Biomass Energy

- What is biomass?
- Chemical and physical properties
- Biomass and energy – thermal conversion to heat and electricity or syngas and hydrolysis/bioprocesses to liquid and gaseous fuels
- Biomass resources and production
- Biomass to electricity
- Biomass to biofuels and hydrogen
  - Grain versus residual lignin-cellulosic feed stocks
  - Gasification, hydrolysis, bioconversion processes
- Biorefineries employing modern biotechnology

Acknowledgements

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Jack Howard

Michael Raab

Jeremy Johnson

Morgan Froling

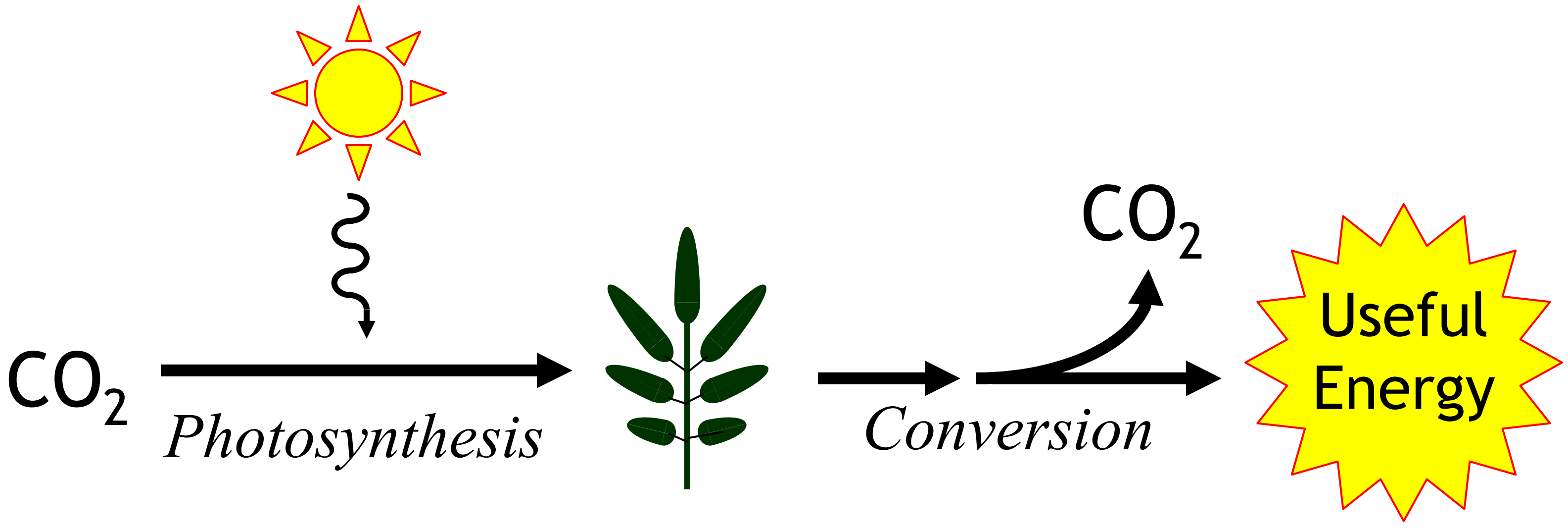
Richard Truly, Stan Bull and NREL staff

Terry Adams and Brian Appel of CWT

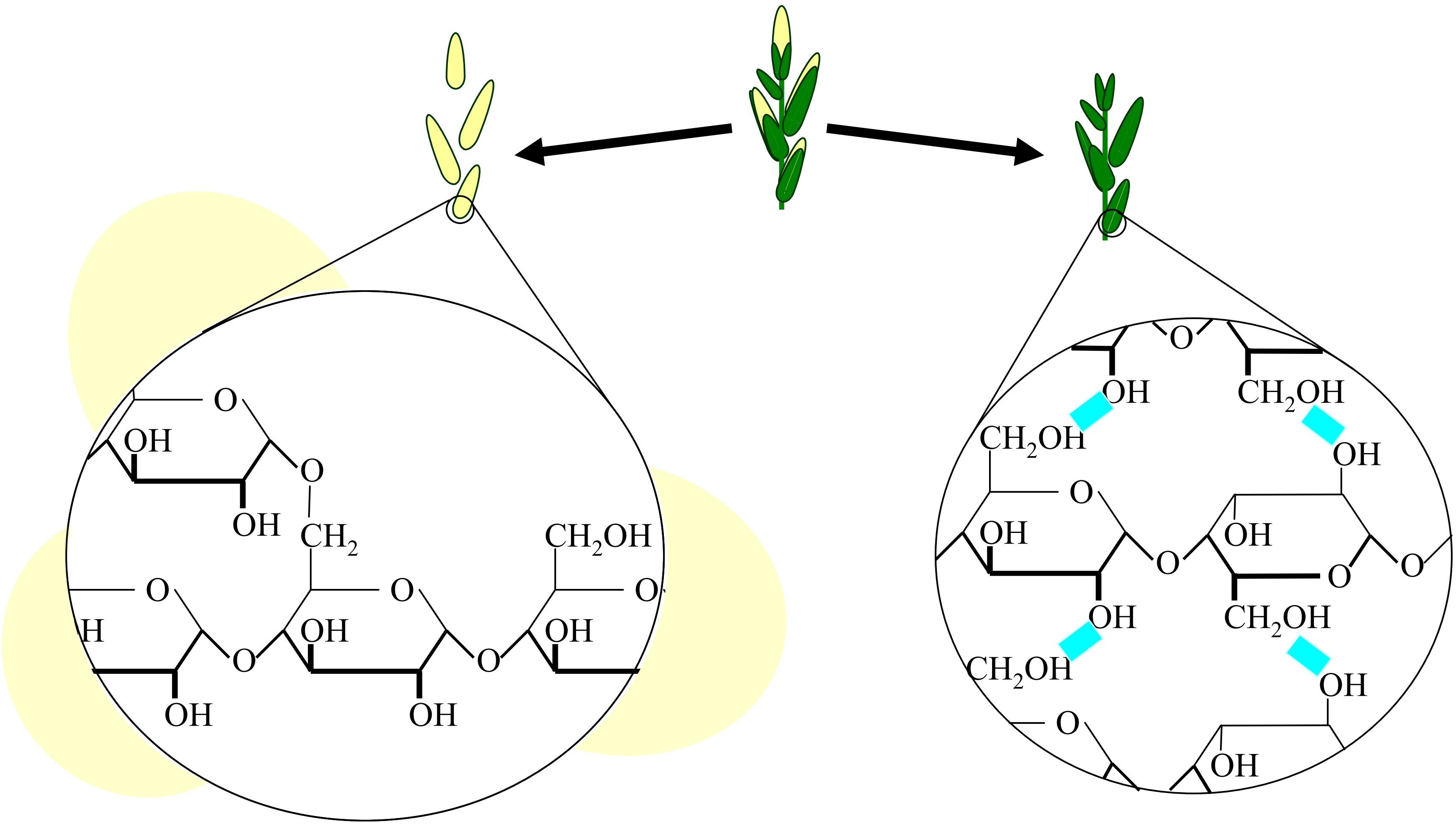
Plus many others

Biomass Attributes

- Renewable
- Connected to farming - economics
- Multiuse – food, shelter, energy, materials
- Environmental concerns include land and water use, fertilizer and other nutrient requirements
- Naturally diffuse and distributed – harvesting and transport and distribution are important



Molecular Plant Composition



Photosynthesis

- Biomass energy is a form of solar energy
- Solar energy is captured via photosynthesis as carbon dioxide is incorporated as fixed carbon during the growth stage of all biomass
- Average solar incidence is about 4000 $W/m^2/day$
- Biomass capture efficiency is ~ 1%
- Thin film photovoltaic efficiency is ~ 10%

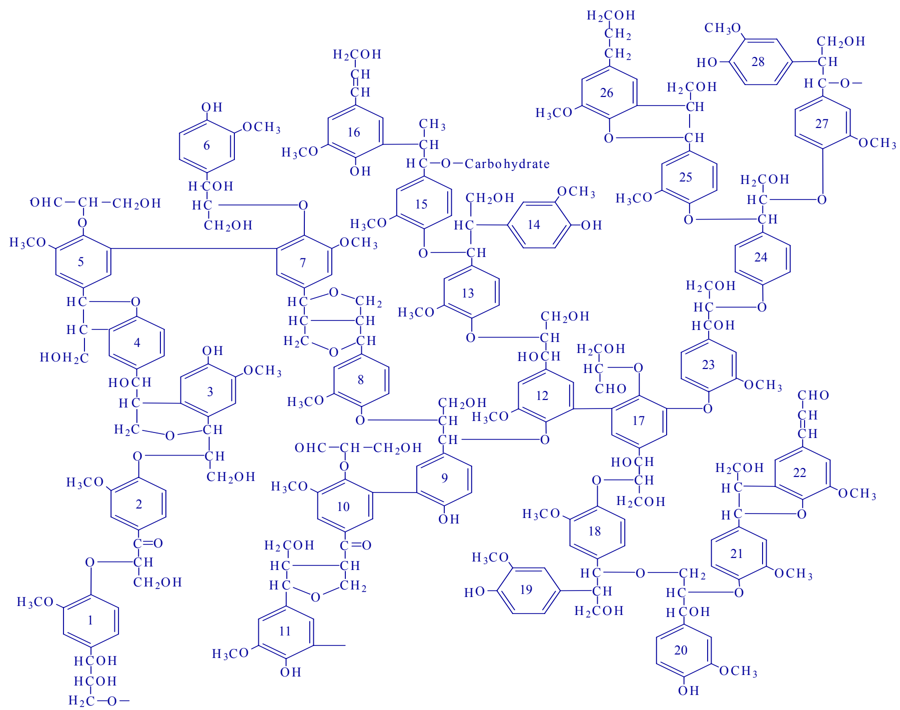
$$nCO_2 + nH_2O \xrightarrow{\text{light, chlorophyll}} (CH_2O)_n + O_2$$

Lignocellulosic Properties

- Macrostructure is polymorphous
  - Crystalline regions
  - Amorphous regions
- Heterogeneous
  - Cellulose, hemicellulose, lignin
- Properties characterized in terms of
  - Degree of polymerization, accessible surface area, lignin distribution

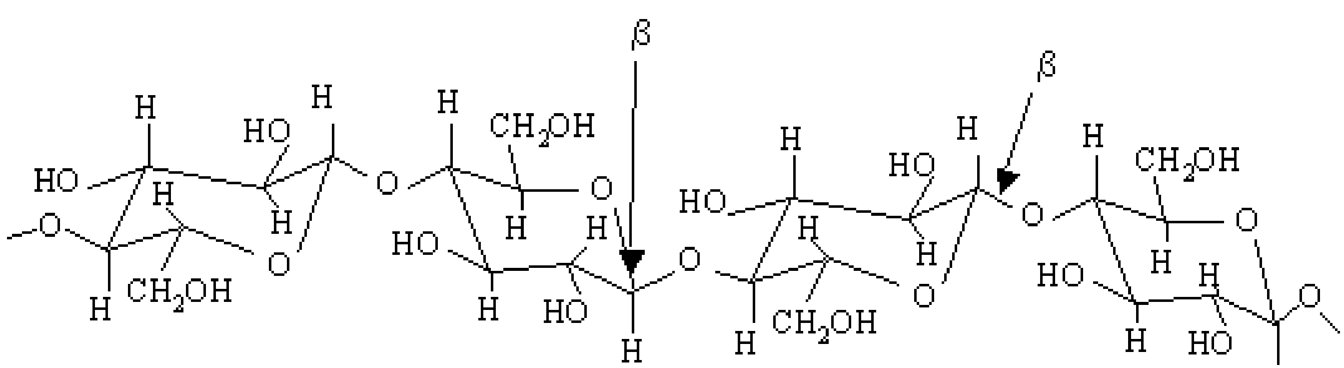
Lignin

- The major noncarbohydrate, polyphenolic structural constituent of wood and other plant material that encrusts the cell walls and cements the cells together
- A highly polymeric substance, with a complex, cross-linked, highly aromatic structure of molecular weight about 10,000 derived principally from coniferyl alcohol (C10H12O3) by extensive condensation polymerization
- Higher heating value: HHV=9111 Btu/lb



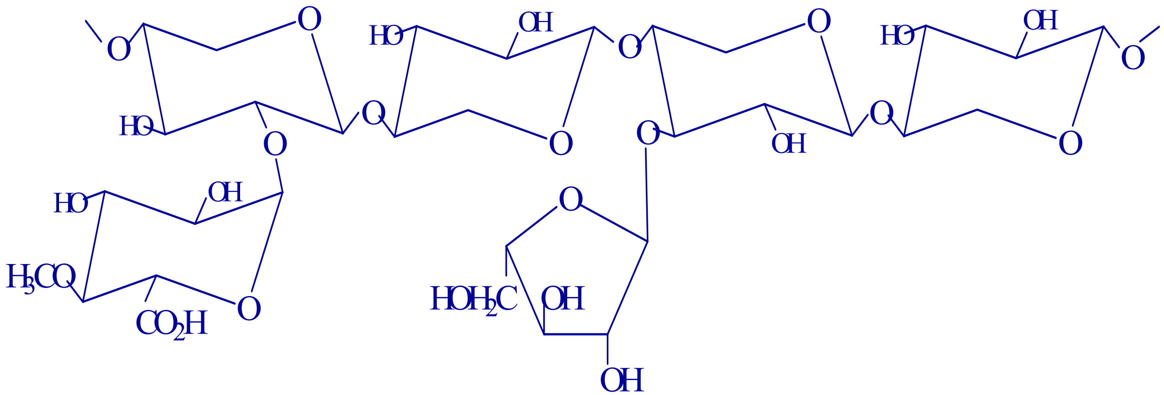
Cellulose

- Composed of long chains of ß-glucose linked together (repeating unit $C_6H_{10}O_4$)
- Principal constituent for the structural framework of wood and other biomass cells
- The ß-linkages form linear chains which are highly stable and resistant to chemical attack because of the high degree of hydrogen bonding that occurs between chains of cellulose, inhibiting the flexing of the molecules that must occur in the hydrolytic breaking of the glycosidic linkages
- Hydrolysis can reduce cellulose to a cellobiose (repeating unit $C_{12}H_{22}O_{11}$) and ultimately to glucose, $C_6H_{12}O_6$
- Higher heating value: HHV = 7500 Btu/lb



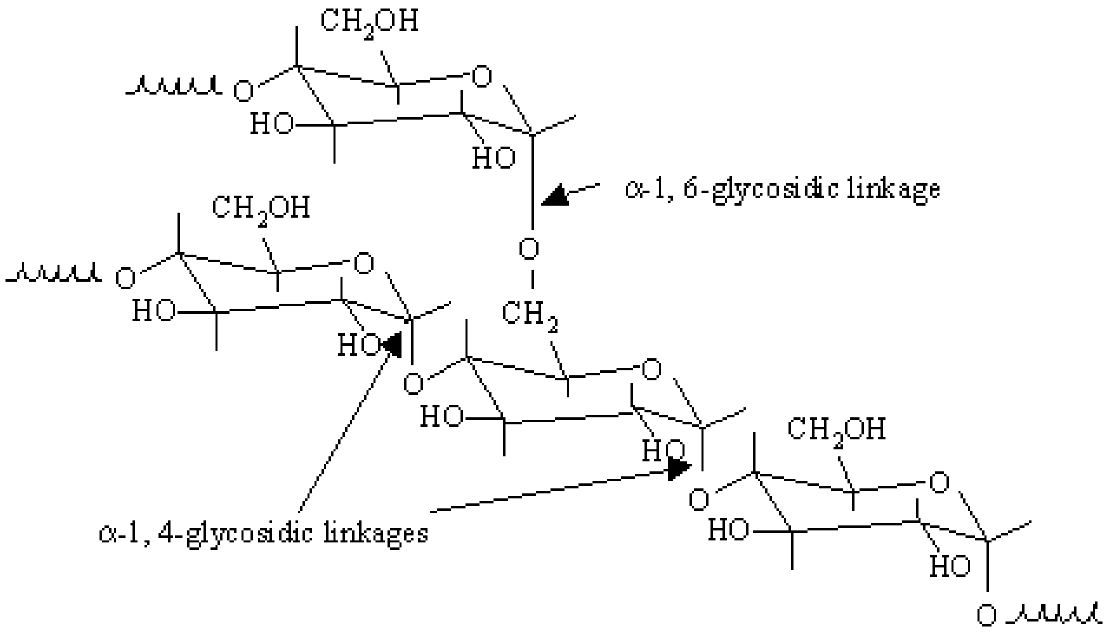
Hemicellulose

- Composed of short, highly branched chains of five different sugars
- Contains five-carbon sugars (usually D-xylose and L-arabinose) and six-carbon sugars (D-galactose, D-glucose, and D-mannose) and uronic acid
- Sugars are highly substituted with acetic acid
- Branched nature of hemicellulose renders it amorphous and relatively easy to hydrolyze to its constituent sugars compared to cellulose



Starch

- Composed of long chains of α-glucose molecules linked together (repeating unit $C_{12}H_{16}O_5$)
- Linkages occur in chains of α-1,4 linkages with branches formed as a result of α-1,6 linkages
- Widely distributed and stored in all grains and tubers
- Due to α linkages in starch, this polymer is highly amorphous, and more readily broken down by enzyme systems into glucose
- Gross heat of combustion: Q_v(gross)=7560 Btu/lb

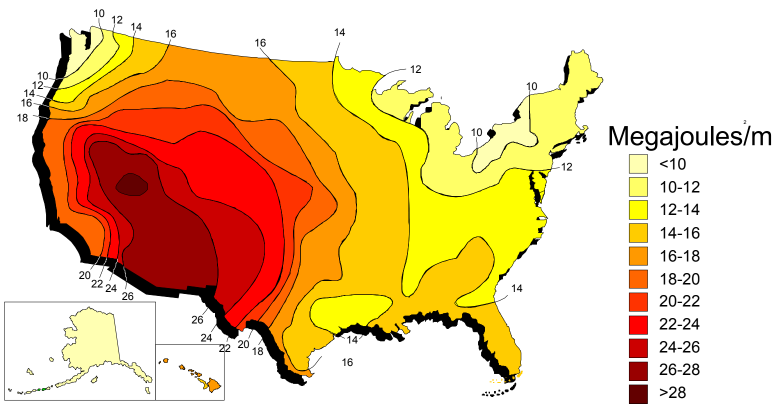


Corn Composition

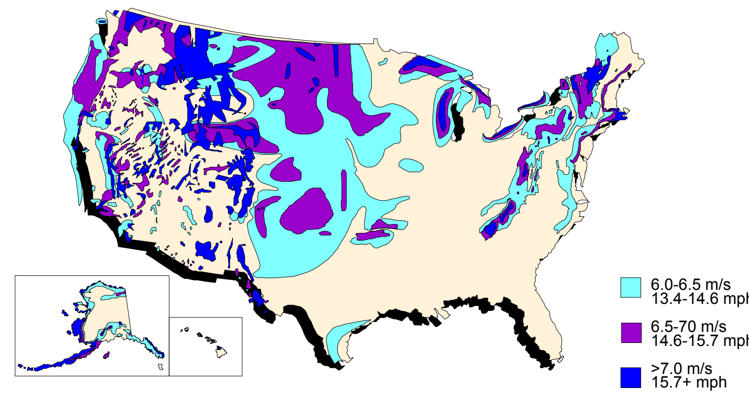
Grain	50%	Stover	50%
• Starch	72.0%	• Cellulose	37.3%
• Cellulose/ Hemicellulose	10.5%	• Hemicellulose	24.1%
• Protein	9.5%	• Lignin	17.5%
• Oil	4.5%	• Acetate	2.0%
• Sugar	2.0%	• Extractives	13.0%
• Ash	1.5%	• Ash	6.1%
• Moisture	15%	• Moisture	15%

U.S. Renewable Energy Resource Assessment

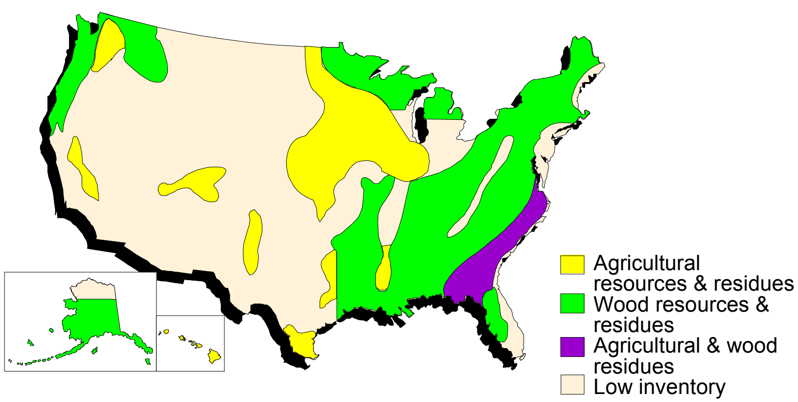
Solar



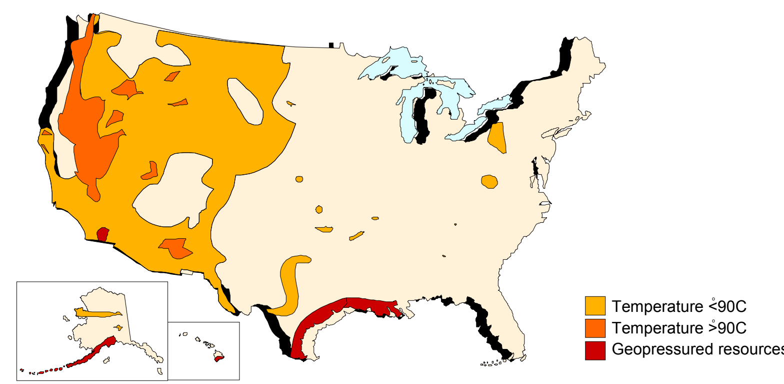
Wind



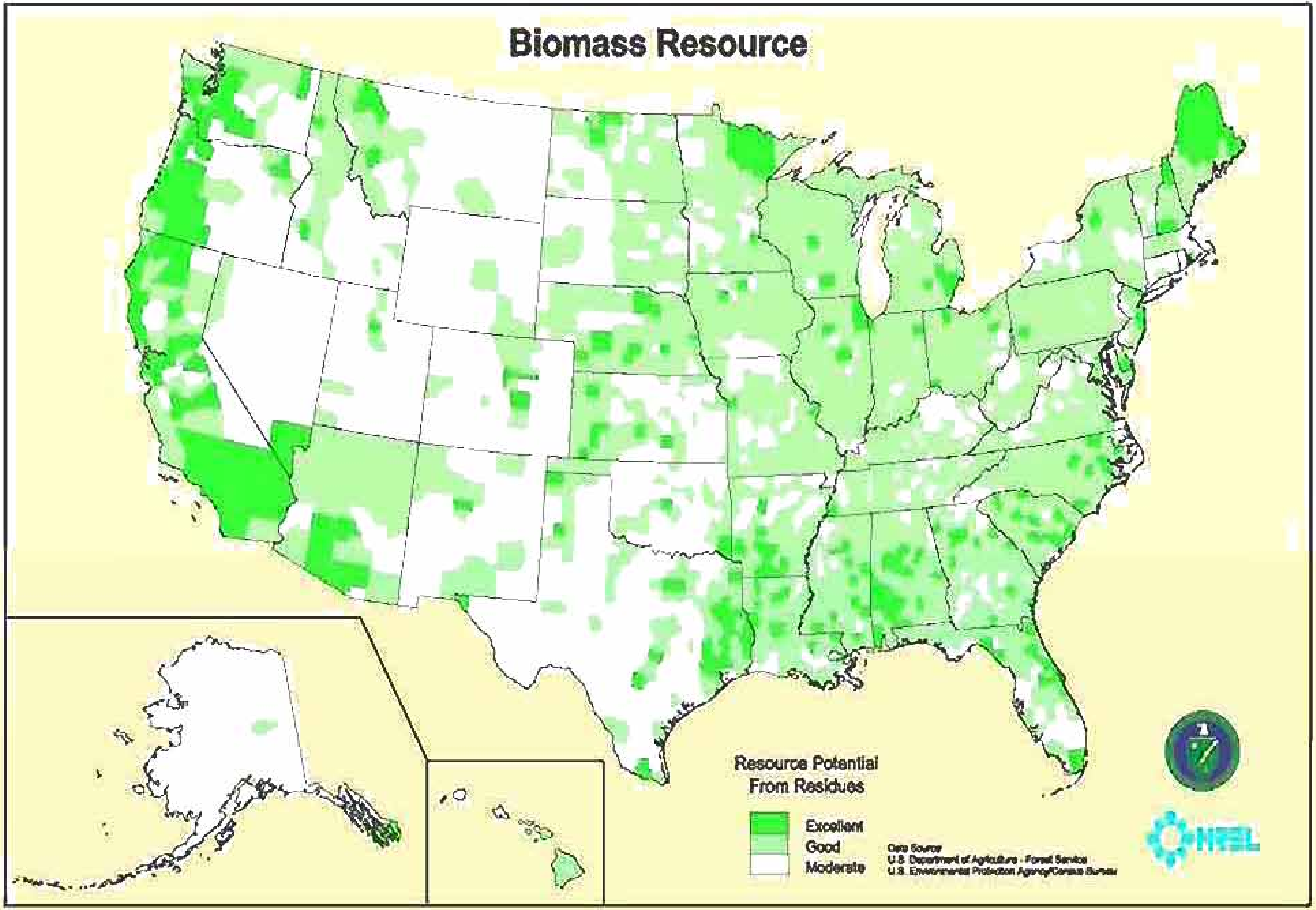
Biomass



Geothermal



Courtesy of NREL.


Biomass Resource
Resource Potential
From Residues
Excellent
Good
Moderate

Bioethanol today in the United States

- Corn grain is the feedstock
  - with a current capacity of ~144 M dry tons
  - equivalent to 10 – 14 B gallons of ethanol
  - ~10% of U.S. fuel consumption
- Current ethanol production is ~2 B gallons
- Liquid fuel additive/replacement
  - environmentally friendly oxygenate
  - fuel flexible cars can use blends up to 85% ethanol
- Subsidized heavily to make it competitive with gasoline

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Economics is important

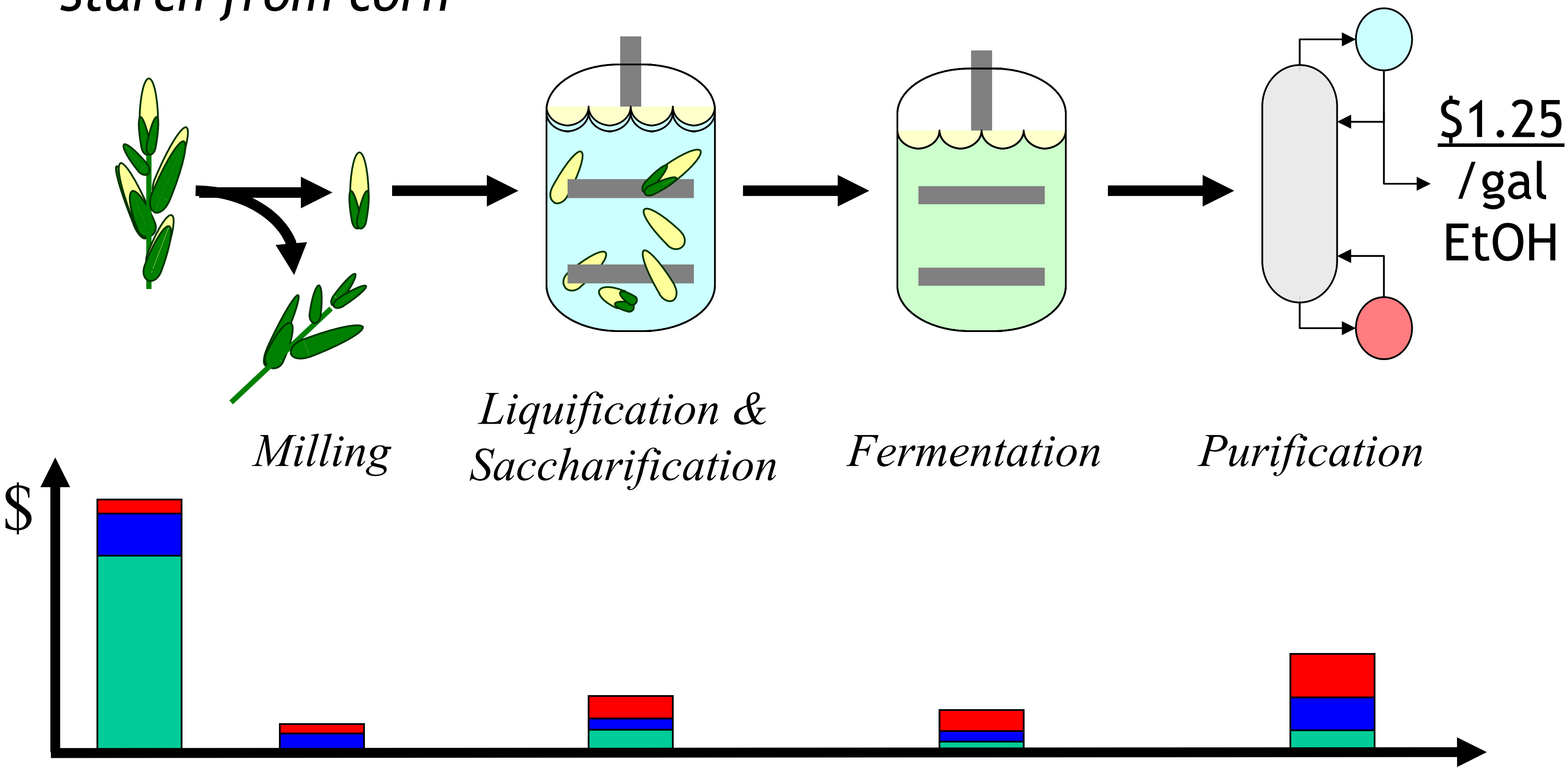
Ethanol From Corn and Residual Cellulosic Biomass US situation

- Federally Idled U.S. Cropland
  - 60 million acres [a]
- Possibly Available for Energy Crops
  - 35 million acres [a]
- Ethanol Yield Fermentation of Cellulosic, Advanced Technology
  - 107.7 gallons/ton [a]
- At 8.4 ton/acre => 905 gallons/acre [a]
- Ethanol Yield from Corn Fermentation (Large Plant)
  - 275 gallons/acre [b]

Sources: (a) Lynd (1996), (b) Pimentel (1991)

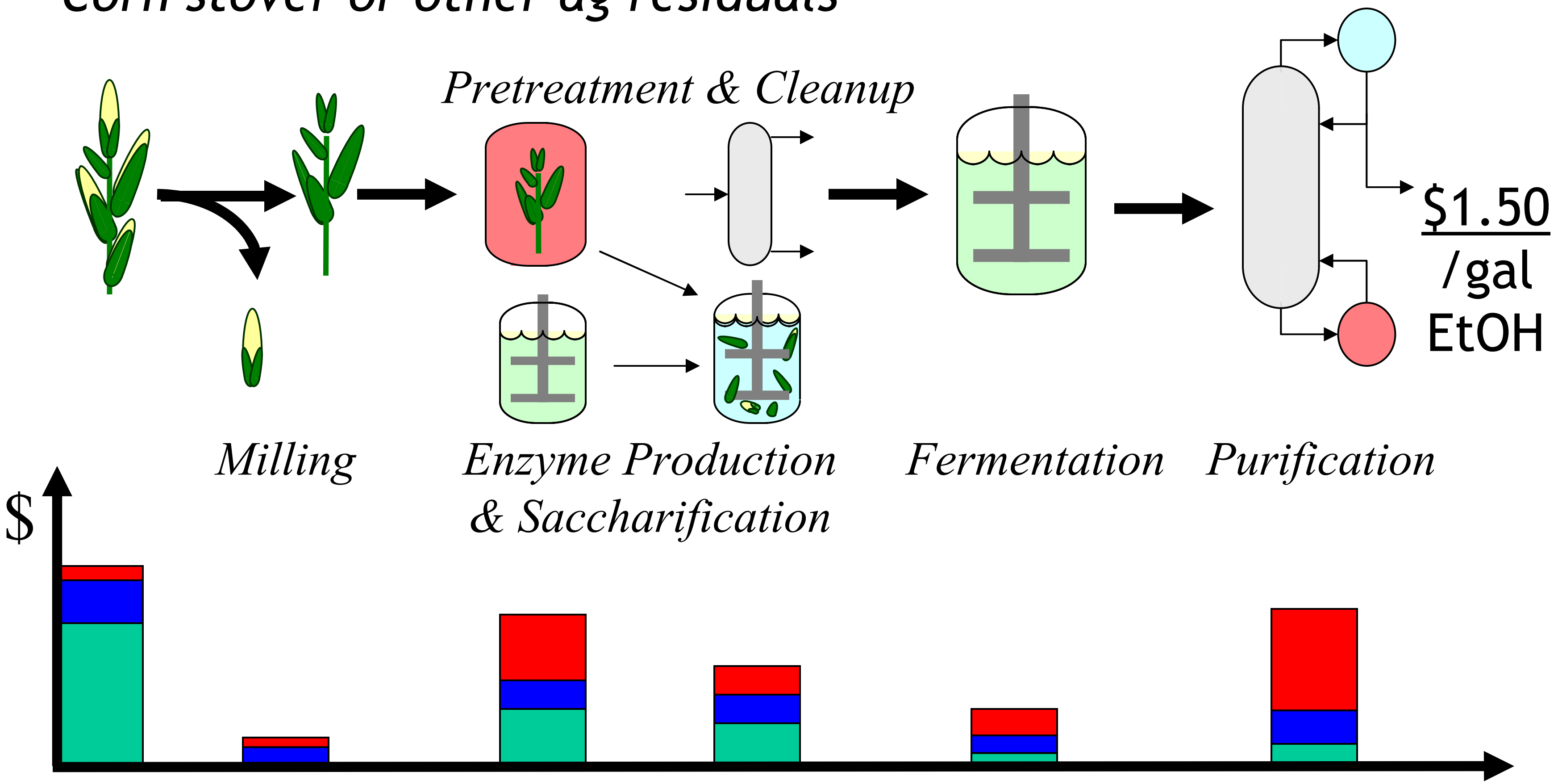
Current technology – bioethanol from *grain corn feedstock*

Starch from corn

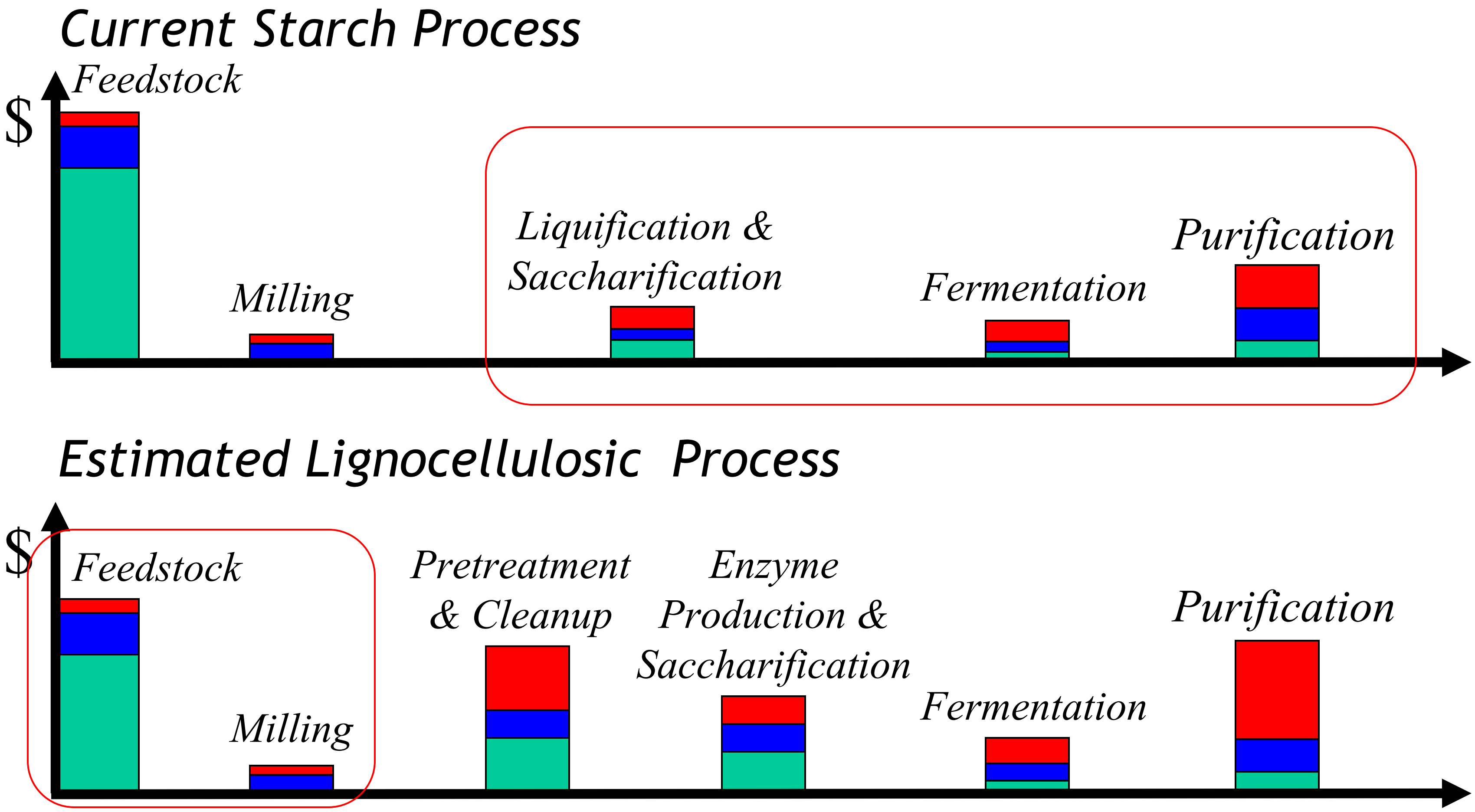


New technology –
bioethanol from lignin-cellulosic feedstocks

Corn stover or other ag residuals



Comparing costs



Opportunities for Biotechnology

- Fermentation
  - Yeasts that can:
    - Use a broader substrate spectrum
    - Have higher yields
    - Are resistant to ethanol or pretreated substrates
  - Production of more valuable co-products
- Improved catalysts -- enzyme production
- Genetic engineering of plant feedstocks

Transitioning to biorefineries

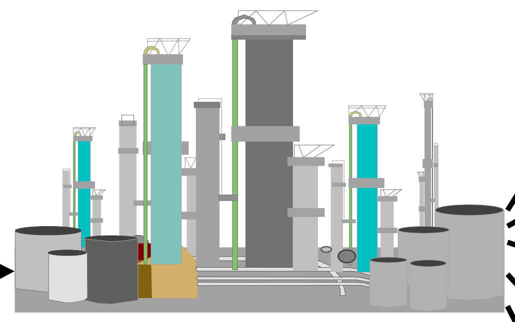
Different resources

Different applications

Municipal Solid Waste

Forest Thinnings, Short Rotation Trees

Agricultural Crops, Grasses, and Residues



Food

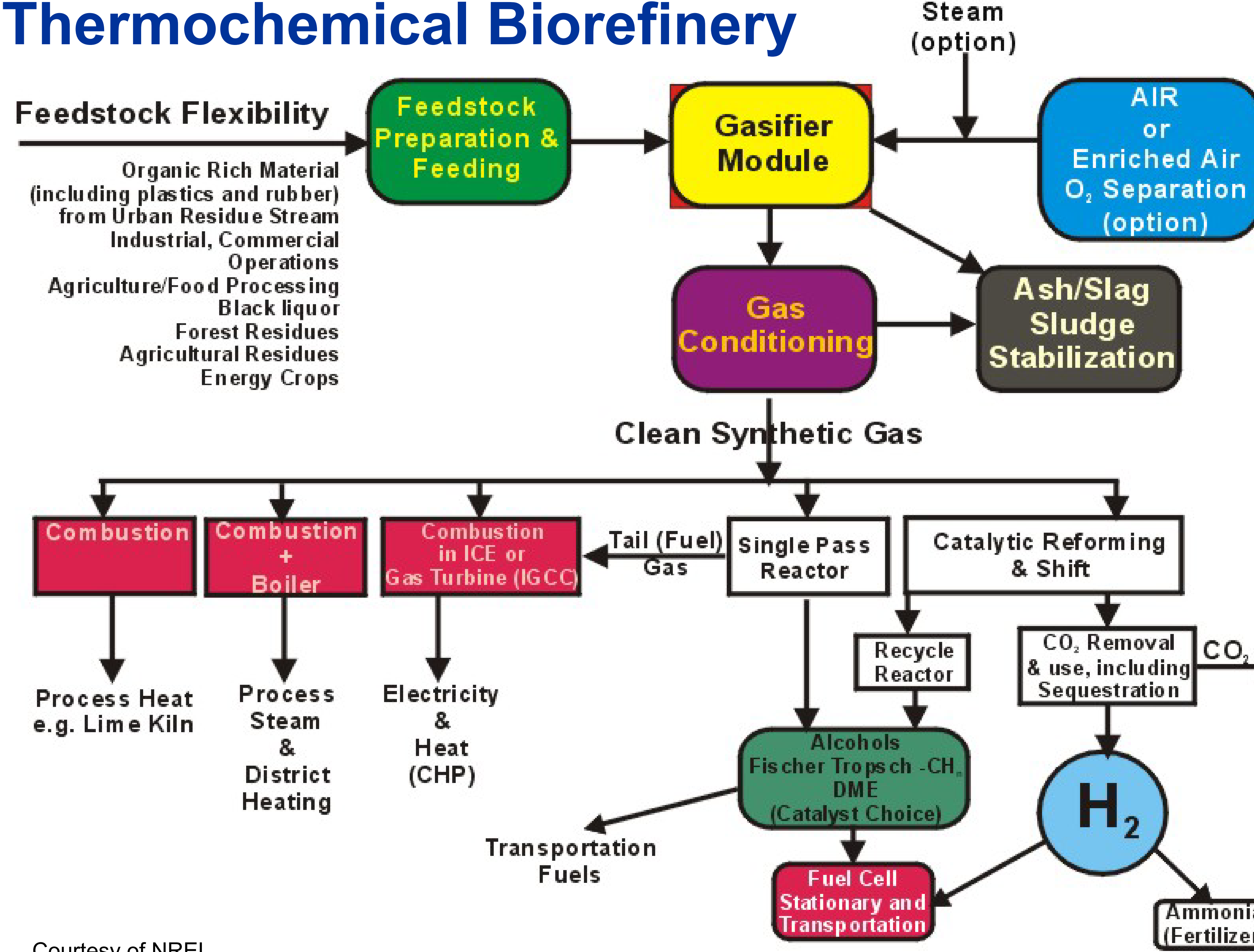
Animal Feed

Electricity

Ethanol

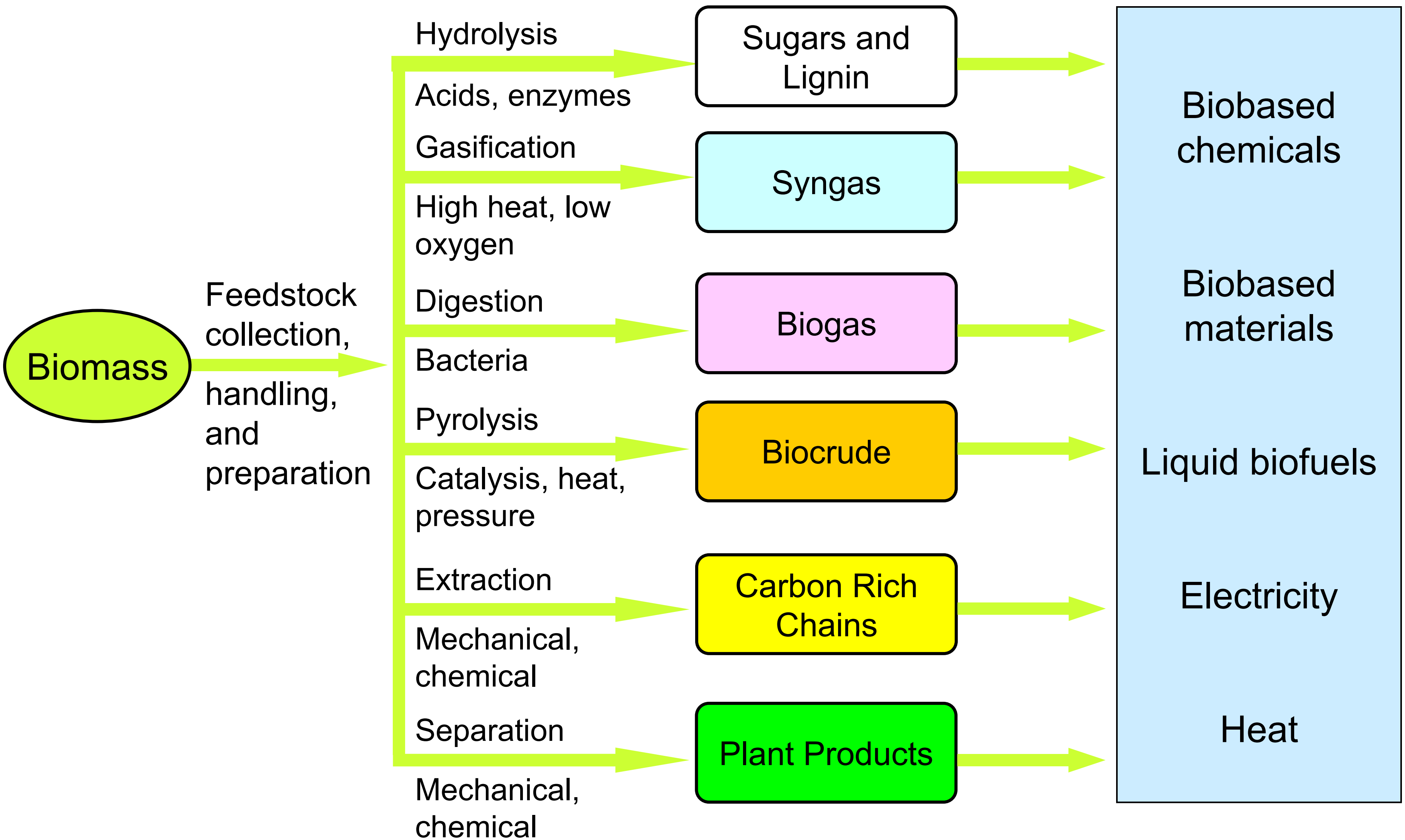
Hydrogen

Thermochemical Biorefinery



Courtesy of NREL.

Biorefinery "Platforms"



Biomass-To-Electricity
Examples of Installed U.S. Capacity

Type of Biomass	Number of Installations	Capacity, MW
Wood	259	5,332
Pulping Liquor	6	443
Bagasse and Other Agricultural Residue	39	669
Digester Gas	61	112
Landfill Gas	174	583
Tires	3	69
Total (Above + Other Sources)	678	10,006

Source: Adapted From Table 5-2 T.C. Schweizer, et al., EPRI Report No. TR-111893 (1998).

Biomass to Electricity – Challenges to Broader-Based Market Share

- Low heat to power efficiency of combustion steam turbines
  - 18-24% (14,000-19,000 Btu/kWh)
- Supply stability and economics
- Alkali and other trace metal deposits and emissions
- Particulate Deposits and Emissions
- NO_x Emissions
- Cost of Electricity
  - $0.065 – 0.08/kWh
- Lower Energy Density
  - Oxygen = 30-45 wt % dry basis
- Use of Land, Water, Nutrients
- Displacement of Higher Value Crops

Biogas

- **~ ½ CH_4, ½ CO_2**
- **From Anaerobic Digestion of wet Biomass**
  - **Animal, Human Wastes**
  - **Sewage Sludge**
  - **Crop Residues**
  - **NOT Lignin**
- **By-Products: Nitrogen-rich Sludge (Fertilizer) and Fewer Pathogens**
- **Extensive Use in India and China (Millions of Digesters); Industrialized Countries (Stockyards, Municipal Sewage, ~5000 Digestors)**
- **Major Goals**
  - **Environmental Neutralization of Waste**
  - **Fertilizer From Waste**

[a]**Source: Larsen (1993)**

Biogas from Anaerobic Digestion

- Gas Production Rates
  - 0.2 Nm^3/m^3/day Floating or Fixed Cover Digesters (Villages: China, India)
  - 4-8 Nm^3/m^3/day industrial Scale Technology (Dilute Industrial, Municipal Wastes)
- Estimated Costs of Biogas $/million Btu

– Household	11.6
– Village	5.8
– Industrial	0.7-1.1

Source: Larson (1993)

Anaerobic Digestion Process Chemistry & Technology

Complex Organic Matter $\xrightarrow[\text{(Fermentive, Acetogenic)}]{\text{Bacteria}}$ Short Chain Fatty Acids, Alcohols, H_2, etc.

$\xrightarrow[\text{(Methanogenic)}]{\text{Bacteria}}$ $CH_4 + CO_2$ + Mineral Rich, N-Rich Effluent Slurry

- 35-55ºC
- Process Variables: pH, feedrate & C/N ratio, solids residence time (SRT), hydraulic residence time (HRT), stirring
- Simple technologies SRT and HRT of order weeks

Source: Larson (1993)

Anaerobic Digester-Fixed Dome

Figure removed for copyright reasons.

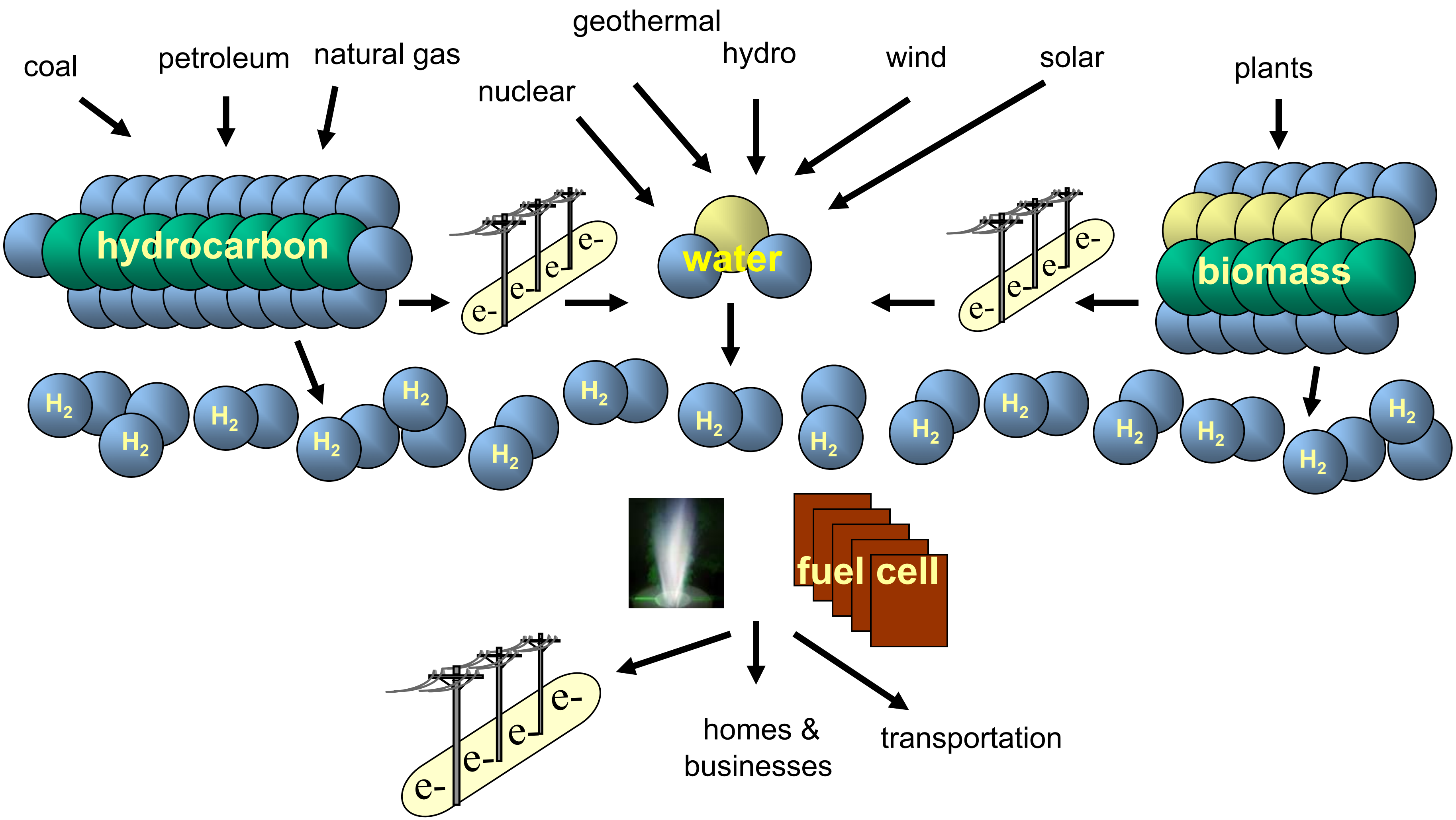
See Figure 10.7 in Tester, J. W., et al. *Sustainable Energy: Choosing Among Options.* Cambridge, MA: MIT Press, 2005.

Anaerobic Digester-Floating Cover

Figure removed for copyright reasons.

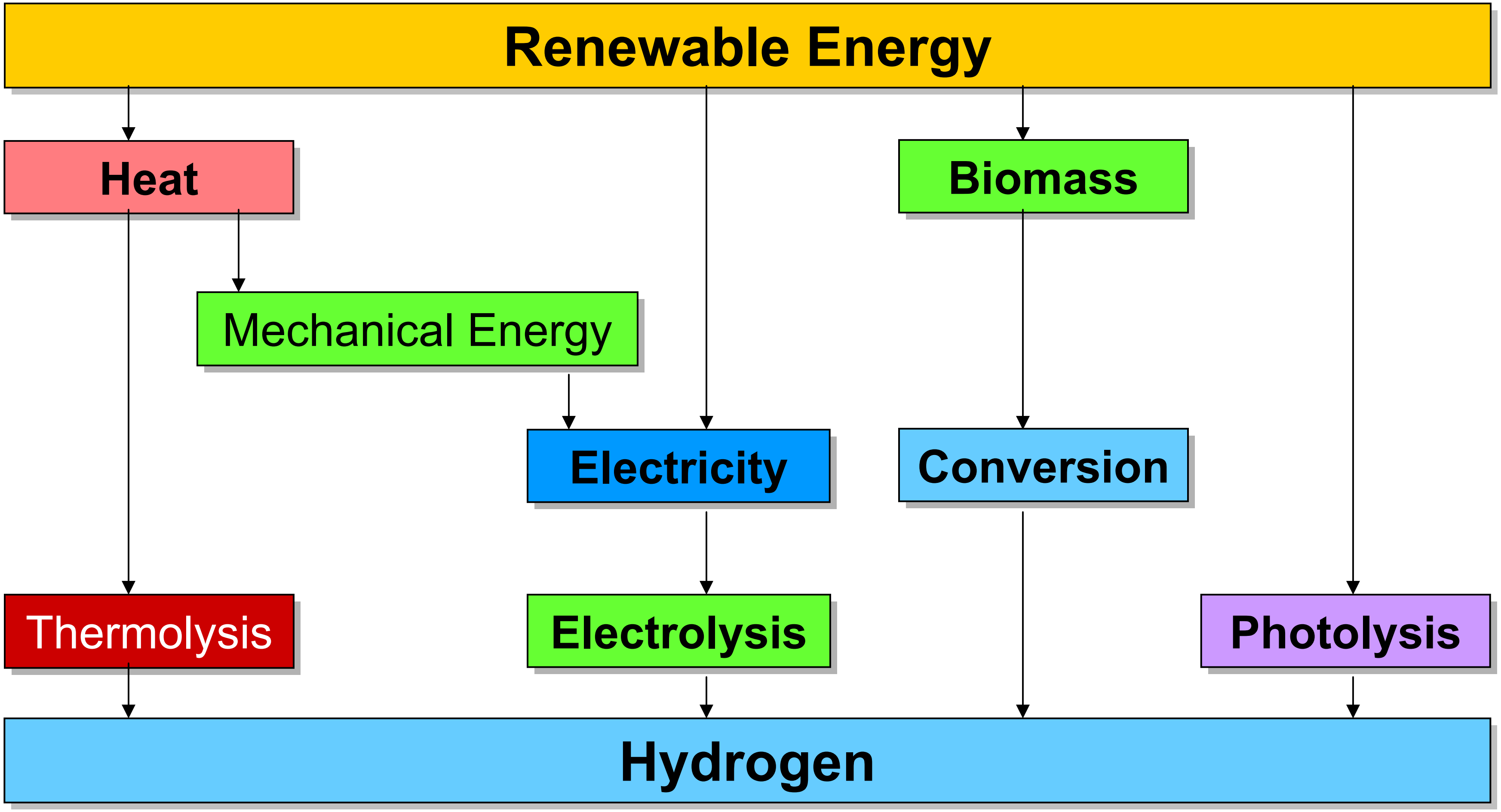
See Figure 10.8 in Tester, J. W., et al. *Sustainable Energy: Choosing Among Options.* Cambridge, MA: MIT Press, 2005.

Hydrogen Pathways

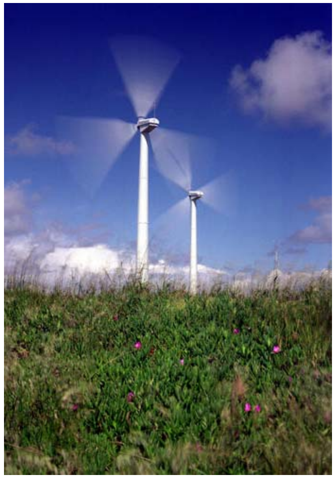


Hydrogen is only an energy carrier – it is produced from other energy sources.

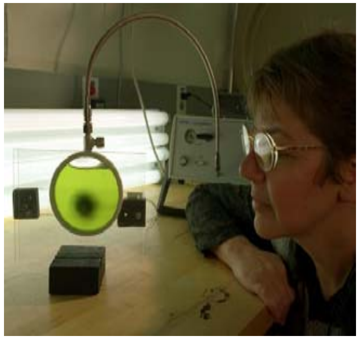
Renewable Paths to Hydrogen



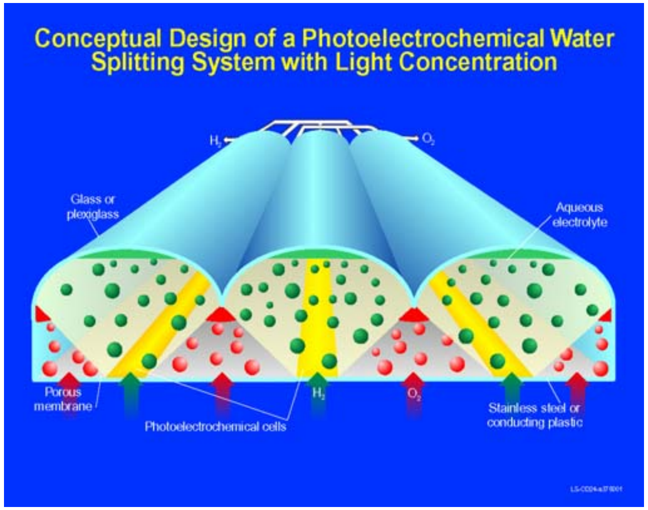
Hydrogen Production



Wind Electrolysis



Photobiological Production



Photoelectrochemical Water Splitting

Biological Water-Gas Shift

Reforming Pyrolysis Streams

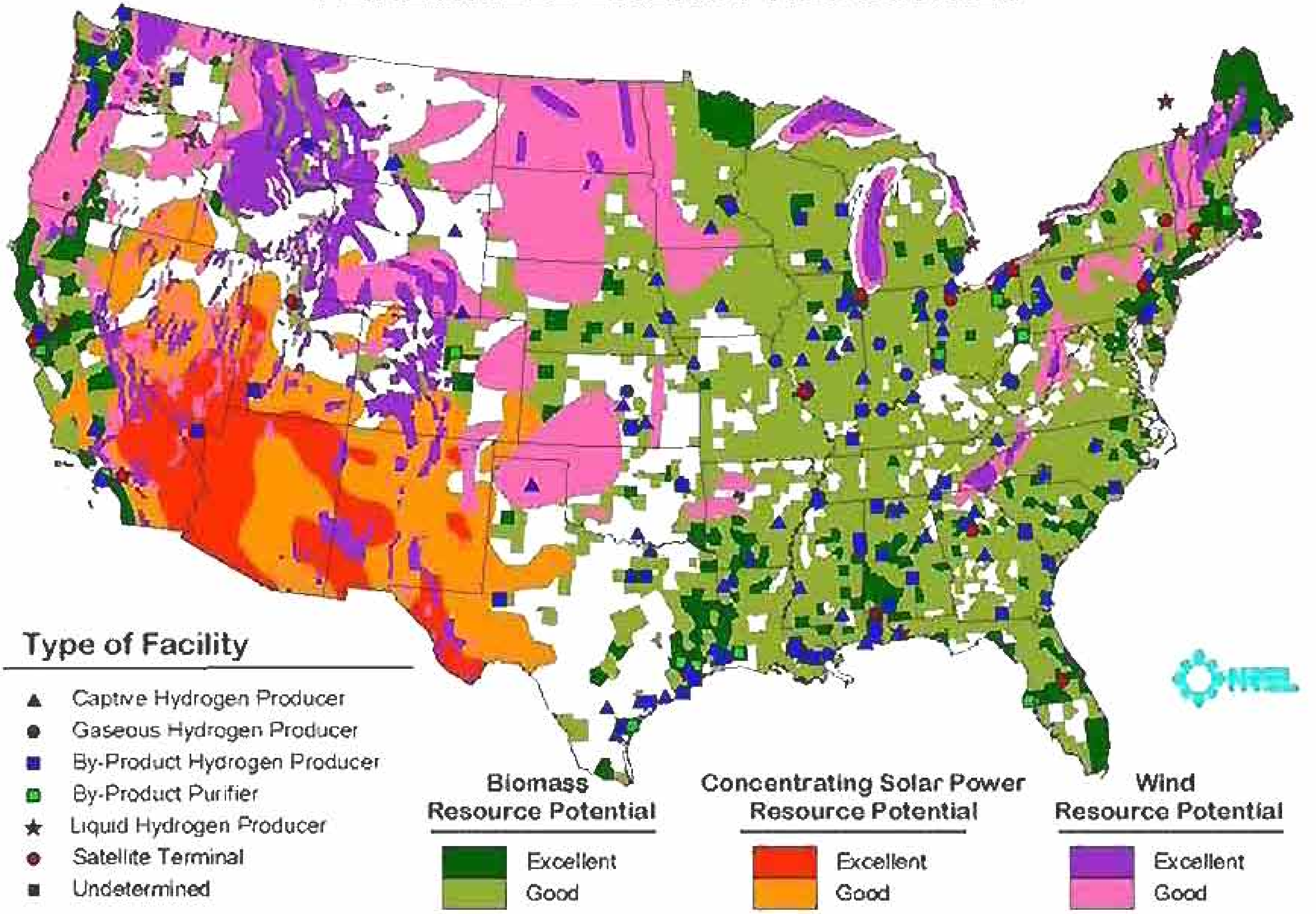
Solar Assisted Production

Courtesy of NREL.

Hydrogen via Biorefineries

- Reforming of pyrolysis or gasification streams
- Demonstrated in an industrial setting
- Potential Impact
  - Broad applicability; biomass resources in many regions
  - Broad economic potential for jobs and byproducts
- In the Future…
  - Farmers, loggers, recyclers work with biorefinery operators, who work with energy service providers, who work with urban and rural developers, who work with transit agencies and consumers….
  - Biorefineries will provide fuels, materials, heat, power, and chemicals

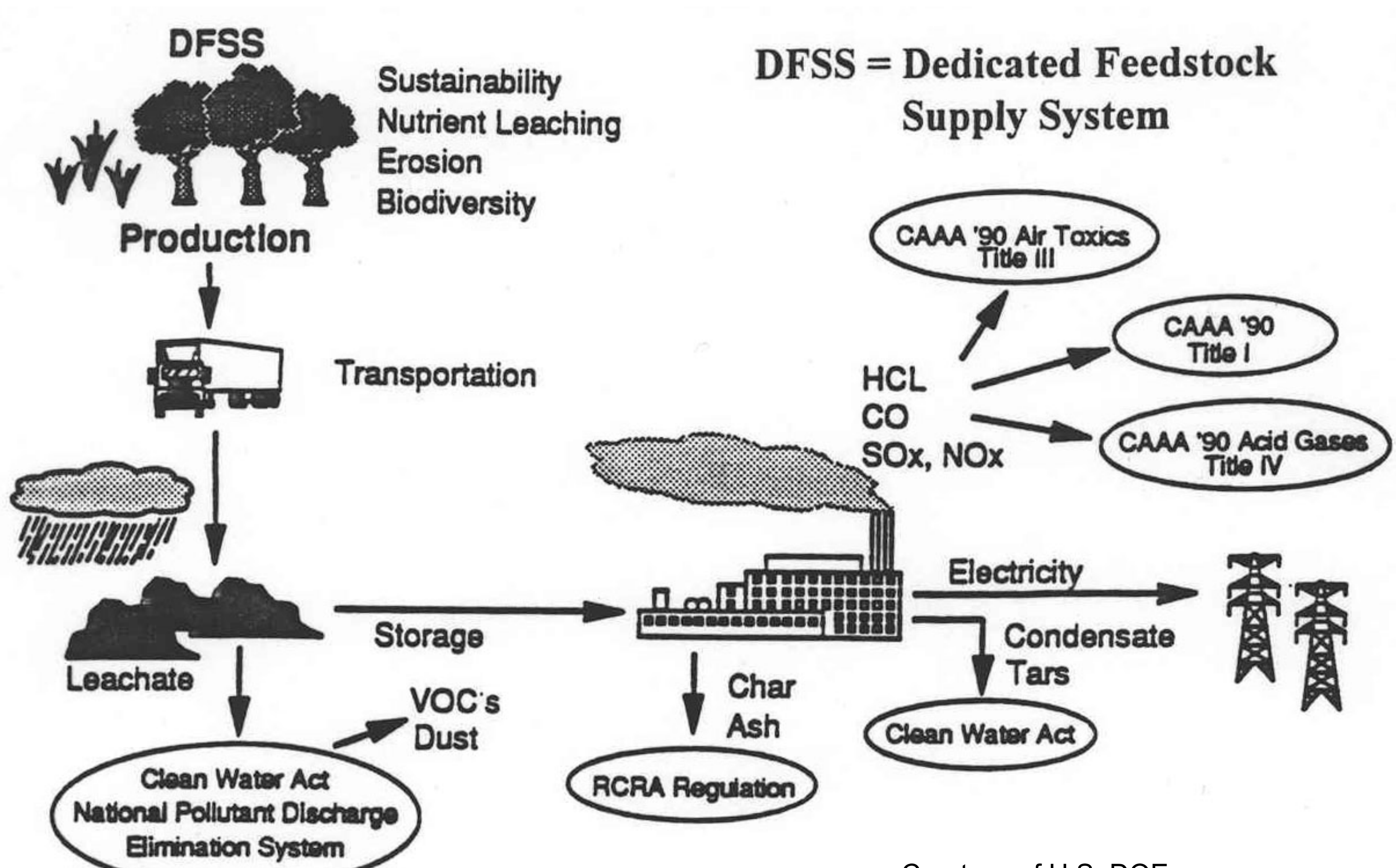
HYDROGEN FACILITIES AND GOOD TO EXCELLENT RENEWABLE ENERGY RESOURCES



Environmental issues for biomass

1. Land, Water, and Nutrient Consumption
2. Pollution From Growing & Harvesting
3. Effluents From Thermal Conversion Processes
4. Combustion Emissions
   - Centralized Steam, Electricity Generation Refuse Based Fuels:
     - Trace Hydrocarbons (PAH), Dioxins, Furans
     - Metals
     - HCl
   - Wood Stoves & Fireplaces
     - PAH
     - Other Complex Organics
     - Particulates
5. CO_2 Management
   - If Fossil and Biomass Consumption Offset by New Biomass Growth

Environment & Biomass Power



Courtesy of U.S. DOE.

Opportunities for biomass

1. Reducing Greenhouse Gas CO_2
2. Restoring Forest Resources
3. Renewable Carbon Source for Energy Future Dominated by Non-Carbon Based Electricity, e.g. Nuclear, Geothermal, and Solar. Biomass Becomes Significant Raw Material for:
   - Liquid Hydrocarbon Fuels
   - Chemicals
   - Other High Value Products

Summary

- Commercial biomass makes contribution to global energy
- For example, in the US
  - 3% of Total
  - Roughly = 2/3 Hydro
  - Roughly = 2/5 Nuclear
- Biomass Percentage Contributions Much Higher in Some Countries, e.g. Brazil and as non-commercial biomass in many LDCs
- Combustion of Biofuels Major Outlet
  - Industrial = 2Q
  - Residential and Commercial = 0.5 Q
- Many Potential Benefits in Electric Power Generation Sector
  - Potentially CO_2 Neutral
  - Low SO_x
  - Co-Firing with Fossil Fuels
  - Clean Air Act Amendments
  - Staged Capacity Additions
  - Dispatchable

Summary (cont.)

- Biomass to electricity and fuels: R&D Opportunities and challenges
  - Increasing Conversion Efficiency
  - Better catalysts
  - Lower land and water use impacts
  - Harvesting and processing
- Municipal and food processing residuals provide opportunities
  - Scarcity of landfills
  - Concerns about disease vectors and toxins
- Environmental effects of biomass utilization warrant careful scrutiny--needs LCA approaches
- Advantages
  - Countermeasure to Global Climate Forcing by Fossil CO_2
  - Renewable Carbon Source for Premium Products
  - Ecosystem Management: Forests, Water
  - Facilitate Transition to Lower Fossil Contribution
  - Genetically Tailored Crops: “Sunshine-to-Gasoline”
- Economics still is a Major Challenge

Biomass continued next time

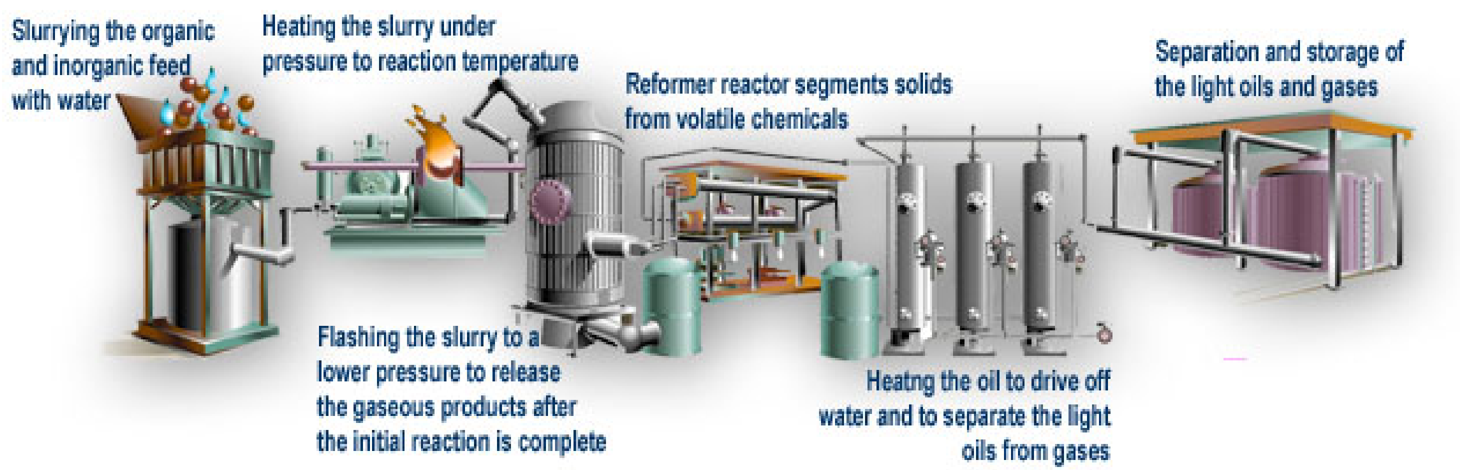
1. Dr. Terry Adams CTO Changing World Technologies – Converting food processing wastes to fuels and other useful products using hydrothermal processing

2. Dr. Morgan Froling Wallenberg Fellow and Jeremy Johnson MIT Chemical Engineering – LCA approaches for biorefineries: food and ag wastes to biobuels and other products

3. Michael Raab MIT and Agrivida– Genetic engineering of plants to improve procressing of food crop residuals

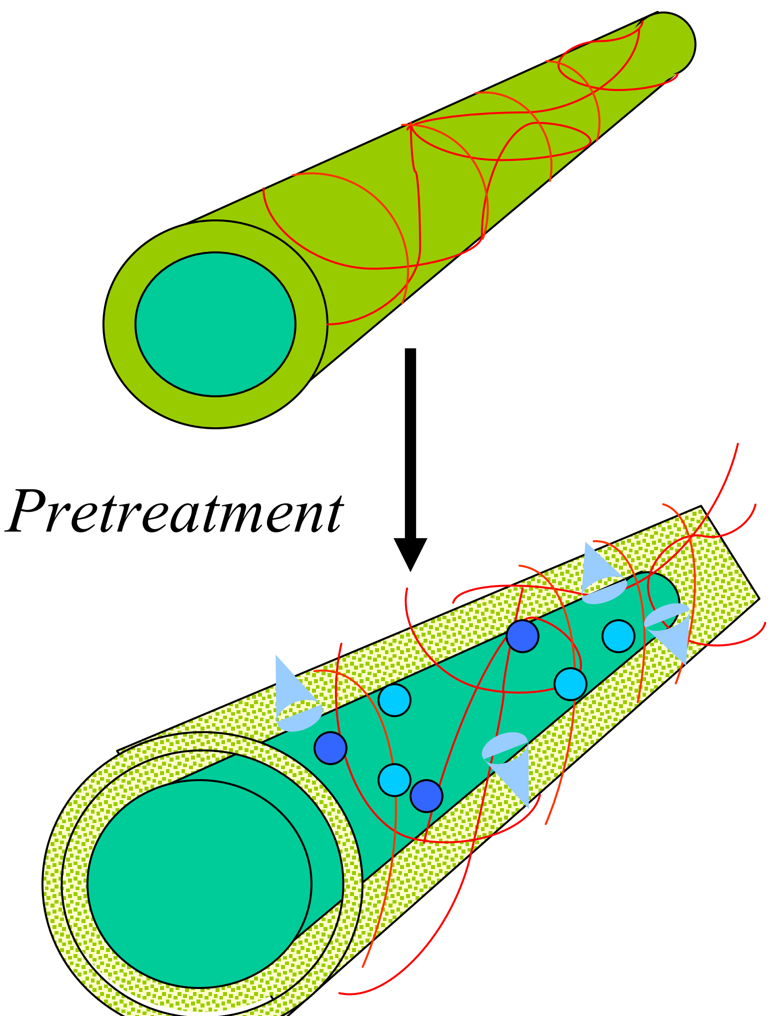
CWT-Thermal Deploymerization Process

- Changing World Technology (CWT) has developed a promising process to convert turkey offal and other wastes to useful products
- CWT has a plant in operation in Carthage, MO, co-located with a ConAgra turkey processing plant
- 210 T/D waste feed efficiently converted to 69.8 T/D TDP-40 oil, 7.5 T/D fuel gas, 6.7 T/D carbon black, 33.6 T/D liquid fertilizer, and other useful products



http://www.changingworldtech.com/techfr.htm

M. Raab - Agrivida process for engineering plants for energy production



Engineering Plants