Energy from Biomass

W. Udo Schröder, 2024

Agenda

- World biomass inventory
  Global challenges: Tree losses, deforestation of tropical/rainl forests

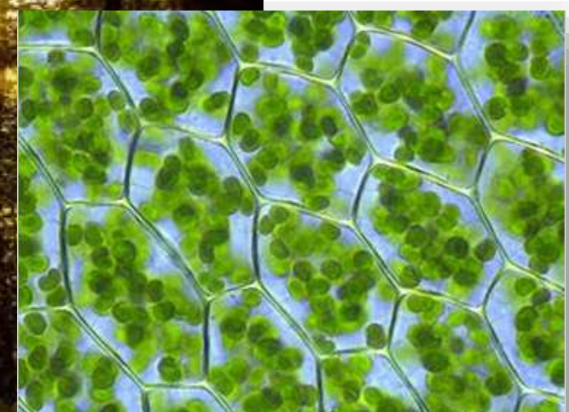
- Biomass energy resources, farming and harvesting
  - Renewable biomass principle,
  - US geographical bio-energy farming areas
  - Biomass energy density, heating value, GHG emission

- Biomass-Energy conversion methods
  - Direct combustion
  - Biomass to gas and liquid, ethanol production
  - pyrolysis, Fischer-Tropsch process

- Current biomass utilization
  - Transportation fuels, ethanol, biodiesel
  - Share in total electricity generation

- Strategic Issues biomass utilization

Photosynthesis



Plant cells with visible chloroplasts (from a moss, *Plagiomnium affine*)

$$Photosynthesis: photochemical + biochemical\ (endoenergetic)\ reaction,\ needs\ 2\left(h\nu = 1.9eV, \lambda = 0.7\mu\right)$$

$$nCO_2 + mH_2O \rightarrow \xrightarrow{chlorophyll} C_n\left(H_2O\right)_m + nO_2 + \Delta H\ \ (= 4.07eV / C\ atom)$$

$$C_n\left(H_2O\right)_m = carbohydrate\ sugar,\ starch,\ cellulose\ (\text{mostly}: n \approx m)$$

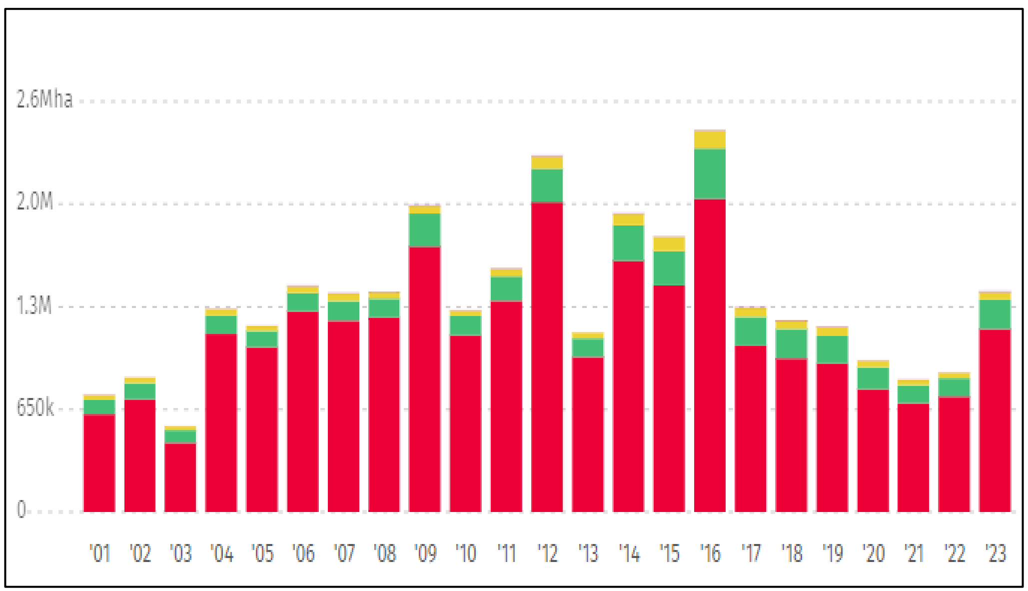
World Biomass Energy Resources/Prospects

Living mass (total)	2	Tt	World population	8.2	B ⇧
Land plants	1.8	Tt	Per capita plant biomass	0.3	kt/p ⇩
Forests	1.6	Tt ⇩	Energy gained in biomass	$3\cdot10^{21}$	J/a
Net annual production	0.4	Tt/a	Biomass energy consumption	$6\cdot10^{19}$	J/a
Energy stored in biomass	$2.5\cdot10^{22}$	J	Food energy consumption	$2\cdot10^{19}$	J/a

Biomass energy gained $30\cdot10^{20}$ J/a → Biomass energy consumed ~10^{20} J/a

Sustainable at present few-% levels. But avoid substantial consumption increases →O_2- Atmosphere!

Example Indonesia: Deforestation for Biofuels



Tree Losses	**1.16 Mha**
Forestry	186.0 kha
Agriculture	45.8 kha
Urbanization	3.8 kha
Commodity (Plant Oil Prod)	1,160.0 kha

World Biomass Losses

Tree Losses	2001-2020
Canada	57.5 Mha
United States	47.9 Mha
Indonesia	30.8 Mha
DRC Congo	19.7 Mha
China	12.1 Mha

Drivers
Wildfires
Forestry
Agriculture
Urbanization
Commodity

https://www.globalforestwatch.org/dashboards/country/IDN/?category=forest-change

Example Deforestation in Brazil

Tropical forests 2% of surface.

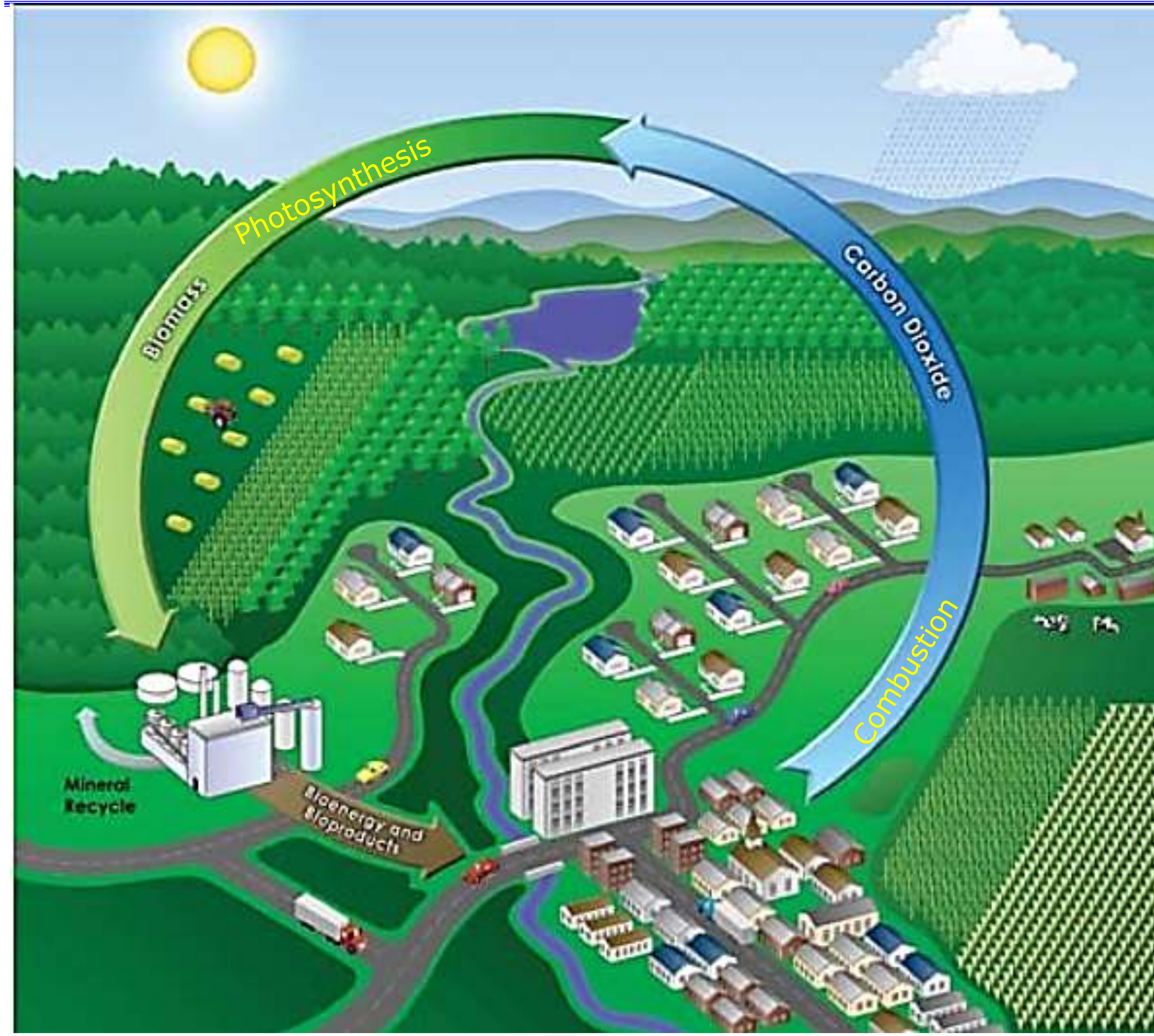
2017:
lost $15.8 \cdot 10^6$ ha of tropical forests.
Humans have destroyed ½ of original forest cover.

2020 -2021: Brazilian **rainforest lost 10,476 square kilometers** – an area 13 times the size of New York City (*Imazon*, a Brazilian research institute).

Every year: Earth loses tropical forestland = size of Bangladesh (Global Forest Watch).

Related: "Rental" of Argentina's former forest areas for soy oil production.

Biomass Renewable Energy: Principle



Sustainable use of ethanol from cellulosic biomass could reduce emissions of green-house gases (CO_2).

Dedicated "fuel plantations": Photosynthetic production of new biomass takes up some of the carbon dioxide released in combustion of biofuel (bioethanol), not all.

Task of scalability: Grow biomass as fast as it is burned!

www.ornl.gov/info/ornlreview/v33_2_00/bioenergy.htm

Harvesting Bio-Energy

Principle: Capture energy carrying carbohydrates from plants → combust fuel (directly or after refining).

Switchgrass

1) Grow annual energy crops: corn (maiz), rape soybean, sugar cane,…, algae.
   Competes with food production/food chain

2) Harvest fast-growing trees, underbrush, grasses, oil palms
   Compromises soil, natural forest/habitat, lessens CO_2 sequester.

3) Collect organic waste (→Combustion)

Rural Resources:

Forest residues and wood (mill, saw)wastes

Crop residues

Manure biogas

Urban Resources:

Urban wood waste

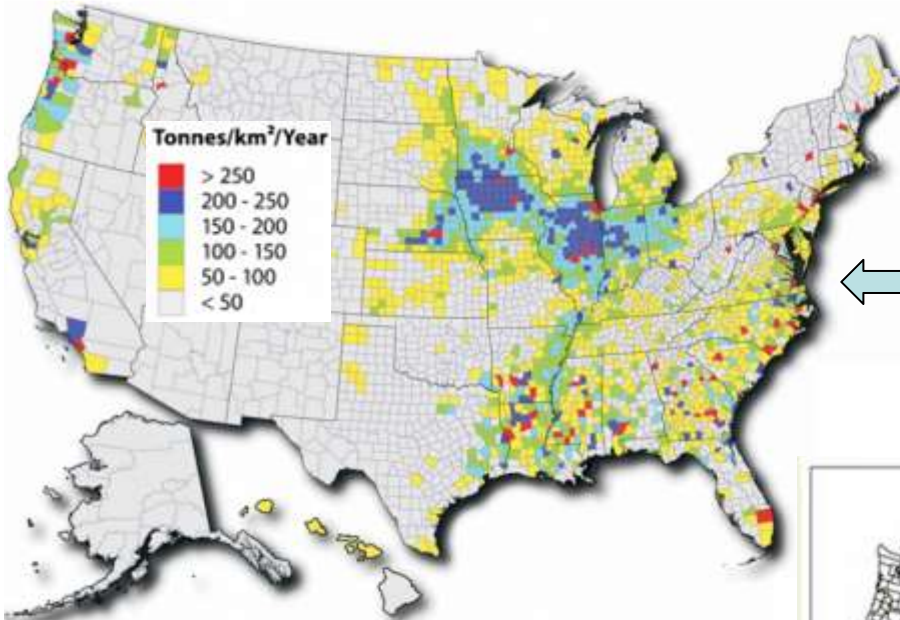
Land fill gas (LFG)

Wastewater treatment biogas

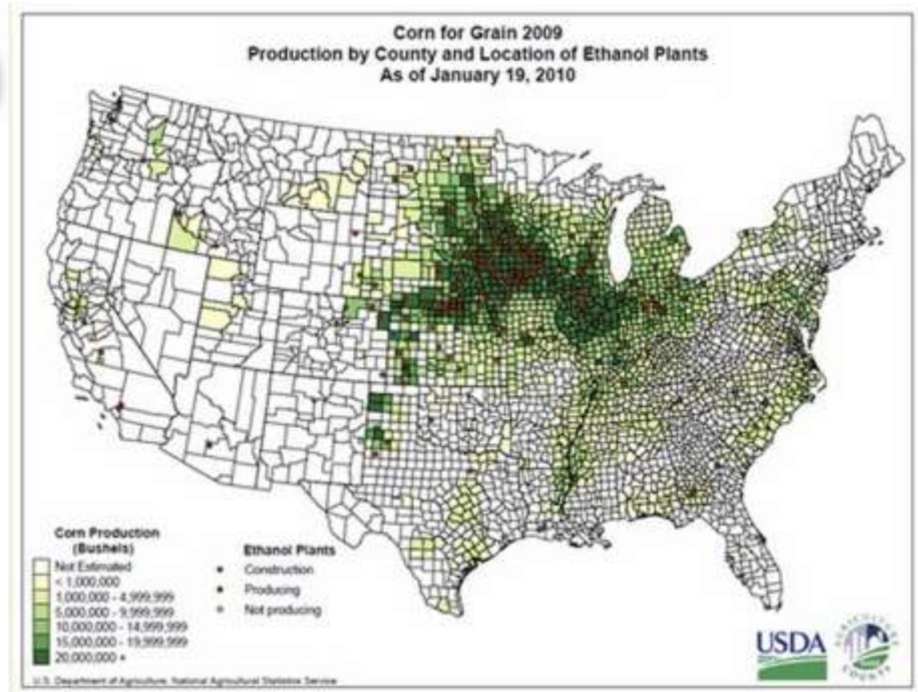
Food processing residue

No known negative side-effects.

U.S. Bio-Energy Generation



Biomass feedstock categories:
crop residues (average 2003-2007),
forest and primary mill residues,
secondary mill and urban wood waste,
biogas (methane) from landfills,
domestic wastewater treatment,
animal manure.
http://www.nrel.gov/docs/fy06osti/39181.pdf.



US: Corn grain monoculture used to produce feedstock for liquid transportation fuel (bio-ethanol, -diesel).

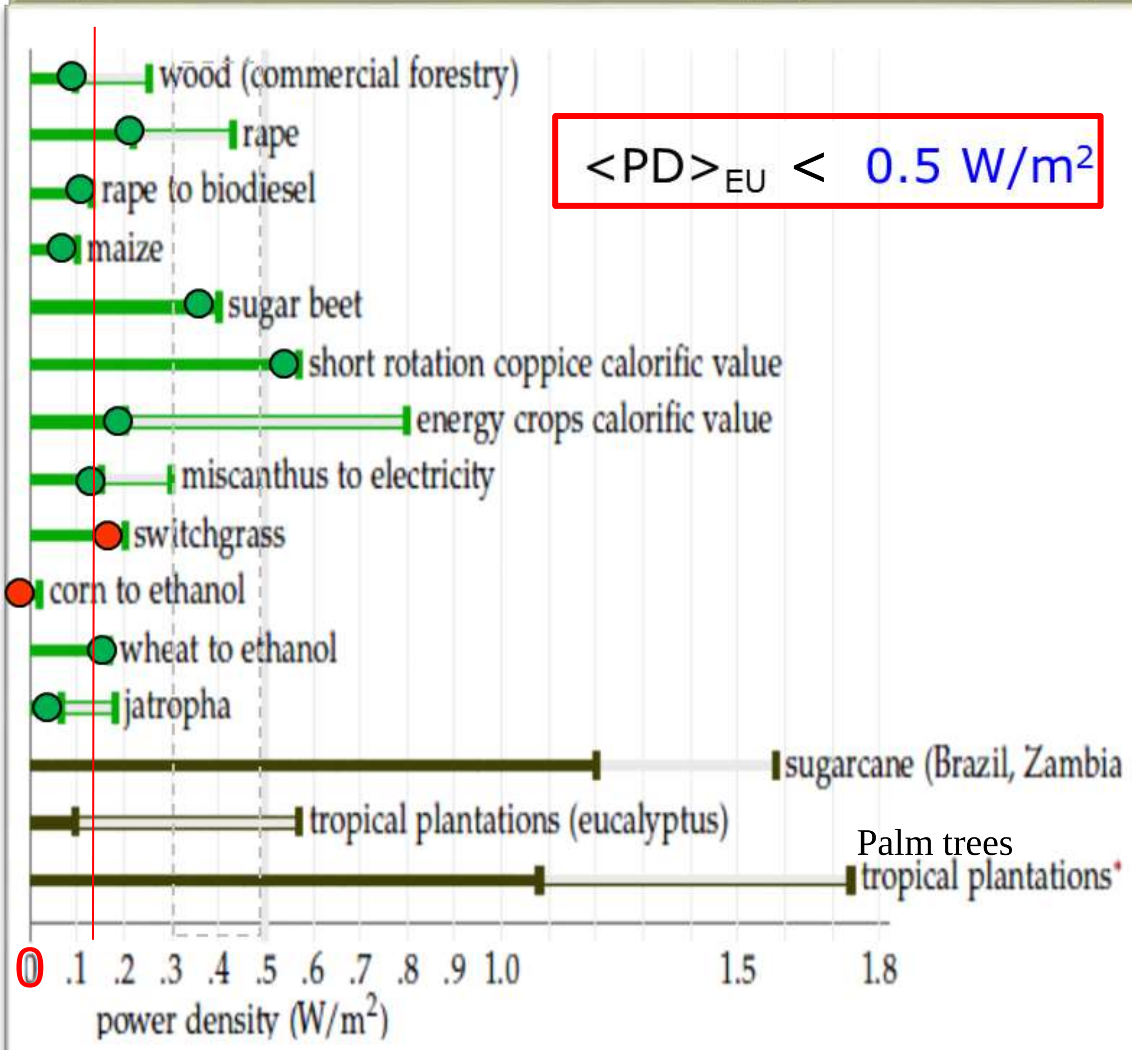
→ Midwest biomass power plants located near agricultural areas

→ Prairie lands for future switch grass harvesting ? (GW Bush adm)

Strong agriculture lobby→ subsidies (farm bill, industrial agr.)

Bio-Energy Crops Energy/Power Density

Upper Limits of Power Density (meas.–CH–)



U.S. arable land ≈18% of total (0.5 ha = 5,000 m^2/cap).
(World Bank report, 2010)

Quantitative studies:
EU > 5 kW/cap;
U.S.> 10 kW/cap continuous. (MacKay, Slim, *The Economist*)

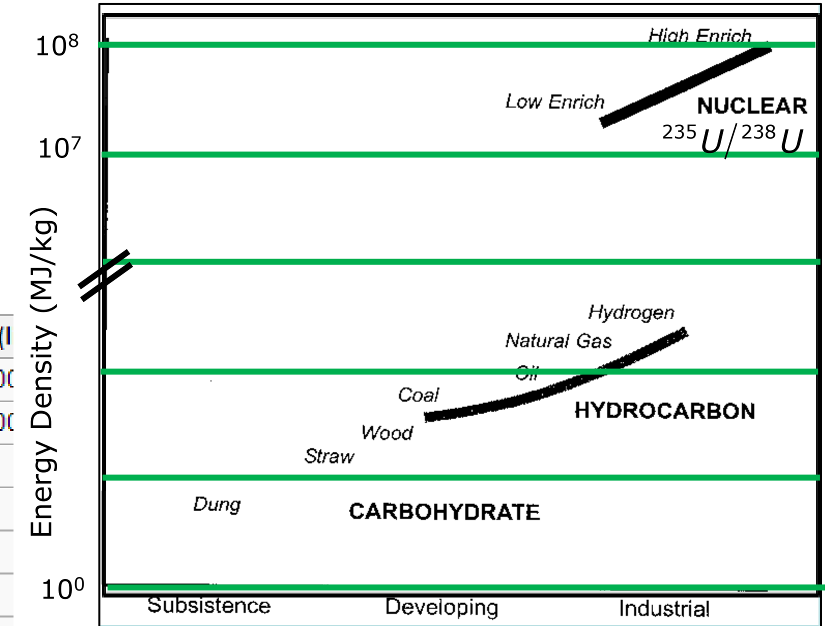
Chris Hallman/University Photography

Ecologist David Pimentel, shown here pumping gas, says that his analysis shows that producing ethanol uses more energy than the resulting fuel generates.

Fuel Energy Density

Competitive cost of biomass < $ 3/GJ.
McNeil Power Station (VT) burns wood for $11-$25.3/1000 "green kg" ($(10-23)/ton, delivered (~$(20-46)/dry ton) or (~$(1.2-2.7)/million Btu).

US & EU subsidize price.



Storage material	Energy type	MJ per kilogram	MJ per liter (l	
Deuterium–tritium	Nuclear fusion	330 000 000	6 368 000 00	
Uranium-235	Nuclear fission	79 500 000	1 534 000 00	
Hydrogen (compressed at 700 bar)	Chemical	123	5.6	
Gasoline (petrol) / Diesel	Chemical	~46	~36	
Propane (including LPG)	Chemical	46.4	26	
Fat (animal/vegetable)	Chemical	37		
Coal	Chemical	24		Electric power plants, home heating
Carbohydrates (including sugars)	Chemical	17		Human/animal nutrition
Protein	Chemical	16.8		Human/animal nutrition
Wood	Chemical	16.2		Heating, outdoor cooking
TNT	Chemical	4.6		Explosives
Gunpowder	Chemical	3		Explosives
Lithium battery	Electrochemical	1.8	4.32	Portable electronic devices, flashlights (non-rechargeable)
Lithium-ion battery	Electrochemical	0.72	0.9-2.23	Laptop computers, mobile devices, some modern automotive engines
Alkaline battery	Electrochemical	0.59		Portable electronic devices, flashlights
Nickel-metal hydride battery	Electrochemical	0.288	0.504-1.08	Portable electronic devices, flashlights
Lead-acid battery	Electrochemical	0.1		Automotive engine ignition
Electrostatic capacitor	Electrical	0.000036		Electronic circuits

Biofuel Properties/Emission/Ecoprint

Fuel	Net calorific value (MJ/kg)	Carbon content (%)	Approx. life cycle CO_2 emissions (including production) See note 1		Annual total CO_2 emissions to heat a typical house (20,000 kWh/yr)		
			kg/GJ	kg/MWh	kg	kg saved compared with oil	kg saved compared with gas
Hard coal	29	75	**134**	**484**	9680	-2680	-4280
Oil	42	85	**97**	**350**	7000	0	-1600
Natural gas	38	75	**75**	**270**	5400	1600	0
LPG	46	82	**90**	**323**	6460	540	-1060
Electricity (UK grid)	-	-	**150**	**530**	10600	-3600	-5200
Electricity (large scale wood chip combustion)	-	-	**16**	**58**	1160	5840	4240
Electricity large scale wood chip gasification)	-	-	**7**	**25**	500	6500	4900
Wood chips (25% MC) Fuel only	14	37.5	**2**	**7**	140	6860	5260
Wood chips (25% MC) Including boiler	14	37.5	**5**	**18**	500	6500	4900
Wood pellets (10% MC starting from dry wood waste) See note 3	17	45	**4**	**15**	300	6700	5100
Wood pellets (10% MC) Including boiler See note 3	17	45	**7**	**26**	660	6340	4740
Grasses/straw (15% MC)	14.5	38	**1.5 to 4**	**5.4 to 15**	108 to 300	6892 to 6700	5292 to 5100

http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,163182&_dad=portal&_schema=PORTAL

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Wood Pellets for Burning/Co-Firing

Starting materials: compacted sawdust + other wastes from sawmilling and other wood products, like palm kernel shells, coconut shells, whole-tree removals, tree tops, branches left over after logging (which otherwise would help replenish soil nutrients).

Manufacturing pellets
→ hammer mill produces uniform dough.
→ press dough through a die with holes (6-8mm dia.)
→ compressing heats pellets, lignin plasticizes = natural glue preserving pellet shape in cooling.

Fuel properties: Biomass contains H_2O +volatiles (aliphatic carbon atoms (open chains) + aromatic hydrocarbons (1-6 six-carbon rings characteristic of benzene series), → low efficiency in burning.

Co-firing of biomass with coal → higher overall thermal.
IEA : Capital cost of dedicated biomass plants= (3-5)x cost of co-fire plants
→ cost of electricity from coal/biomass co-firing = 50% of electricity from biomass.

Europe (Germany): The MAP-program pays > € 2,000 for replacement of fossil-fuel boiler with pellet boiler, low-interest loans, 7% VAT (instead of 19%) for wood pellets.

Also in US →

2013 NEW HAMPSHIRE Wood Pellet Boiler Rebate Program
30% Rebate (with max $6,000) in NEW HAMPSHIRE for Whole House Wood Pellet Heating Systems

Gasification/Liquefaction

Biomass-Energy Conversion Methods

1. Combustion/co-combustion → burned in boilers, furnaces, stoves, (with coal)
2. Gasification → converted to syngas (H_2, CO,..)
3. Liquefaction → converted to synfuel (Fischer-Tropsch)
4. Pyrolysis → thermal decomposition into gas, liquids, solids
5. Fermentation → +distillation: ethanol (C_2H_5OH), liquid fuel
6. Anaerobic digestion → mix of CO_2, CH_4 gas, low heat value

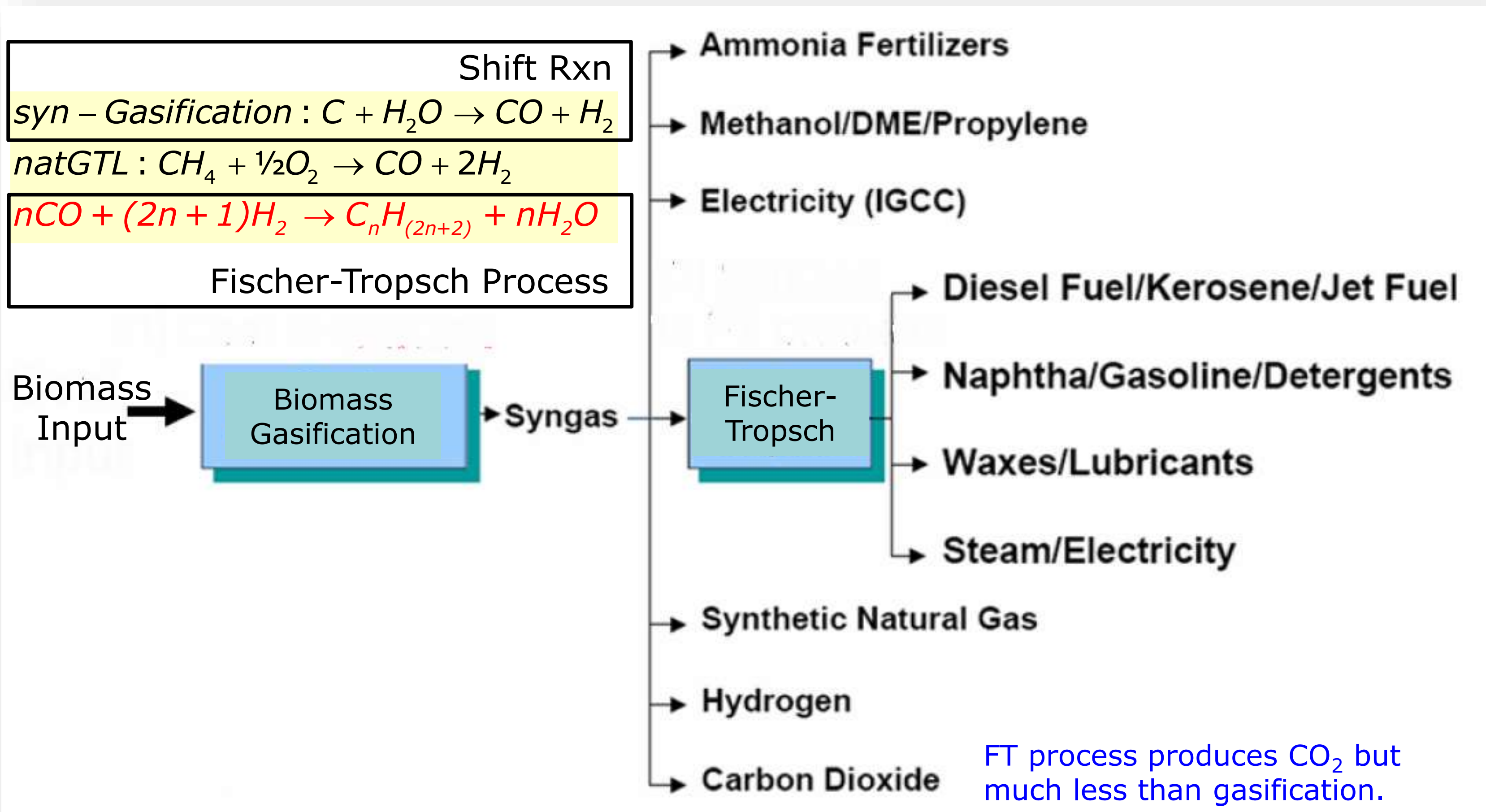
Europe 1940s: truck fueled by "wood gas" =(50% nitrogen, 20% carbon monoxide, 18% hydrogen, 8% carbon dioxide and 4% methane)

Biogas (CO, H_2, CH_4) made by pyrolysis = heating of organic materials in the absence of O_2.

Biomass to Gas and/or Liquid

Common scheme for biomass/coal gasification and subsequent liquefaction.

Fischer-Tropsch Process = catalyzed chemical reaction converting CO and H_2 (from syngas) to mix of hydrocarbons of different weights.



After: Indiana Center f. Coal Technol. Res.

Fischer-Tropsch Synfuel Process

Fischer–Tropsch **synthesis** [150–300 °C (302–572 °F)] → mix of alkanes

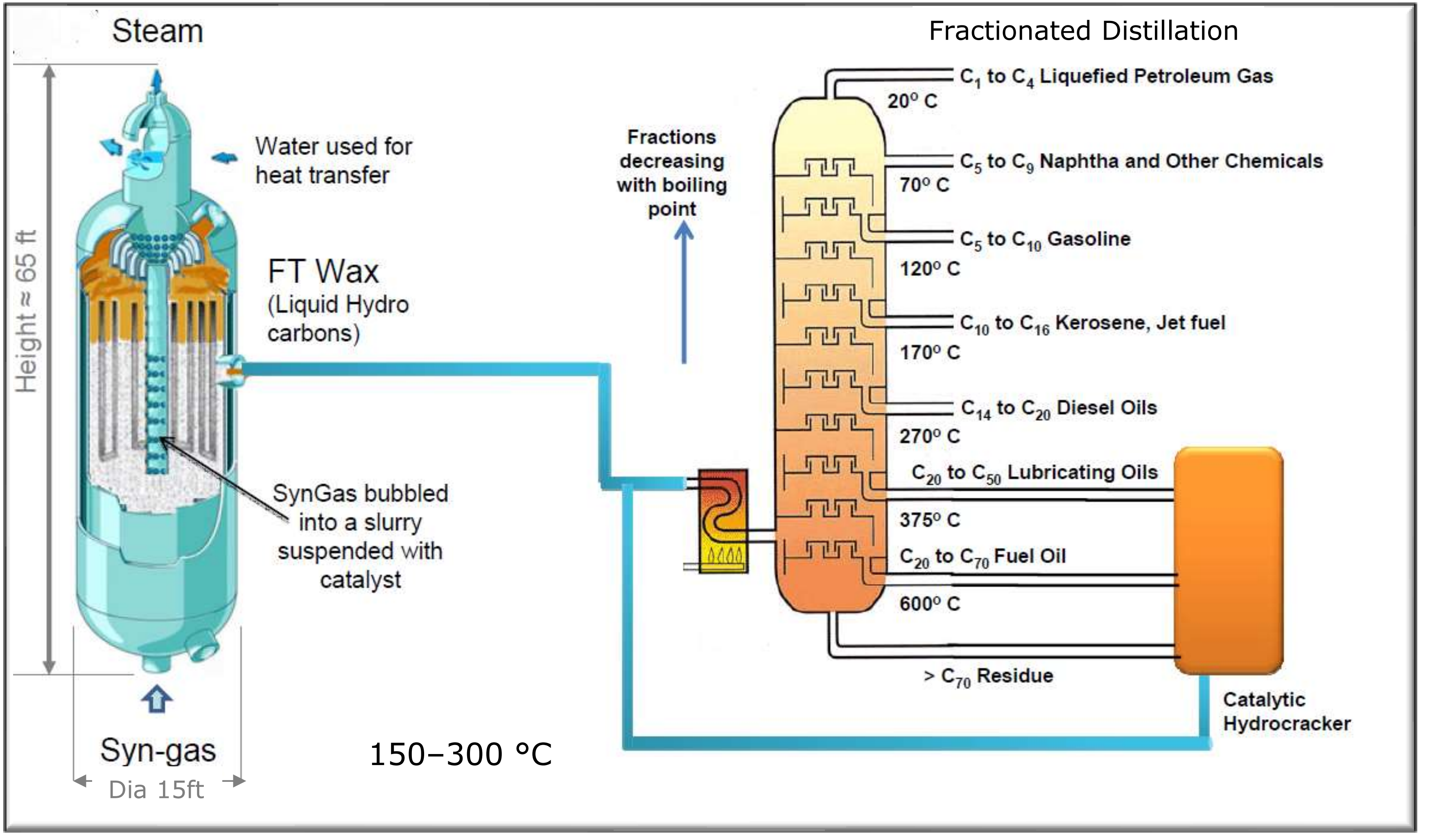
Process: Catalytic conversion Syngas →

$$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O \rightarrow \text{Diesel+...}$$

For methane feedstock → steam reforming, $CH_4 + H_2O \rightarrow CO + 3\ H_2$

In addition, competing reactions → small amounts of alkenes, alcohols, oxygenated hydrocarbons. Common catalysts: Co, Fe, Ru (Ni for methanation).

Fischer-Tropsch Products



Reforming and Shift Reactions

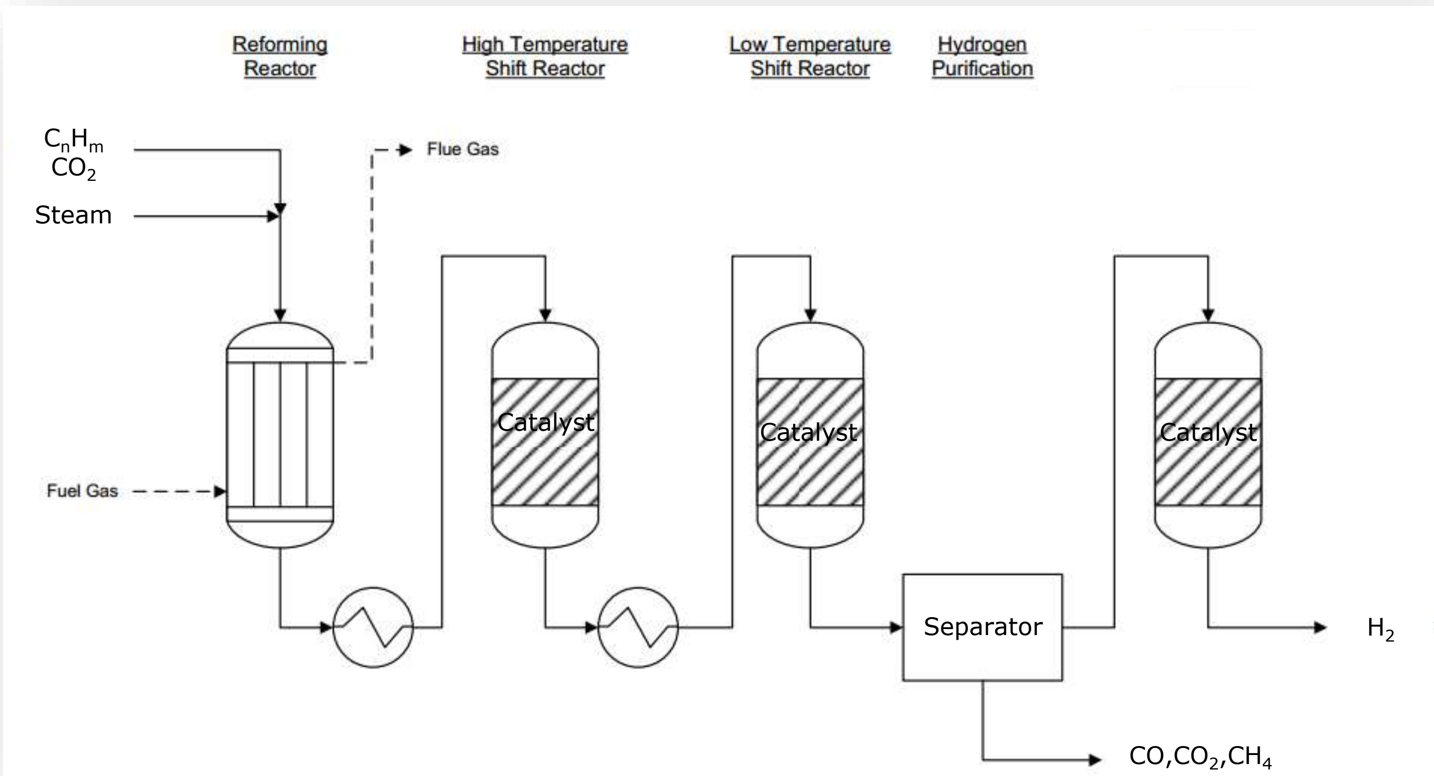
Main high-temperature, catalytic reactions of carbon oxides, hydro-carbons with H_2O, H_2:

Steam reforming: $C_nH_m + nH_2O \leftrightarrow (n+m/2)H_2 + nCO$ (syngas) endothermic, catalytic

Water-gas shift: $CO + H_2O \leftrightarrow CO_2 + H_2$, (syngas) exothermic, catalytic

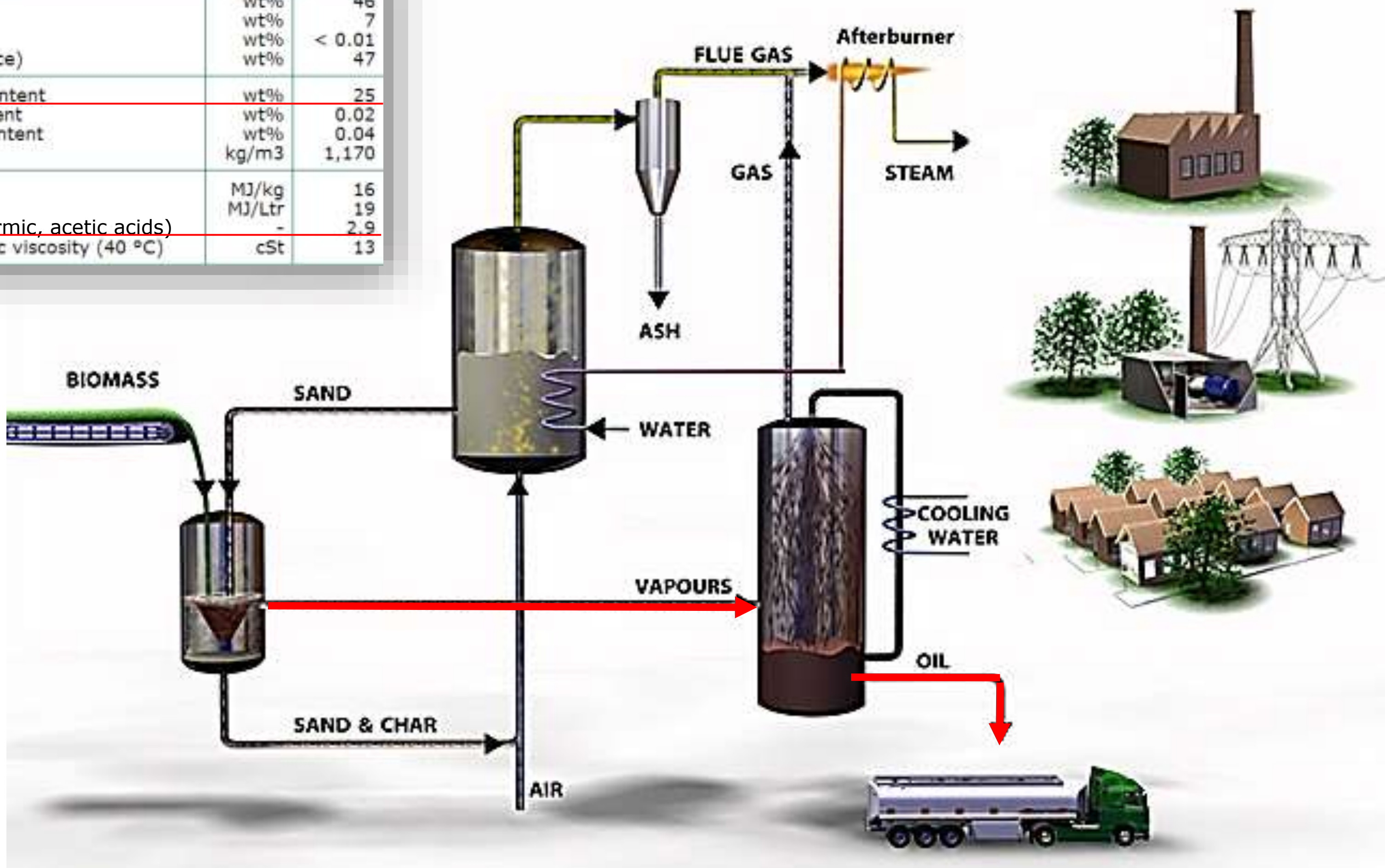
Methanation: $CO + 3H_2 \leftrightarrow CH_4 + H_2O$, exothermic, catalytic

$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$, exothermic, catalytic



Biomass Pyrolysis

Property	Unit	Value
C	wt%	46
H	wt%	7
N	wt%	< 0.01
O (Balance)	wt%	47
Water content	wt%	25
Ash content	wt%	0.02
Solids content	wt%	0.04
Density	kg/m3	1,170
LHV	MJ/kg	16
LHV	MJ/Ltr	19
pH (Formic, acetic acids)	-	2.9
Kinematic viscosity (40 °C)	cSt	13



Fast pyrolysis: organic materials heated to 450 - 600 °C in the absence of air → organic vapors, pyrolysis gases, charcoal. Condense vapors to bio-oil. Typical conversion (60-75) wt.% of feedstock. **Ash**= (inorganic matter): limestone, iron, aluminum, clay, silica, and trace elements Zn, Co, B, Pb, As, Cd, Cr, Se (concentrations < 1000 ppm).

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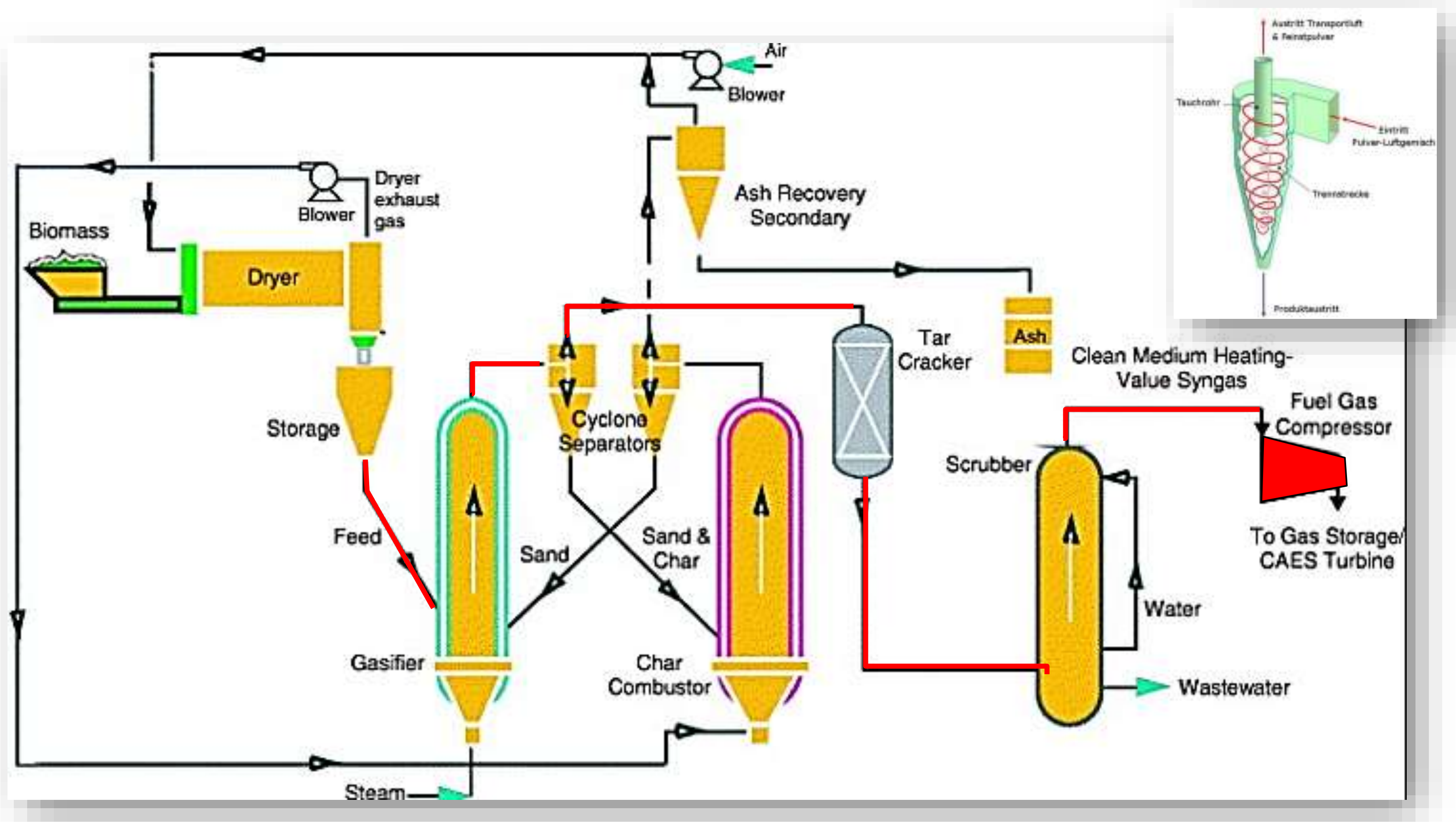
Biomass Gasification

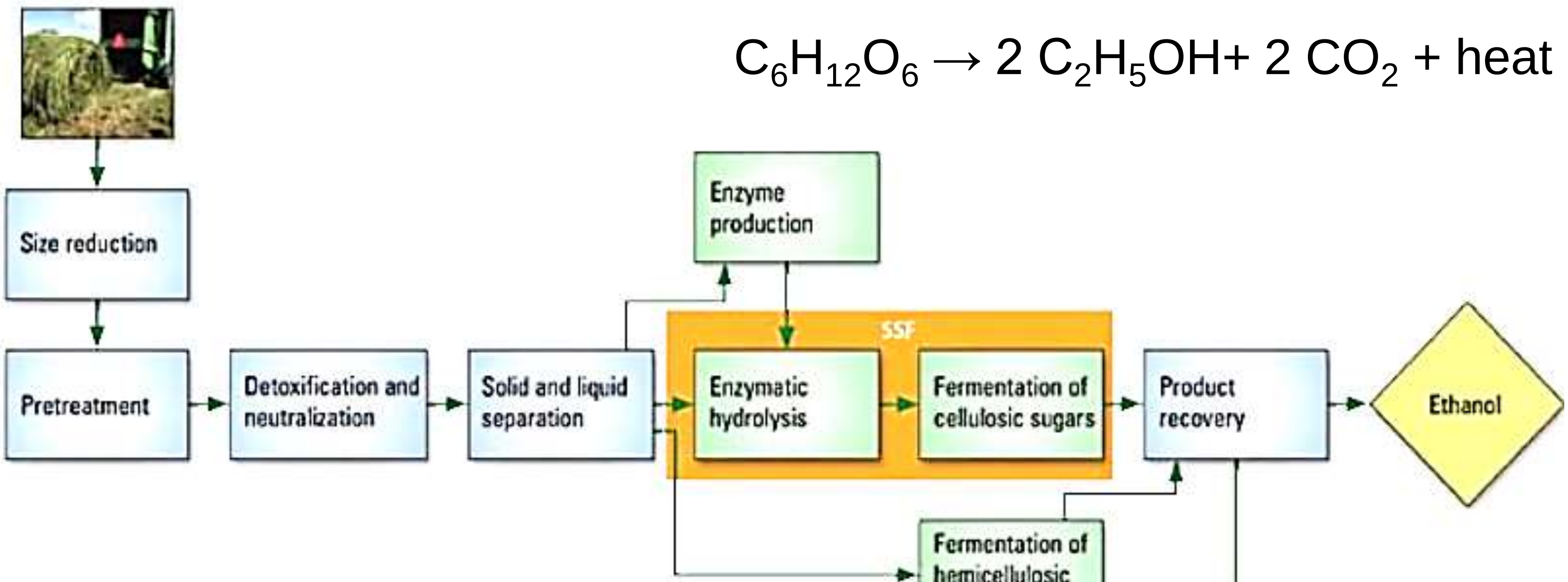


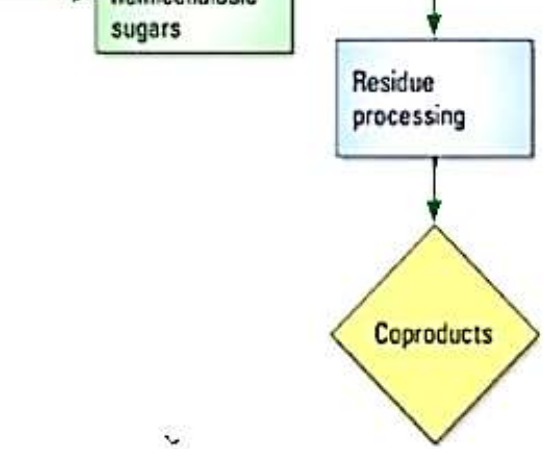
The (SilvaGas) process indirectly heats the incoming biomass to generate a medium heating value (11-14 MJ/Nm^3) gas (rather than low heating). Sand is used as a heat transfer medium to rapidly heat the incoming biomass and convey char from the gasification reactor into the process combustor. Steam reforming, shift reactions.

Pyrolysis Plant

Biological Bio-Ethanol Production

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2 + \text{heat}$$





1. Size reduction and thermochemical pretreatment of raw cellulosic biomass to make cellulose polymers more accessible to enzymatic breakdown and free up hemicellulosic sugars (blue boxes on left);

2. Production and application of special enzyme preparations (cellulases), hydrolyze plant cell-wall polysaccharides, producing a mixture of simple sugars (green boxes);

3. Fermentation, mediated by bacteria or yeast, sugars → ethanol +co-products (yellow diamonds).
4. Distillation/dehydration to remove water.

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- Potential Energy crops, strategic issues
  - Switchgrass, algae cultures, geo-engineering
  - Strategic issues of biomass utilization

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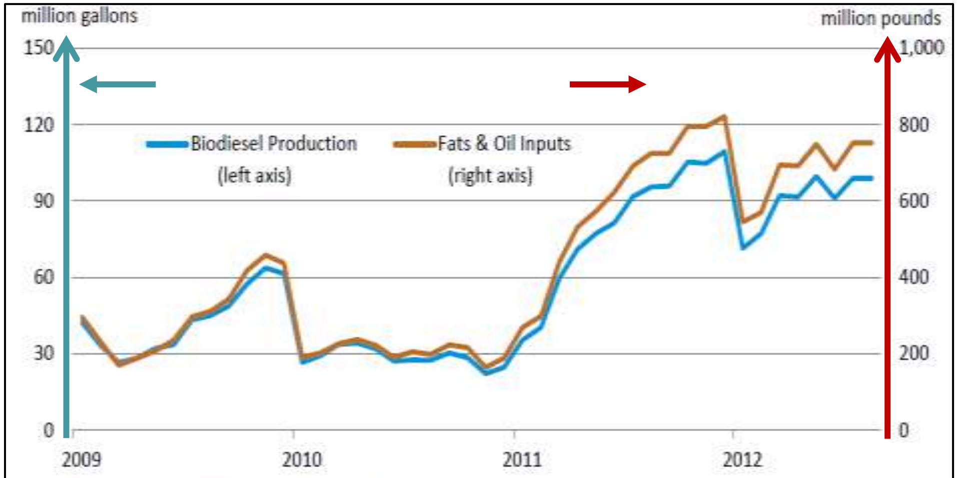
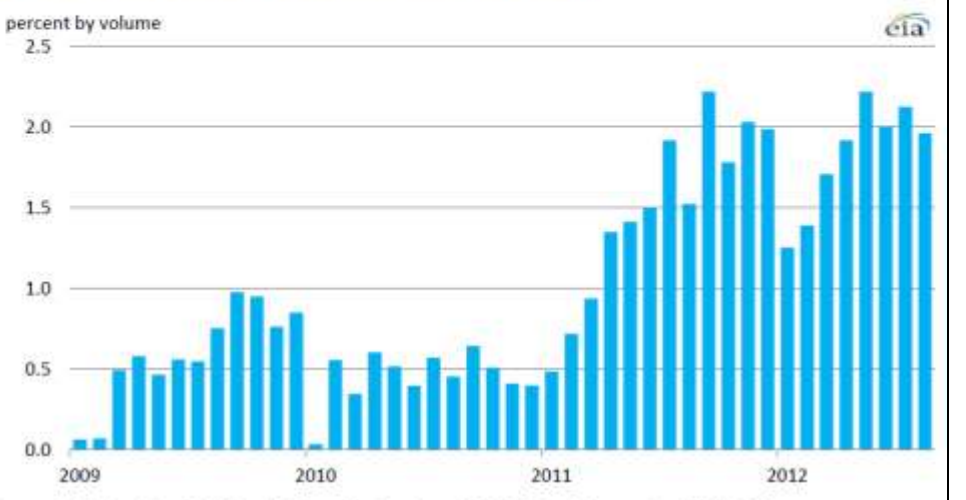
US Biofuel Consumption: Ethanol & Biodiesel



Source: EIA, *Monthly Energy Review*, August 2012, Table 10.4,

US 2020 gasoline consumed:
123.73 billion gallons
(= 2.95 billion barrels)
= 338 million gallons/d
(= 8.05 million barrels/d)

Figure 6. Biodiesel share of U.S. distillate consumption, 2009-12



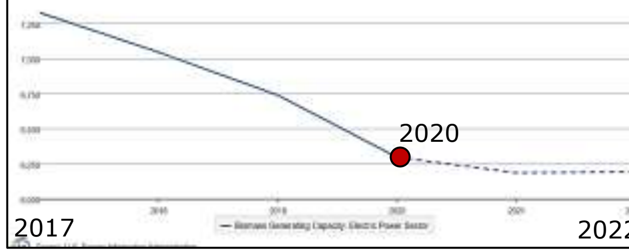
Sources: Calculated from EIA, *Monthly Energy Review*, August 2012, Biodiesel Consumption, Table 10.4, http://www.eia.gov/totalenergy/data/monthly/query/mer_data_excel.asp?table=T10.04, Distillate Fuel Oil Product Supplied, Table 3.5, http://www.eia.gov/totalenergy/data/monthly/query/mer_data_excel.asp?table=T03.05, and STEO Custom Table Builder.

Biomass Renewable Electricity Capacity and Generation

US Energy Information Administration: Short Term Energy Outlook 2021:

US: Diminishing importance of biomass for electricity generation.

Biomass Generation Capacity (MW)



Electric Generating Capacity (MW)	2020	2021	2022
Electric Power Sector (a)			
Biomass	**6,295**	*6,184*	*6,190*
Waste	**3,790**	*3,822*	*3,829*
Wood	**2,505**	*2,362*	*2,362*
Conventional Hydroelectric	**78,671**	*78,765*	*78,840*
Geothermal	**2,483**	*2,500*	*2,525*
Large-Scale Solar (b)	**47,586**	*63,333*	*81,531*
Wind	**118,045**	*135,042*	*141,903*
Other Sectors (c) Not Electricity			
Biomass	**6,302**	*6,289*	*6,281*
Waste	**777**	*778*	*778*
Wood	**5,525**	*5,510*	*5,503*
Conventional Hydroelectric	**279**	*279*	*279*
Large-Scale Solar (b)	**468**	*538*	*541*
Small-Scale Solar (d)	**27,724**	*33,487*	*41,276*
Residential Sector	**17,238**	*21,354*	*26,865*
Commercial Sector	**8,430**	*9,892*	*11,893*
Industrial Sector	**2,056**	*2,241*	*2,518*
Wind	**346**	*346*	*346*

Renewable Electricity Generation (billion kilowatthours) (GWh)	2020	2021	2022
Electric Power Sector (a)			
Biomass	**27.5**	*27.1*	*26.3*
Waste	**16.1**	*15.6*	*15.6*
Wood	**11.4**	*11.5*	*10.8*
Conventional Hydroelectric	**289.9**	*254.6*	*267.7*
Geothermal	**16.5**	*16.0*	*16.0*
Large-Scale Solar (b)	**90.1**	*114.3*	*145.7*
Wind	**336.7**	*377.3*	*420.4*
Other Sectors (c) Not Electricity			
Biomass	**28.6**	*28.0*	*28.0*
Waste	**2.7**	*2.7*	*2.7*
Wood	**25.8**	*25.3*	*25.3*
Conventional Hydroelectric	**1.2**	*1.2*	*1.2*
Large-Scale Solar (b)	**0.8**	*0.9*	*0.9*
Small-Scale Solar (d)	**41.7**	*49.8*	*61.6*
Residential Sector	**25.4**	*30.6*	*38.9*
Commercial Sector	**12.9**	*15.3*	*18.3*
Industrial Sector	**3.5**	*3.9*	*4.3*
Wind	**0.8**	*1.0*	*0.9*

Strategic Issues Renewable Bioenergy (Plants & Algae)

1. Energy density, heating value
2. Pollution from combustion, net emission of various GHG
3. CO_2 atmospheric residence time during vegetation regrowth (not ren.)
4. Climate/weather dependence
5. Use of arable land competes with food production → food prices
6. Excessive use of water
7. Use of fertilizer feed stock (nitrogen, phosphates)
8. Deterioration of land by mono-crop plantations, deforestation (Indonesia)
9. Efficiency in fermentation process
10. Economics, subsidies

For scalability & sustainable use: Need technological breakthroughs