Biomass Part I: Resources and uses

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Sustainable Energy: Big Picture

- People want electricity, transport, heat
- Now use: coal oil gas
- Major Challenges:
  - CO_2 to atmosphere: climate change
  - Run short on oil? Security, price
  - **Price**: most people in the world can't afford the energy they want

Possible Solutions

- CO_2: switch from conventional coal
  - Efficiency: lighting, cooling?
  - Coal → gas combined cycle
  - Non-emitting power sources
  - CO2 underground sequestration
  - Burn Biomass instead of coal
- Oil running out: Efficiency, Alternatives
  - Vehicle efficiency, urban planning
  - Batteries or natural gas for land transport
  - Coal, tar, gas → synfuels with CO_2 sequestration
  - Biomass → liquid fuels
- Price?
  - Can Biomass energy be cheap??

History, overview of biomass

- Largest historical energy source
- Largest current renewable energy source
- Many historical examples of resource depletion
  - England, Easter Island deforestation
  - Sahel desertification
  - Whale oil
- Scalability and land use resources are a challenge
- Possible better ways:
  - Waste from agriculture, forestry
  - Energy crops / algae on waste land

Solar insolation

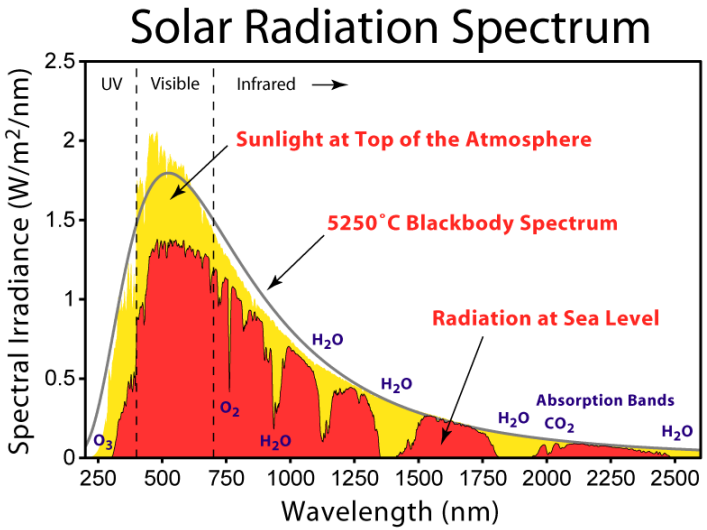


Image by Robert A. Rohde / Global Warming Art.

Maps of insolation at the top of the atmosphere and the Earth's surface removed due to copyright restrictions.

- Solar "constant": 1366 W/m^2
  - Measured outside the earth's atmosphere
  - Varies with seasons
- On planet's surface effected by geometry and filtering.
- Photosynthetically active region (PAR):
  ~ 400-700 nm

Photosynthesis ~ 1% efficient
Energy stored <3 MW / (km)^2 arable land

Biomass: The Source

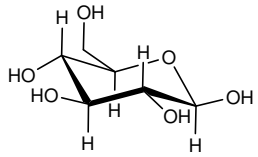
- Photosynthesis stores ~300 EJ/yr as biomass energy
  - Human energy use ~400 EJ/yr
  - Carbon cycle: plants die, decay to CO2
  - In fertile areas ~ 10^{-5} EJ/$(km)^2$/yr
    - Requires ~250 kg H_2O to grow 1 kg biomass
  - Earth's total land surface ~$10^8(km)^2$
- For large scale biomass energy NEED LOTS OF LAND (even much more than solar) and WATER
- If you have spare land and fresh water, relatively inexpensive to grow and harvest (e.g. much less capital than solar!)

What is biomass? Properties

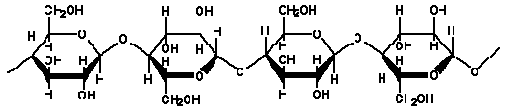
- Solid carbon-based fuel (like coal)
  - H:C ~1.5 , O:C ~1
  - Significant metals, S, N
  - Minor elements come from soil
    - Nitrogen fertilizers often required
- Wet: about 50% water before drying
  - Low energy density ~9 MJ/kg wet
- Diffuse, relatively low energy density: expensive to harvest, ship.
- Annual cycle: biomass available only at harvest time, may need to be stored.

The main components of biomass are carbohydrates & lignin (+proteins, lipids)

Carbohydrates



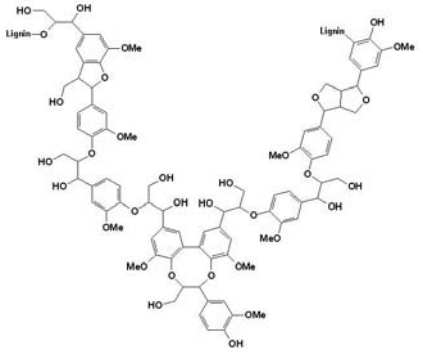
D-glucose



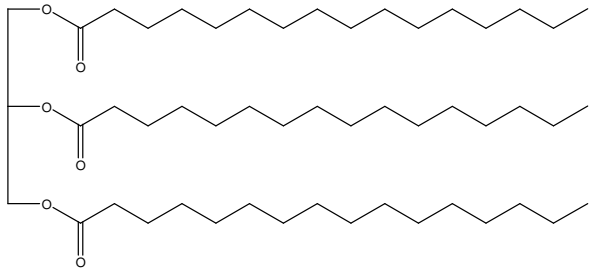
Cellulose

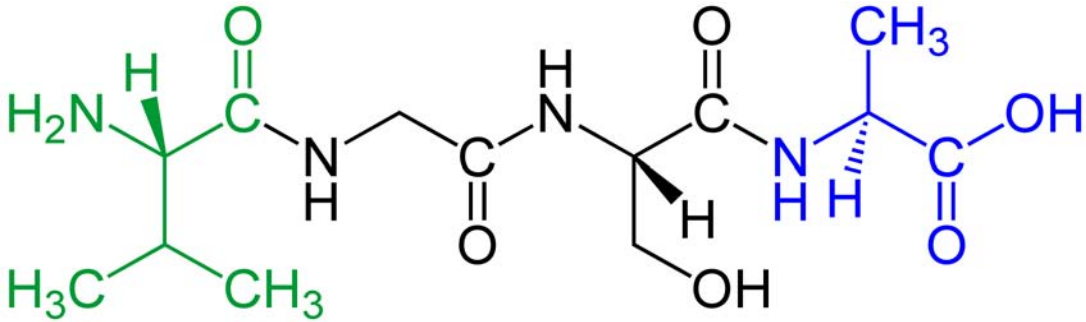
Mostly cellulose & hemicellulose

Lignin



Fats





Proteins

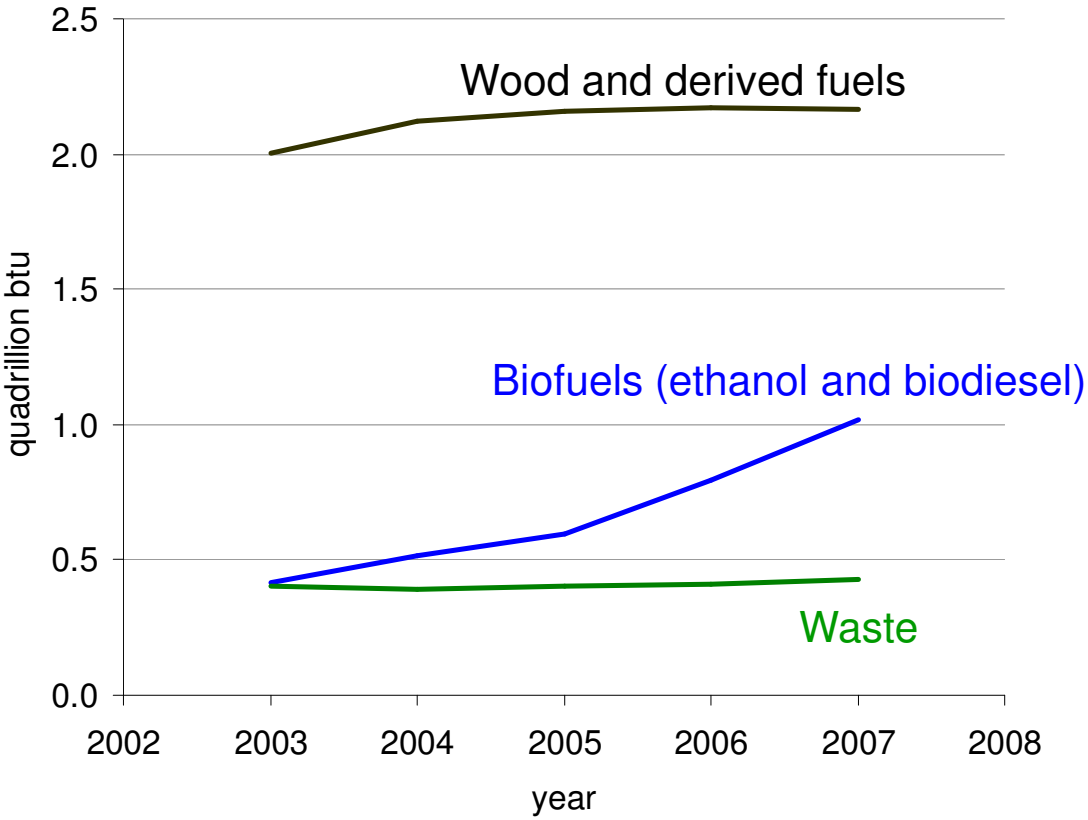
Lignin and Protein images, public domain from Wikimedia Commons.

Uses of biomass

- Energy uses
  - Heat
  - Electricity (including co-firing)
  - Liquid Fuels for Transportation

- Many important non-energy uses
  - Food for humans
  - Animal feed (a major and growing use)
  - Lumber & other construction materials
  - Clothing (cotton, wool, linen, leather)
  - Paper, packaging, etc.

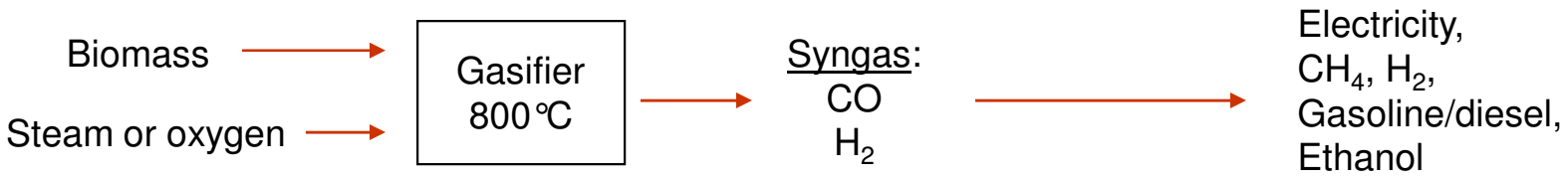
Biomass energy use is currently dominated by wood, but government regulations driving rapid expansion of ethanol and biodiesel production.



Using biomass for energy: options

- Burn it for electricity or heat
  - US Paper/Wood industry: 6 GWe
  - Coal is usually cheaper for large-scale
  - Good option with carbon cap: mix biomass with coal.
- Convert to Gas (CH_4 or CO/H_2)
  - Practiced on small-scale using waste
  - Coal-to-syngas and natural gas are cheaper, but maybe with carbon cap…
- Convert to Liquid Fuels

Syngas is a mixture of CO/H_2 used for many purposes. Usually made from natural gas, but can also be made from biomass.



$$\underbrace{CH_{1.5}O_{0.67}}_{\text{wood}} + 0.33\ \underbrace{H_2O}_{\text{steam}} \rightarrow \underbrace{CO + 1.08\ H_2}_{\text{syngas}}$$

ΔH_r = +101 kJ/mol
700-900°C, 1 atm

Depending on biomass composition, desired stoichiometry, mix in some O_2 (partial combustion) to provide the heat of reaction

Image by Gerfriedc on Wikimedia Commons.

Source: National Renewable Energy Lab; F. Vogel, Paul Scherrer Institut, Switzerland.
Image source: Güssing Burgenland (Austria) gasifier, via wikimedia commons.

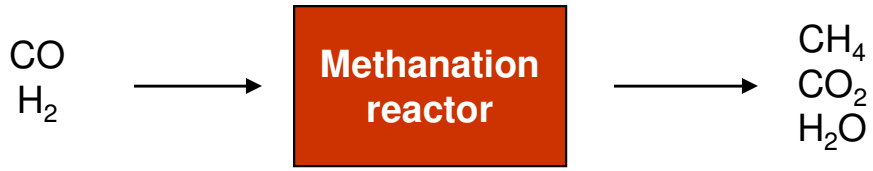
Syngas → electricity.

- Large-scale electricity generation
  - IGCC: Integrated-gasification combined cycle (clean coal)
  - Easier to capture CO2 and more efficient than direct combustion, but more capital intensive
  - Proposed integration with Fischer-Tropsch to make synfuels.

- Small-scale cogeneration
  - combined heat and power
  - 5 kW to 5 MW
  - waste streams, off-grid operation

Source: DOE EERE.

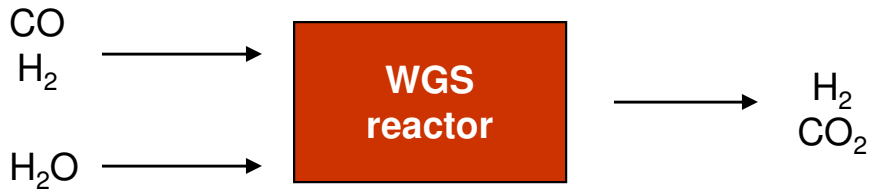
Syngas → CH_4 or H_2



Methanation

$CO + 1.08\ H_2 \rightarrow 0.52\ CH_4 + 0.48\ CO_2 + 0.04\ H_2O$

ΔH_r = -127 kJ/mol
400 ℃, 10-20 atm
Ni catalyst



Water gas shift

$CO + H_2O \rightarrow CO_2 + H_2$

ΔH_r = -41 kJ/mol
400-500 ℃, 1 atm
Iron oxide catalyst

Source: F. Vogel, Paul Scherrer Institut, Switzerland;
& Cat Comm 4 215-221 (2003).

Syngas: Diesel and alcohols can be made via Fischer-Tropsch process.

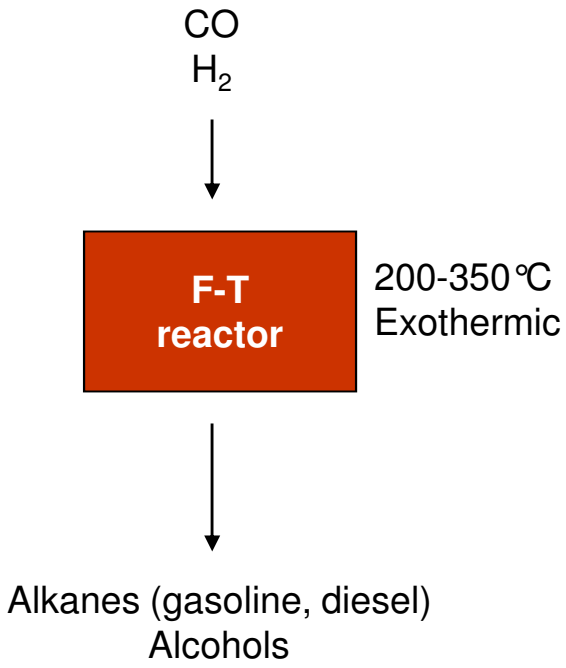
- Coal-to-liquids and gas-to-liquids technology
  - Germany; South Africa

- "Ideal" reaction:

$$(2n+1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$$

- Many simultaneous reactions
  - alcohols, alkenes, etc.

- Selectivity
  - Catalyst, temperatures, pressures, H_2/CO ratio



Syngas can be used as a biological feedstock.

Image removed due to copyright restrictions.
Please see descriptions of the INEOS Bio Ethanol process.

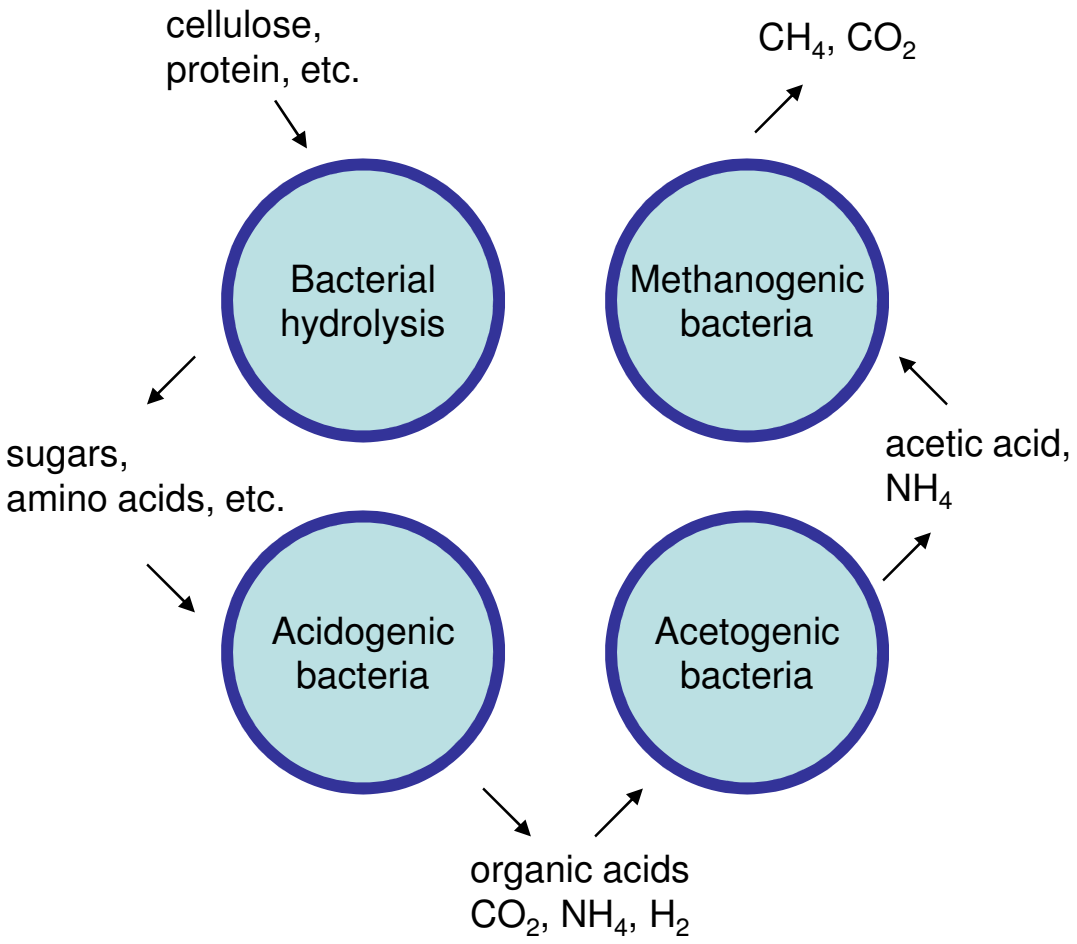
- Hybrid thermochemical / biological process
- Syngas produced from biomass
- Syngas fermented into ethanol
- Ethanol from the whole plant, rather than only sugars
  - Both cellulose & lignin gasified; most other cellulosic ethanol doesn't use lignin

Source: BRI company website, http://www.brienergy.com/pages/process01.html

BIOGAS: Anaerobic digestion is a simple, robust method for mixed wet waste streams.

Natural bacterial process degrades most organic material (cellulose, hemicellulose, starches, sugars, proteins, fats)
- Exception: lignin

Figure removed for copyright reasons. See Figure 10.7 in Tester, J. W., et al. *Sustainable Energy: Choosing Among Options*. Cambridge MA: The MIT Press, 2005.



CH_4	50-75%
CO_2	25-50%
N_2	0-10%
H_2	0-1%
H_2S	0-3
O_2	0-2

Bioenergy as Goal or Bioenergy as Byproduct

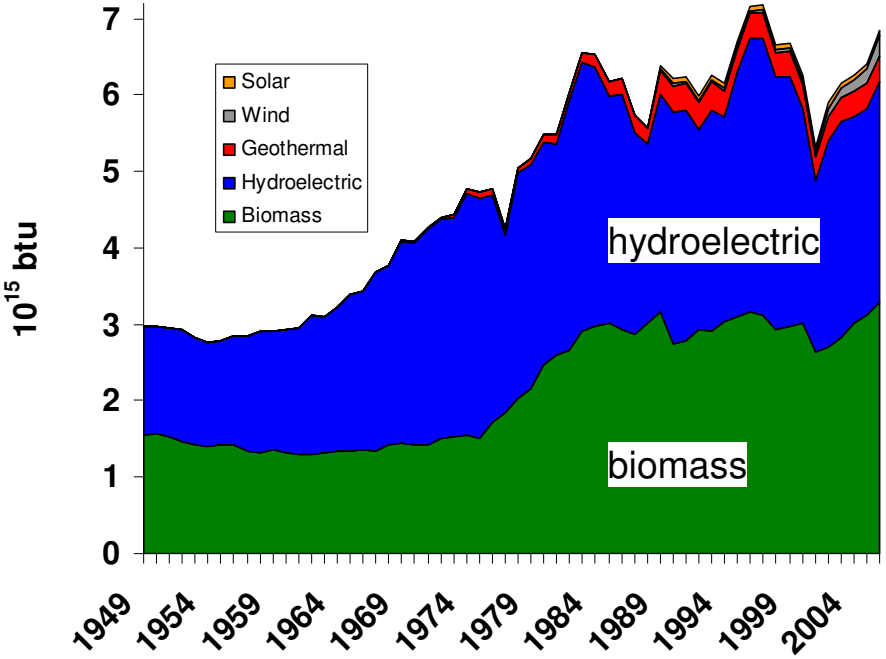
- Historically, biomass products (food, lumber) have been considered more valuable than biomass energy…
- …So existing policies and practices focus on agriculture, lumber, & land use.
- Usually waste or surplus biomass used as energy
  - Usually more economic to use fossil fuels than biomass for energy.
  - There is a lot of waste biomass, but often inconvenient to collect, use.
- If biomass-to-energy were economically competitive with fossil fuels, could see rapid large shifts in land use (e.g. deforestation, conversion of arable land to energy crops) and jumps in food prices…
- …but if it is not economically competitive, will biomass ever be used on a large scale for energy?
- Food price shocks and food riots a few years ago have raised awareness of the issues…

Using biomass for energy: options

- Burn it for electricity or heat
  - US Paper/Wood industry: 6 GWe
  - Coal is usually cheaper for large-scale
  - Good option with carbon cap: mix biomass with coal.
- Convert to Gas (CH_4 or CO/H_2)
  - Practiced on small-scale using waste
  - Coal-to-syngas and natural gas are cheaper
- Convert to Liquid Fuels
  - Looks to be most profitable on large scale:

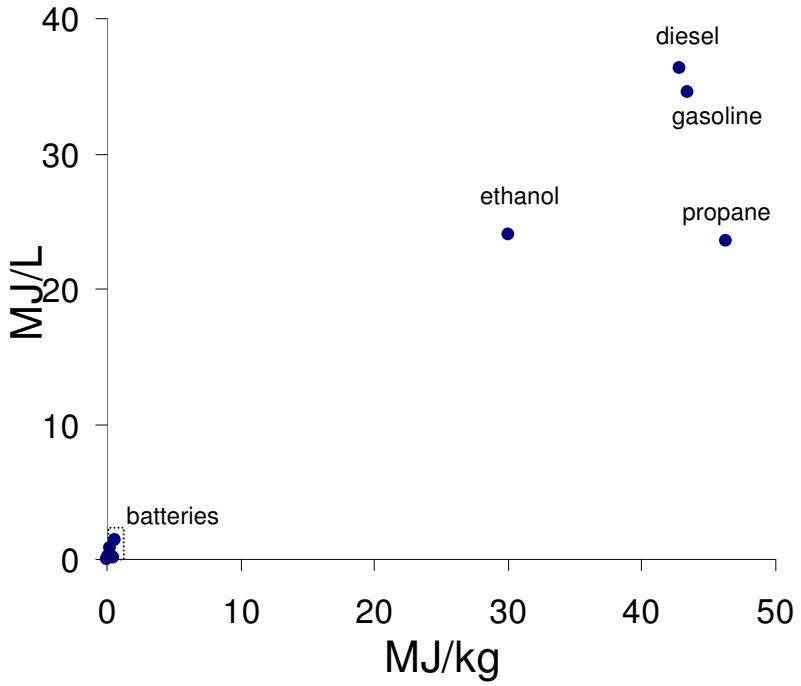
  not many good competing alternatives to oil!

Biomass is the only major renewable source of liquid and gaseous fuels.

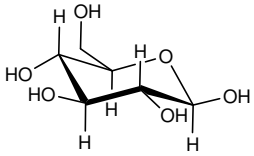


Biomass is currently the largest source of renewable energy in the US and the world, and the only renewable source capable of producing fuels with current technology.

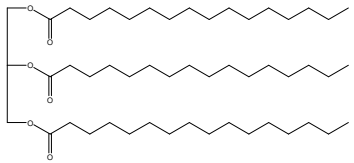
Liquid fuels offer superior energy storage and transportability.

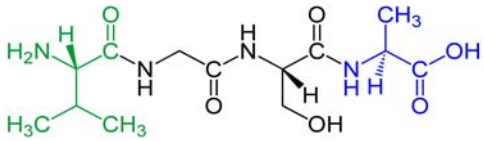


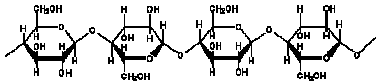
Biomass contains more oxygen and is structurally different from fuels.

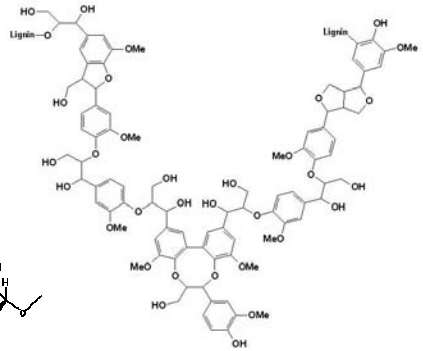


D-glucose





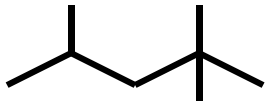




Carbohydrates **Fats** **Proteins** **Cellulose** **Lignin**

H_2

CH_4



Hydrogen

Natural Gas
Methane

Propane
LPG / NGL
Autogas

Gasoline
Petrol
Naptha

Diesel

Lignin and Protein images, public domain from Wikimedia Commons.

End of Biofuels lecture #1

Part 2 is about how to make biomass into biofuels…

- Break time!

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Introduction to Sustainable Energy
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