Pathways to Renewable Fuels

Robert C. Brown
Office of Biorenewables Programs
Iowa State University

Governors' Ethanol Coalition
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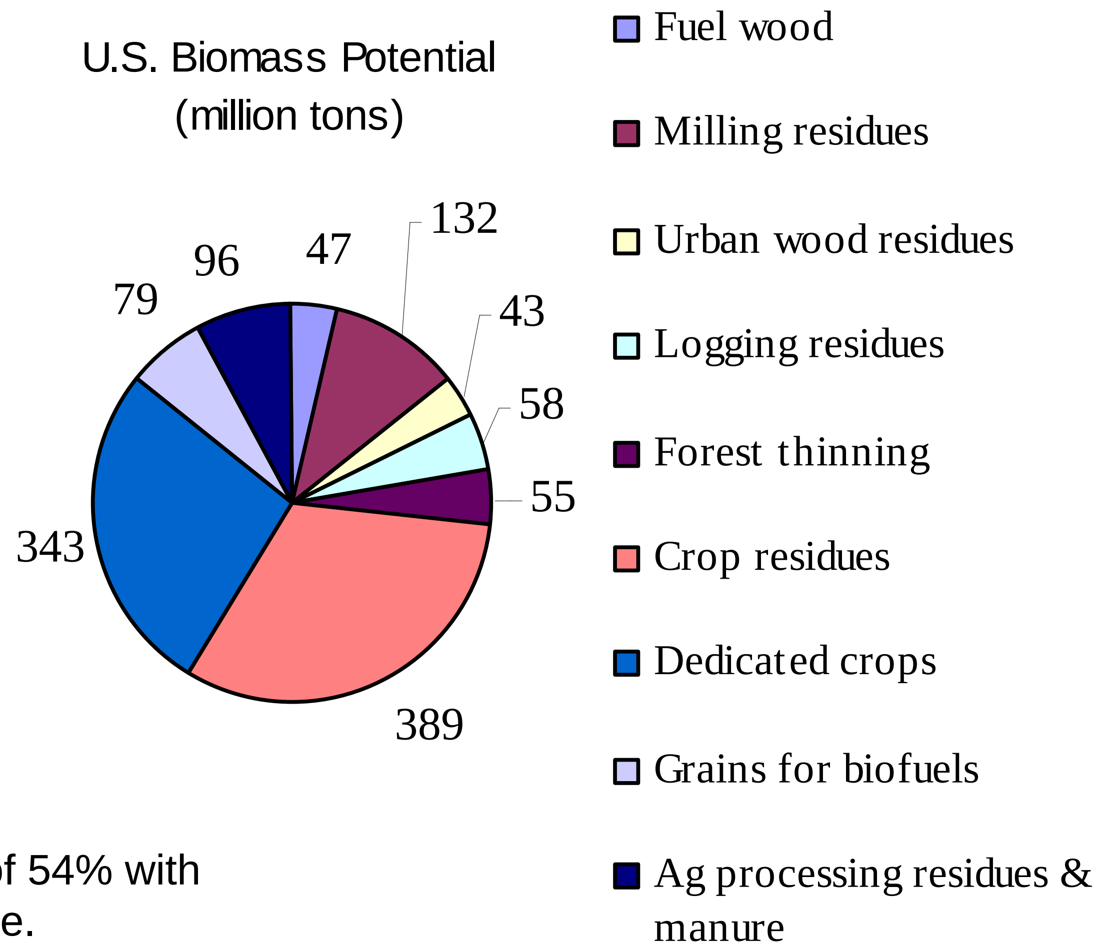
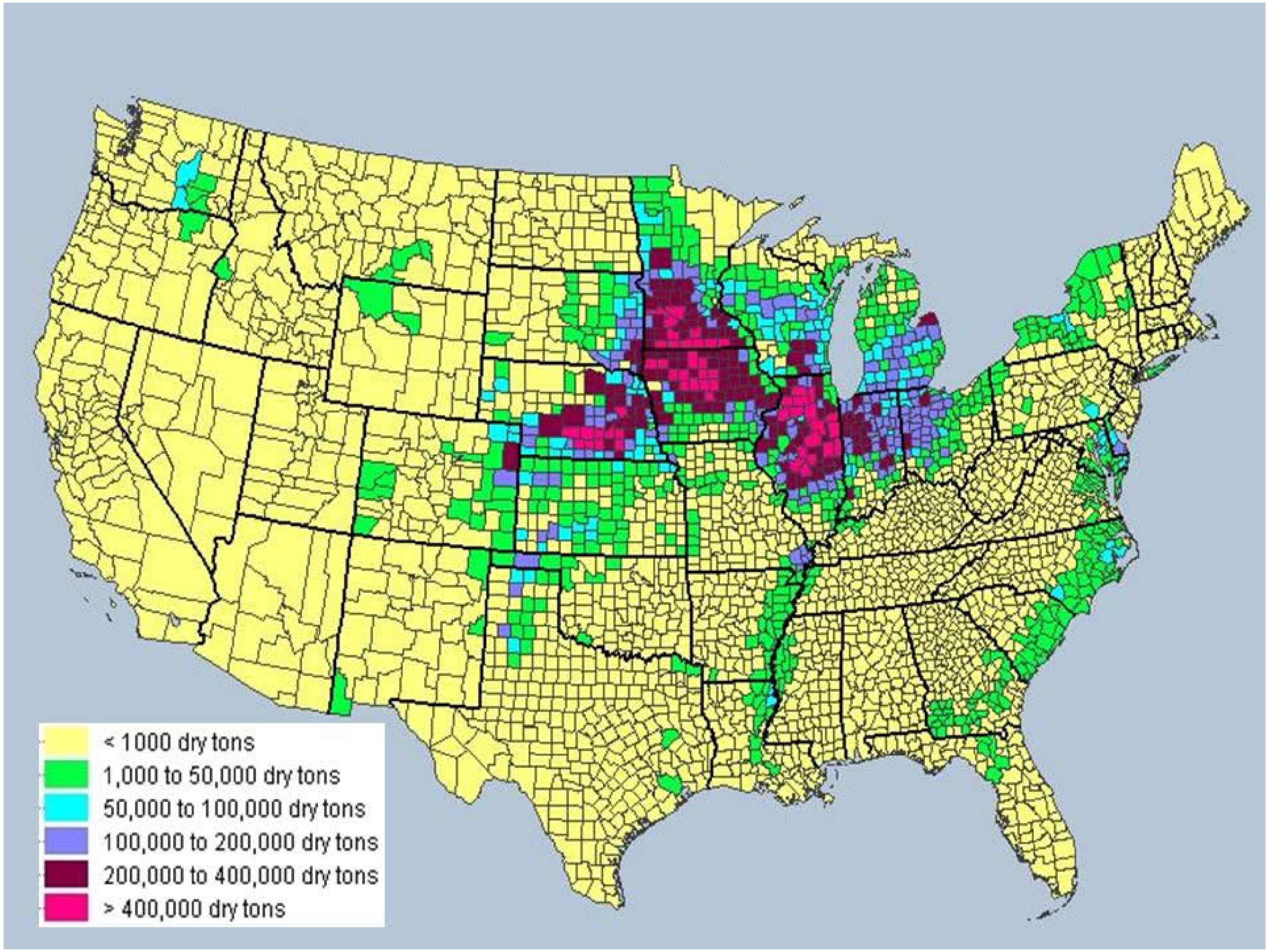
How Much Biomass Could Be Produced?

- Total potential in U.S. is in excess of 1.3 billion tons (about 21 EJ)
- Equivalent to 66% of U.S. gasoline demand*



*Cellulose-to-ethanol efficiency of 54% with heating value of 66% of gasoline.

U.S. DOE Biomass Supply Forecasting Analysis : 1.3 Billion Ton Study

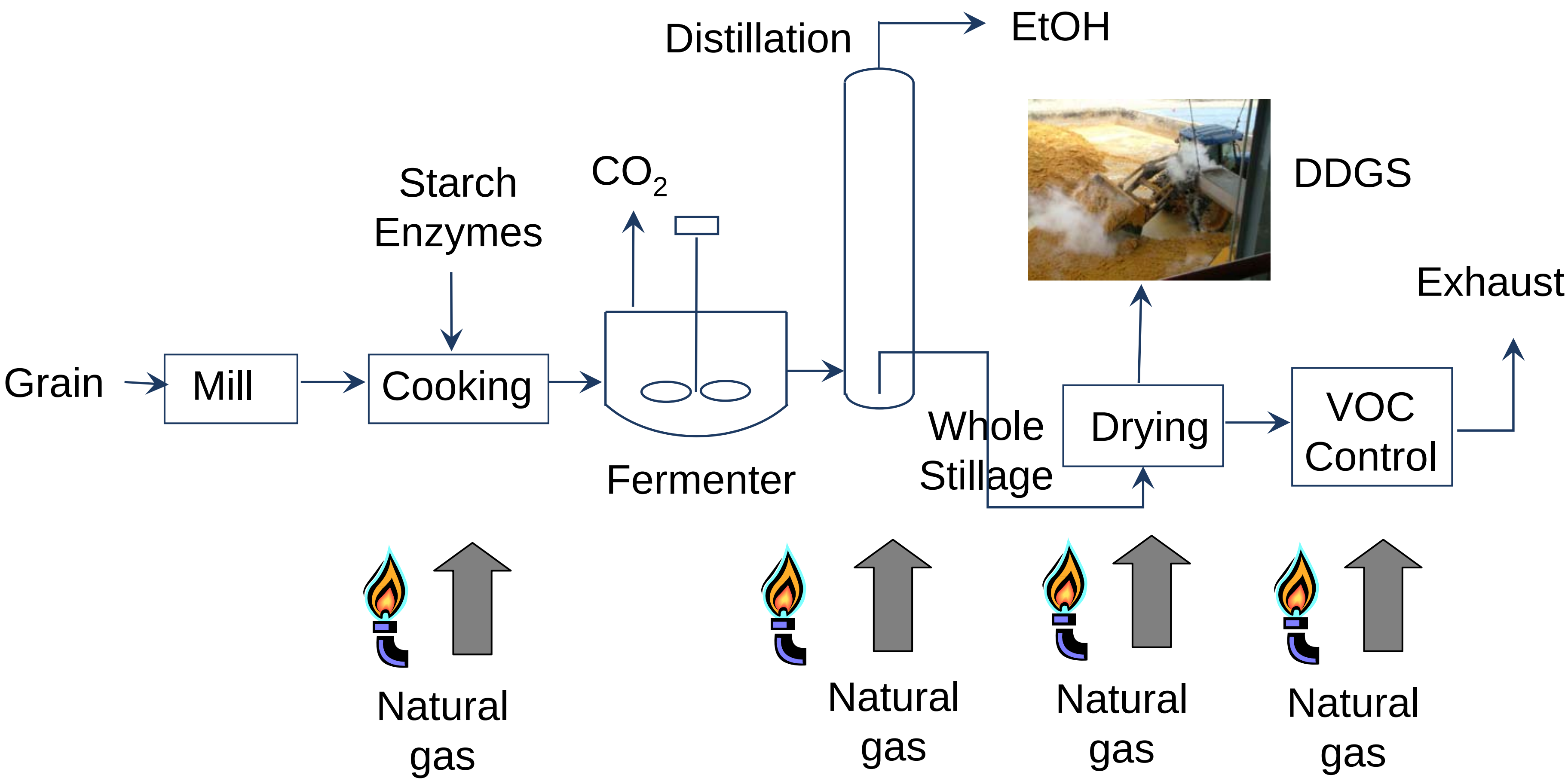


Future for Fibrous Crops?

Crop	Fuel (GJ/acre)	Protein (kg/acre)
Soybeans	7.7	393
Corn	39	457
Switchgrass	95	400

- Soybeans: 38 wt% protein, 20 wt% oil, 38 bu/acre
- Corn: 10 wt% protein, 2.7 gal/bu, 180 bu/acre
- Switchgrass: 4 wt% protein, 117 gal/ton, 10 ton/acre

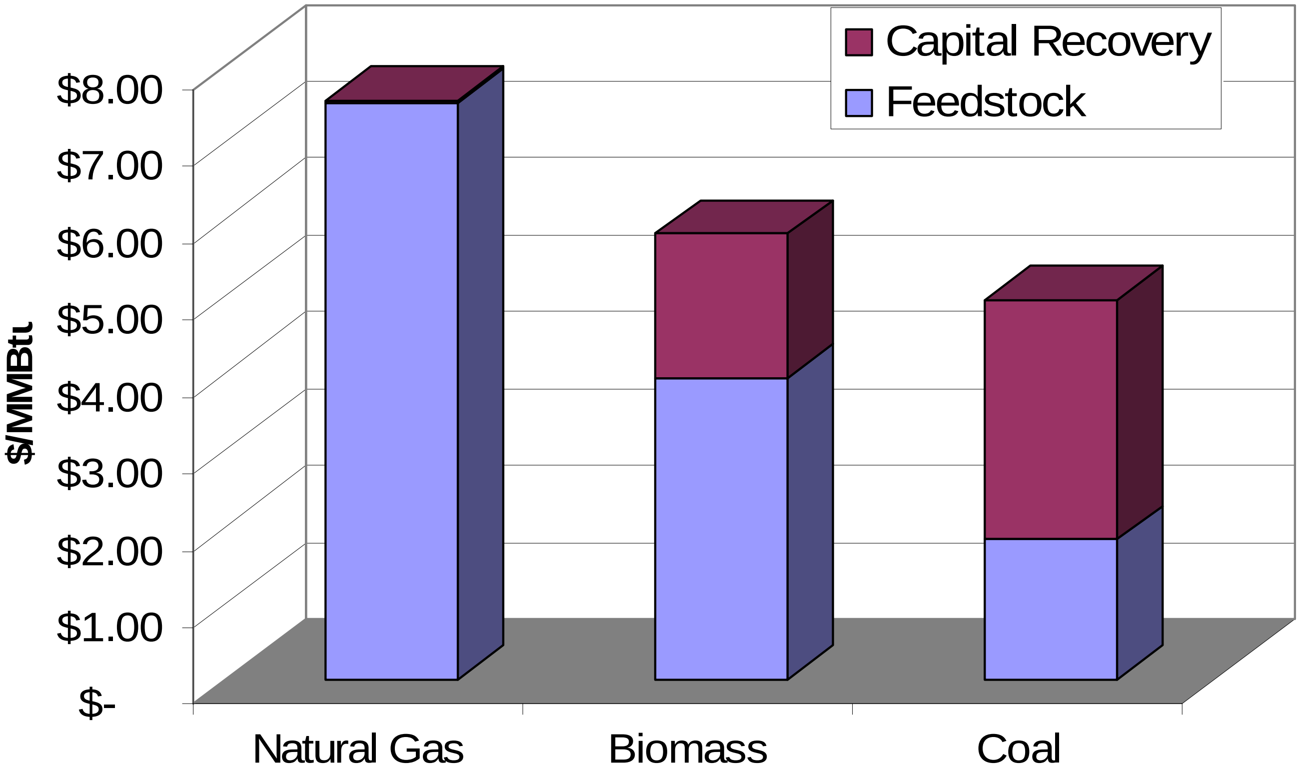
Energy Consumption in Ethanol Plant



Natural Gas Use in Grain Ethanol Production

- Natural gas consumption:
  - Production of NH_3 fertilizer: 7,500 Btu/gallon EtOH
  - Process heat in plant: 34,700 Btu/gallon EtOH
- Ethanol production consumes equivalent of 20% of natural gas use in Iowa
  - 3.5% for fertilizer to grow corn
  - 16% for process heat in ethanol plants

Opportunities to Reduce Natural Gas Usage



Assumptions

Capital Costs:
- $0.3M nat gas
- $15M biomass
- $25M coal
- 5 year amort.

Fuel costs:
- $7.50 nat gas
- $50/ton biomass
- $40/ton coal

Biomass is Cost Competitive and Renewable!

Biorefinery

“A processing and conversion facility that (1) efficiently separates its biomass raw material *into individual components* and (2) converts these components into marketplace products, including biofuels, biopower, and conventional and new bioproducts.”

The Biomass Research and Development Technical Advisory Committee (2002)
U.S. Departments of Energy and Agriculture

Ethanol and Biodiesel are not the Only Possible Biobased Fuels

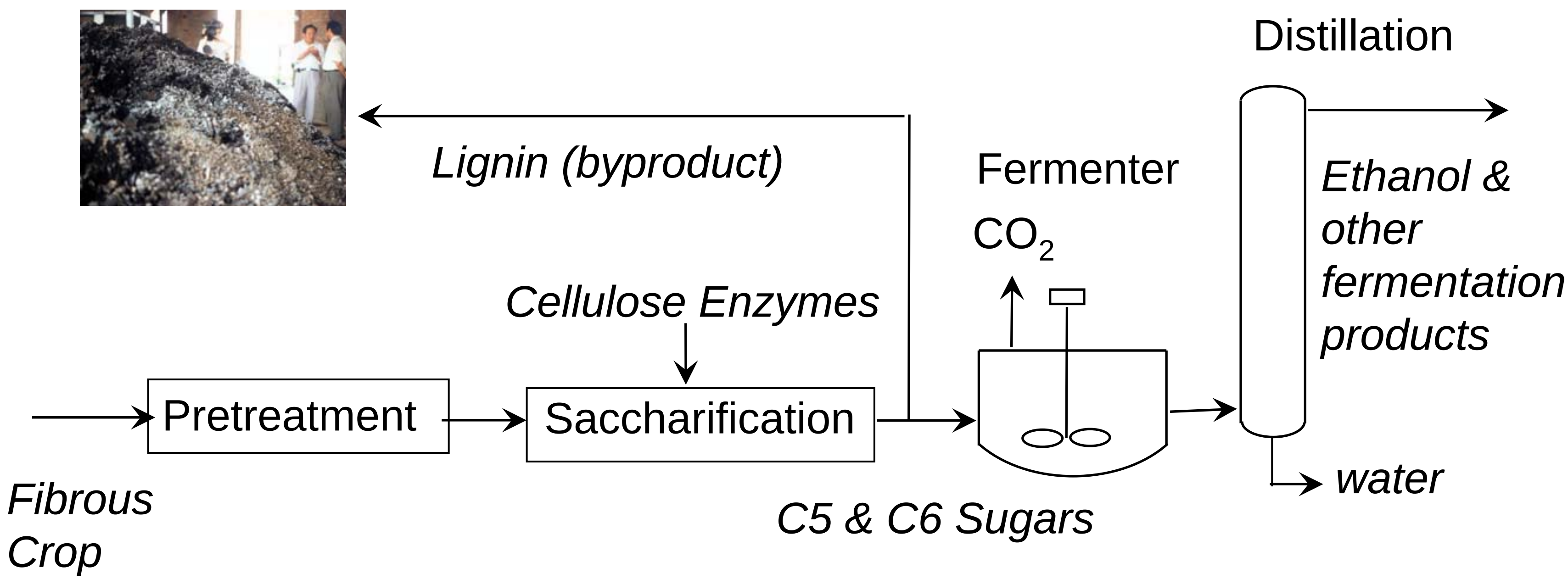
Fuel	Specific Gravity	LHV (MJ/kg)	Octane Number	Cetane Number
Ethanol	**0.794**	**27**	**109**	**-**
Biodiesel	**0.886**	**37**	**-**	**55**
Methanol	0.796	20.1	109	-
Butanol	0.81	36	96 - 105	-
Fischer-Tropsch Diesel	0.770	43.9	-	74.6
Hydrogen	0.07 (liq)	120	>130	-
Methane	0.42 (liq)	49.5	>120	-
Ammonia	0.68 (liq)	18.8	110	-
Dimethyl Ether	0.66 (liq)	28.9	-	>55
Gasoline	0.72-0.78	43.5	91-100	-
Diesel	0.85	45	-	37-56

Approaches to Biorefineries

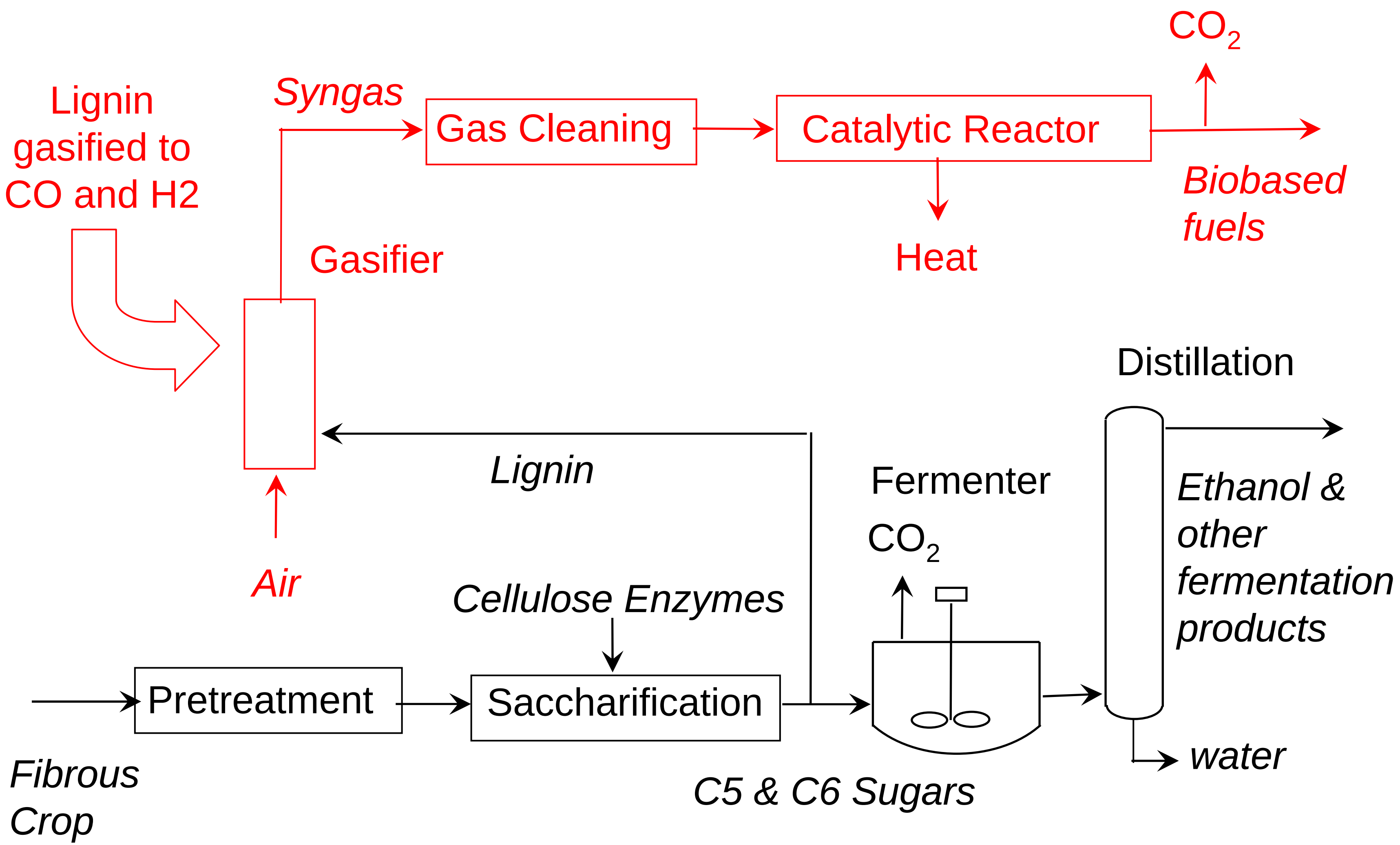
- Biochemical (sugar platform)
- Thermochemical
  - Gasification
  - Fast pyrolysis
- Hybrid thermochemical/biochemical
  - Syngas fermentation
  - Bio-oil fermentation

Biochemical Biorefinery

- Similarities with conventional corn ethanol plant:
  - Pretreatment
  - Saccharification (release C5 and C6 sugars)
  - Fermentation (both C5 and C6 sugars)



Biochemical Biorefinery
(with thermochemical boost)

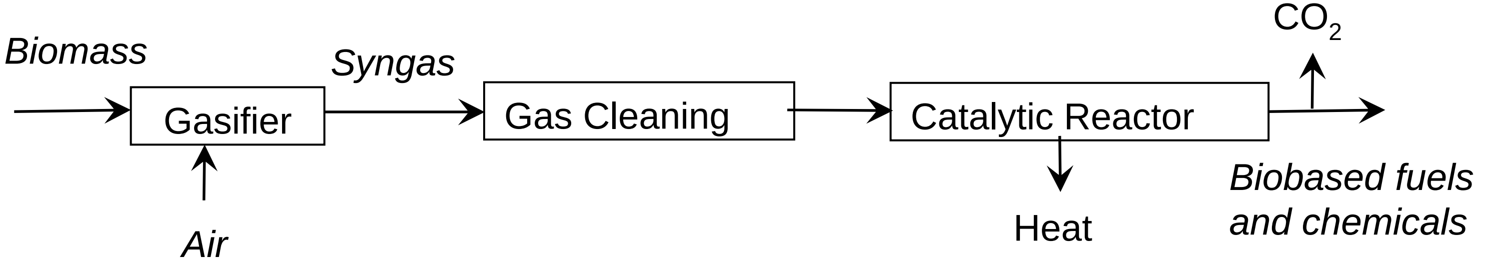


Gasification Biorefinery

- Fibrous or mixed feedstock heated in absence of oxygen to yield mixture of CO and H_2 (syngas) and char byproduct
- Gas clean-up followed by high pressure catalytic synthesis to products
  - Alcohols
  - Hydrocarbons

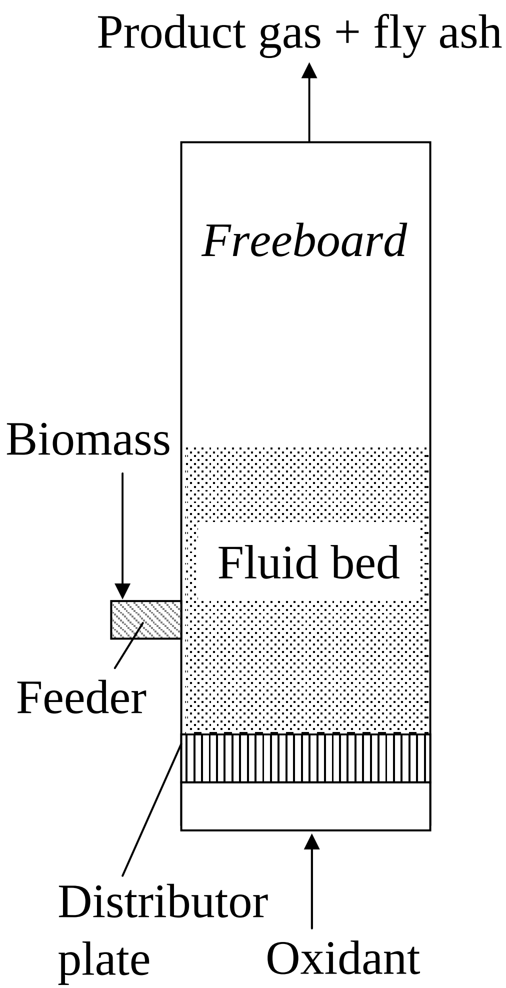
Gasification Biorefinery

- Advantages (compared to biochemical platform)
  - Tolerates relatively dirty biomass feedstock
  - Produces uniform intermediate product (syngas)
  - Proven method for “cracking the lignocellulosic nut”
  - Allows energy integration in biorefinery
- Disadvantages (compared to biochemical platform)
  - Gas cleaning technologies still under development
  - Synfuel processing occurs at high pressures
  - Capital costs thought to be higher

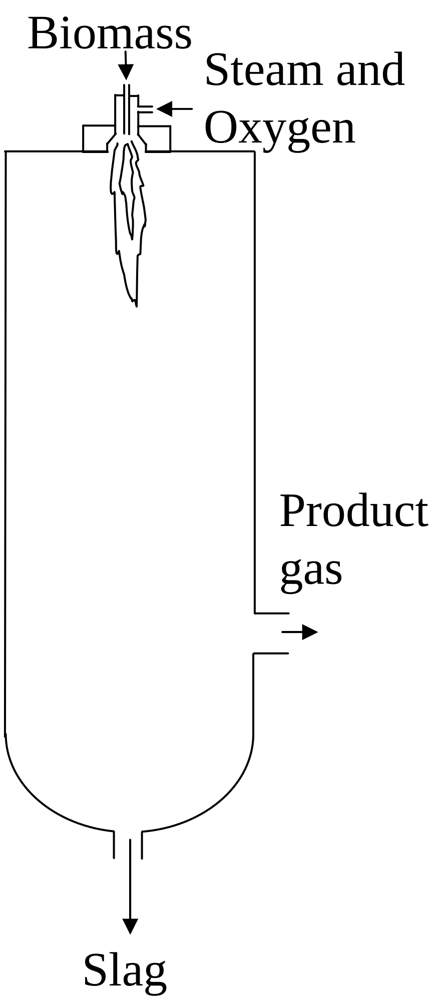


Candidate Gasifiers

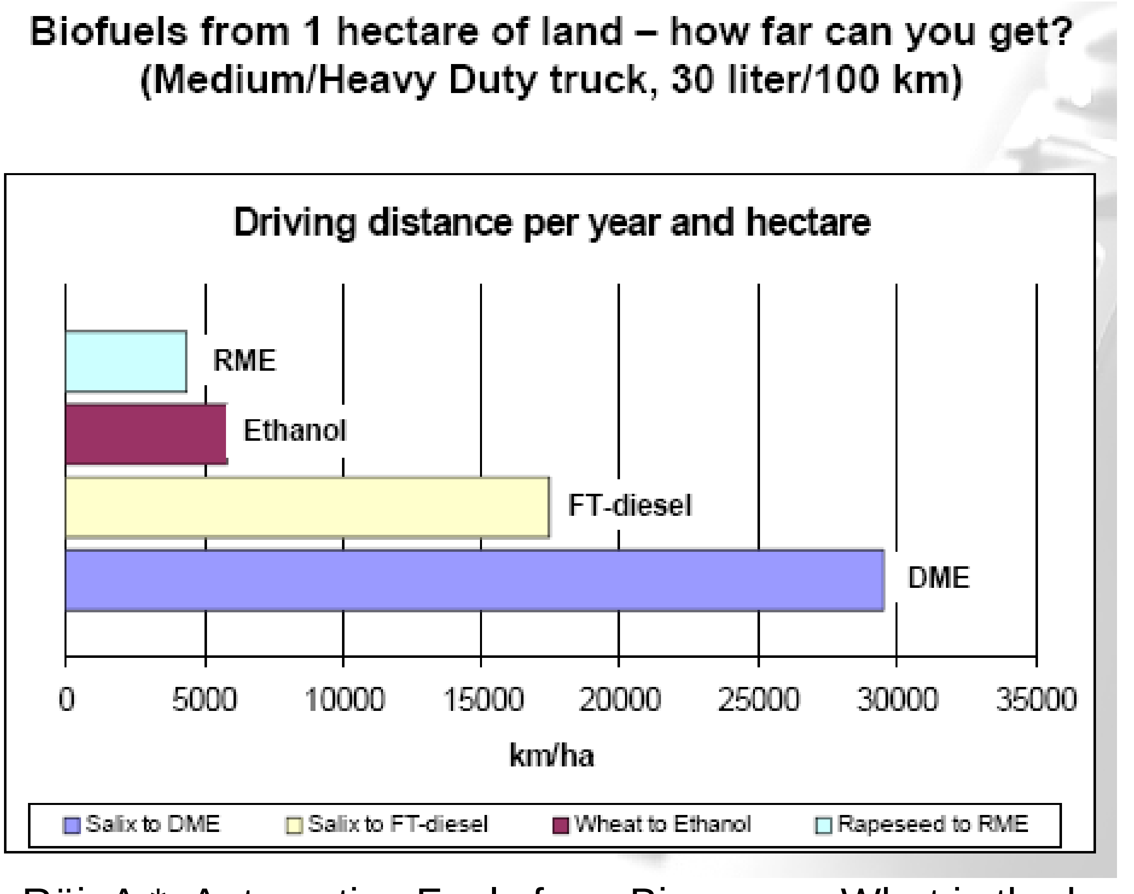
Fluidized Bed



Entrained Flow



Thermochemical Synfuels Have Yield Advantage

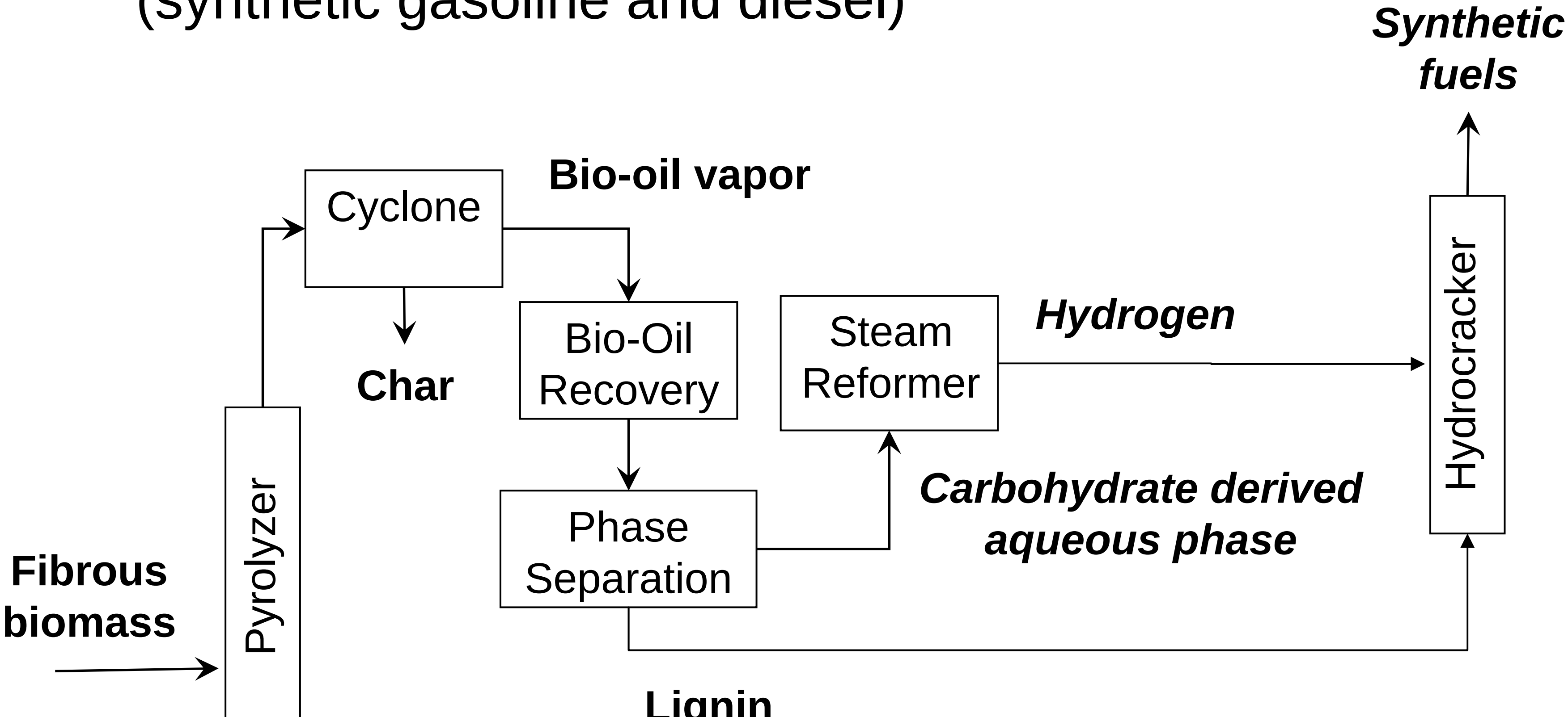


Source: Röj, A.*, Automotive Fuels from Biomass – What is the best road forward, First International Biorefinery Workshop, Washington, D.C., July 20-21, 2005, http://www.biorefineryworkshop.com/presentations/Roj.pdf

* Volvo Technology Corporation, anders.roj@volvo.com

Fast Pyrolysis Biorefinery

- Directly converts biomass into liquid bio-oil (lignin, carbohydrate derivatives, and water) and char
- Bio-oil catalytically converted into hydrocarbon fuel (synthetic gasoline and diesel)

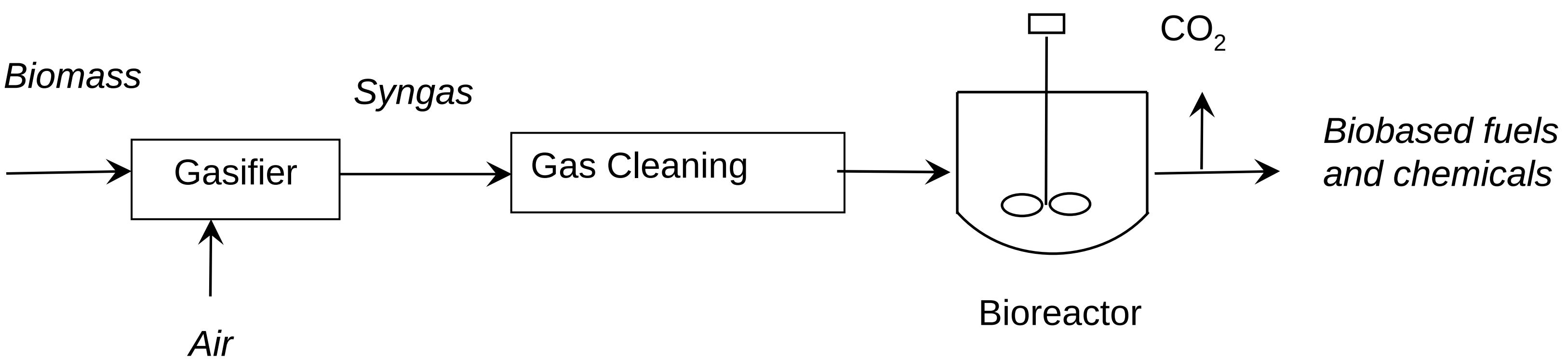


Fast Pyrolysis Biorefinery

- Advantages (compared to biochemical platform)
  - Opportunity for distributed preprocessing (densifies biomass)
  - Separates and uses both carbohydrate and lignin
  - Integrates into existing petroleum refineries
- Disadvantages (compared to biochemical platform)
  - Bio-oil can be unstable, corrosive
  - Technology less developed

Syngas Fermentation

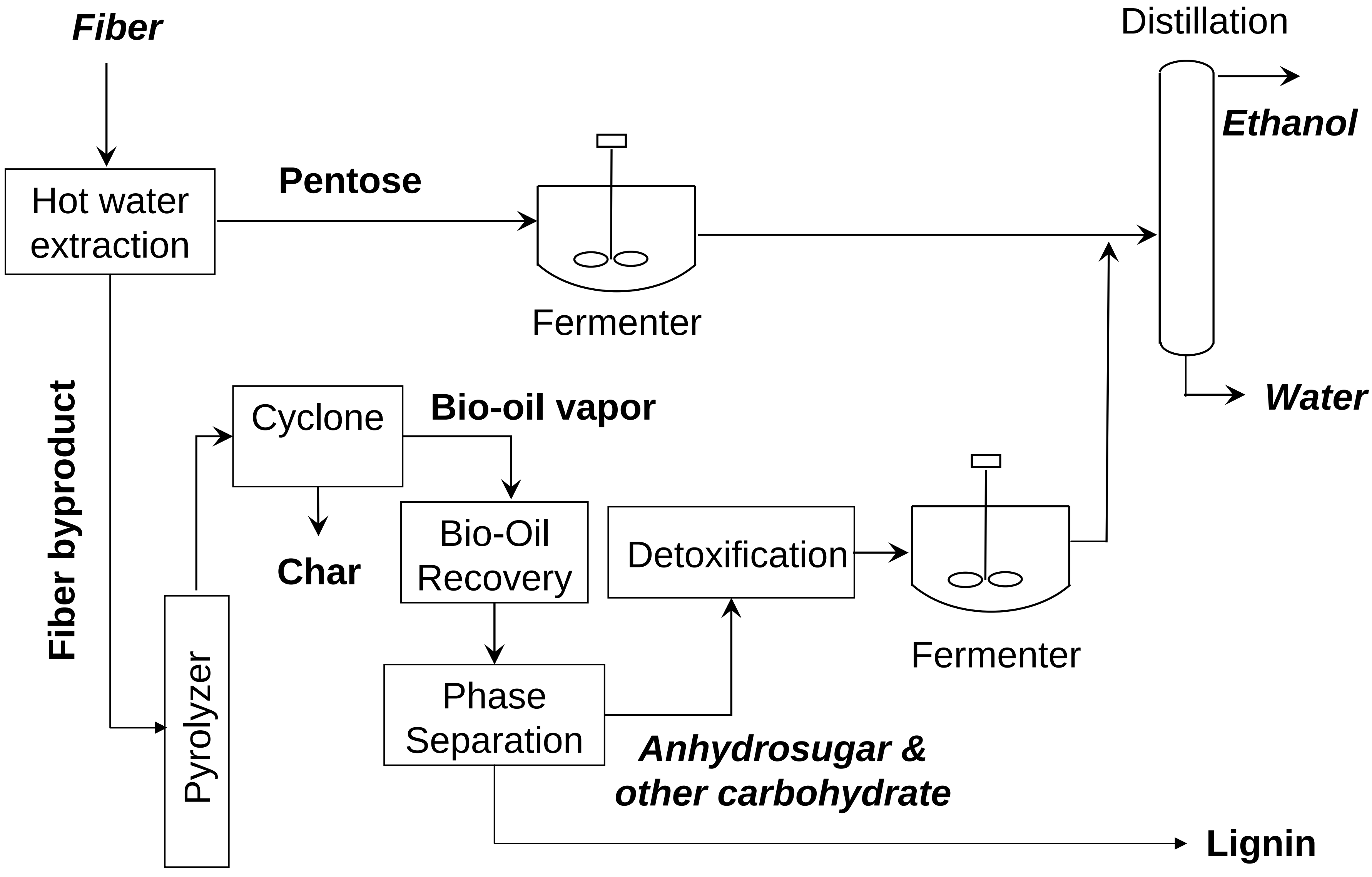
- Biomass gasified to CO, CO_2 and H_2
- Autotrophic organisms ferment CO or CO_2 and H_2 into metabolic products
  - Alcohols, carboxylic acids, esters



Syngas Fermentation Biorefinery

- Advantages (compared to gasification biorefinery)
  - Biocatalysts tolerant to sulfur and chlorine contaminants
  - Flexibility in the pressures and CO/H_2 ratios employed
  - High selectivity in products produced
  - Genetic engineering can expand portfolio of products
- Disadvantages (compared to gasification biorefinery)
  - Low rates of gas-liquid exchange
  - Less developed technology

Bio-Oil Fermentation Biorefinery



Bio-Oil Fermentation Biorefinery

- Advantages (compared to biochemical)
  - Opportunity for distributed preprocessing
  - Avoids enzymatic hydrolysis bottleneck
- Advantages (compared to thermochemical)
  - Avoids high pressure operations
  - Opportunities for biotechnology advances (such as direct fermentation of anhydrosugar)
- Disadvantages
  - Bio-oil is complex mixture of compounds
  - Technology not well developed

Cost of Renewable Fuels from Biomass

	Capital Cost[b]	Operating Cost[b]	Plant Size
Grain Ethanol[1a]	$23,202/bpd	$1.32/gal	25 MMGPY
Lignocellulosic Ethanol[1a]	$113,183/bpd	$2.25/gal	25 MMGPY
Methanol[2c]	$76,509/bpd	$1.25/gal	100 MMGPY
Hydrogen[2c]	$67,134/bpd	$1.09/gal	240 MMGPY
Fischer-Tropsch[3]	$52,942/bpd	$1.83/gal	>100 MMGPY

Notes

[a] Online time of 330 days per year. Year for cost basis is 2000.

[b] All volume units based on gasoline equivalents.

[c] Year for cost basis was 2002. The uncertainty of the analysis is +/- 30%.

References:

[1] McAloon A. et. al. “Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks”
NREL October 2000

[2] Hamelinck et. al. “Future prospects for production of methanol and hydrogen from biomass”
Utrecht University (2002)

[3] Handbook biomass gasification.

[4] National Association of Fleet Administrators, INC. “Energy equivalents of various fuels” 09/2006
http://www.nafa.org/Content/NavigationMenu/Resource_Center/Alternative_Fuels/Energy_Equivalents/Energy_Equivalents.htm

Summary

- Biorefineries based on lignocellulosic biomass will be essential to meeting future renewable fuel demand
- Future renewable fuels not necessarily ethanol
- Several options for lignocellulosic biorefineries
  - Biochemical (sugar platform)
  - Thermochemical
  - Hybrid thermochemical/biological
- Unclear at this time whether one technology will dominate future markets