National Renewable Energy Laboratory

Hydrogen from Terrestrial Biomass

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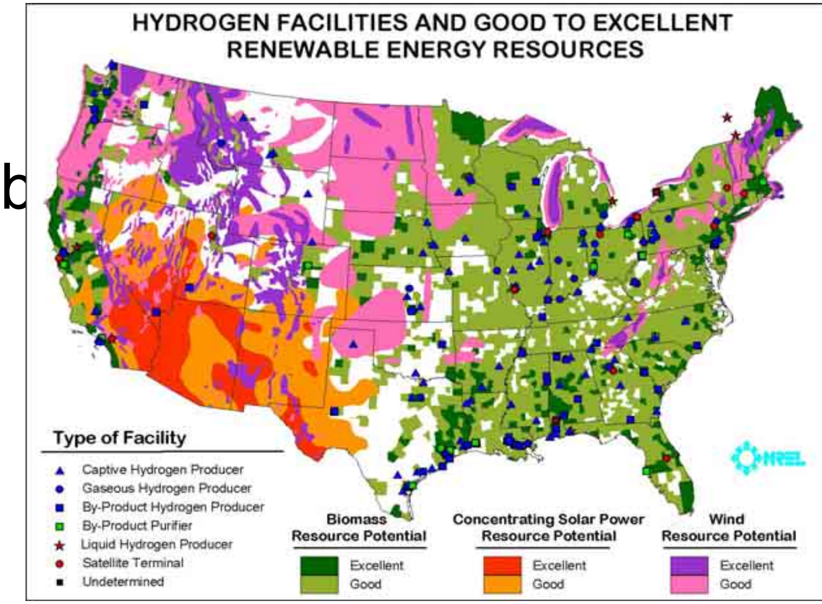

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Outline and Issues (1)

Resource

Biomass is the World's 4th fuel

- Potential is a function of land and energy competitions:
  - Land: Food, Urbanization, Fibre, Water, Conservation
  - Energy: Utility and cost as a delivered energy form
- US has land and significant capability
- Both US and Rest of the World (ROW) require energy crops to reach full potential
- Evaluation does not cover all conversions

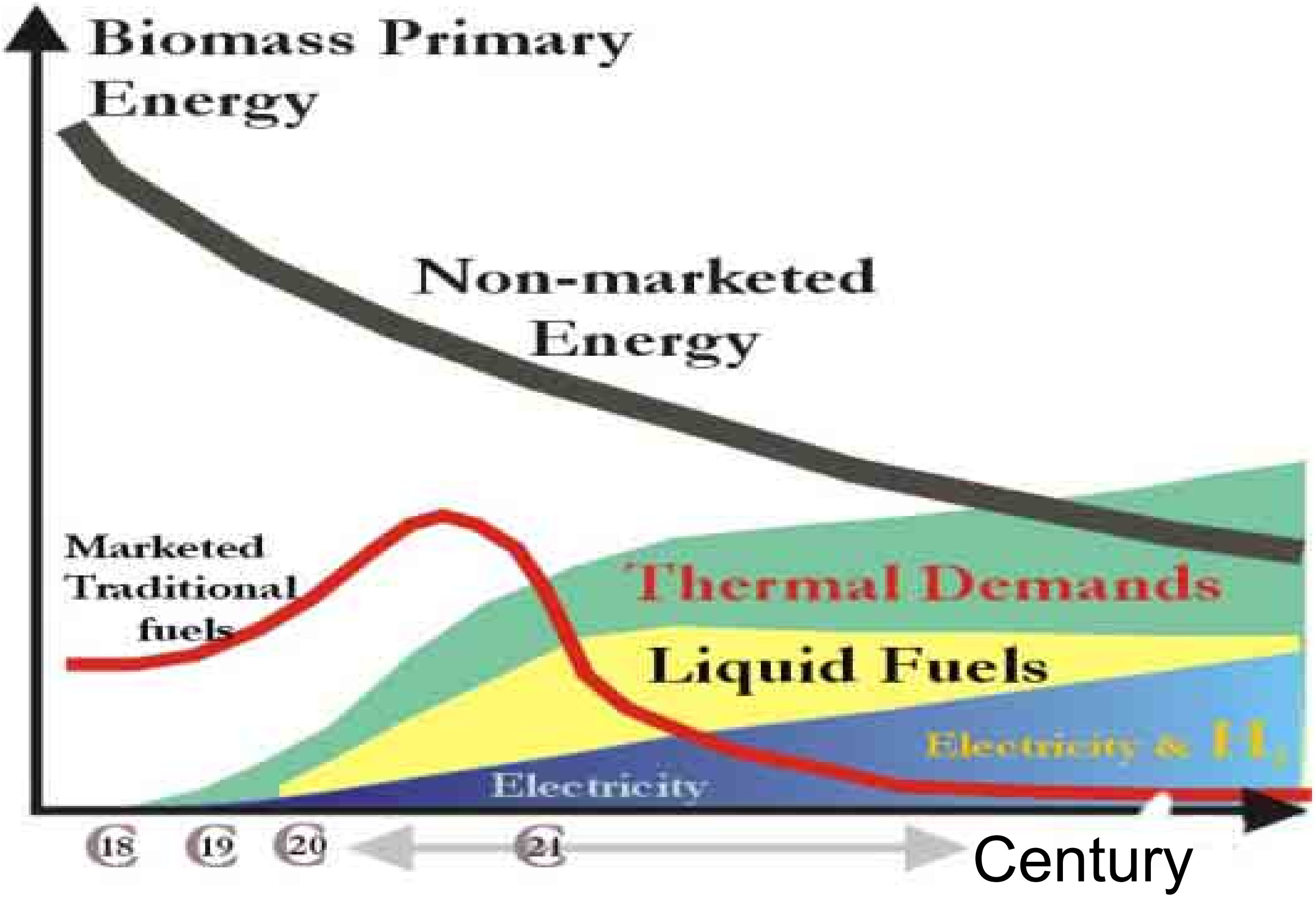
Outline and Issues (2)

Technology

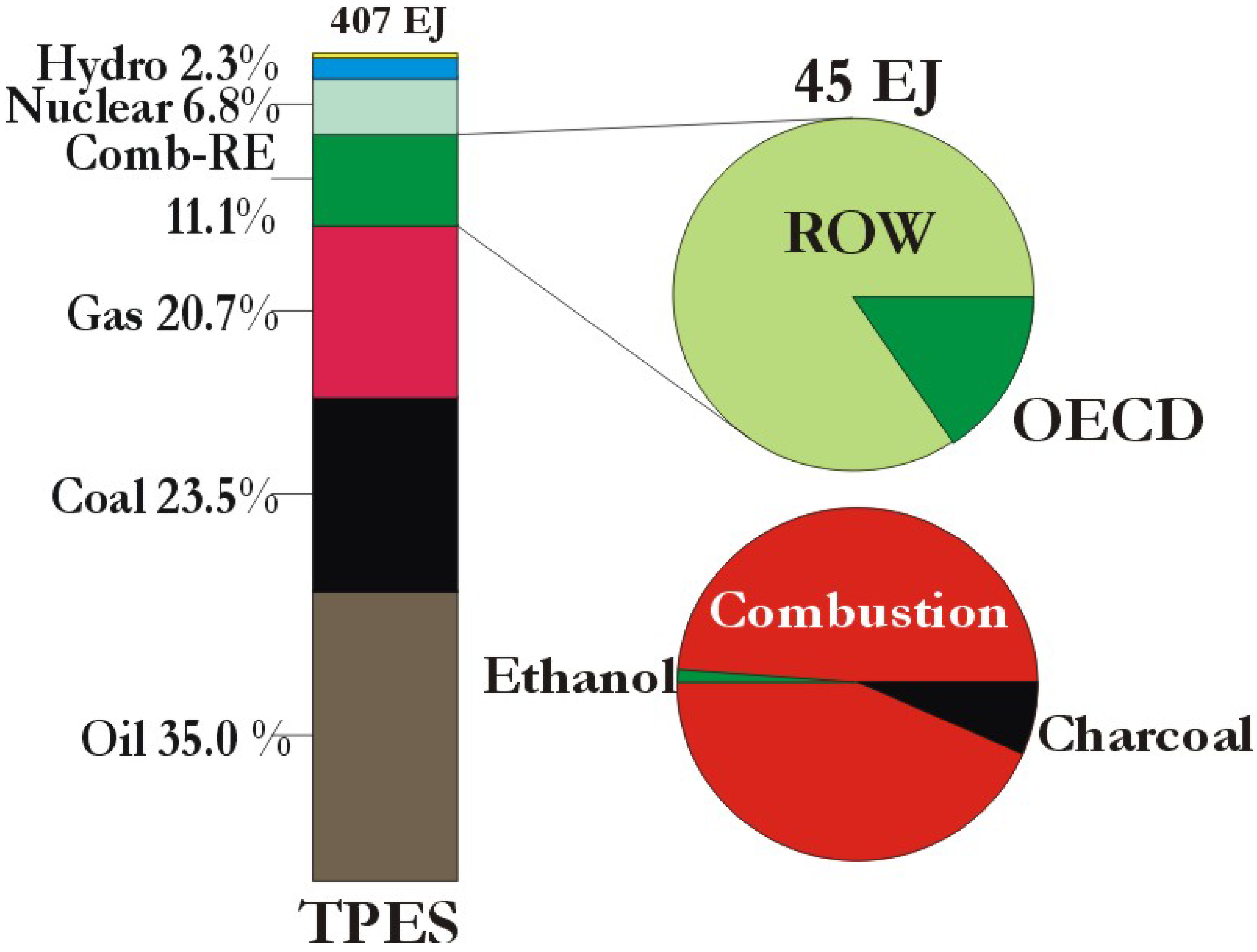
Biomass is a complementary resource to other renewable hydrogen resources

- Hydrogen from biomass is based on demonstrated gasification and pyrolysis technologies allied with proven hydrocarbon reforming technology
  - Conversion efficiency is high
  - Cost of H_2 at the plant is predicted with a medium level of confidence
  - GHG offset is significant and large
- Biorefinery approaches offer economics at moderate scale
  - Medium value coproducts
- RD&D investment can address efficiency and cost improvements in the near term

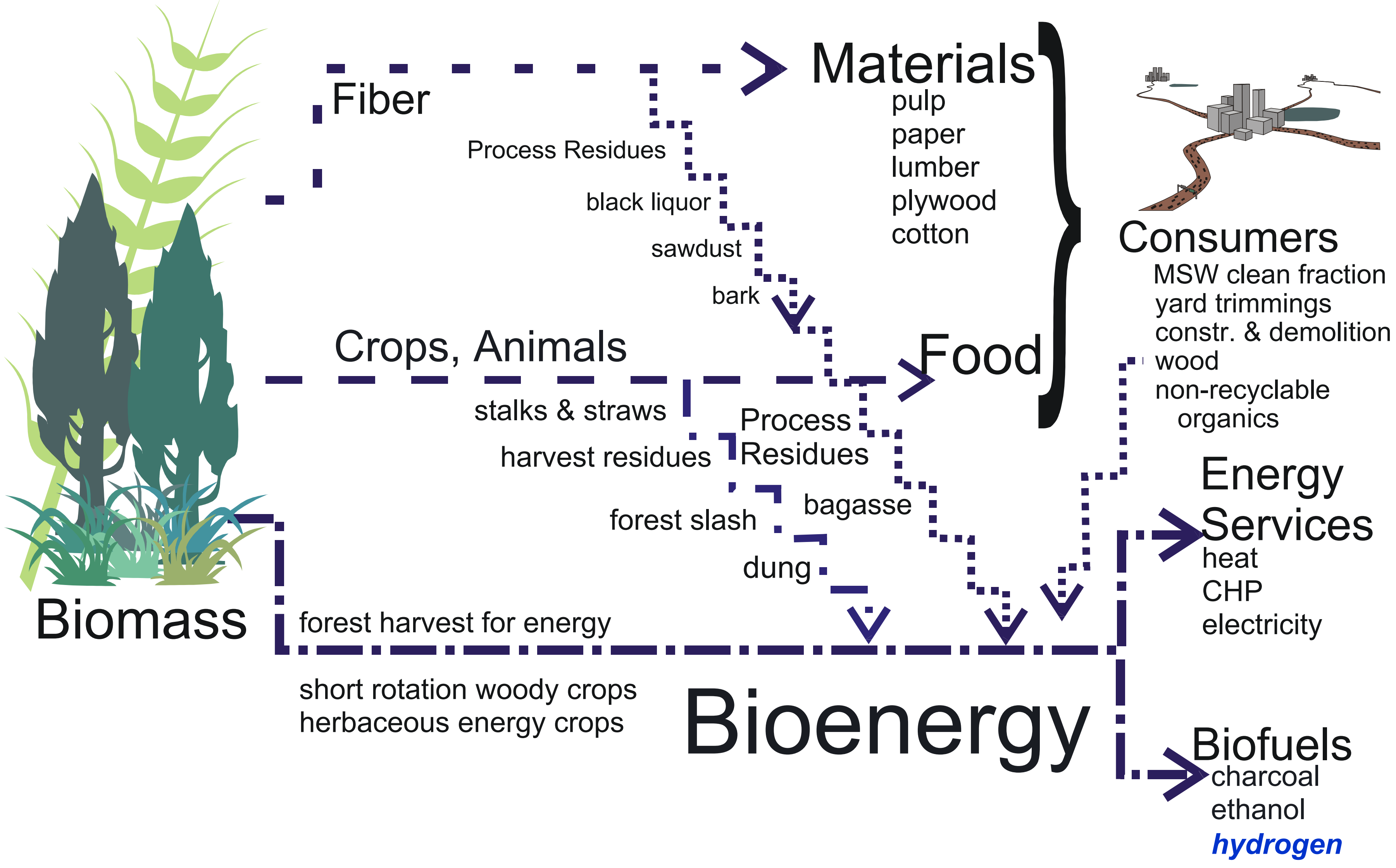
A vision of the Biomass Future



Biomass and Bioenergy 1999 IEA



Biomass Flows in the U.S. Economy



Biomass

Fiber

Materials
pulp
paper
lumber
plywood
cotton

Process Residues
black liquor
sawdust
bark

Crops, Animals

Food

stalks & straws
harvest residues
forest slash
dung

Process
Residues
bagasse

Consumers
MSW clean fraction
yard trimmings
constr. & demolition
wood
non-recyclable
organics

forest harvest for energy

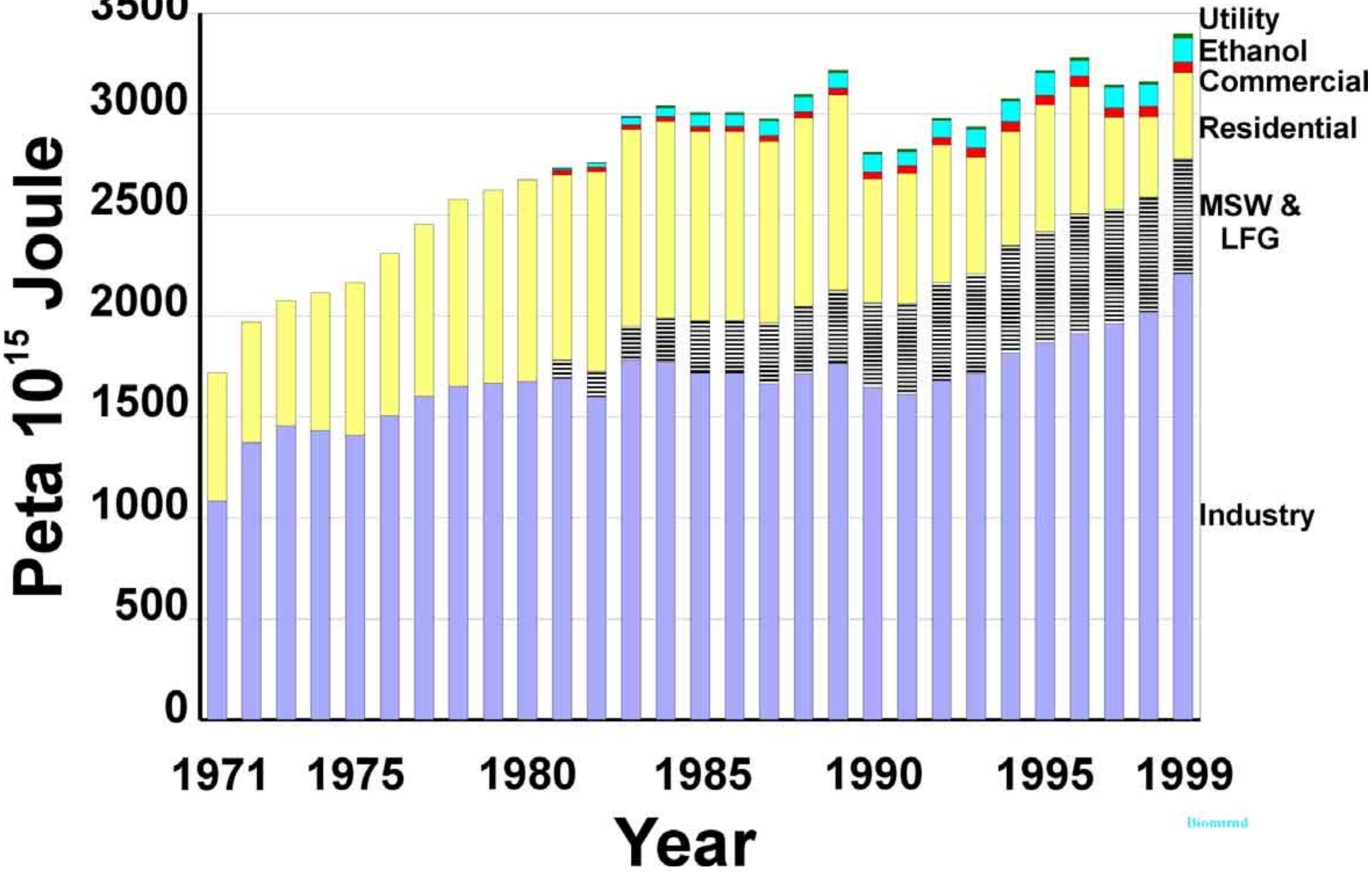
short rotation woody crops
herbaceous energy crops

Bioenergy

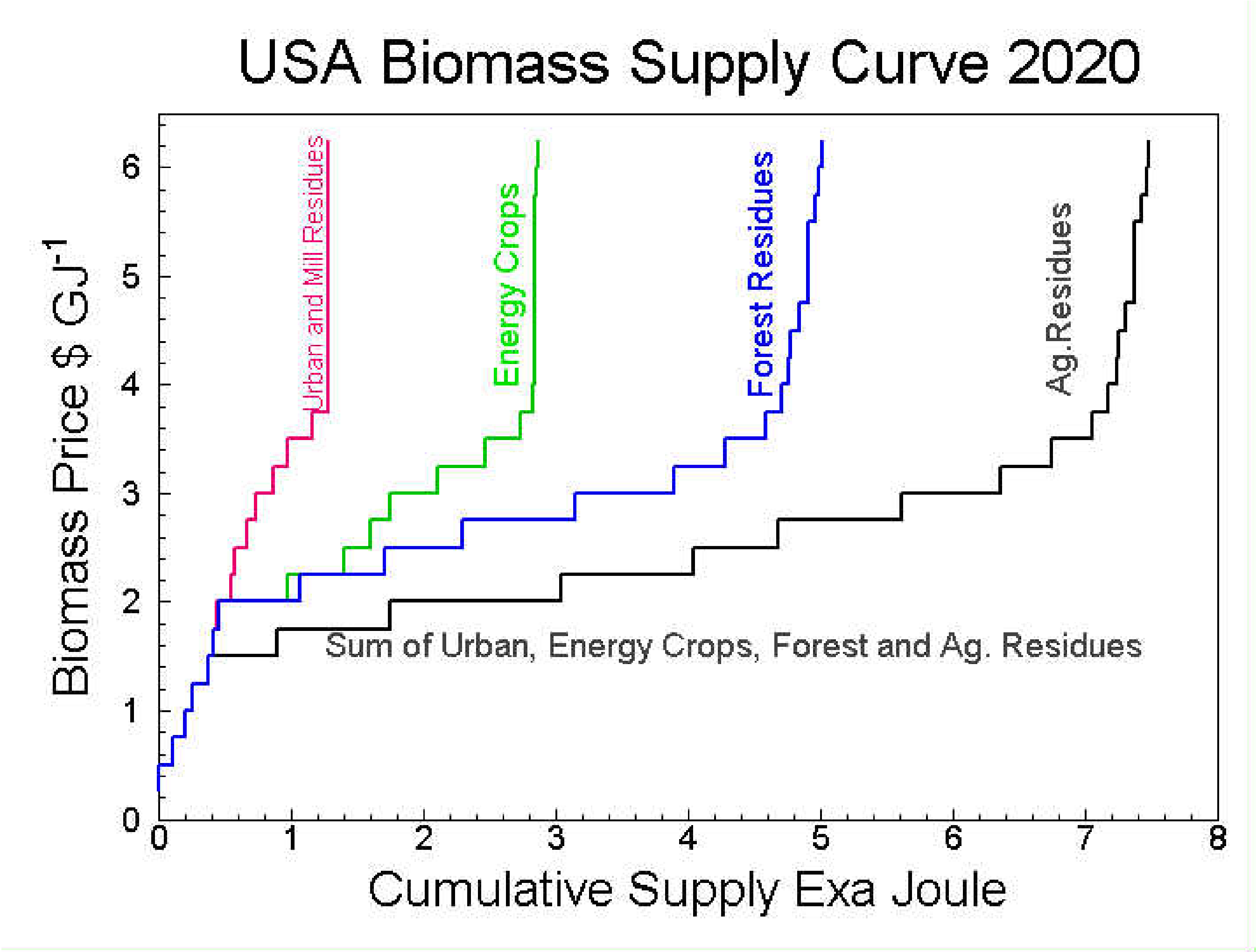
Energy
Services
heat
CHP
electricity

Biofuels
charcoal
ethanol
hydrogen

US Biomass Primary Energy

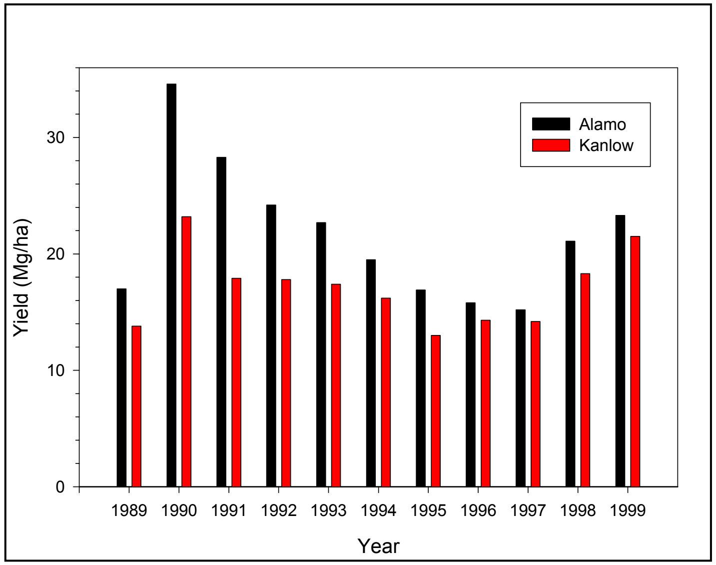


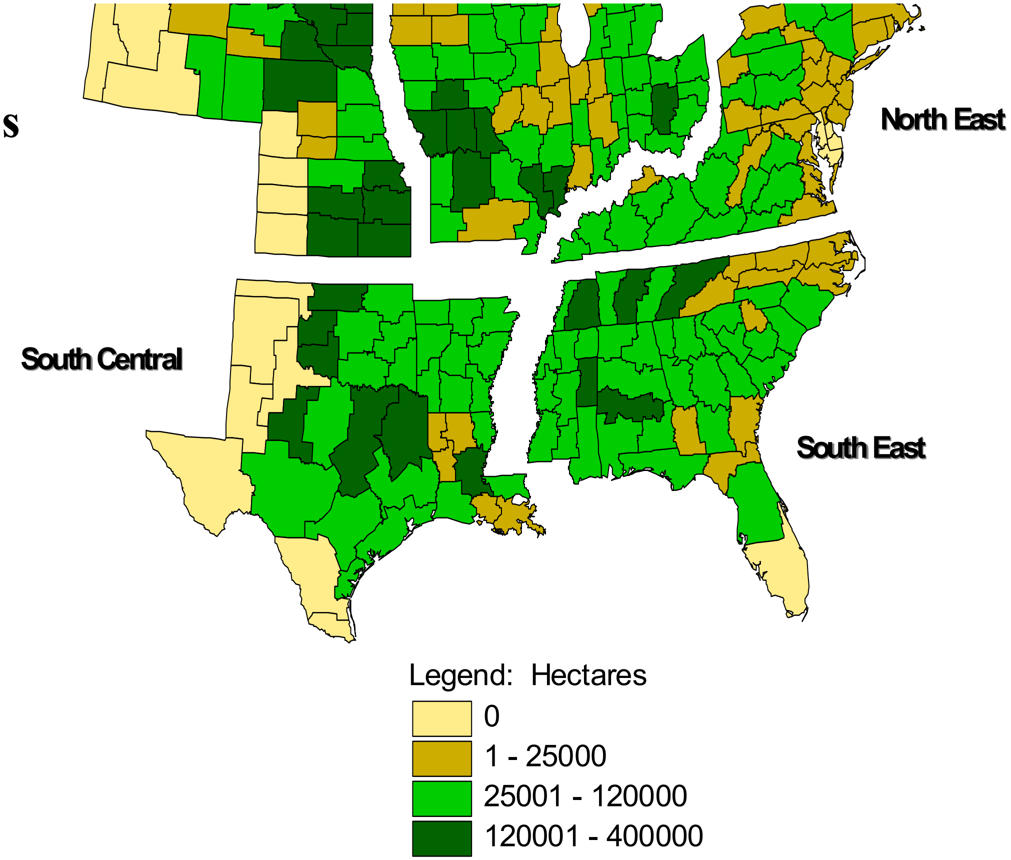
EIA - USA Supply Curve



Potential switchgrass production density within the U.S. by agricultural supply cells.

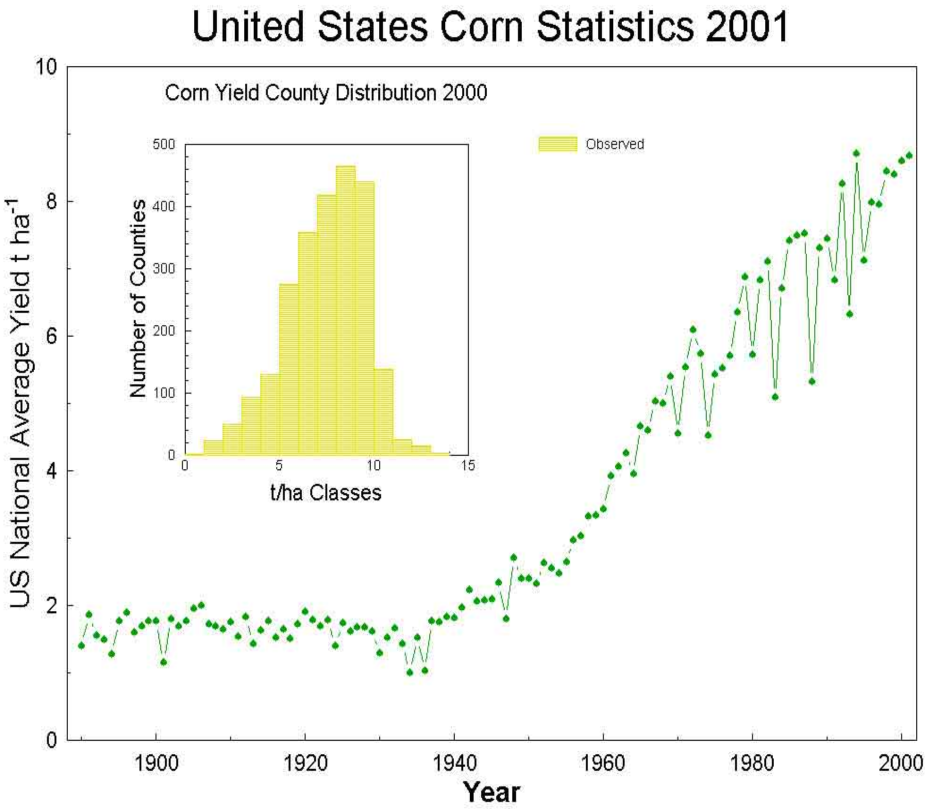
production density is based on the distribution of counties That convert from orginal Agricultural crop to Switchgrass At a price level of 44 \$ Mg^{-1} .





Energy Crops follow Agricultural Model

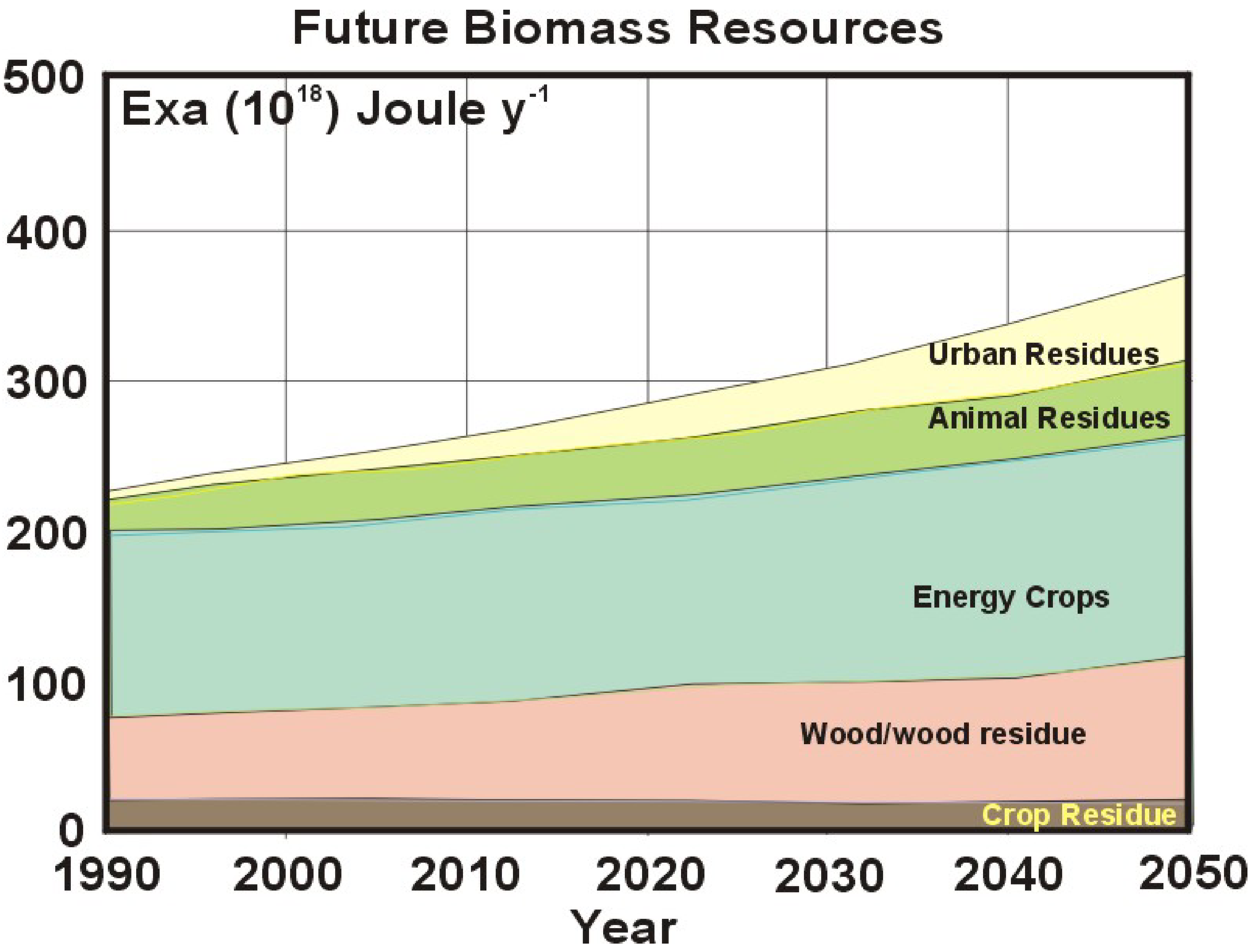
- Yield gains in Corn
- Energy crops at an early stage
  - Plant selection
    - Herbaceous crops
    - Tree crops
  - Breeding with genomics assistance
  - Management (cultivation, nutrients, pests etc) needs large field trials



Status of 2050 Global Estimates

- 17 studies analyzed
  - Highest – 675 EJ/y (EPA – v-high yields assumed)
  - Lowest – 45 EJ/y (less than today – land competition)
- Biomass resources (central estimates)
  - Energy crops range from 45 – 250 EJ/y
  - Ag residues < 20 EJ/y
  - Animal excreta < 50 EJ/y
  - Wood residues (primary + traditional reuse)
  - Urban residues
- IIASA projection on next slide

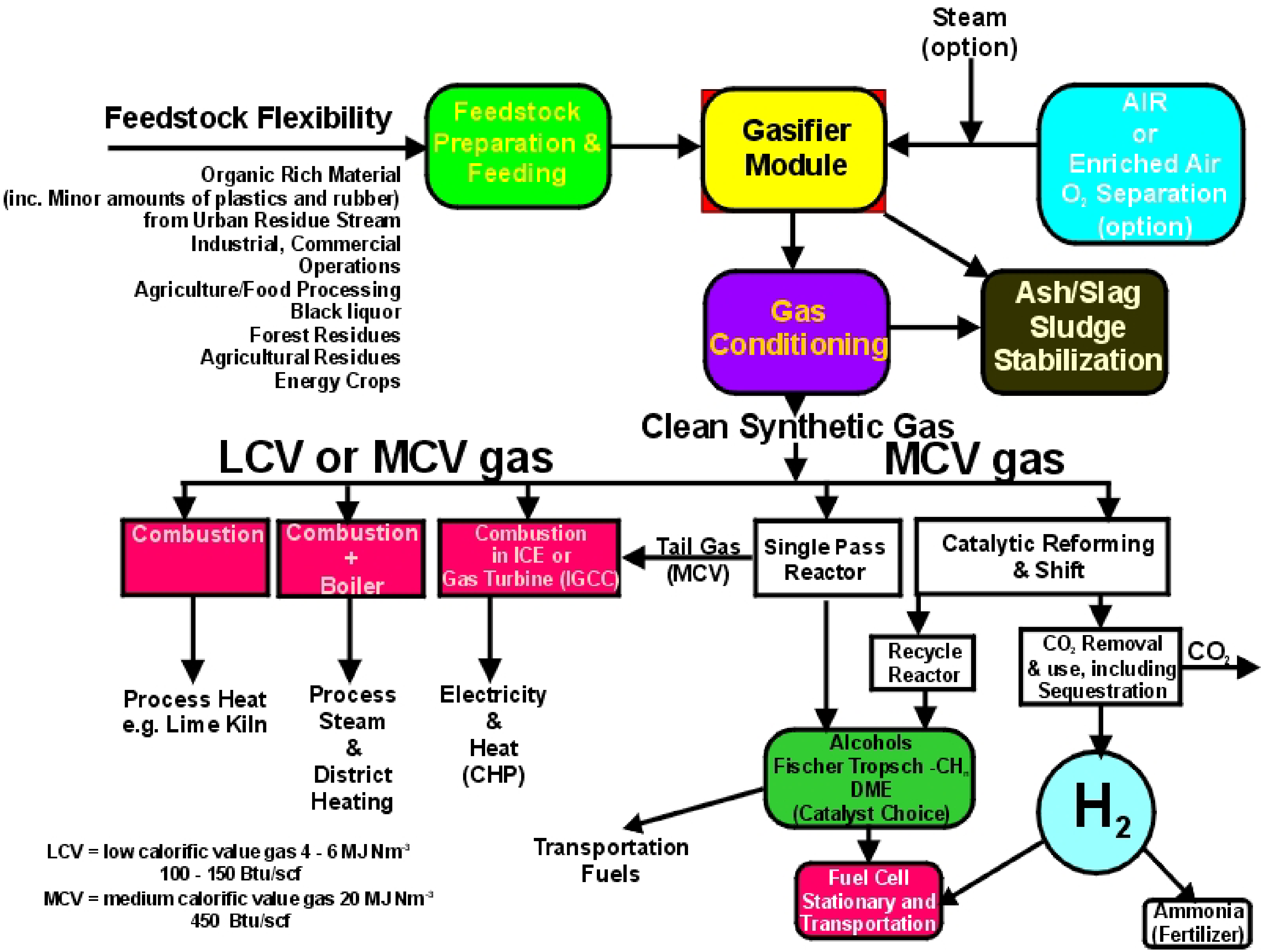
IIASA Estimate (resource based)



Uncertainties in Global Estimate

- Food – land competition
  - Population forecast and *per capita* income estimates
  - Calories not a problem
    - High animal vs. low animal protein future is significant issue
  - Only Sub-Sahara Africa is food – fuel issue likely, SE Asia a possibility
- Fiber – Wood demand for population
- Effects of Climate Change and Emissions
  - Brown cloud, ground level ozone – growth inhibition
  - Water availability and variability
  - Weather extremes, and plant pathogens

The Gasification Biorefinery



Steam (option)

Feedstock Flexibility

Organic Rich Material
(inc. Minor amounts of plastics and rubber)
from Urban Residue Stream
Industrial, Commercial
Operations
Agriculture/Food Processing
Black liquor
Forest Residues
Agricultural Residues
Energy Crops

Feedstock Preparation & Feeding

Gasifier Module

AIR or Enriched Air O_2 Separation (option)

Gas Conditioning

Ash/Slag Sludge Stabilization

Clean Synthetic Gas

LCV or MCV gas

MCV gas

Combustion

Combustion + Boiler

Combustion in ICE or Gas Turbine (IGCC)

Tail Gas (MCV)

Single Pass Reactor

Catalytic Reforming & Shift

Recycle Reactor

CO_2 Removal & use, including Sequestration

CO_2

Process Heat e.g. Lime Kiln

Process Steam & District Heating

Electricity & Heat (CHP)

Alcohols
Fischer Tropsch -CH_n
DME
(Catalyst Choice)

H_2

Transportation Fuels

Fuel Cell Stationary and Transportation

Ammonia (Fertilizer)

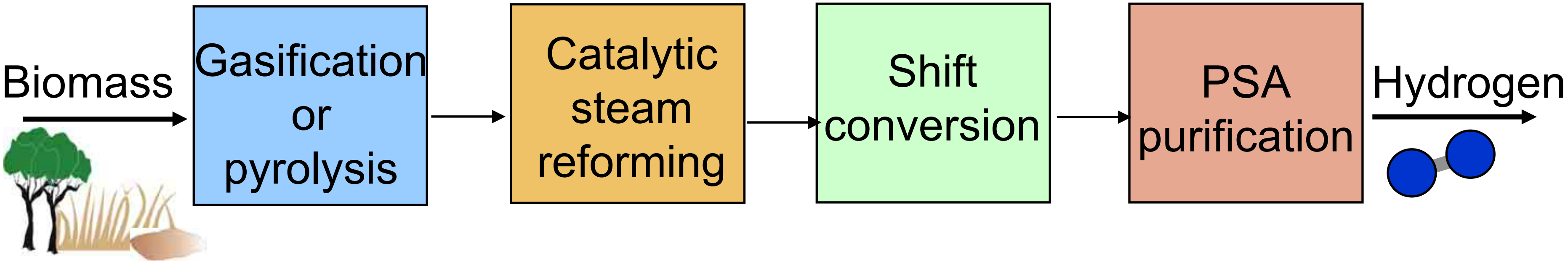
LCV = low calorific value gas 4 - 6 MJ Nm^{3}
100 - 150 Btu/scf
MCV = medium calorific value gas 20 MJ Nm^{-3}
450 Btu/scf

Biomass to H_2 Technologies

Most mature biomass conversion technologies for H_2:

- Indirectly-heated gasification
- Oxygen-blown gasification
- Pyrolysis
- Biological gasification (anaerobic digestion, landfill gas)

General Process:

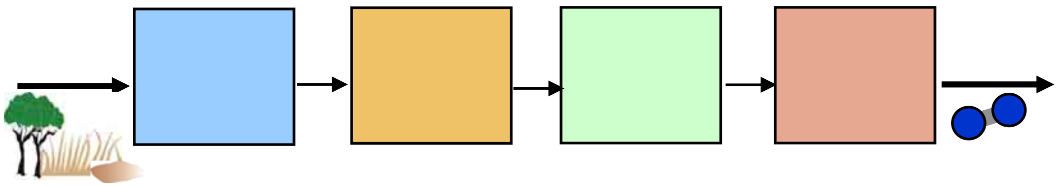


Biomass → Gasification or pyrolysis → Catalytic steam reforming → Shift conversion → PSA purification → Hydrogen

Reforming Hydrocarbons to Hydrogen

- Steam methane reforming:
  - Half from water, half from feedstock
  - $CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2$
- Biomass gasification / reforming:
  - Biomass contains only 6% hydrogen, by weight
  - Many people erroneously argue this point as a reason to not make hydrogen from biomass
  - $CH_{1.4}O_{0.6} + 1.4H_2O \longrightarrow CO_2 + 2.1H_2$
  - Carbon in biomass is chemical template for removing oxygen from water (makes CO_2)
  - 33% of the hydrogen produced comes from water

Common Process Steps



Reforming

$C_xH_y + H_2O \longrightarrow CO + H_2 + CO_2$ $\quad C_xH_y \quad CH_4$

$C_xH_yO_Z + H_2O \longrightarrow CO + H_2 + CO_2$ $\quad C_xH_yO_Z \quad CH_4$

Tubes in a steam reformer

Shift conversion

$CO + H_2O \longrightarrow CO_2 + H_2$ $\quad CO \quad C_xH_y \quad CH_4 \quad C_xH_yO_Z$

Purification (PSA)

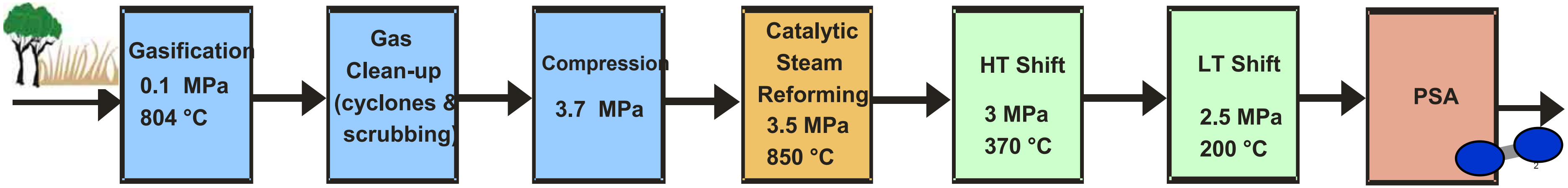
$CO_2 + H_2$ → H_2 >99.99% purity

$CO_2 + H_2$ → CO_2 $\quad CO \quad C_xH_y \quad CH_4$

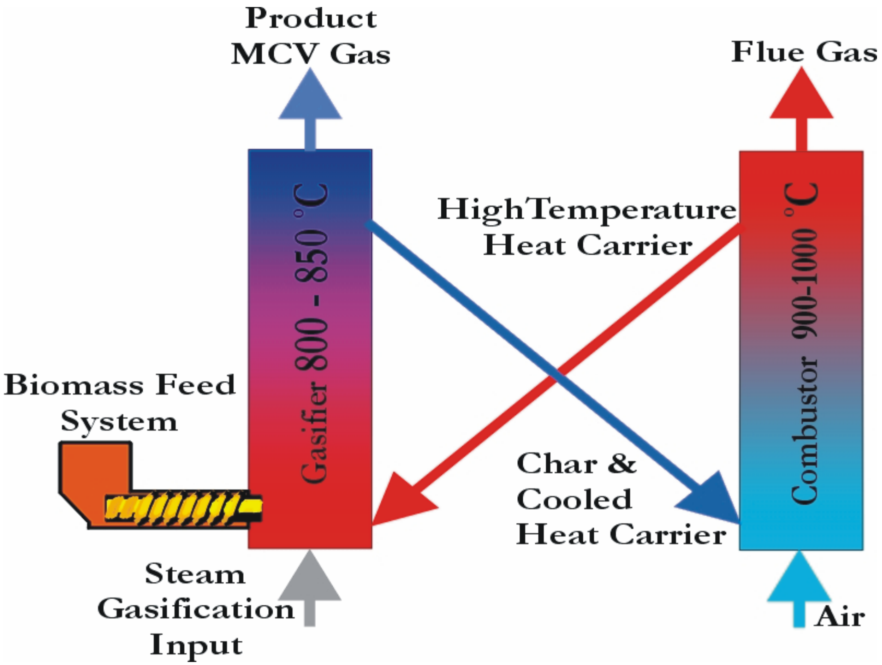
Technology #1

Indirectly-heated gasification / steam reforming

Gasification/conditioning **Reforming** **Shift** **Purification**

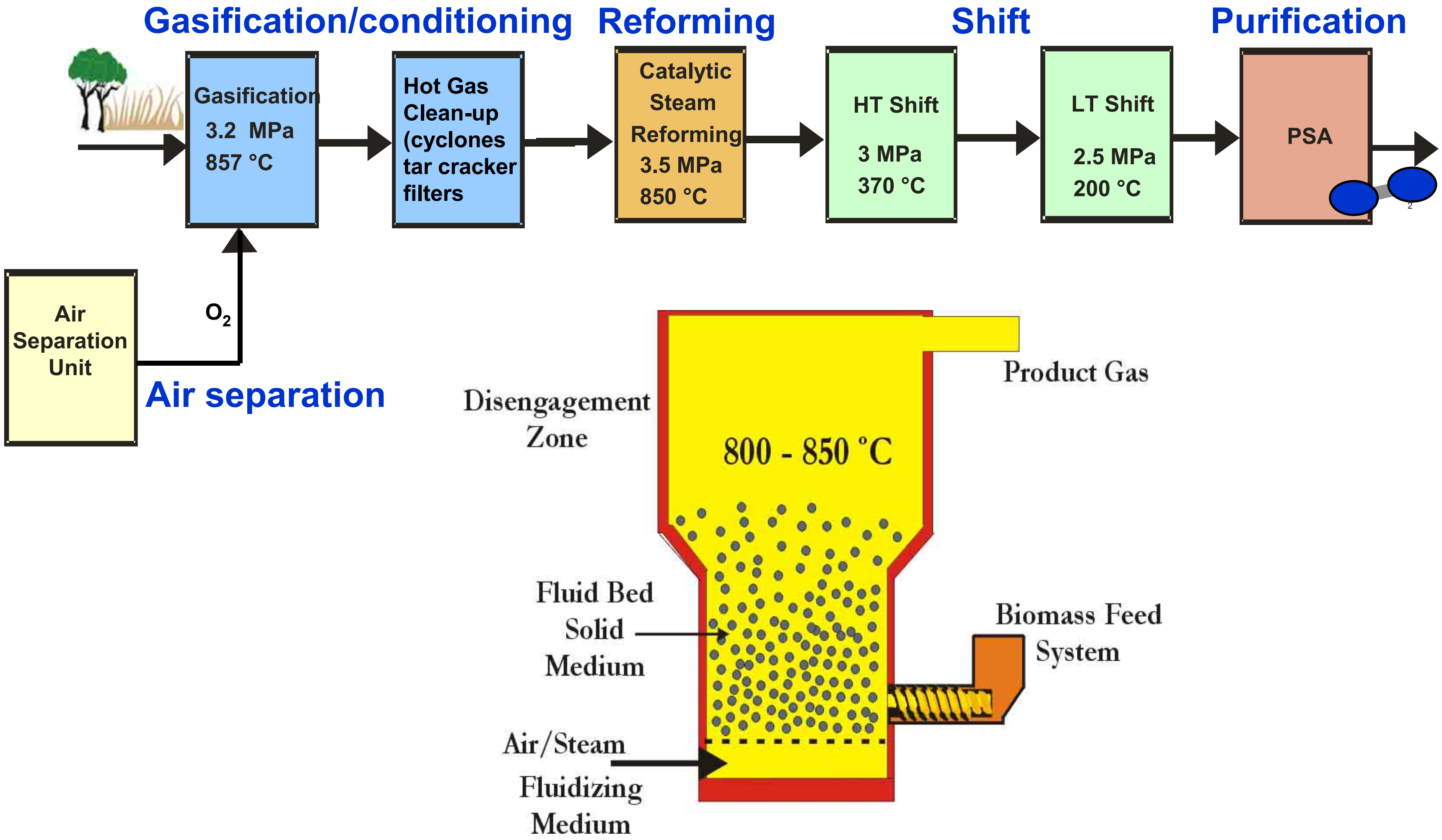


- Gasification 0.1 MPa 804 °C
- Gas Clean-up (cyclones & scrubbing)
- Compression 3.7 MPa
- Catalytic Steam Reforming 3.5 MPa 850 °C
- HT Shift 3 MPa 370 °C
- LT Shift 2.5 MPa 200 °C
- PSA



Technology #2

O_2-blown gasification / steam reforming



Gasification/conditioning

Reforming

Shift

Purification

Gasification
3.2 MPa
857 °C

Hot Gas Clean-up (cyclones tar cracker filters

Catalytic Steam Reforming
3.5 MPa
850 °C

HT Shift
3 MPa
370 °C

LT Shift
2.5 MPa
200 °C

PSA

Air Separation Unit

O_2

Air separation

Disengagement Zone

800 - 850 °C

Product Gas

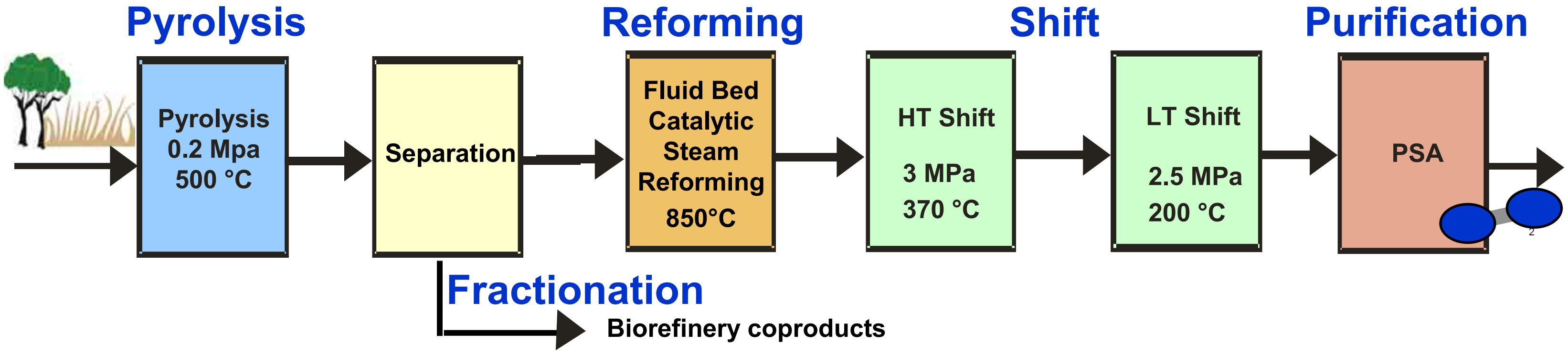
Fluid Bed Solid Medium

Biomass Feed System

Air/Steam Fluidizing Medium

Technology #3

Pyrolysis / steam reforming, with coproducts



Pyrolysis

Pyrolysis
0.2 Mpa
500 °C

Separation

Fractionation

Biorefinery coproducts

Reforming

Fluid Bed Catalytic Steam Reforming
850°C

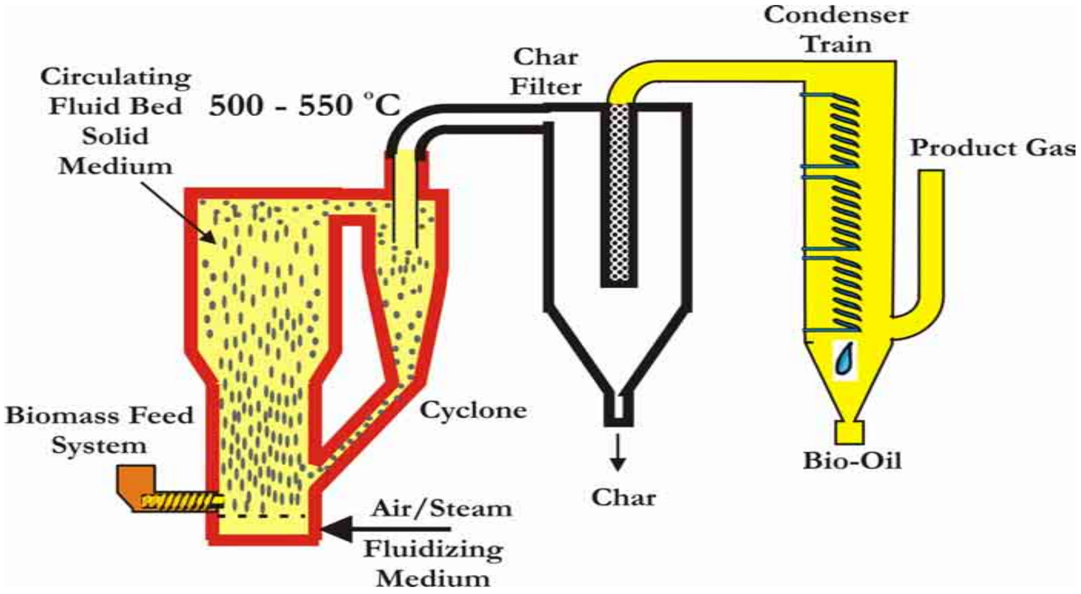
Shift

HT Shift
3 MPa
370 °C

LT Shift
2.5 MPa
200 °C

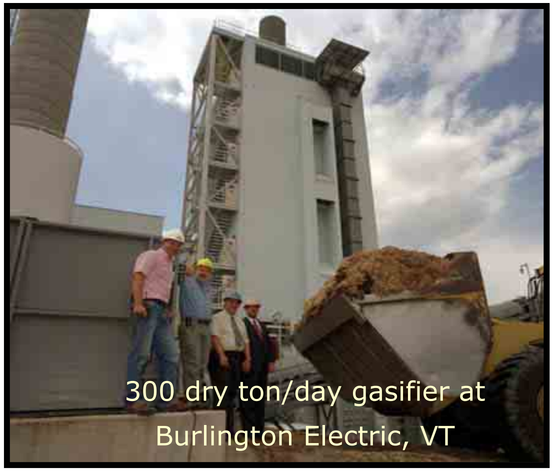
Purification

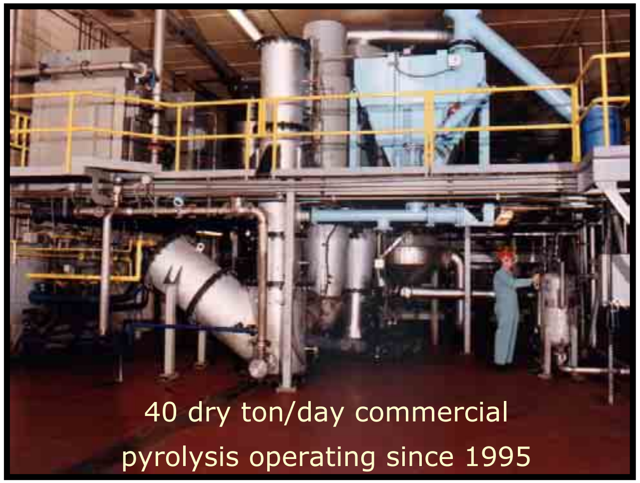
PSA



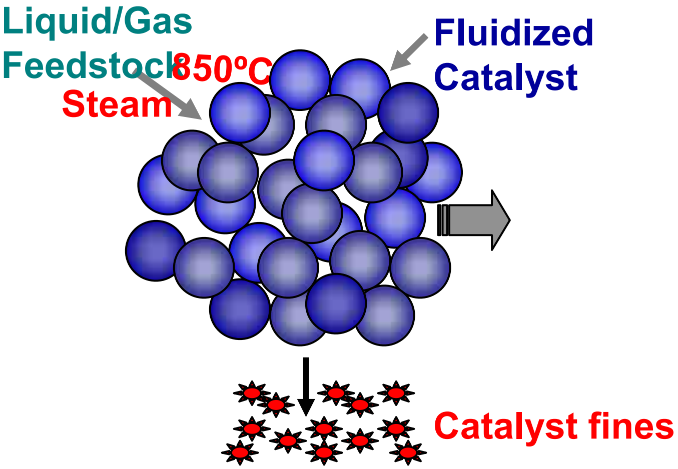
Status of Technology

- Biomass gasification demonstrated at 100-400 tons biomass/day
- Biomass pyrolysis commercial (Liquid Smoke, Ensyn)
- H_2 process demonstrated at 10 kg/hr for:
  - biomass pyrolysis vapors
  - biomass-derived liquids (carbohydrate fraction)
  - waste streams ("trap grease")
  - gasifier product gas
- Developed fluidizable, attrition-resistant catalyst matching activity of commercial catalysts.
- Reforming process scaled-up from lab to engineering


300 dry ton/day gasifier at Burlington Electric, VT


40 dry ton/day commercial pyrolysis operating since 1995

Catalyst Development



- Conventional reforming reactor
  - Fixed catalyst bed at 850°C
- Conventional reforming catalysts
  - 10-33% NiO on Al_2O_3 support

Reforming biomass oils is most successful in fluidized bed - coking

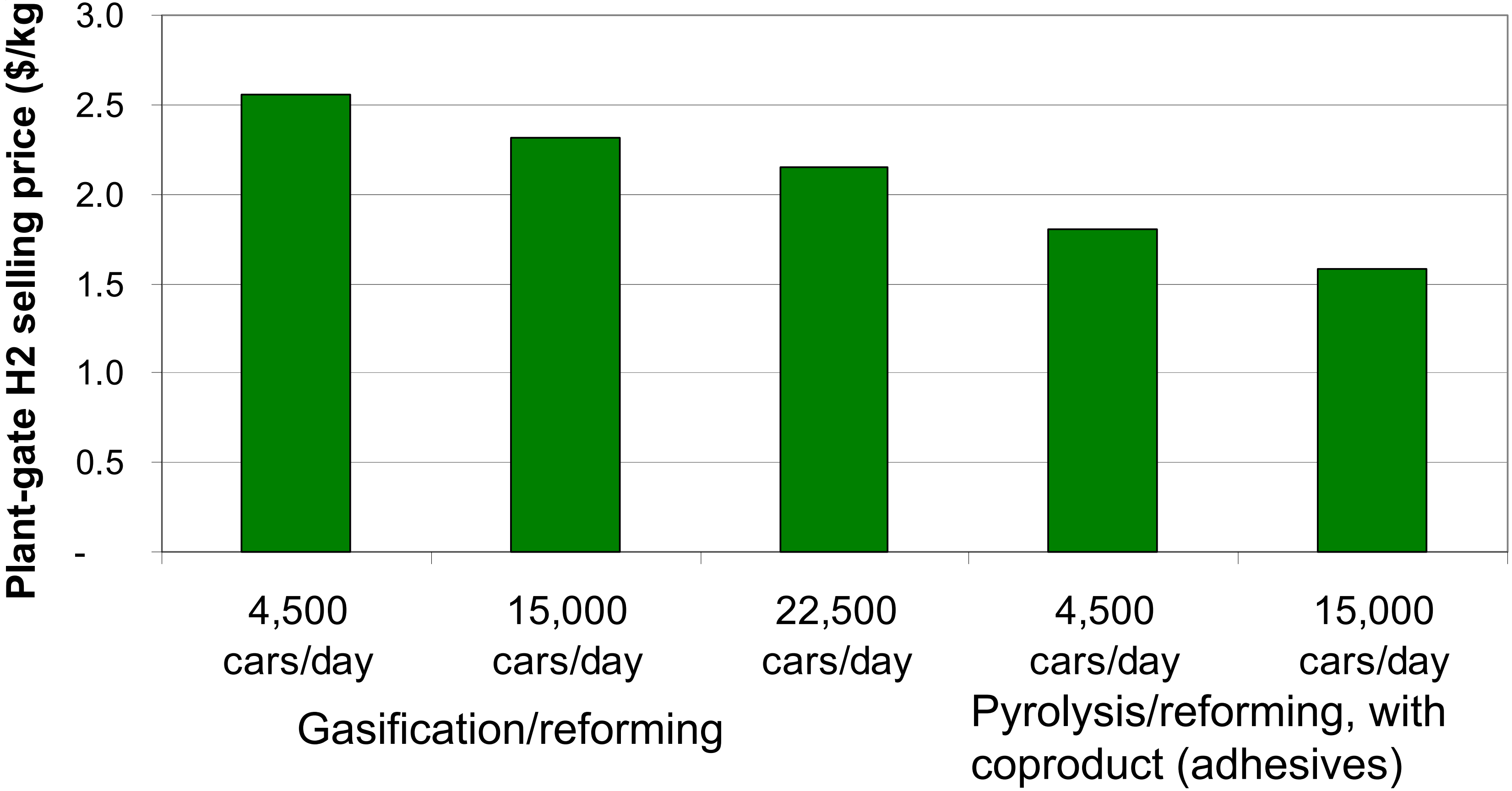
New problem: catalyst attrition

Ceramic support reduces cost of attrition by three orders of magnitude

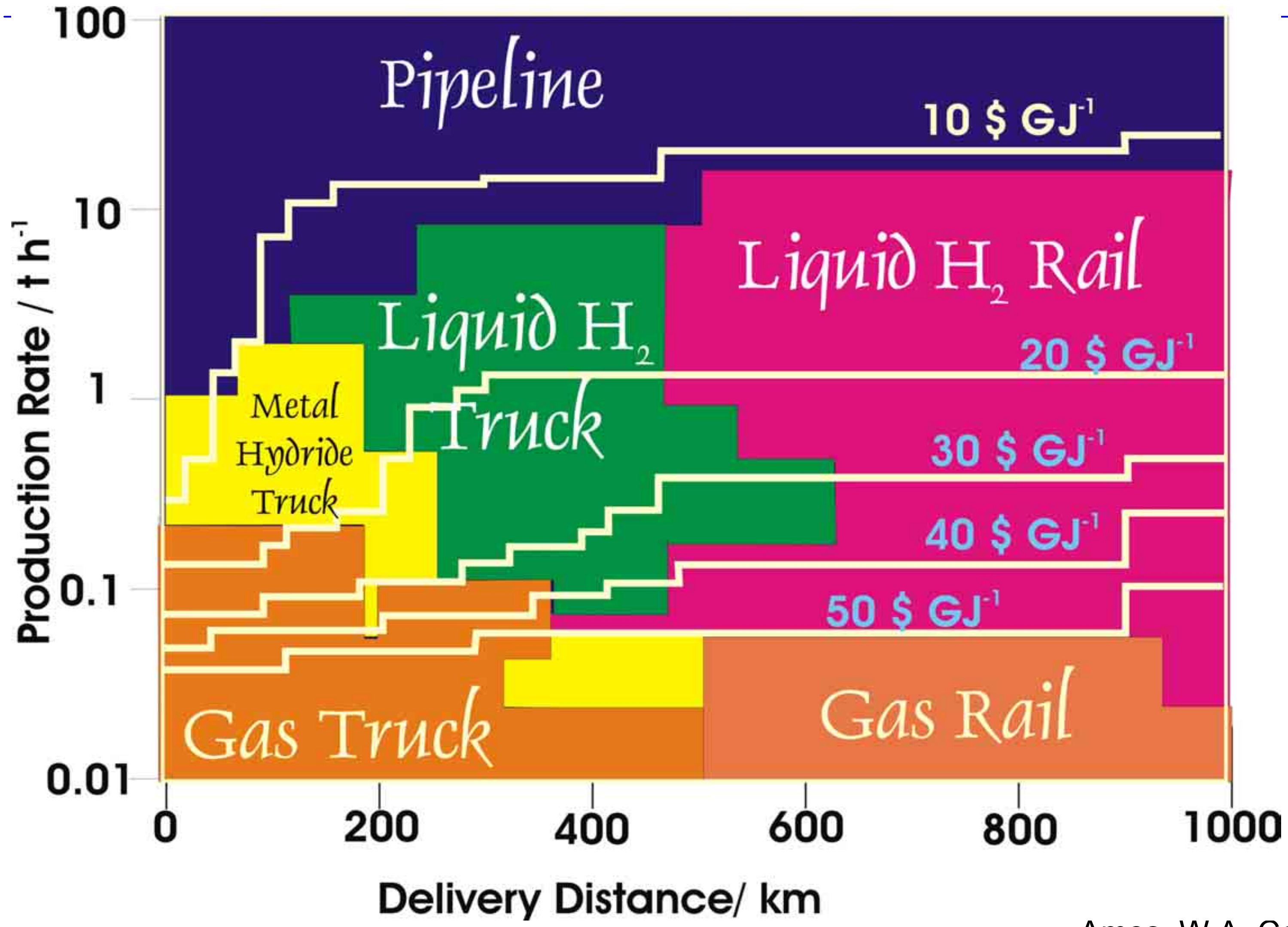
Economics Examples

Major assumptions:

- 15% after-tax IRR
- 20 year plant life
- n^{th} plant
- MACRS depreciation
- 90% capacity factor
- Equity financed

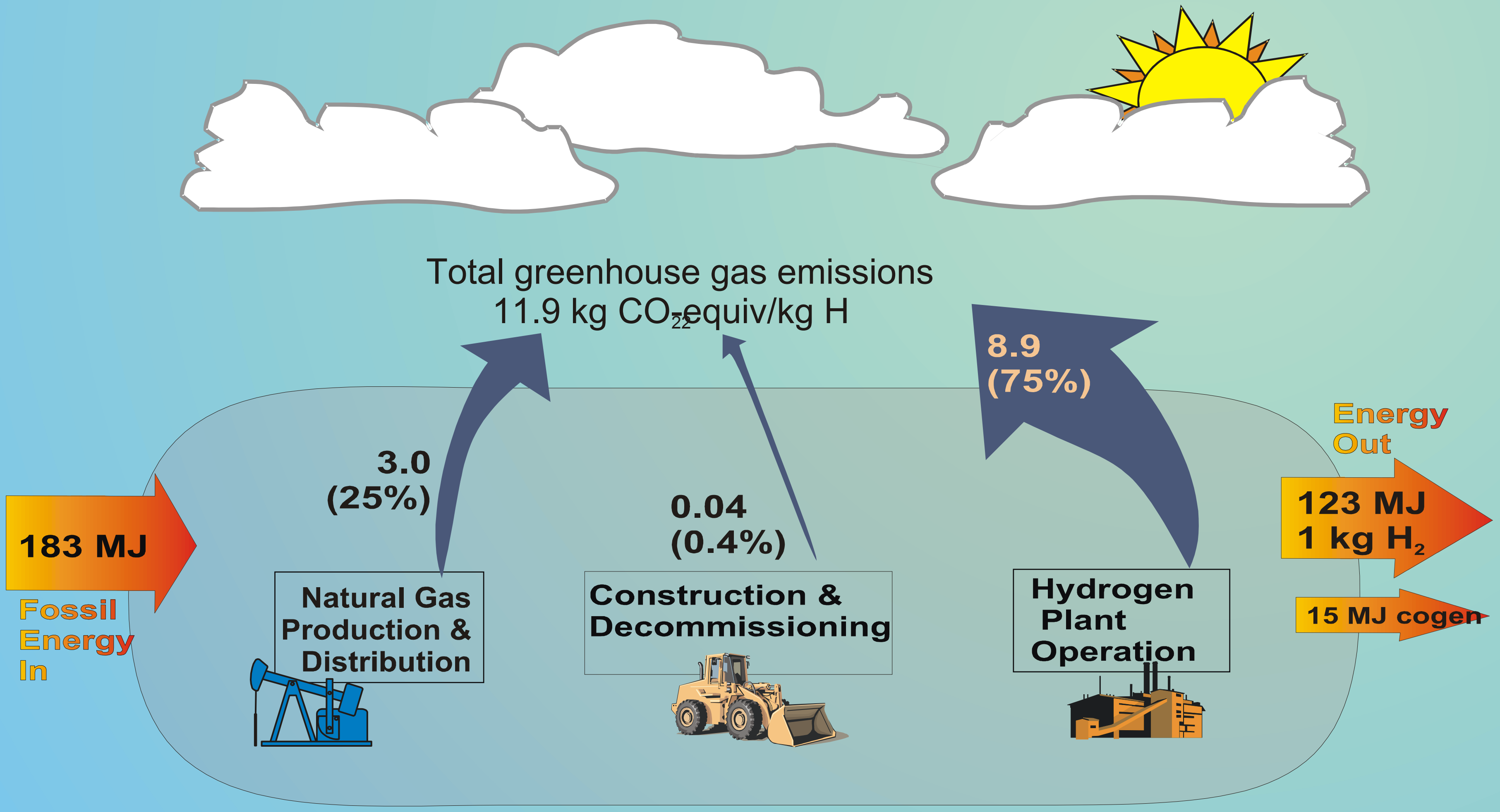


Storage & Transport Costs



Amos, W.A. Costs of Storing and Transporting Hydrogen. NREL/TP-570-25106.

Life Cycle GWP and Energy Balance for Steam Methane Reforming



Total greenhouse gas emissions
11.9 kg CO_2-equiv/kg H_2

183 MJ

Fossil Energy In

3.0 (25%)

Natural Gas Production & Distribution

0.04 (0.4%)

Construction & Decommissioning

8.9 (75%)

Hydrogen Plant Operation

Energy Out

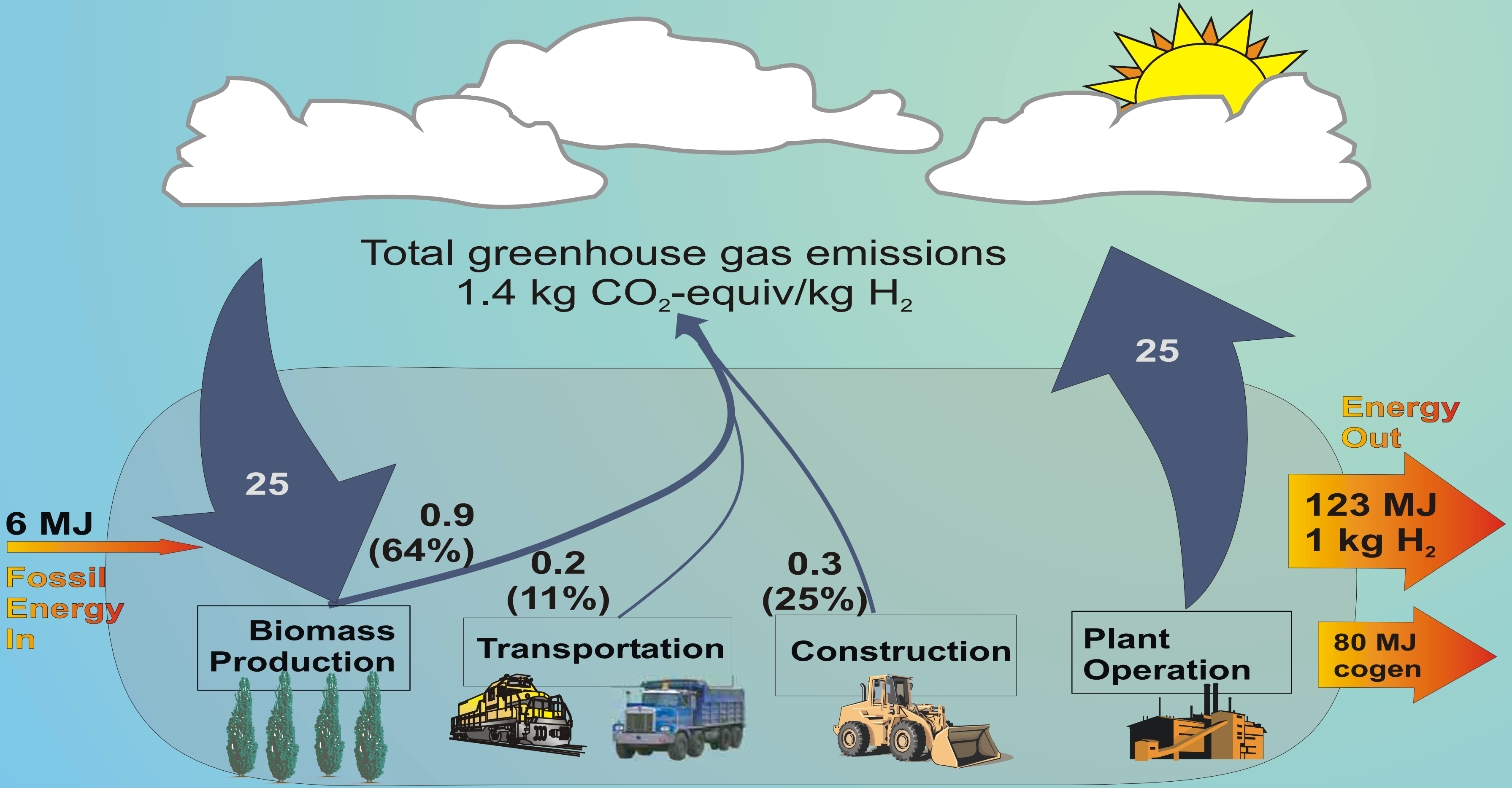
123 MJ
1 kg H_2

15 MJ cogen

Net energy ratio = (123 MJ + 15 MJ) / 183 MJ = 0.75

Avoided Operations = steam production from a natural gas boiler and natural gas production & distribution required to obtain the natural gas

Life Cycle GWP and Energy Balance for Biomass Gasification / Reforming using Energy Crop Biomass



Net energy ratio = (123 MJ + 80 MJ) / 6 MJ = 33.8

Hydrogen Potentials

Estimate 29 Tg H_2/y from 7 EJ biomass available in 2020

- 40% of the current U.S. light duty vehicle demand
- Assumes 50% energy conversion ratio (biomass to hydrogen)
- Assumes 2x efficiency of use with fuel cell vehicle
- EIA - Biomass scenario – 17 Mha (42 million acres)

Petroleum demand impact

- 1.2 billion bbl/year
- 22% of total consumption (2001)
- 36% of imported consumption (2001)

Greenhouse gas savings

- 84 million metric tonnes of carbon equivalent/year

Prospects 2020 +

  - Improved process efficiency + 10%
  - Higher yield energy crops + 25%
  - Access to more marginal land with adapted crops to produce reasonable yield ?

Research Needs

Higher process efficiencies => lower cost

- Gasification & pyrolysis
- Reforming
- Single-stage shift

Feedstock development

- Residue harvest / collection / storage technologies
- Energy crop yield optimization
- Crops that can be economically grown on marginal lands

Biorefinery

- Suite of bioproducts
- Heat and mass optimization

System integration

- Combined heat, power, and fuels
- Modular system development
- Catalyst regeneration
- Gas conditioning

Utilization of wet biomass streams

- Biological gasification
- Liquid-phase catalytic gasification

Summary

- Benefits
  - – Resource diversification
  - – More sustainable energy production
    - Fewer greenhouse gas emissions (-17% in transportation sector)
    - Positive net energy balance (net energy ratio = 33.8)
    - Life-cycle, not just tailpipe environmental benefits
  - – Dispatchability reduces storage costs
  - – Biorefinery coproduct opportunities
- Quantities and technologies provide near-term opportunity for renewable hydrogen
  - – Accessible residues and available technologies provide immediate starting point for biomass to hydrogen
  - – Potential: 40% of current light duty fuel market from biomass hydrogen
  - – Economics provide good incentive for renewable hydrogen