Energy and the New Reality, Volume 2:

C-Free Energy Supply

Chapter 4: Biomass Energy

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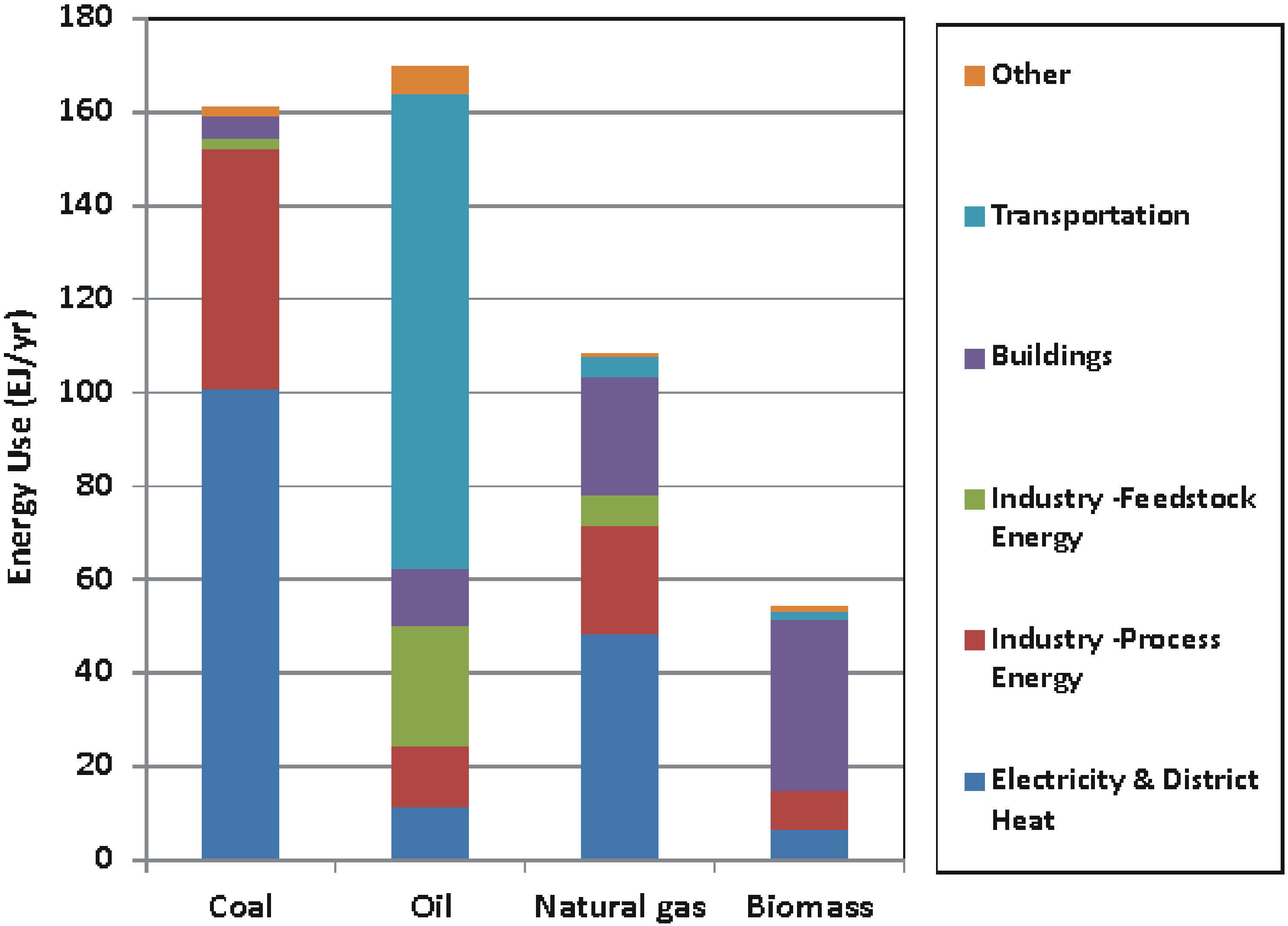
The challenge: replacing uses of fossil fuels other than for the generation of electricity

- Most electricity in the world today is generated from fossil fuels, but there are lots of C-free electricity-generation options (wind, solar, hydro, geothermal, nuclear)
- But what about fossil fuels used as a fuel for industry and transportation, and to heat buildings, produce hot water, and cook food?

Solutions?

- Shift as many direct uses of fossil fuels (such as in cars and for heating buildings) to electricity (and decarbonize the electricity grid)
- Replace the remainder with C-free or C-neutral fuels, namely: hydrogen or biomass
- Produce the H_2 by electrolysis of water (or some other method) using C-free electricity sources
- Produce the biomass on a sustainable basis, so that it is just recycling atmospheric CO_2 and is therefore C-neutral

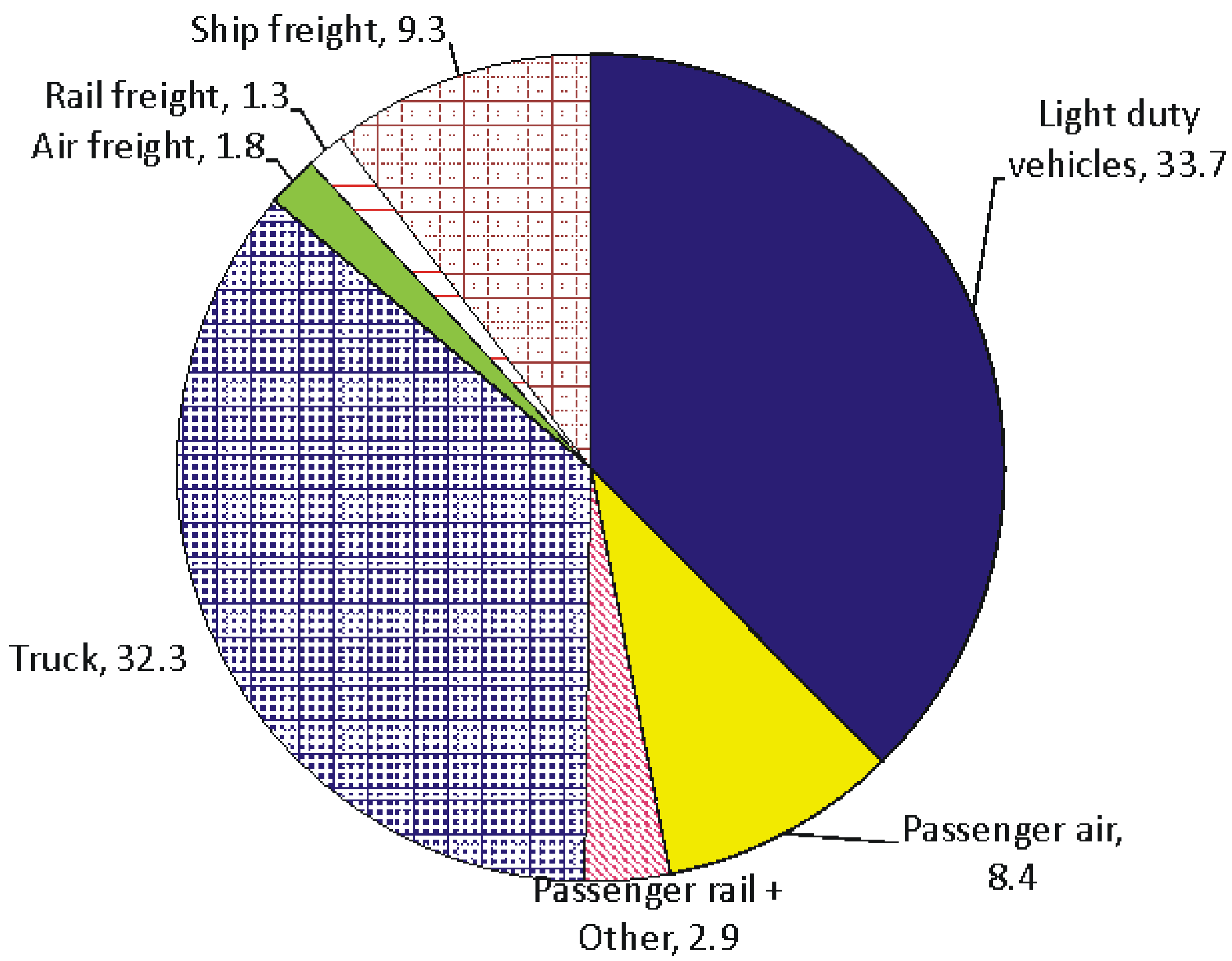
Global fuel use in 2014



Referring to some of the big fuel-end use combinations in the previous slide,

- Most of the industrial coal use is for the steel industry – can replace with electrolytic H_2
- Most of the natural gas industrial use is for the production of nitrogen fertilizer (combining atmospheric N_2 with H_2 from the CH_4 molecule (NG is ~ 98% methane)) – use electrolytic H_2 instead
- Oil industrial feedstock use is for the production of plastics – we will surely need biomass as an alternative feedstock
- A large amount of biomass is used for heating buildings, producing hot water, and for cooking (in developing countries), and is used very inefficiently in poorly insulated buildings – so there is room for a huge reduction in existing uses of biomass

Breakdown of transportation oil use (EJ) in 2014



Eliminating transportation oil use

- Make LDVs (light duty vehicles: cars, SUVs, light trucks) 3-4 times more efficient when running on fuel (as in advanced HEVs), then transition to PHEVs or perhaps fully electric vehicles
- Use H_2–powered fuel cells for freight trucks and rail
- Use H_2 or biofuel for ships (supplemented with advanced wind propulsion!)
- H_2-fueled aircraft are a possibility but the transition might not be achievable in any practical way, so:
- We might have to rely on biofuels for passenger and freight air transportation

Eliminating natural gas use in buildings

- Mandate that new buildings meet the German Passive House standard (10 x less heating energy per m^2 floor area than current average in Canada)
- Retrofit the entire building stock over a 40-50 yr period to reduce heating energy use by 50-80%
- Where-ever possible, switch to electric ground-source heat pumps (incorrectly referred to by many as "geothermal" energy) for space heating and hot water
- Second-best choice is to use electric air-source heat pumps
- Where this is not possible, either

  - feed CH_4 from biomass digestion into the natural gas system (in urban areas), or

  - use biomass pellets in efficient pellet furnaces (in rural areas), or

  - use biomass as a fuel source in district heating systems

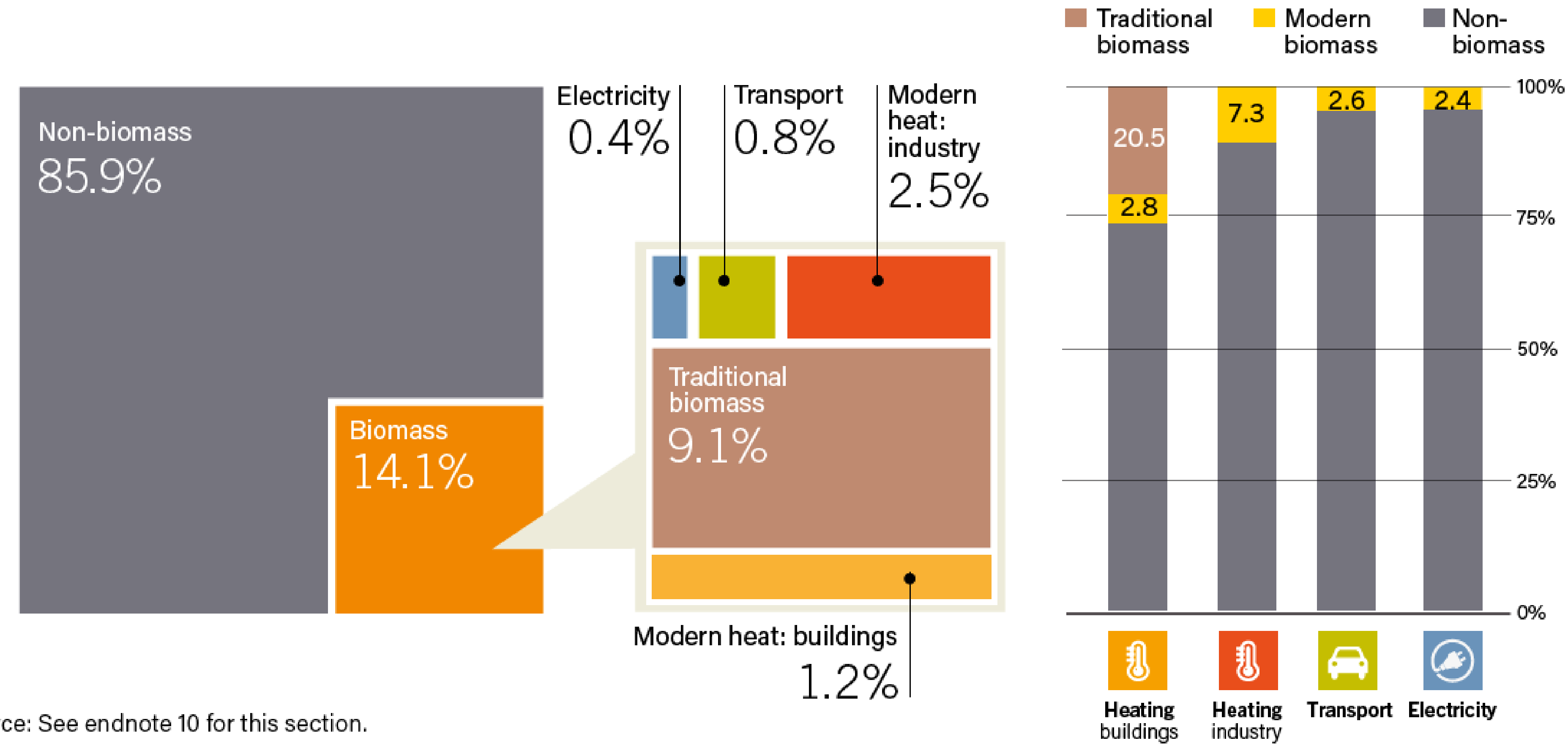
Likely minimum global biomass need based on present energy end use demand:

• Air transportation:	**10 EJ/yr**
• Feedstocks:	25 EJ/yr
• Electricity and district heating:	20 EJ/yr
• Buildings:	10 EJ/yr
• Total:	65 EJ/yr

By comparison, total biomass energy supply in 2014 was 58 EJ, and total fossil fuel energy supply was about **470 EJ**.

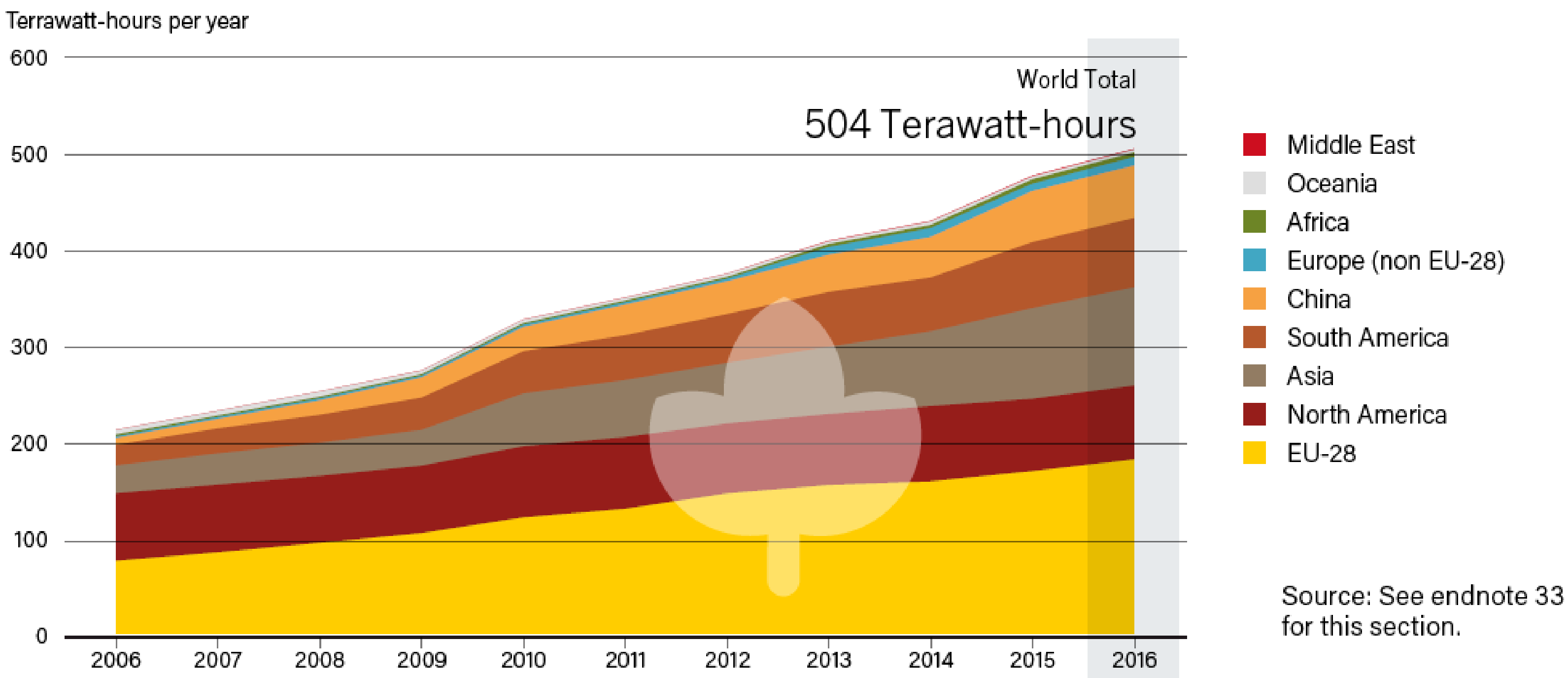
Thus, the essential biomass need is about the same as the current total, highly inefficient use of biomass at present. This would grow as poor regions get richer, so the challenge will be to sufficiently limit the growth through efficiency that the required amount of biomass can be met sustainably.

Uses of biomass in 2015



Source: Renewables 2017: Global Status Report

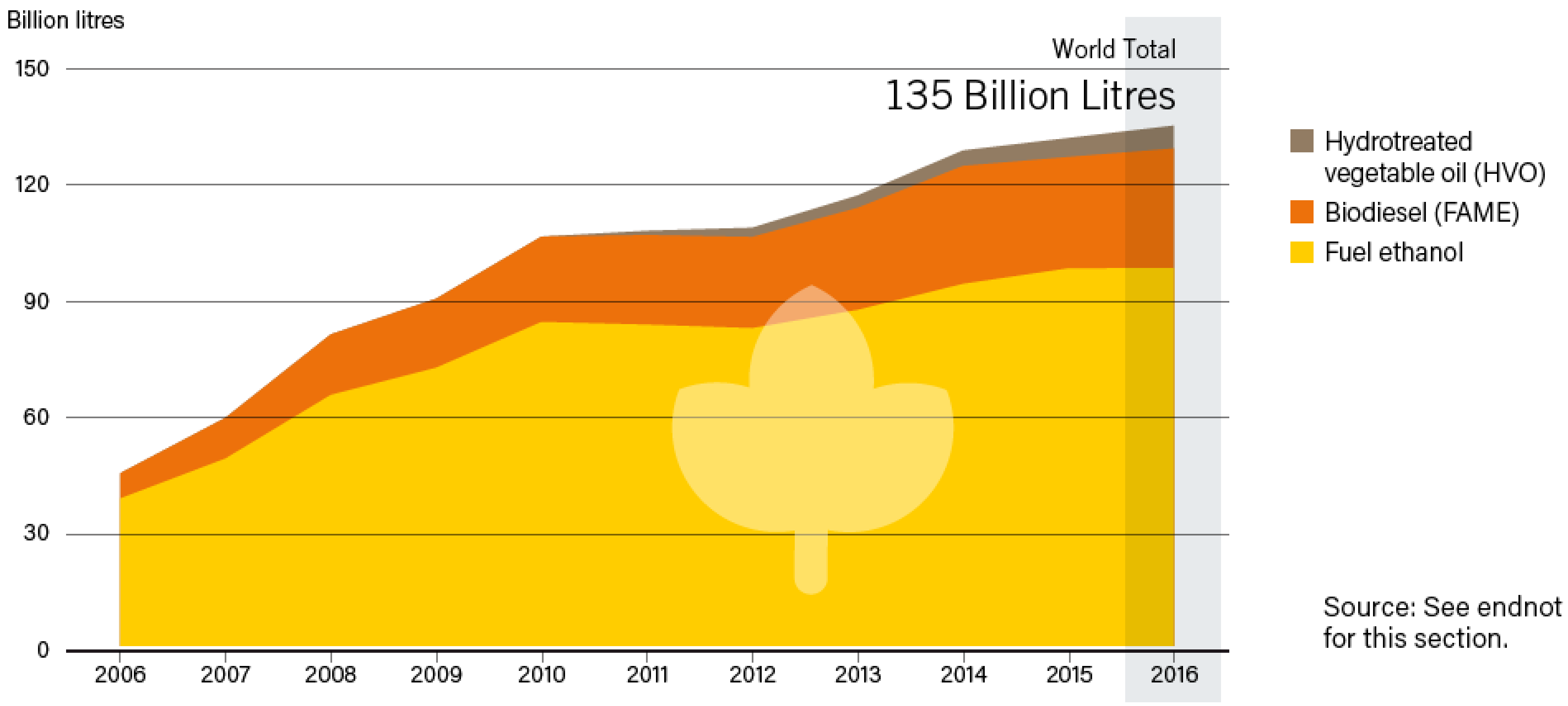
Trend in biomass use for generating electricity



500 TWh is 2.5% of the total global electricity generation of about 20,000 TWh/yr

Source: Renewables 2017: Global Status Report

Trend in biofuels production



Source: Renewables 2017: Global Status Report

Advantages of biomass:

- Can be stored
- Provides rural income & employment
- Potentially cleaner than coal for most pollutants
- Can be irrigated and fertilized with sewage water
- Can be cultivated in such a way as to improve the landscape and remediate soils
- Can make use of animal wastes and agricultural residues while providing an effective fertilizer byproduct

Disadvantages of biomass energy

- Land intensive (efficiency of photosynthesis is ~ 1%, with further losses when biomass is converted to secondary forms of energy)
- Can compete with land for food
- Complex to initiate and manage
- Must be tailored to the biophysical and socio-economic circumstances of each region

Comparison with fossil fuels

- Heating value ranges from 14 GJ/t (sugar cane, straw) to 18-20 GJ/t (air-dried wood), compared to 28-31 GJ/t for coal
- This makes biomass bulky and more expensive to transport (in both dollar and energy terms) than coal

Table 4.3: Biomass energy resource categories

Category I	Biomass grown on surplus agricultural land that becomes available as agricultural yields increase
Category II	Biomass grown on degraded or deforested land that is still suitable for reforestation
Category III	Agricultural residues (primary – taken from the field, or secondary – generated during food processing)
Category IV	Forestry residues (primary and secondary)
Category V	Animal manure
Category VI	Organic wastes (such as municipal solid waste)
Category VII	Biomaterials (used as a feedstock in place of petroleum)

Source: Hoogwijk (2003, *Biomass and Energy, 25,* 119-133)

Bioenergy Crops

- Annuals
- Perennial grasses
- Woody Crops (trees)

Annuals

- Starch-rich crops (maize (corn), wheat, potatoes) (used to produce ethanol)
- Sugar-rich crops (sugarcane, sugar beets) (used to produce ethanol)
- Oil-rich crops (coconut oil, palm oil, sunflower oil) (used to produce biodiesel)

Figure 4.3a Sugarcane (a sugar-rich crop)

Source: www.wikipedia.org

Figure 4.3b Sugarcane harvesting

Source: www.wikipedia.org

Figure 4.3c Cut sugarcane stalks

Source: www.wikipedia.org

Figure 4.4 Palm oil (an oil-rich crop)

Sources: Left, Photo by Jeff McNeely in Howarth and Bringezu (2009, *Biofuels: Environmental Consequences and Interactions with Changing Land Use*, SCOPE); upper right, Stone (2007, *Science*, vol 317, pp149); lower right, Koh and Wilcove (2007, *Nature*, vol 448, pp993–994)

Perennial grasses

- Switchgrass (*Panicum virgatum*)(native to North America)
- *Miscanthus* (native to tropical Africa and tropical and temperate Asia)
- Napier grass (native to tropical Africa)
- *Jatropha curcas* (a poisonous weed native to Central America, used in India)

Figure 4.5 Switchgrass (*Panicum virgatum)*

Source: US Gov public domain

Figure 4.6 *Miscanthus sinensus* (upper) & Napier grass (*Pennisetum pupureum)* (lower)

Source: www.wikipedia.org

Figure 4.7 Close-up of *Jatropha* (left), and degraded land before (upper right) and after being planted with *Jatropha* (lower right) in India

Source: Left, photo by Jeff McNeely in Howarth and Bringezu (2009, *Biofuels: Environmental Consequences and Interactions with Changing Land Use*, SCOPE); right, Fairless (2007, Nature, vol 449, pp652–655)

Woody crops

- Short-rotation coppicing
  - Willow (*Salix*)
  - Poplar (*Populus*)
- Modified conventional forestry
  - *Acacia* (N-fixing)
  - Pine (*Pinus*)
  - *Eucalyptus*

Figure 4.8 Harvest of coppice willow and irrigation of new growth with sewage water in Sweden.

Source: Dimitriou and Aronsson (2003, *Unasylva* 56, 221, 47-50)

Figure 4.9a Five-year old *Acacia* plantation

Source: Doug Maquire, Oregon State University, www.forestryimages.org

Figure 4.9b ***Eucalyptus*** **plantation in Spain (left) and 4-year old** ***Eucalyptus*** **in Hawaii (right).**

Source: NREL Photo Exchange, www.nrel.gov/data/pix)

Figure 4.9c 14-year old loblolly pine (*Pinus taeda*) in Georgia, USA

Source: Dennis Haugen, www.forestryimages.org

Yields of bioenergy crops

- Annals
  - Sunflower 1.5 t/ha/yr
  - Maize: 4 t/ha/yr
  - Sugarcane, sugar beet: 60 t/ha/yr
- Grasses
  - *Jatropha*: 10-15 t/ha/yr
  - *Miscanthus* 10-15 t/ha/yr
  - Switchgrass 10-25 t/ha/yr
  - Napier grass 30 t/ha/yr
- Trees
  - Loblolly pine: 4-5 t/ha/yr
  - Poplar, willow: 10-20 t/ha/yr
  - *Eucalyptus*: 10-50 t/ha/yr

Agricultural Residues

- A variety of residues (stalks, shells, husks, leaves) from a wide variety of crops (such as coconut, maize, cotton, groundnuts, pulses, rice, sugarcane) are produced and used for household energy use in rural areas of developing countries already
- Straw is co-fired with coal in Denmark
- Bagasse is a fibrous residue produced during the processing of sugarcane into sugar

Figure 4.10 Bagasse, a residue from processing of sugarcane

Source: Warren Gretz and DOE/NREL

Source: Kartha and Larson (2000, *Bioenergy Primer, Modernized Biomass Energy for Sustainable Development*, United Nations Development Programme, New York)

Forestry residues

- Primary (left in the field): From thinning of plantations and trimming of felled trees
- Secondary (produced during processing): Sawdust, bark, wood scraps from production of marketable wood; bark and black liquor from the production of pulp for paper

Processes of extracting energy from biomass

To simplify the discussion, we will group the various transformation processes into the following categories:

- Direct combustion
- Various gasification processes to produce either a gaseous carbon fuel or hydrogen, or as a first step in producing liquid fuels (Fischer-Tropsch liquids)
- Anaerobic digestion to produce CH_4 (the main ingredient in natural gas)
- Fermentation of sugars in non-woody biomass (such as corn or sugarcane) to produce ethanol – a substitute for gasoline
- Hydrolysis & fermentation of woody biomass to produce ethanol
- Transesterification of vegetable oils to produce biodiesel

As noted earlier, it looks like electric LDVs will beat out biofuel LDVs for passenger transportation, and electricity or hydrogen will beat out biodiesel for truck freight transportation. Thus we will omit altogether the last 3 transformation processes in the previous slide, although probably well over half the biomass literature (and probably even more of the government bioenergy subsidies) are in these areas.

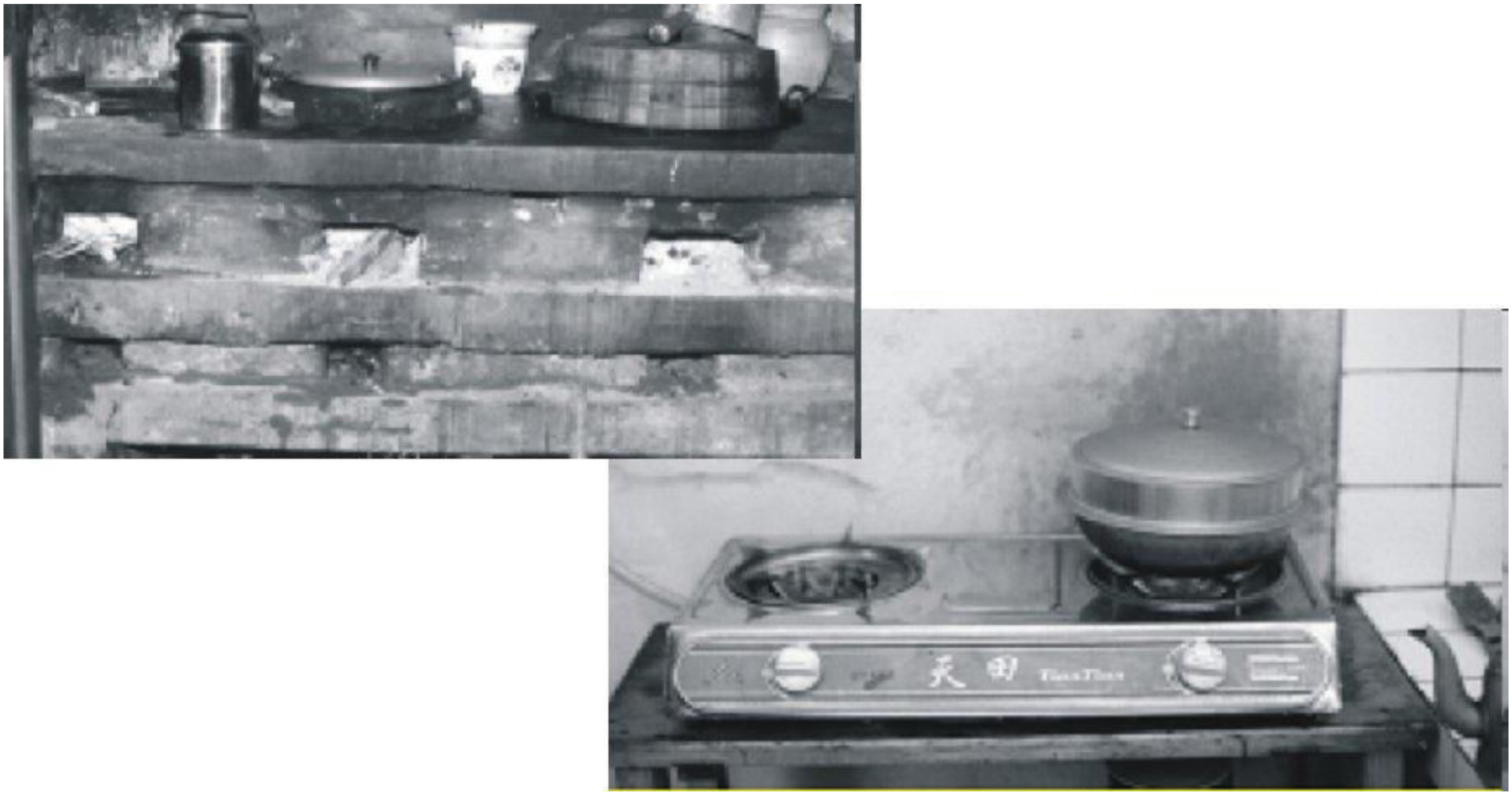
Direct combustion

- Cooking with firewood in developing countries, typical cook-stove efficiency is 10-20%, 30% with improved stoves (vs. 45-60% with gaseous fuels)
- Pellet heating, central Europe in particular
- District heating in Sweden, Atlantic Canada
- Issues include ash content (which is related to the non-combustible silica in the biomass, which can be high) and K and Ca in the fuel, which can cause agglomeration in boilers

Figure 4.11 Traditional wood-burning stove (upper), improved wood-burning stove (middle), and charcoal-burning stove (lower) in Kenya

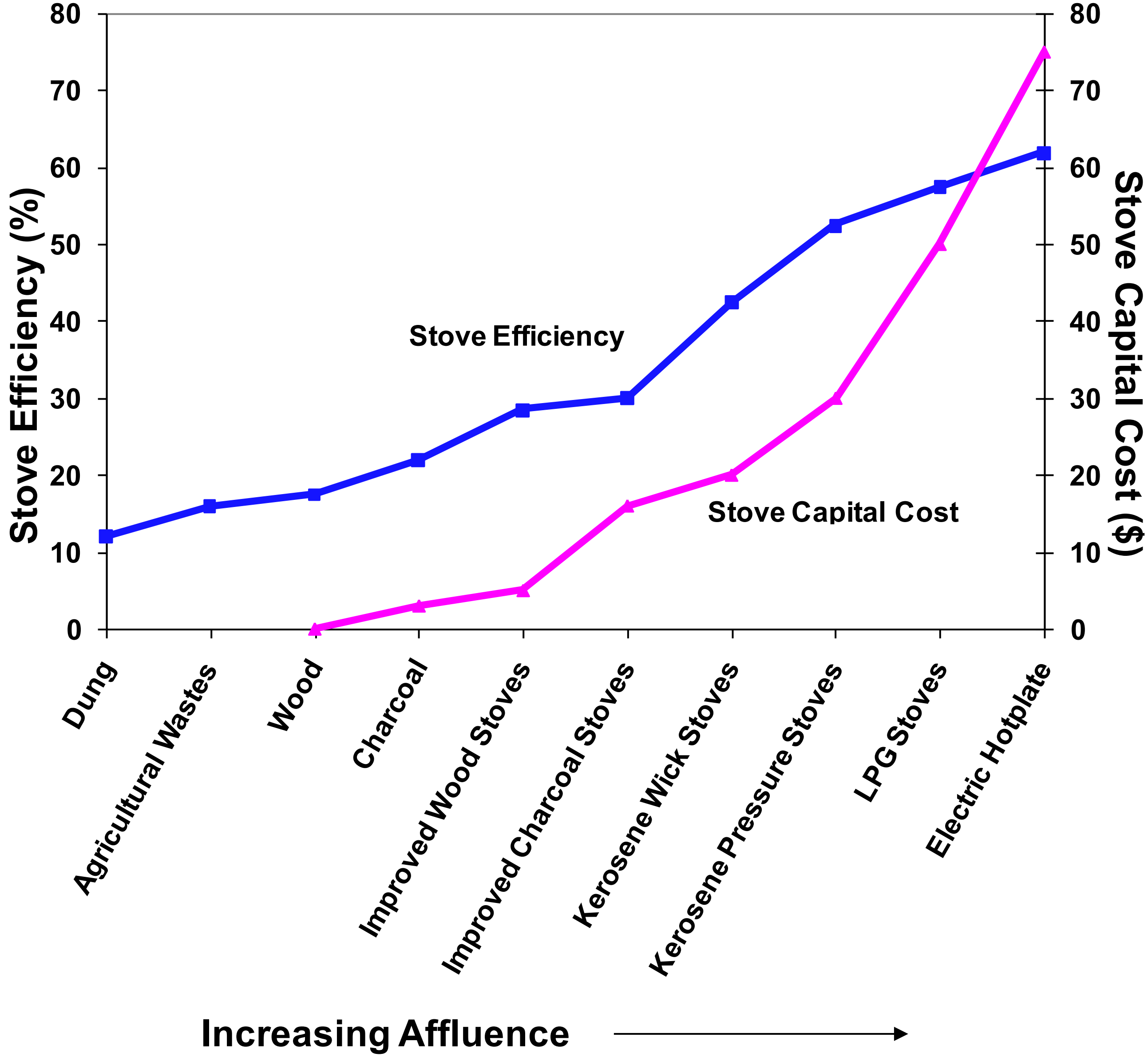
Source: Bailis et al (2003, *Environmental Science & Technology* 37, 2051–2059)

Figure 4.12 A wood-burning hearth in China and its replacement with a biogas-fueled stove



Source: Kartha and Larson (2000, *Bioenergy Primer, Modernized Biomass Energy for Sustainable Development*, United Nations Development Programme, New York)

Figure 4.13 Cookstove efficiency and cost



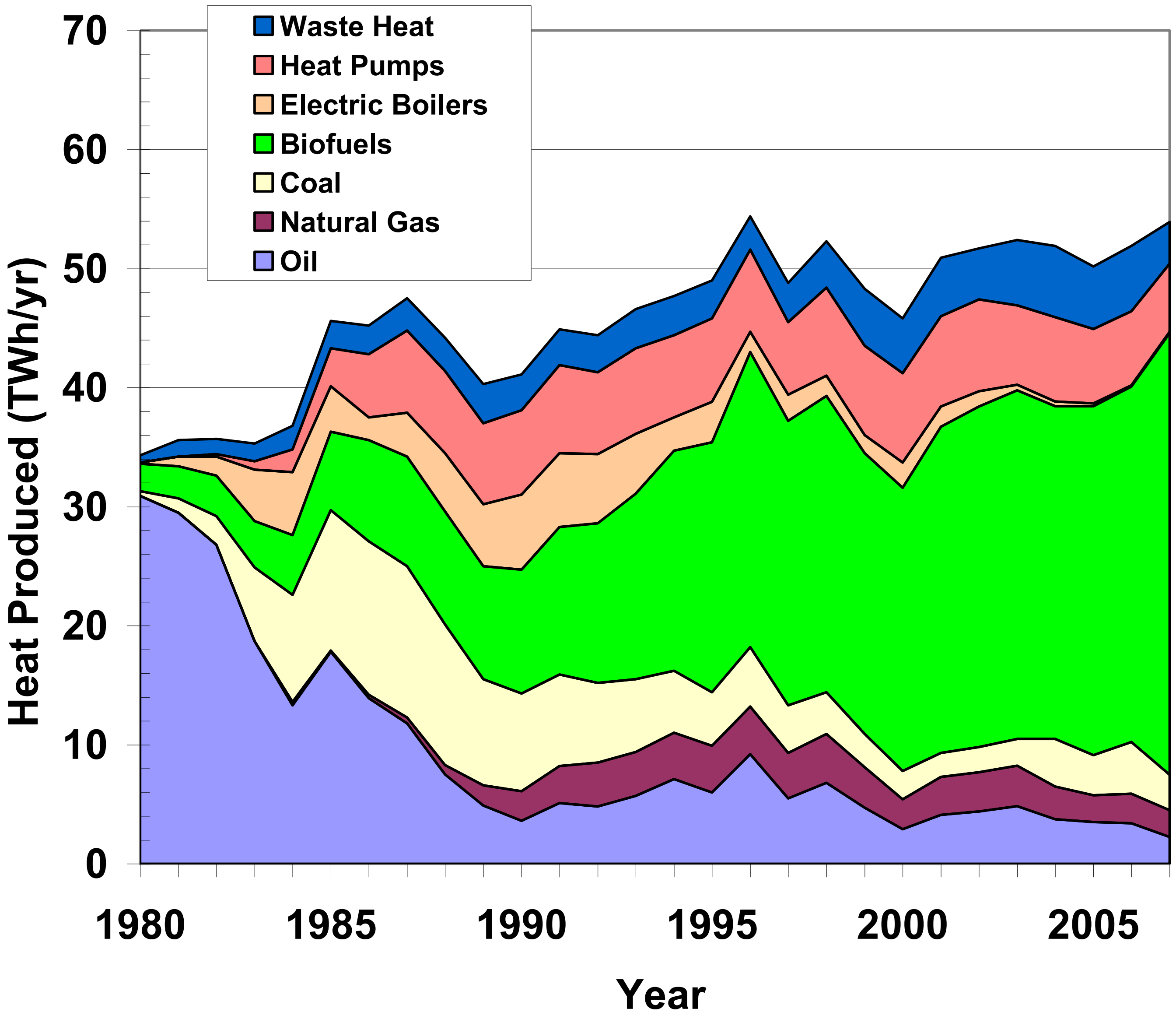
Source: Kammen et al (2001, Policy Discussion Paper for the United Nations Development Program, Environmentally Sustainable Development Group (ESDG) and the Climate Change Clean Development Mechanism (CDM))

Figure 4.14 Biomass pellets (left) and pneumatic delivery by truck (right)

Figure 4.15 Pellet-burning stove (left) and furnace (right)

Source: www.harmonstoves.com

Figure 4.16 Fuel sources for Swedish district heating

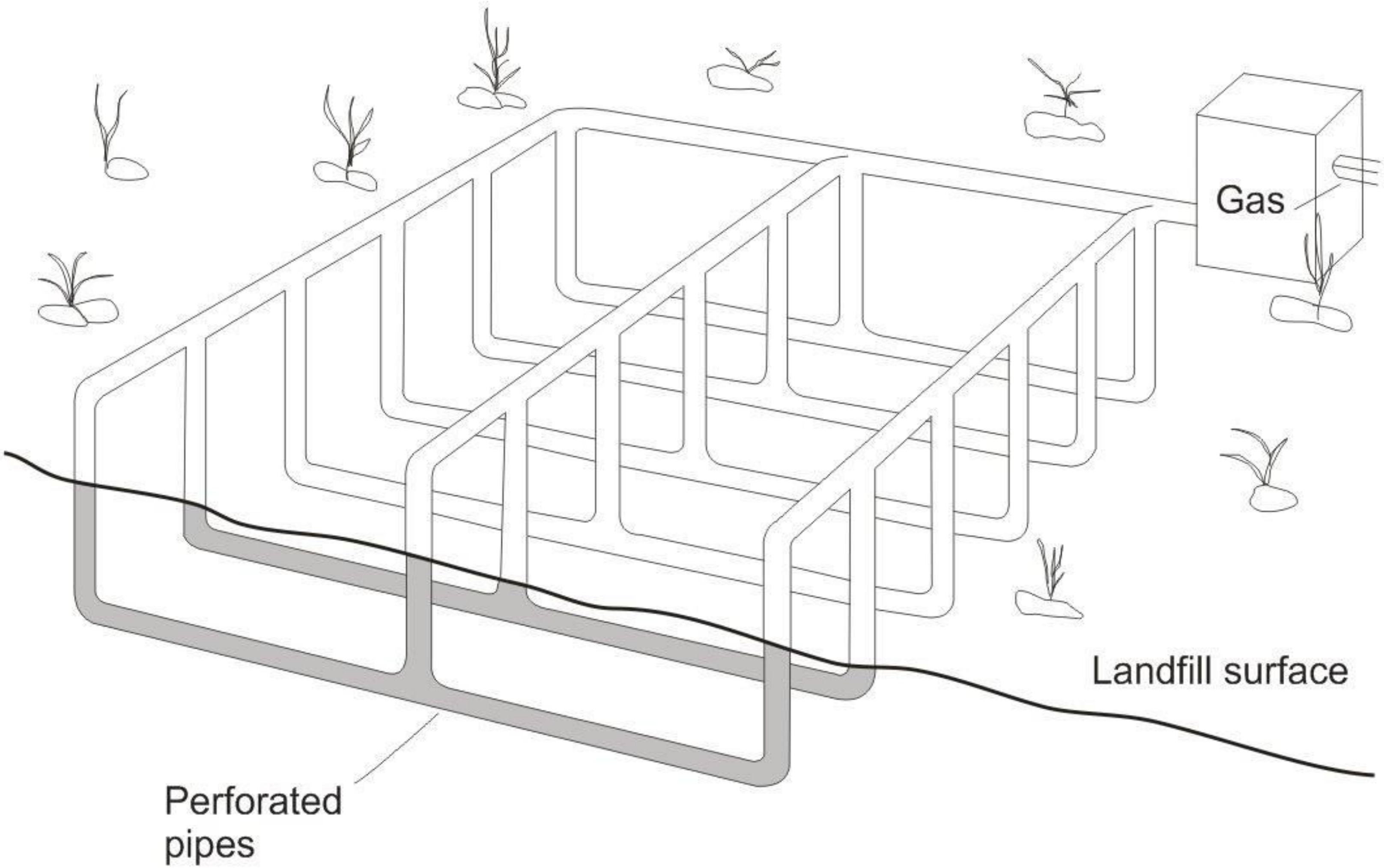


Source: Swedish Energy Agency (2008, *Energy in Sweden 2008*, www.stem.se)

Biological gasification (anaerobic digestion)

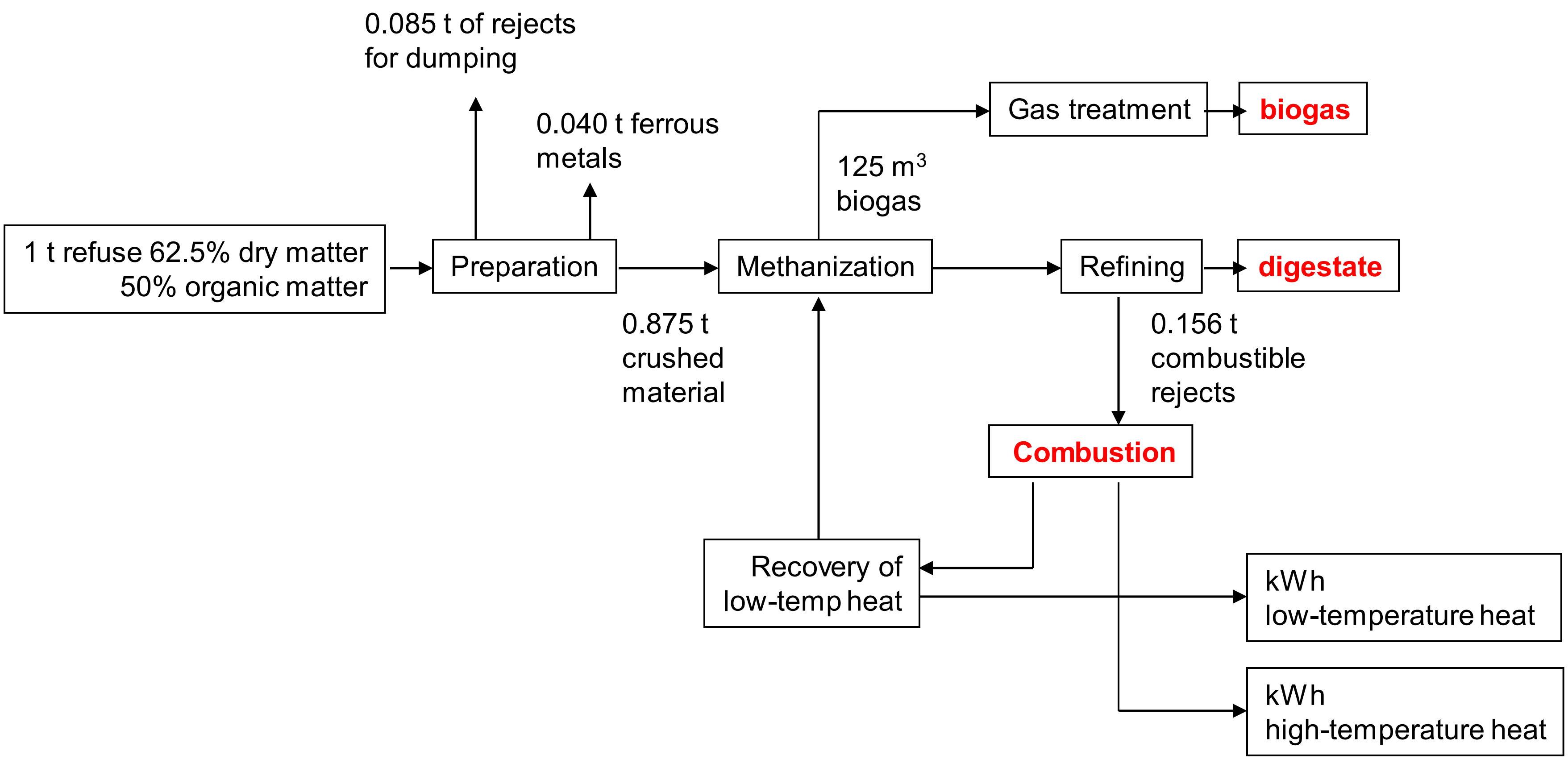
- Anaerobic decomposition is decomposition in the absence of oxygen that produces methane
- Among other places, it occurs in sanitary landfills (in which waste including organic matter alternates with clay layers, creating anaerobic conditions and temporarily trapping any methane produced from anaerobic decomposition)
- The methane is extracted with perforated pipes
- The efficiency (heating value of extracted methane over heating value of the organic waste is only ~ 20%)
- Can be done with greater efficiency (50-55%) in dedicated digesters

Figure 4.19 Collection of biogas from a municipal landfill



Source: Ramage and Scurlock (1996, *Renewable Energy, Power for a Sustainable Future*, Oxford University Press, Oxford, 137-182)

Figure 4.20 Dedicated anaerobic digestion of organic solid waste with recovery of biogas, low- & high-temperature heat, and digestate as fertilizer



Source: Ramage and Scurlock (1996, *Renewable Energy, Power for a Sustainable Future*, Oxford University Press, Oxford, 137-182)

Anaerobic digestion of animal and sewage wastes

- 5 million household cattle-dung digesters in China, along with 500 large-scale digesters at pig farms and other agro-industrial sites, and 24,000 digesters at sewage treatment plants
- 20 million households in China use biogas from digesters for cooking and lighting needs, and 4 million households in India
- 5000 digesters in industrialized countries, primarily at livestock processing facilities and municipal sewage treatment plants

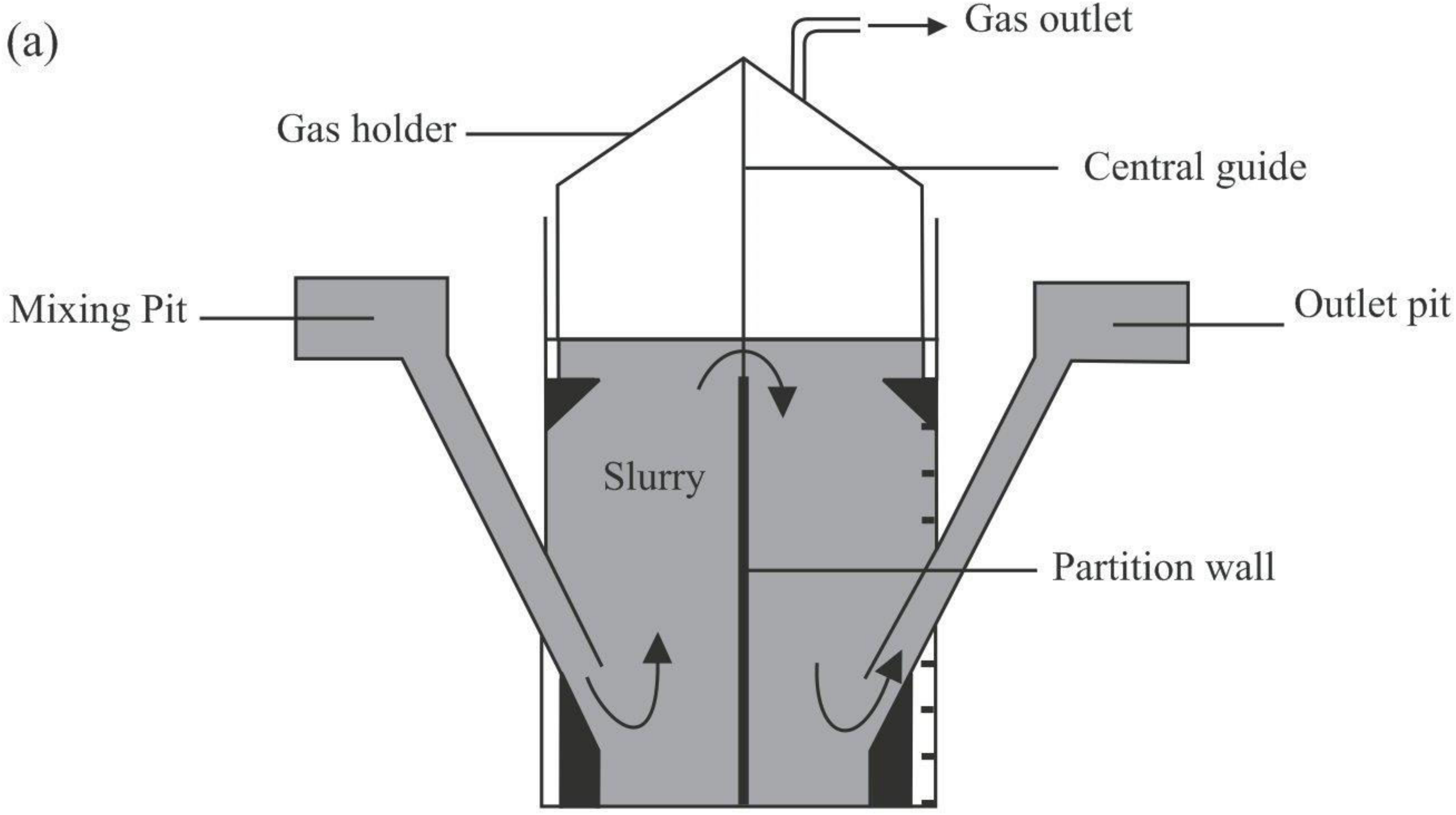
Figure 4.21 Cattle dung digester in India

Source: Kartha and Larson (2000, *Bioenergy Primer, Modernized Biomass Energy for Sustainable Development*, United Nations Development Programme, New York)

Figure 4.22 Digester on a pig farm in England

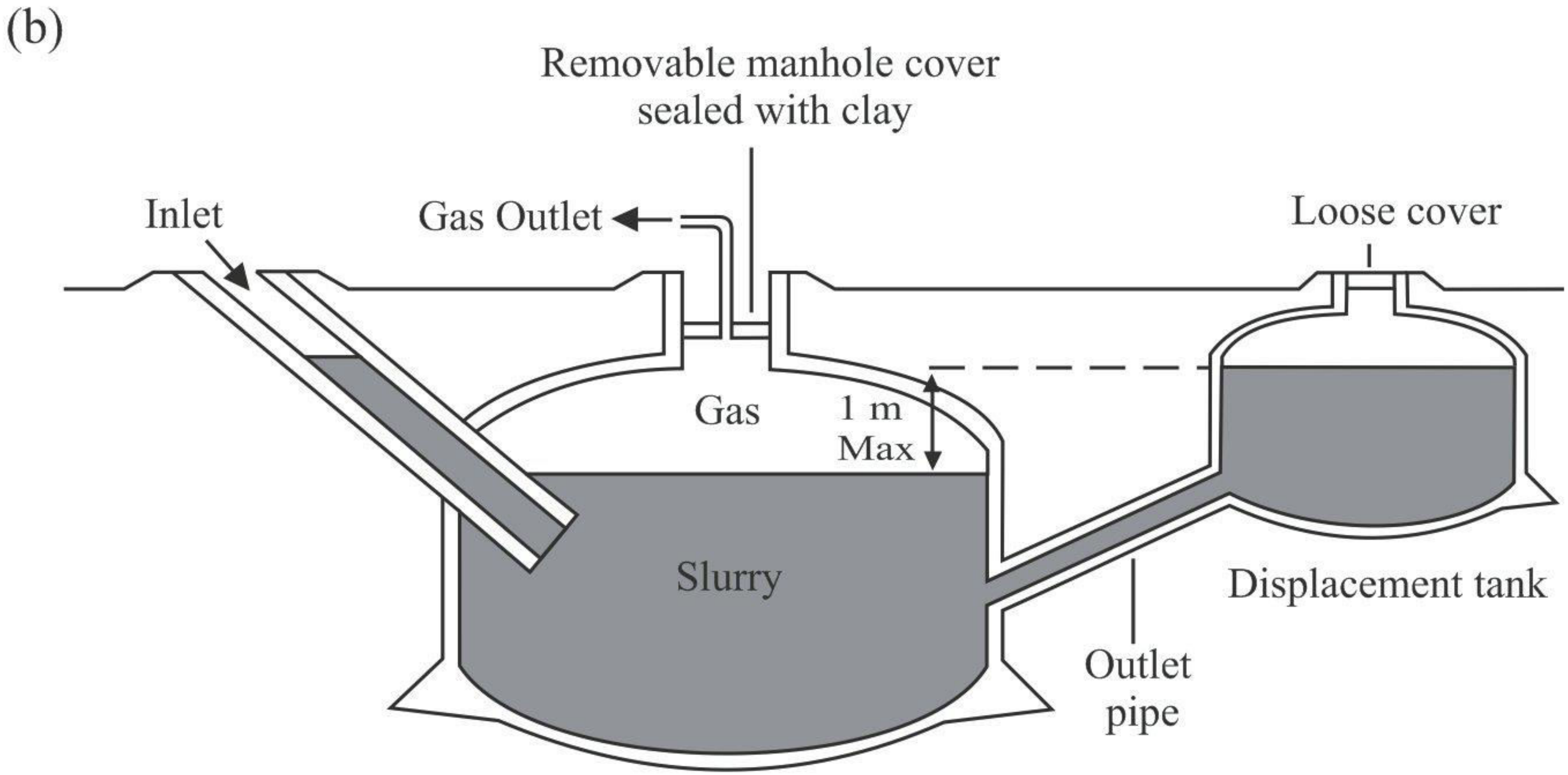
Source: Unknown

Figure 4.23a Indian digester design



Source: Kartha and Larson (2000, *Bioenergy Primer, Modernized Biomass Energy for Sustainable Development*, United Nations Development Programme, New York)

Figure 4.23b Chinese digester design



Source: Kartha and Larson (2000, *Bioenergy Primer, Modernized Biomass Energy for Sustainable Development*, United Nations Development Programme, New York)

Anaerobic digestion of animal wastes in Denmark

- 20 centralized plants and 35 farm-scale plants, making it one of the leading industrialized countries in the world
- The residue is an effective fertilizer
- Yet, these plants process only 3% of the manure produced in Denmark
- Processing of 50% of the available manure would allow the complete elimination of oil for heating and of coal for electricity generation

Fischer-Tropsch liquids

- Fischer-Tropsch synthesis converts solid hydrocarbons or natural gas into liquids
- Biomass is gasified under high temperature and pressure to produce CO and H_2 (this differs from the first step in thermo-chemical gasification, discussed earlier, which is carried out in the near-absence of air)
- The gases are then sent to a reaction chamber, where catalysts are used to produce chains of various lengths
- F-T diesel is cleaner-burning than regular diesel
- **Overall biomass-to-fuel conversion efficiency of 46-52% is expected**

Fischer-Tropsch liquids (continued)

- The process is more expensive using biomass than coal (break-even oil prices of $70-80/barrel and $50-55/barrel, respectively, are required)
- It can make use of plant material that has too much lignin for production of ligno-cellulosic ethanol
- There are still problems related to impurities and fouling of equipment that need to be solved, and there is room for better process integration
- Overall, this is a promising method for large-scale production of biofuels from a wide range of biomass sources

Solar-driven biomass gasification

- In conventional thermo-chemical gasification or F-T synthesis, some of the biomass energy is combusted to produce heat that drives the reactions, and only a portion of the C atoms end up as part of the product gases or liquid fuels
- Use of high-temperature heat from solar thermal towers would allow essentially all of the biomass to be converted to fuel, reducing the biomass and land requirements by a factor of 3 (with ethanol yields of ~ 42,000 litres per ha of biomass plantation per yr)
- As solar thermal energy can be stored, the production facility would operate 24 hours per day
- Biomass would be produced in the regions with highest productivity, then transported by ship or train to semi-arid regions where concentrating solar thermal energy is viable

End Uses of Biomass

Generation of Electricity from Biomass

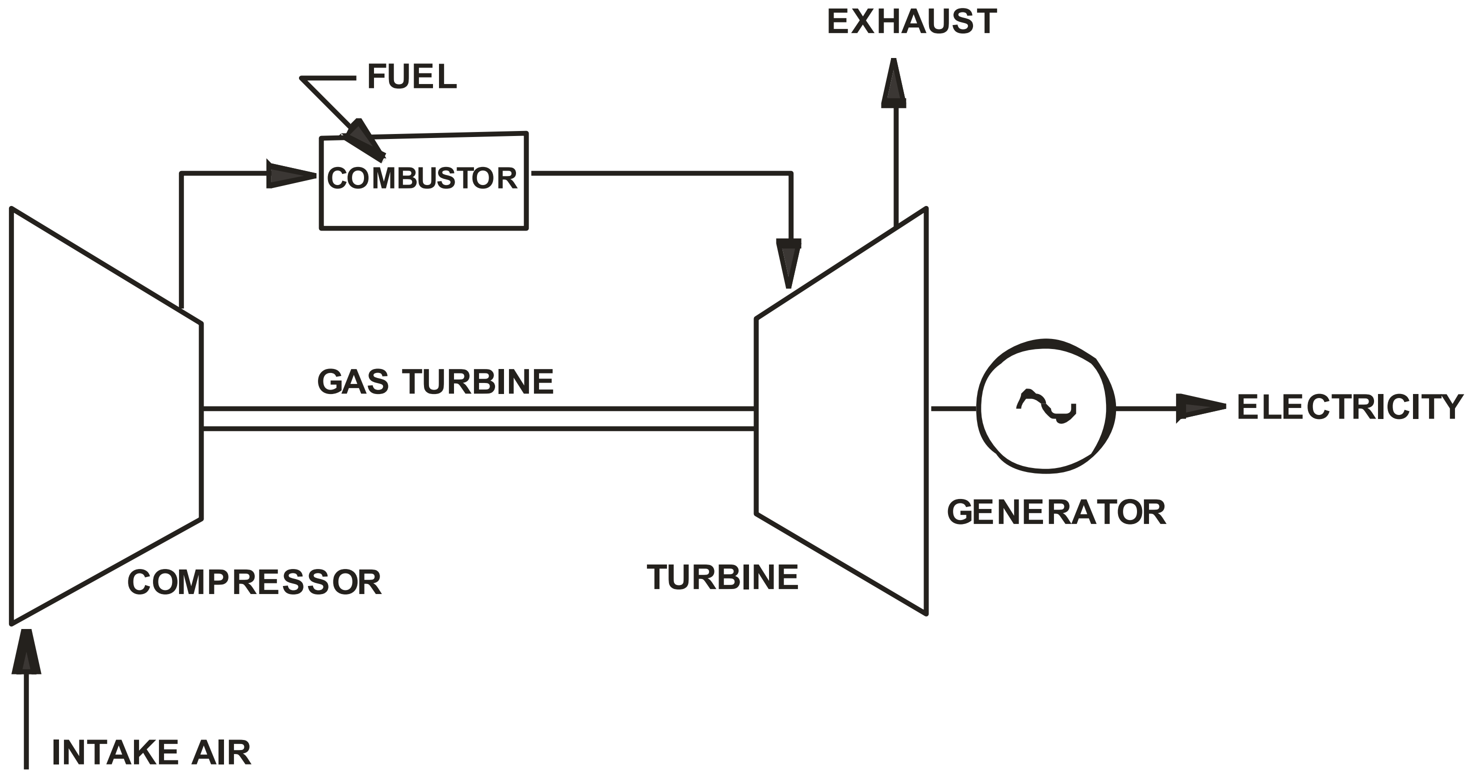
- Co-firing of solid biomass with coal, using steam turbines
- Biogas in place of diesel in small (5-100 kW) internal combustion engines
- Integrated gasification/combined cycle (BIGCC)
- Co-firing of biogas with natural gas
- Integrated gasification/fuel cell
- Cogeneration in the sugarcane and palm oil industries
- Cogeneration in the pulp and paper industry

The conventional way to generate electricity from biomass is to burn the biomass to generate steam, then use the steam in a steam turbine. Efficiency is low (typically 20-30%)

Advanced techniques (still under development) involve thermal gasification of the biomass and use of the gases either in gas/steam turbine combined cycle powerplant or in fuel cells. Waste heat from the steam turbine or fuel cell would provide at least part of the heat required for gasification. Expected overall efficiencies in generating electricity are in the 40-50% range. The option using gas and steam turbines to generate electricity is referred to as **biogas integrated gasification combined cycle (BIGCC).**

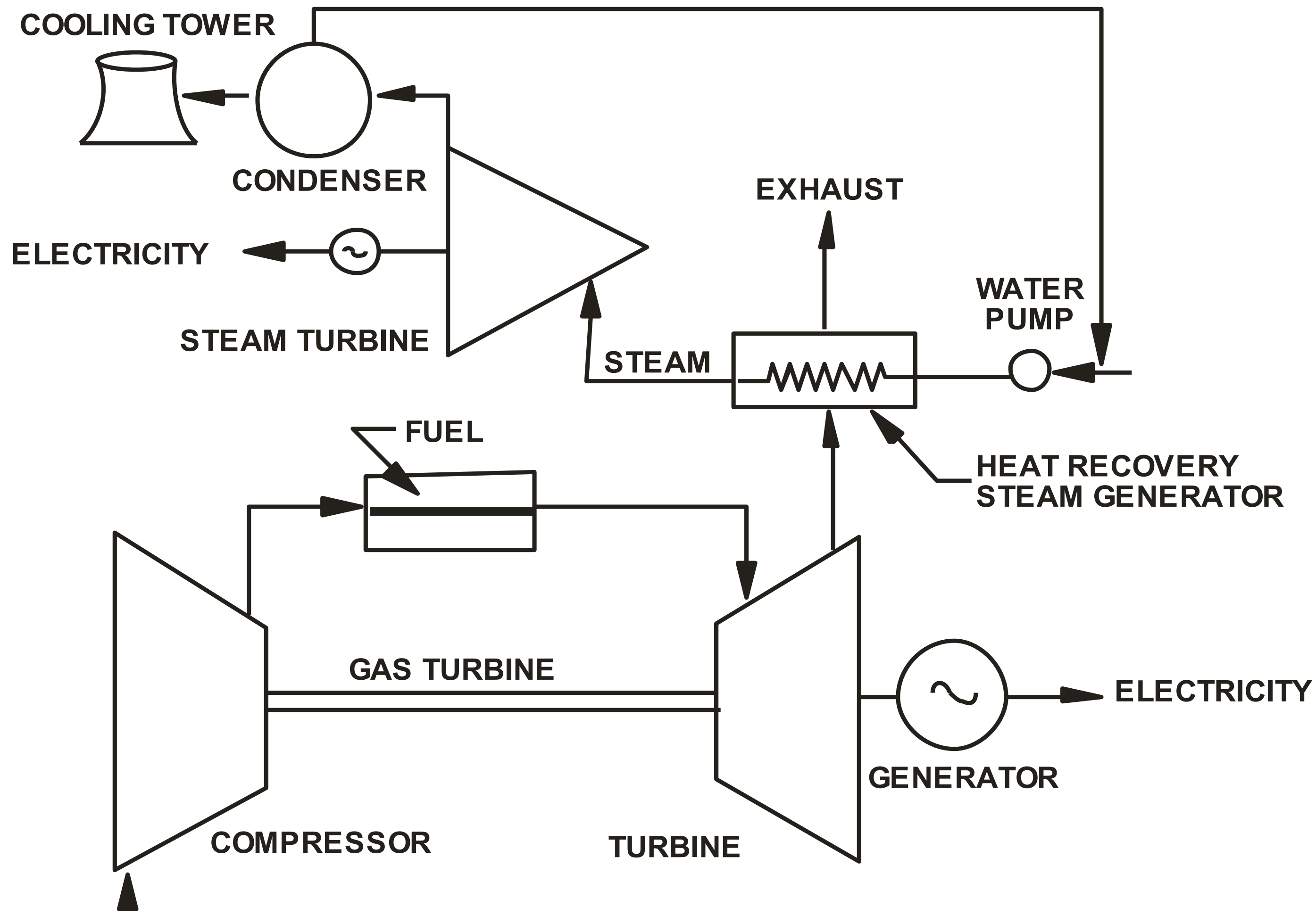
Recap from Volume 1 Chapter 3 (Fig. 3.6a): Simple-cycle gas turbine and electric generator

(a)



Source: Williams (1989, *Electricity: Efficient End-Use and New Generation Technologies and Their Planning Implications*, Lund University Press)

Recap from Volume 1 Chapter 3 (Fig. 3.6c): Combined-cyclepower generation using natural gas



(c)

Source: Williams (1989, *Electricity: Efficient End-Use and New Generation Technologies and Their Planning Implications*, Lund University Press)

Table 4.13 Comparison of a typical natural gas and biogas composition (mole %) and heating value.

	Natural Gas	Biogas
CH_4	87.6	5.0
Other HC	10.9	-
CO_2	1.2	12.0
CO	-	16.0
H_2O	-	12.0
H_2	-	11.0
N_2	0.3	44.0
LHV (MJ/kg)	**47.62**	**4.4**

Source: Marbe et al (2004, *Energy* 29, 1117–1137)

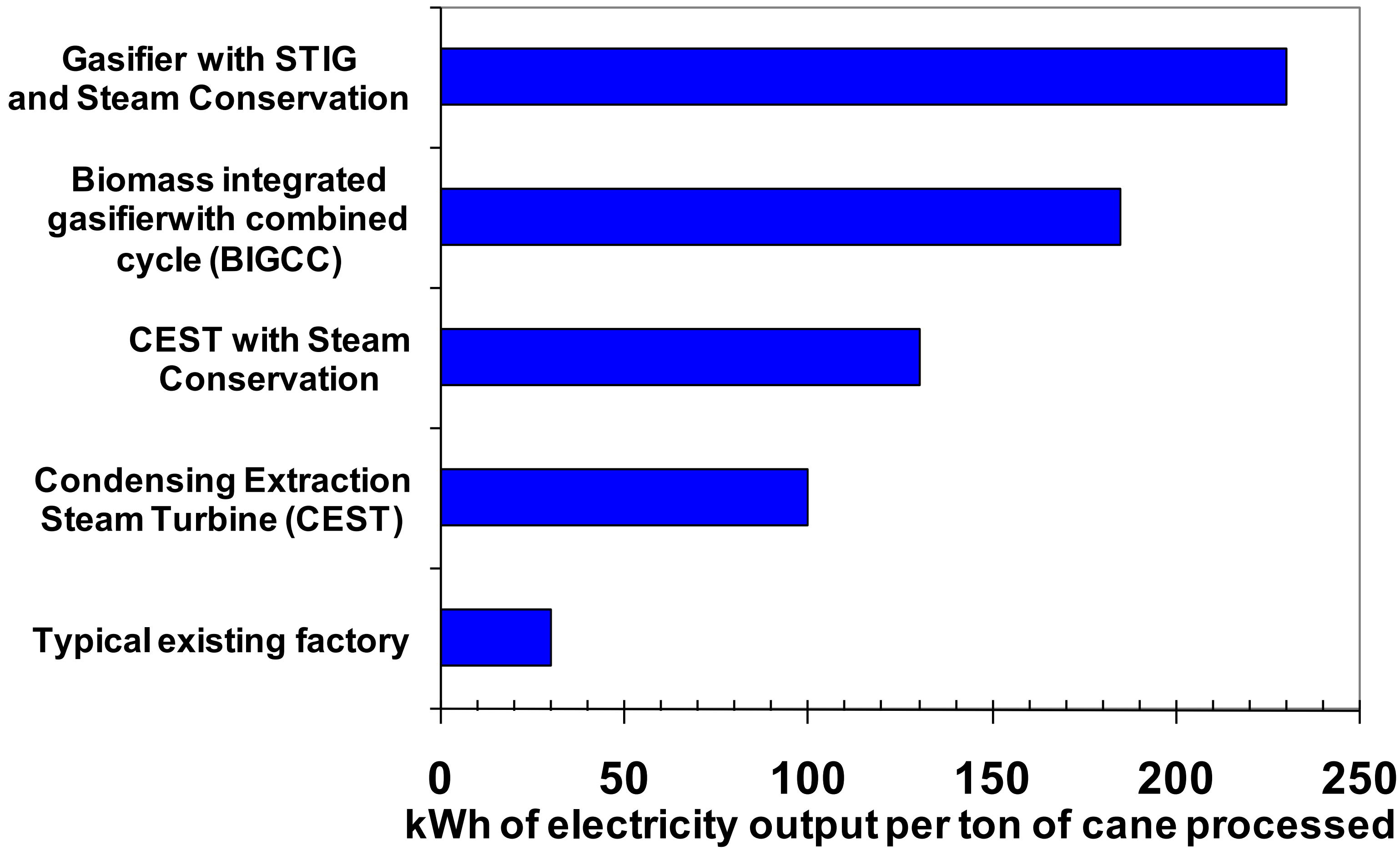
Sugarcane industry

- Sugar refineries require both heat and electricity, and have access to substantial amounts of biomass residue
- Today this residue is used to produce on average 30 kWh of electricity per tonne, but the potential is 180-230 kWh/t with biomass gasification/combined cycle
- The potential is at least 500 kWh/t if residues on the field, which are currently largely burned off in Brazil, are also used

Palm oil industry

- Currently produces 25-40 kWh per tonne of fresh fruit bunch that is processed, using a back-pressure steam turbine
- Could produce 75-160 kWh/t with alternative steam turbines, presumably close to 200 kWh/t with gasification/combined cycle

Figure 4.29 Electricity from Sugar Cane



Source: Modified from Kammen et al (2001, *Clean Energy for Development and Economic Growth: Biomass and Other Renewable Energy Options to Meet Energy Development Needs in Poor Nations*, Policy Discussion Paper)

Note: In the preceding, I am not talking about making ethanol for sugarcane or biodiesel from palm oil. Rather, I am talking about the production of heat in the processing of these plants into products (sugar and vegetable oil). For reasons to be elaborated upon later, I do not consider ethanol or biodiesel to be environmentally acceptable uses of biomass, and economics seems to be about to kill them anyway.

Environmental Issues

- Soil fertility and productivity
- Water use
- Use of fertilizers, herbicides, and pesticides
- Atmospheric and water pollutant emissions (biomass production, processing, and end use)
- Genetically-modified organisms

Environmental Issues (continued)

- Removal of heavy metals from soils
- Utilization of ash and separation of heavy metals
- Opportunities to treat municipal waste
- Impact on erosion
- Impact on biodiversity
- Indoor air pollution
- Employment and rural poverty

Emissions associated with production and use of ethanol

- Burning of sugarcane fields (still occurs)
- Greater risk of corrosion of tanks with ethanol-gasoline mixtures, increased solubility of petroleum contaminants
- No clear benefit compared to gasoline in terms of tailpipe emissions

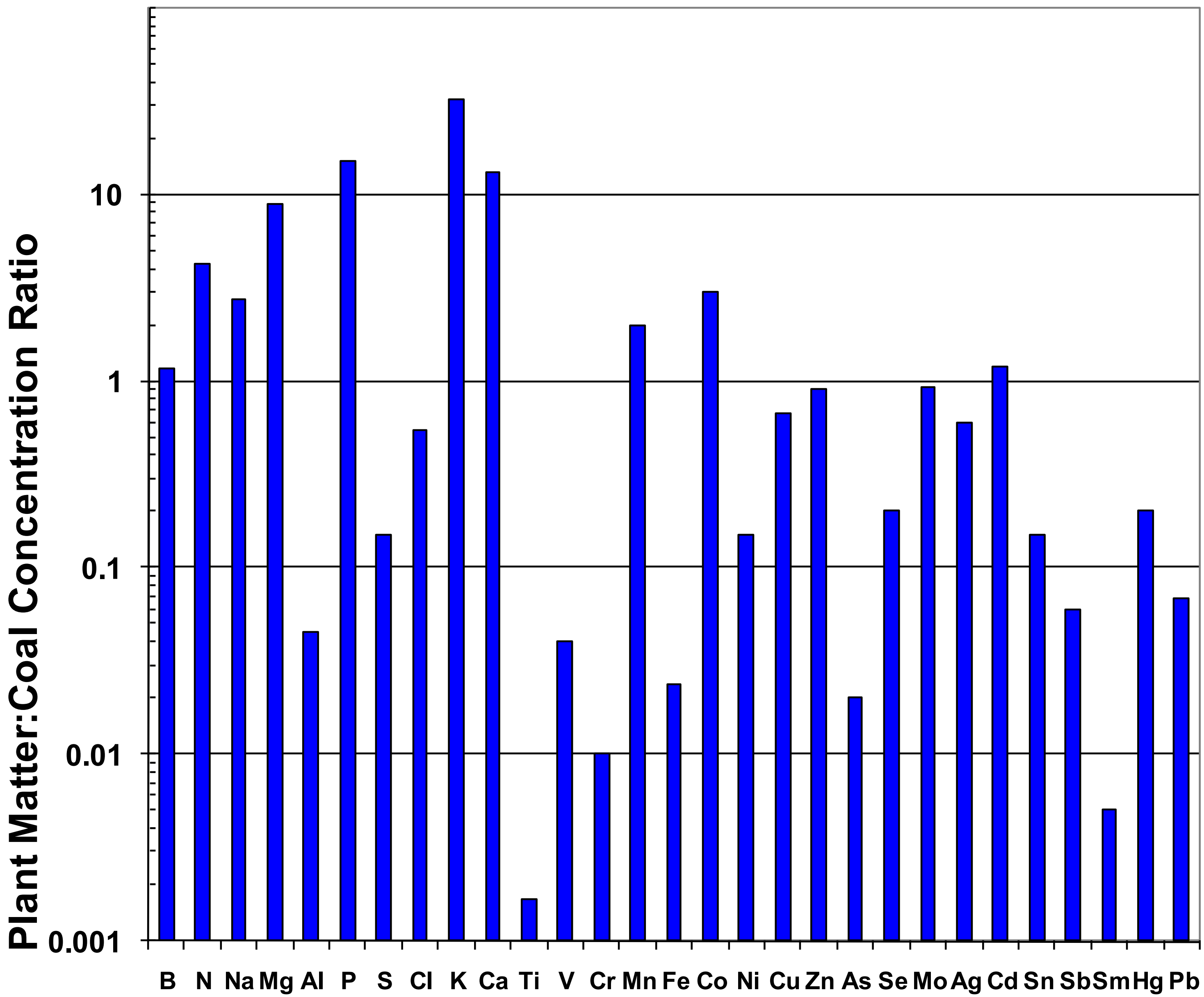
Figure 4.30 Smoke plumes from sugarcane plantations in Brazil that are burned prior to manual harvesting

Source: Howarth and Bringezu (2009, *Biofuels: Environmental Consequences and Interactions with Changing Land Use*), photo by Edmar Mazzi

Emissions associated with combustion for heat and/or power

- Depend on element ratios in the fuel
- Depend on total fuel requirements
- Depend on conversion technologies used

Figure 4.31 Dry matter to coal element ratios



BIGCC vs Coal for Electricity Generation

Table 4.16 Comparison of pollutant emissions (gm/kWh) and CO_2 emissions (gmC/kWh) associated with BIGCC using short-rotation willow fuel, and associated with coal powerplants.

	Willow-BIGCC				Coal Powerplant	
	Crop Production	Crop Transport	Power-plant	Total	Pulverized Coal	IGCC
SO_2	0.024	0.001	0.071	0.096	0.38	0.2
NO_x	0.267	0.006	0.214	0.487	90.3	0.64
Dust	0.029	0.000	0.029	0.057	0.05	0.07
CO	0.267	0.006	0.290	0.563		
HC	0.057	0.002		0.059		
CO_2	5.85	0.55		6.40	222	217

Source: Faaij et al (1998, *Biomass and Bioenergy* 14,125–147, http://www.sciencedirect.com/science/journal/09619534)

Removal of heavy metals from soil and separation from flue gas

- Soils in polluted areas tend to have high concentrations of heavy metals, which are absorbed by the plants
- Heavy metal concentrations are higher in wood chips and bark than in straw or cereals
- Ash can be separated into 4 different fractions, and most of the heavy metals end up in a small fraction of the total ash
- The majority of plant nutrients occur in the ash fractions that have minimal concentrations of heavy metals, so these ash fractions can be returned to the soil

Figure 4.33 Distribution of wastewater for the irrigation and fertilization of a willow plantation in Sweden

Source: P. Aronsson

Figure 4.34 Sewage treatment plant (foreground), aeration pond (middle ground), and willow plantation at Enkoping, Sweden

Source: Photograph by P. Aronsson in Dimitriou and Aronsson (2003, *Unasylva* 56, 221, 47-50)

Impacts on biodiversity

- Positive if short-rotation forestry and grasses replace agricultural crops
- Negative if large-scale clearing of tropical forests for soybeans of palm oil, or clearing of the *cerrado* for sugarcane or soybeans, occurs

Figure 4.35 The Brazilian *cerrado*, potential land for soybean and sugarcane cultivation and home to > 900 species of birds and 300 species of mammals, many threatened with extinction

Source: (C) by Luiz Claudio Marigo/naturepl.com

Global warming impact of biomass for cooking compared to natural gas

- Combustion of solid biomass in various kinds of stove emits CO and NMHCs (which produce ozone), and CH_4 and N_2O (which are GHGs)
- The global warming effect of these emissions (excluding CO_2, which is a valid exclusion if the biomass is produced sustainably) is several times that of the CO_2 released from the combustion of natural gas, as seen in the next figure
- **Thus, dirty use of renewable biomass for cooking has a greater global warming effect than use of clean-burning natural gas**

The key parameter of interest is the
Energy Return Over Energy Invested (EROEI)

This is the ratio of the energy value of the biofuel and any co-products produced from the biomass, to the total energy input. It should be substantially > 1 if producing the biofuel is to be worthwhile

Energy Inputs to be considered during the production of biofuel feedstocks

- Energy to make fertilizers, herbicides, and pesticides
- Energy to produce seeds
- Energy for irrigation
- Energy used by farm machinery (for soil preparation, seeding, harvesting)
- Energy used to make the farm machinery
- Energy for drying prior to transportation

Energy used during the processing of feedstocks into biofuels

- Transportation of biomass inputs and of solid wastes
- Energy used to manufacture the processing facility
- Energy used by the processing facility (some of it coal or natural gas)
- Energy used to supply and treat water

Figure 4.39 A 450 million litre-per-year corn ethanol plant in South Dakota

Many facilities like this one in the US use coal as an energy input, and others use natural gas to power the conversion of the biomass into ethanol

Source: Tollefson (2008, *Nature* 451, 880–883)

Some EROEIs for biofuels

- Ethanol from corn: 1.0-2.0
- Ethanol from sugarcane in Brazil: 10 today, 20-40 in the future with production of electricity from crop residues
- Ethanol from woody crops: 5-7 projected (the process is still under development)

The future EROEIs for sugarcane and woody crop require use of crop residues to generate electricity (rather than being returned to the soil). This might not be sustainable.

Impact of the production and use of biofuels on GHG emissions

- The avoided emissions are the emissions associated with the production and use of the fuels (gasoline and diesel) that the biofuels replace
- The *direct* emissions are the emissions of CO_2 from the fossil fuels used in the production of biofuels (substantial coal or natural gas in the case of corn ethanol) and emissions of N_2O from the application of N fertilizers
- There are additional *indirect* emissions due to clearing of forests or peatland in order to establish palm oil plantations, or deforestation in the Amazon due to crops displaced by new sugarcane plantations, or changes in land use due to induced changes in the prices of agricultural commodities (in the case of corn ethanol, for example)

Indirect effect on GHG emissions through induced changes in land use when land formerly used for food or pasture is converted to biofuel production

- If corn is devoted to ethanol production, more soybean feed is needed for animals, so the price of soybeans goes up, which encourages expansion of soybean plantations into tropical rainforests
- One assessment with a model of the global agricultural economy predicts that replacement of gasoline with US corn-ethanol *increases* GHG emissions by 100%, rather than reducing them by 20%!

GHG debt incurred when grassland, tropical forests, or tropical peatland are converted to biofuels production (Table 4.28)

Original land type	Crop and biofuel	Initial debt (tC/ha)	Portion of debt assigned to biofuels	Time required to pay back initial debt (years)
Indonesian and Malaysian peatland	palm oil biodiesel	941	87%	423
Indonesian and Malaysian lowland tropical forest	palm oil biodiesel	191	87%	86
Brazilian Amazon	soybean biodiesel	201	39%	319
Brazilian cerrado	soybean biodiesel	23	39%	37
Brazilian cerrado	sugarcane ethanol	45	100%	17
US central grassland	corn ethanol	37	83%	93
US abandoned farmland	corn ethanol	19	83%	48

Source: Fargione et al (2008, *Science* 319, 1235–1238)

There is a second, just recently-recognized indirect effect: Production of biofuels reduces the demand for oil and hence its price, leading to a rebound in demand that partly offsets the savings in GHG emissions from the use of biofuels. To fix this, taxes would need to be raised on oil to prevent its price from falling as demand decreases.

EROEI for the use of solid biomass fuels for heating

EROEI for combustion use of solid biomass, accounting for production and transportation of the biomass fuels:

- Willow in New York state: 36-48 (Table 4.29)
- Willow pellets in Norway: 167 (Table 4.31)
- Switchgrass pellets in Canada: 15 (Table 4.35)
- Napier grass in Brazil: 2.6-5.2 (Table 4.36)

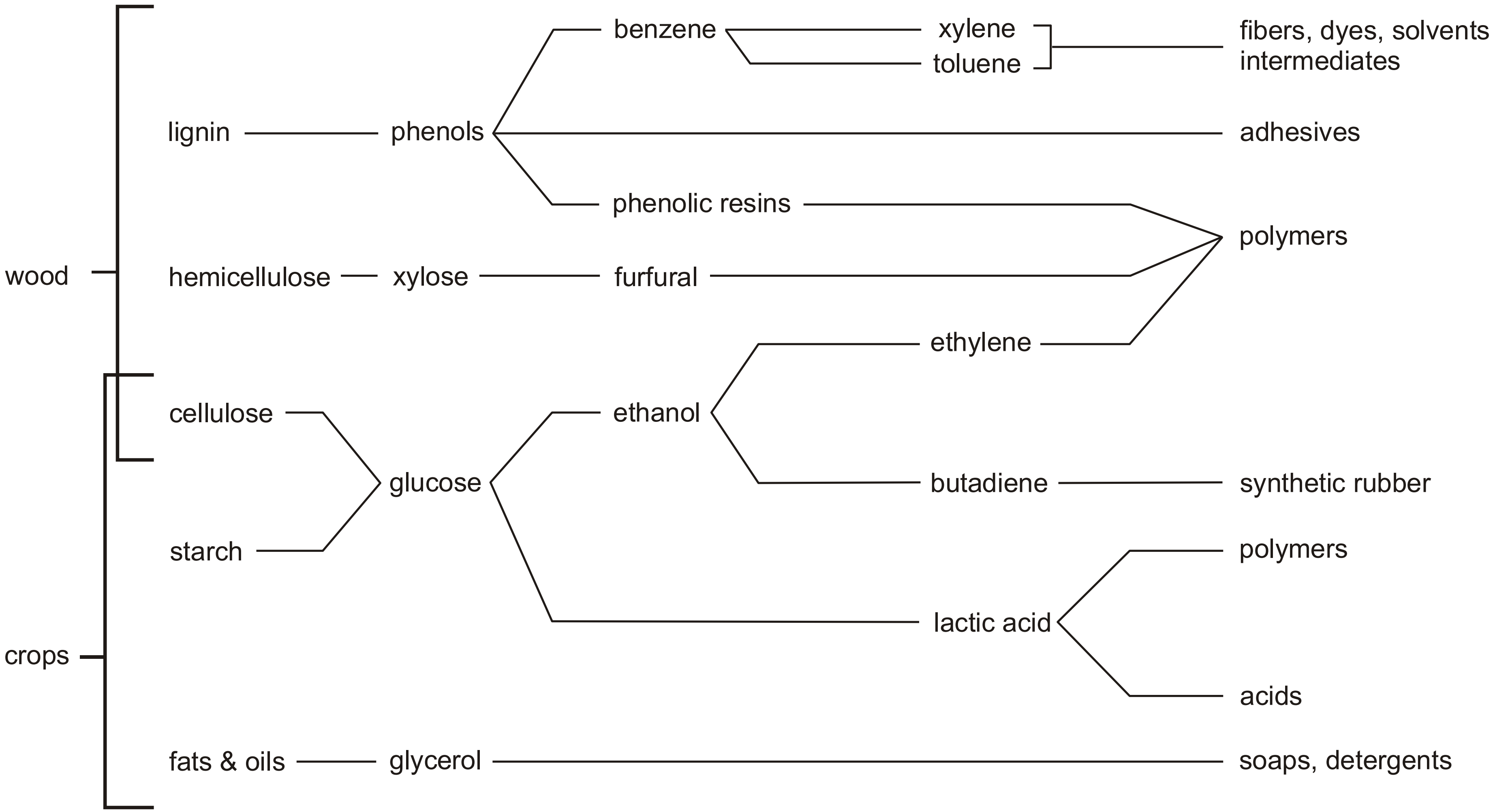
Biomass supply to Europe (Table 4.33)

Biomass Location	Biomass Source	Transport Mode	Distance	Biomass loss GJ/tonne$_{dry}$	Energy Input delivered	EROEI
Scandinavia	Forestry residues	Chips by ship	1100 km	1.6	1.6	12.6
Scandinavia	Forestry residues	Chips by trains	1100 km	1.6	4.6	4.3
Scandinavia	Forestry residues	Pellets by ship	1100 km	0.5	1.2	16.7
Scandinavia	Forestry residues	Pellets by train	1100 km	0.5	2.5	8.0
E Europe	Short-rotation willow coppice	Pellets by ship	2000 km	0.1	1.0	9.4
Latin America	Eucalyptus plantation	Pellets by ship	11500 km	0.4	1.4	14.1

Source: Hamelinck et al (2005, *Biomass and Energy* 29, 114–134, http://www.sciencedirect.com/science/journal/09619534)

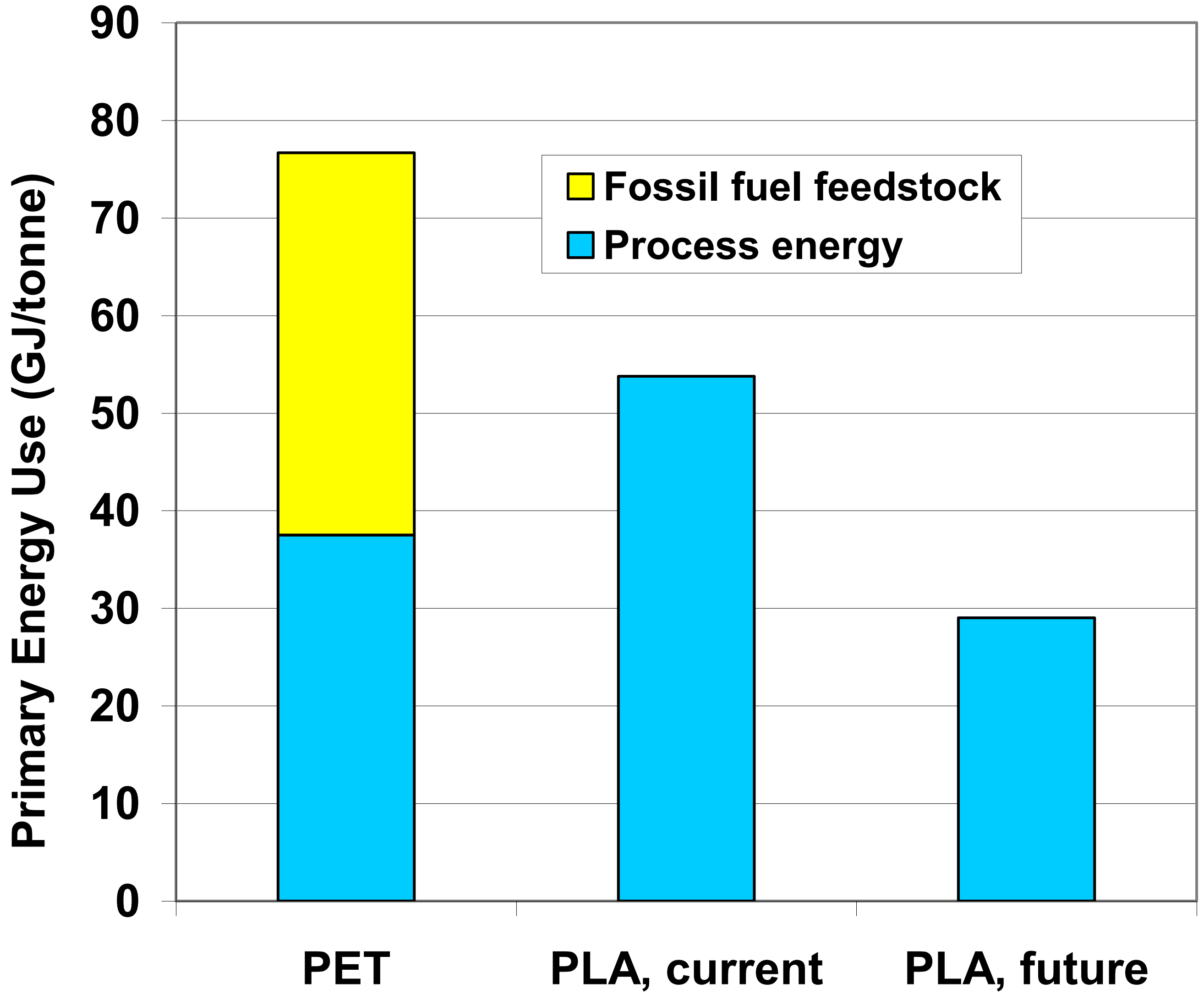
Biomaterials

Figure 4.44 Principle routes for the synthesis of organic chemicals from biomass feedstocks



Source: Geiser (2001, *Materials Matter: Towards a Sustainable Materials Policy*, MIT Press, Cambridge)

Figure 4.45 Energy requirements to produce PET (from petroleum) and PLA (from biomass)



Source: Detzel et al (2006, in *Renewables-Based Technology*, John Wiley and Sons, Chichester)

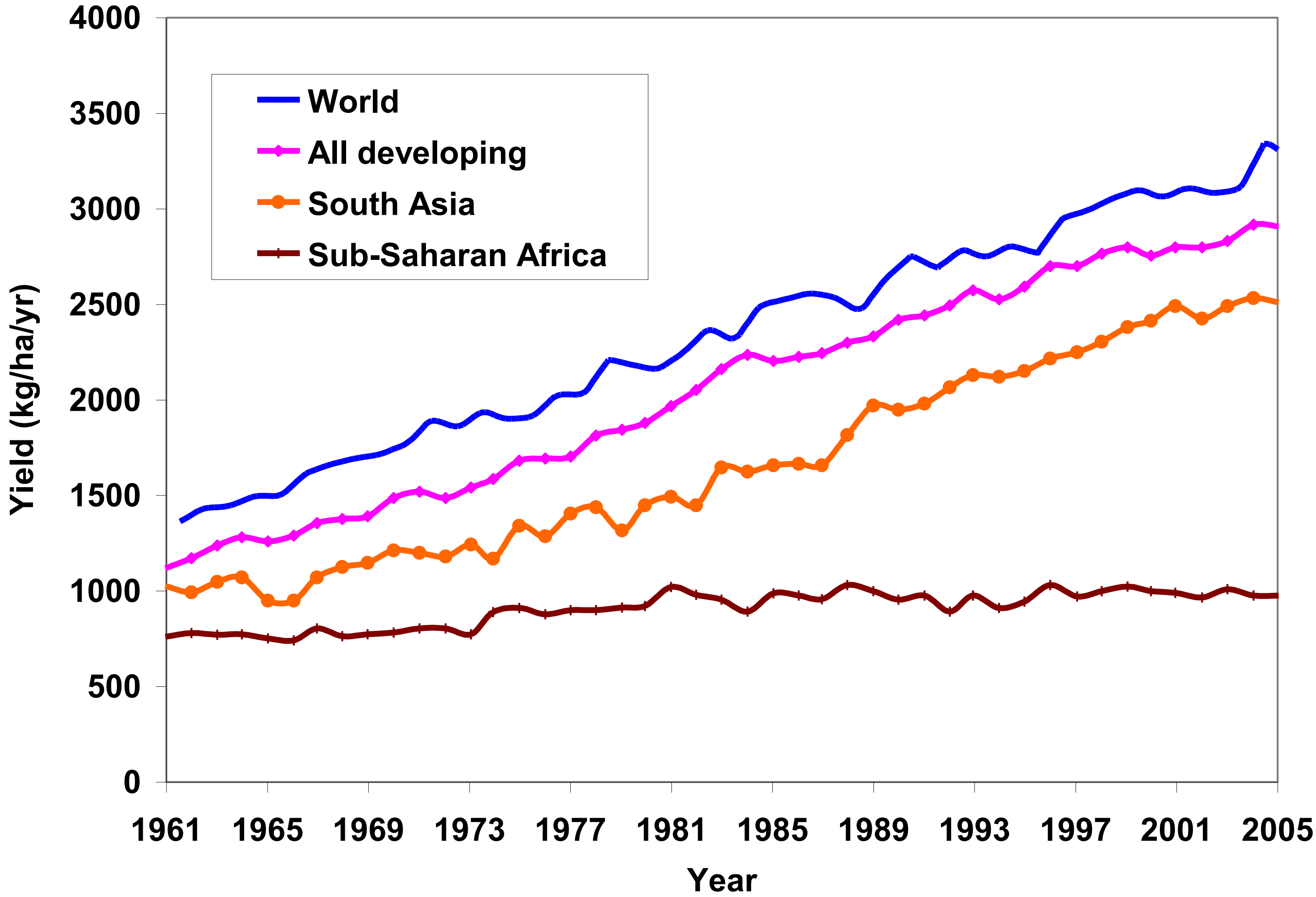
Future biomass potential from plantations

- Depends on the available land area for plantations
- Depends on the productivity (biomass/hectare/year) of the plantation

Assuming no expansion of current agricultural and pasture land areas, the only land available for plantations will be surplus agricultural and pasture land. Whether there is any surplus in the future, and how much, depends on

- Human population
- Phytomass requirements per person
- Productivity of agricultural land and of pastureland

Figure 4.46 Trend in grain yield averaged over various regions



Source: Hazell and Wood (2008, *Phil. Trans. Royal Soc. B*, 363, pp495–515)

Large increases in the productivity (food/area) of agricultural lands are projected

Table 4.43 Projected ratio of agricultural yields in 2050 compared to 1998 according to a range of scenarios, in the absence of increasing CO_2 and climatic change.

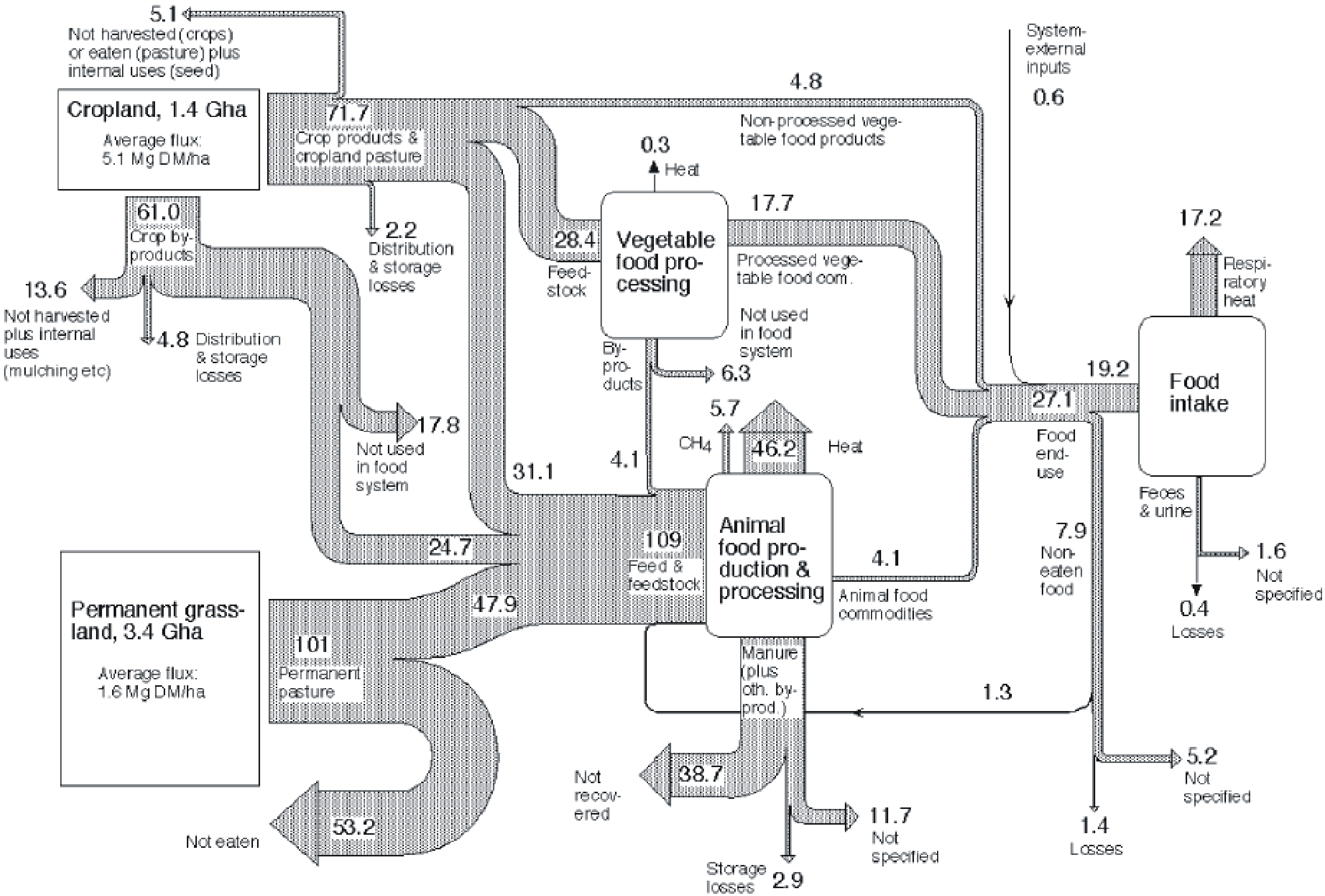
Region	Yield Ratio
North America	1.6-3.2
Western Europe	0.9-1.9
Eastern Europe	2.1-4.1
Former Soviet Union	3.2-6.7
Japan	2.7-3.0
East Asia	2.3-3.2
South Asia	3.7-5.6
Oceania	2.4-4.6
Sub-Saharan Africa	5.6-7.7
Caribbean and Latin America	2.8-4.5
World	**2.9-4.6**

Source: Worldwatch Institute (2006, *Biofuels for Transportation: Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century*)

Phytomass requirements per person depend on

- Proportion of meat in the diet, and
- Inverse feed efficiency for production of animal meat (kg phytomass per kg of meat produced)

Recap of Volume 1 Figure 7.12: Phytomass energy flows in the world food system.



Source: Wirsenius (2003, *Journal of Industrial Ecology* 7, 47–80)

From the preceding slide, it can be seen that:

- The efficiency in producing animal food products for human consumption is about 4% (4.1/109)
- The efficiency in producing processed plant food products (i.e., bread) is about 60% (17.7/28.4)
- The efficiency in consuming raw plant foods is 100% (neglecting peeling waste)

From Table 4.45: Amount of phytomass (in terms of its energy value) needed to produce 1 kg of food product or 1 kg of protein for human consumption

	kg phytomass per kg of wet animal product	MJ phytomass per MJ of animal product	MJ phytomass per kg of animal protein
Lamb	79	142	6823
Bovine meat	45	80	4597
Pork	6.7	13	950
Poultry	3.6	12	287
Milk	1.6	11	894
Eggs	3.6	11	590
Plant food, mid protein	1	1	146
Plant food, high protein	1	1	73

Big increases in the yield of bioenergy crops are projected

Table 4.49 Current and projected future yields of switchgrass in different regions of the US, assuming no change in climate

Region	Yield in 2000 (dry tonne/ha/yr)	Projected Yield (dry tonne/ha/yr)	
		2025	2050
Northern Plains	7.8	10.2	13.2
Southern Plains	9.7	19.8	31.9
Great Lakes & Northeast	10.8	14.3	18.4
Corn Belt	13.4	21.9	31.9
Appalachia	13.1	26.9	43.3

Source: Larson (2006, *Energy for Sustainable Development* 10, 109–126

Solid fuel and bio-electricity Costs

- Cost of solid fuels: typically \$2-4/GJ, vs \$2-3/GJ for coal at present
- Costs of liquid fuels from biomass: generally less than \$1/litre
- Capital costs of powerplants using biomass: \$2000-4000/kW, vs \$600-900/kW for natural gas powerplants (but natural gas is likely to be expensive in the long run) and \$1200-1600/kW for coal powerplants without CO_2 capture)
- Cost of electricity from biomass at \$2/GJ: 7-13 cents/kWh