary coursework and collaboration among engineers, chemists, biologists and plant scientists.

Training is needed in life-cycle analysis and quantification of uncertainty.

Students in technical subjects need training in economics, policy and sociology and to be able to work in multidisciplinary teams that include specialists in these areas.