Econ674

Economics of Natural Resources and the Environment

Session 12

Dimensions of Renewable and Alternative Storage and Conversion Technologies

Renewable Natural Resource Technologies

As noted previously, renewable natural resources are those that within a given positive rate horizon can be renewed. Solar energy is the underlying source, which in turn affects the level of photosynthesis in plants, and the magnitude of wind, solar, and tidal energy. We include in this category also the role of geothermal and hydro technologies as they also are affected by solar energy radiation.

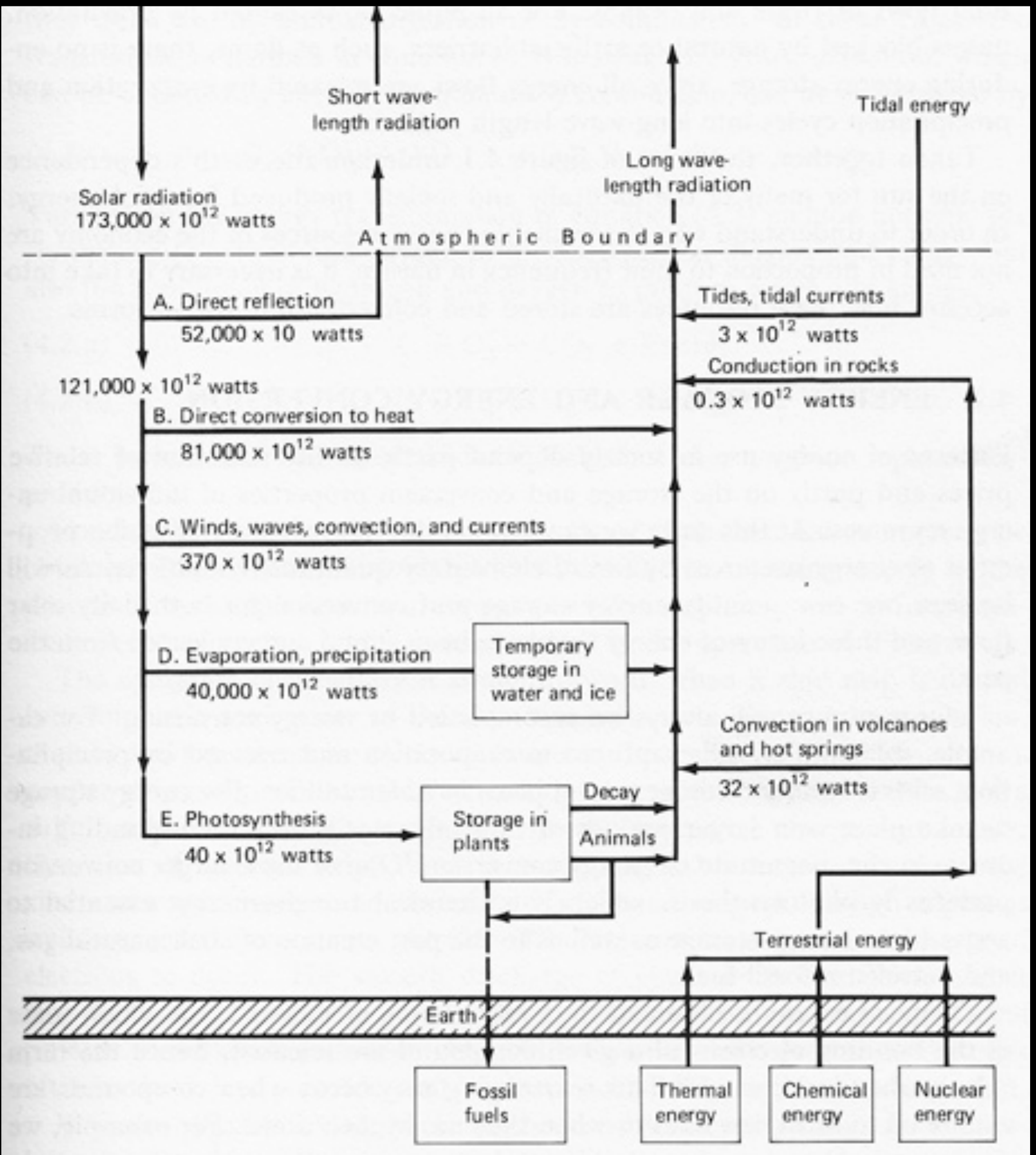


Figure 4.1. The Earth's Energy Flows. Adapted from M. King Hubbert, *Energy Resources* (Washington, D.C.: National Academy of Sciences, National Resources Council, 1962), reprinted in idem, "The Energy Resources of the Earth," *Scientific American* 224 (September 1971): 60–70.

Water Resources

From the earth's hydrological cycle, we focus on three dimensions of a key natural resource, namely, water. Rainfall is critical to agriculture, to human settlement densities, to the availability of hydropower mechanical and electrical energy, as well as to common property fishing resources. Rainfall also is erratic in many parts of the world, and the variability of rainfall subjects populations to periodic drought in agricultural crops, as well as the risk of famine for some populations. How accumulated stocks of water are used depends in part on the technology of accumulation, purification, and the disposal of waste products from human activity. Since only a fraction of the world's accumulated stocks of water are potable, how water is priced ultimately has a significant bearing on economic and environmental efficiency.

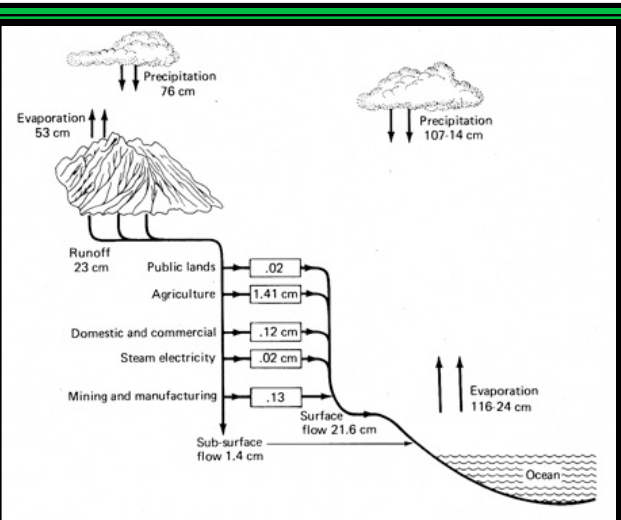
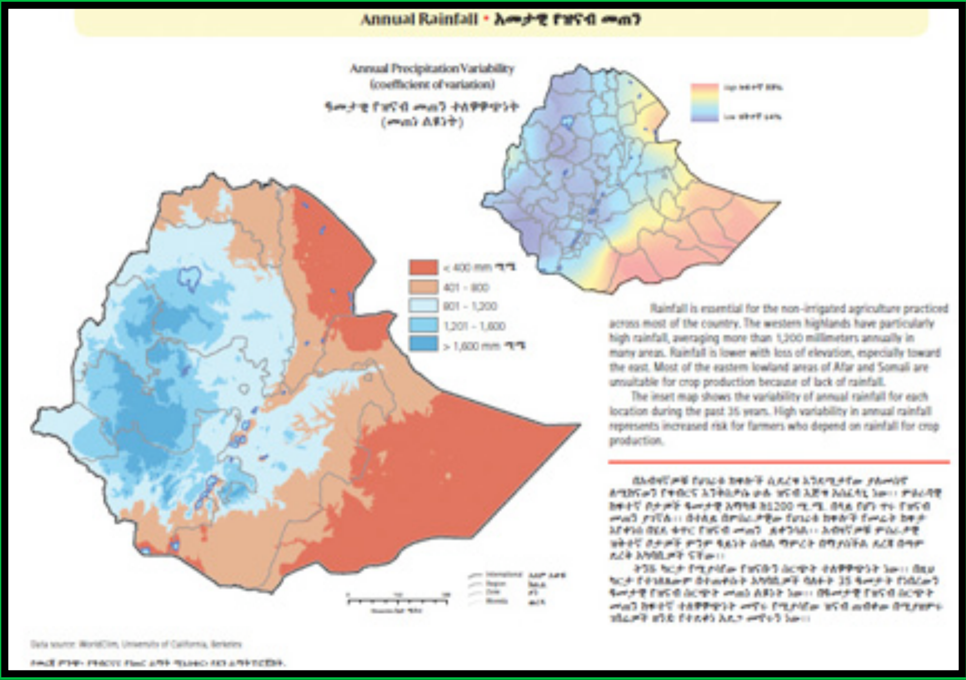


Figure 7.1. Average Annual Water Rates for the Contiguous United States. Data from U.S. Water Resources Council, *The Nation's Water Resources* (Washington, D.C.: U.S. Government Printing Office, 1968).



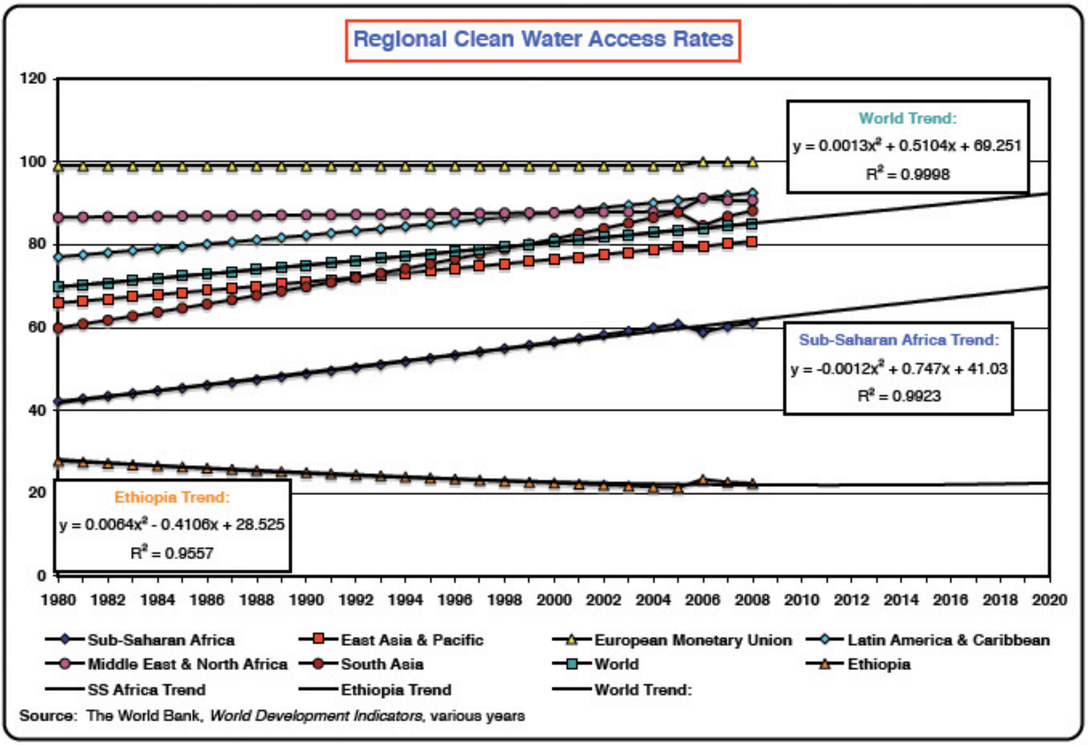
Rainfall is essential for the non-irrigated agriculture practiced across most of the country. The western highlands have particularly high rainfall, averaging more than 1,200 millimeters annually in many areas. Rainfall is lower with loss of elevation, especially toward the east. Most of the eastern lowland areas of Afar and Somali are unsuitable for crop production because of lack of rainfall.

The inset map shows the variability of annual rainfall for each location during the past 35 years. High variability in annual rainfall represents increased risk for farmers who depend on rainfall for crop production.

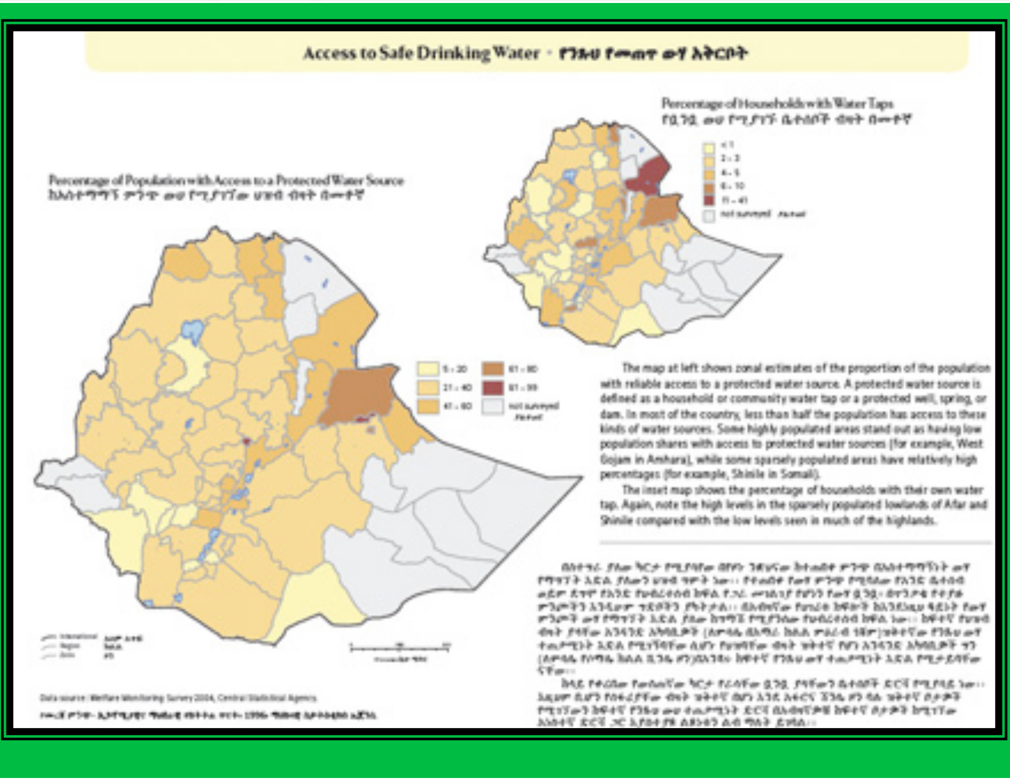
Data source: WorldClim, University of California, Berkeley

Clean Water Access Rates

As population growth expands, unless offset by energy efficient technologies, access rates to clean potable water may not expand, and may even decline. Much of the failure to improve clean water access rates can be traced to the absence of clearly defined and judicially enforced property rights, with the result that populations may remain at rising levels of health risks.



Source: The World Bank, *World Development Indicators*, various years



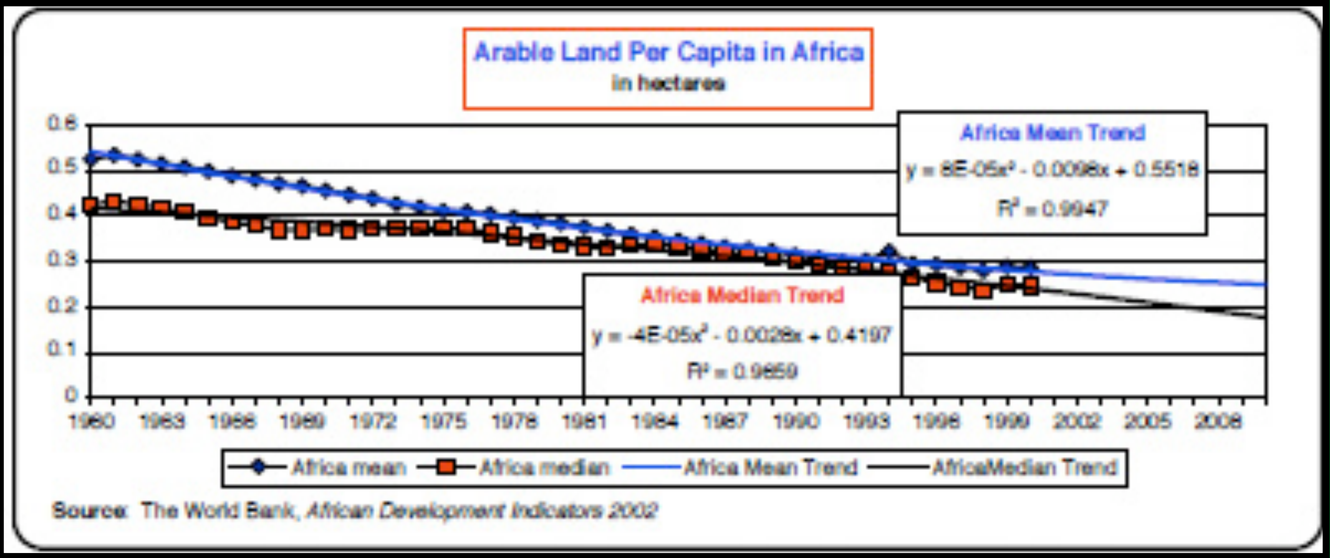
The map at left shows zonal estimates of the proportion of the population with reliable access to a protected water source. A protected water source is defined as a household or community water tap or a protected well, spring, or dam. In most of the country, less than half the population has access to these kinds of water sources. Some highly populated areas stand out as having low population shares with access to protected water sources (for example, West Gojam in Amhara), while some sparsely populated areas have relatively high percentages (for example, Shinile in Somali).

The inset map shows the percentage of households with their own water tap. Again, note the high levels in the sparsely populated lowlands of Afar and Shinile compared with the low levels seen in much of the highlands.

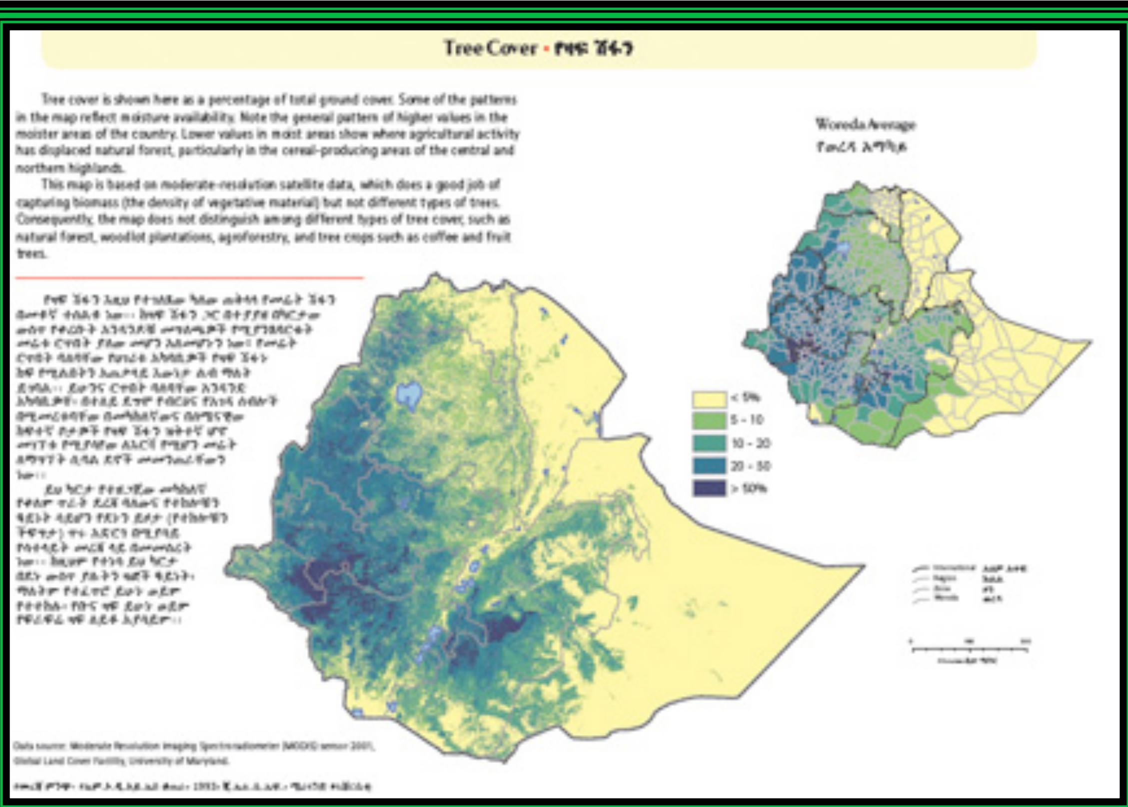
Data source: Welfare Monitoring Survey 2004, Central Statistical Agency.

Climatic Dimensions in Natural Resource Decisions

The level and variability of rainfall has a critical impact on agriculture. Terracing, fertilizer additions, seed multiplication and genetic modification, and the use of irrigated systems can maintain productivity, but the net gain in terms of energy use may not be as great as it appears, once one considers the cost of these innovations. In turn, yields may be affected as deforestation expands and the amount of arable land declines as conversion proceeds to accommodate larger population levels.



Source: The World Bank, *African Development Indicators 2002*

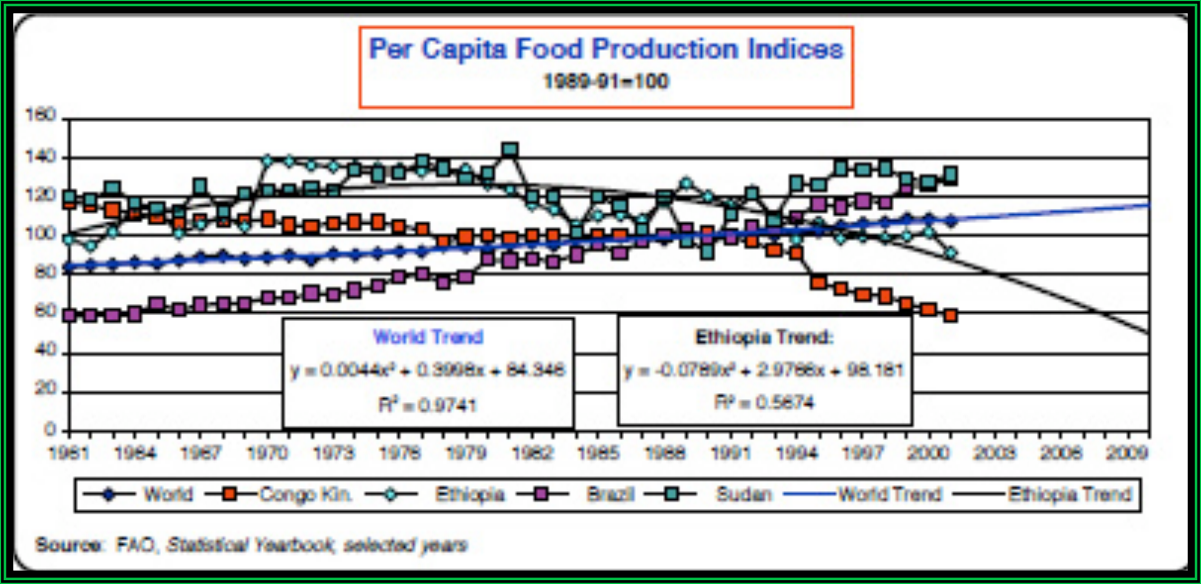


Tree cover is shown here as a percentage of total ground cover. Some of the patterns in the map reflect moisture availability. Note the general pattern of higher values in the moister areas of the country. Lower values in moist areas show where agricultural activity has displaced natural forest, particularly in the cereal-producing areas of the central and northern highlands.

This map is based on moderate-resolution satellite data, which does a good job of capturing biomass (the density of vegetative material) but not different types of trees. Consequently, the map does not distinguish among different types of tree cover, such as natural forest, woodlot plantations, agroforestry, and tree crops such as coffee and fruit trees.

Data source: Moderate Resolution Imaging Spectroradiometer (MODIS) sensor 2001, Global Land Cover Facility, University of Maryland.

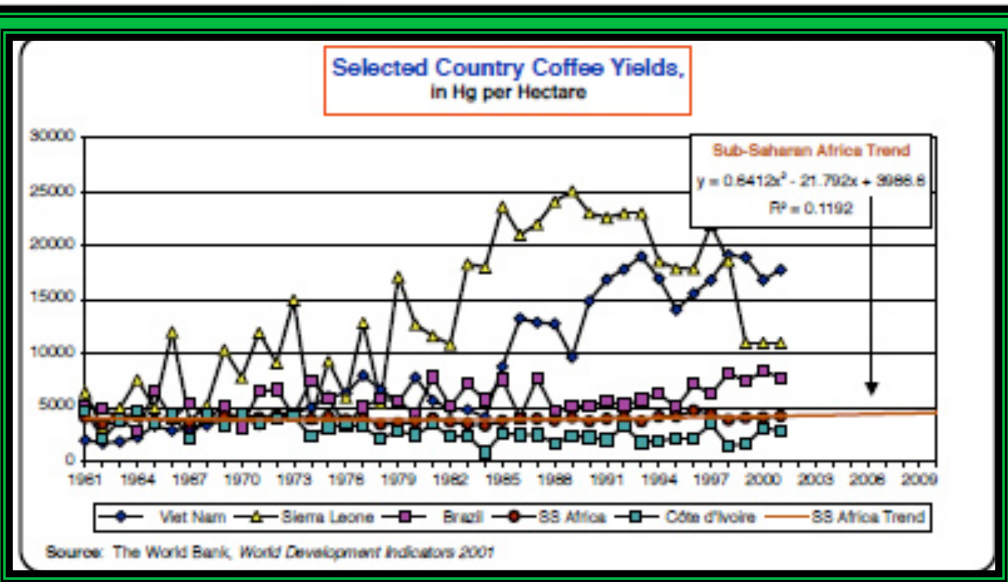
Comparative Agricultural Yields



Per Capita Food Production Indices

1989-91=100

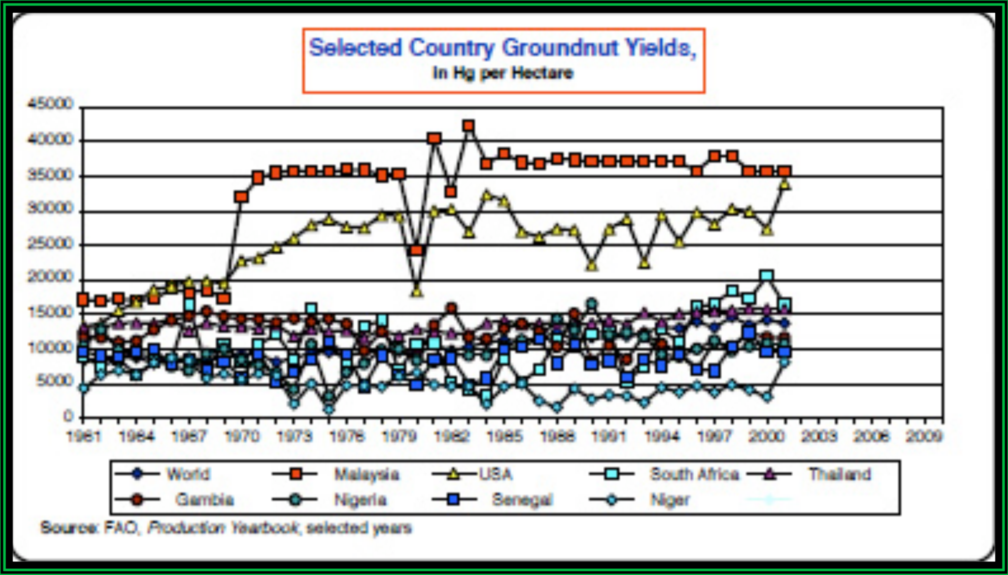
Source: FAO, *Statistical Yearbook, selected years*



Selected Country Coffee Yields,

in Hg per Hectare

Source: The World Bank, *World Development Indicators 2001*

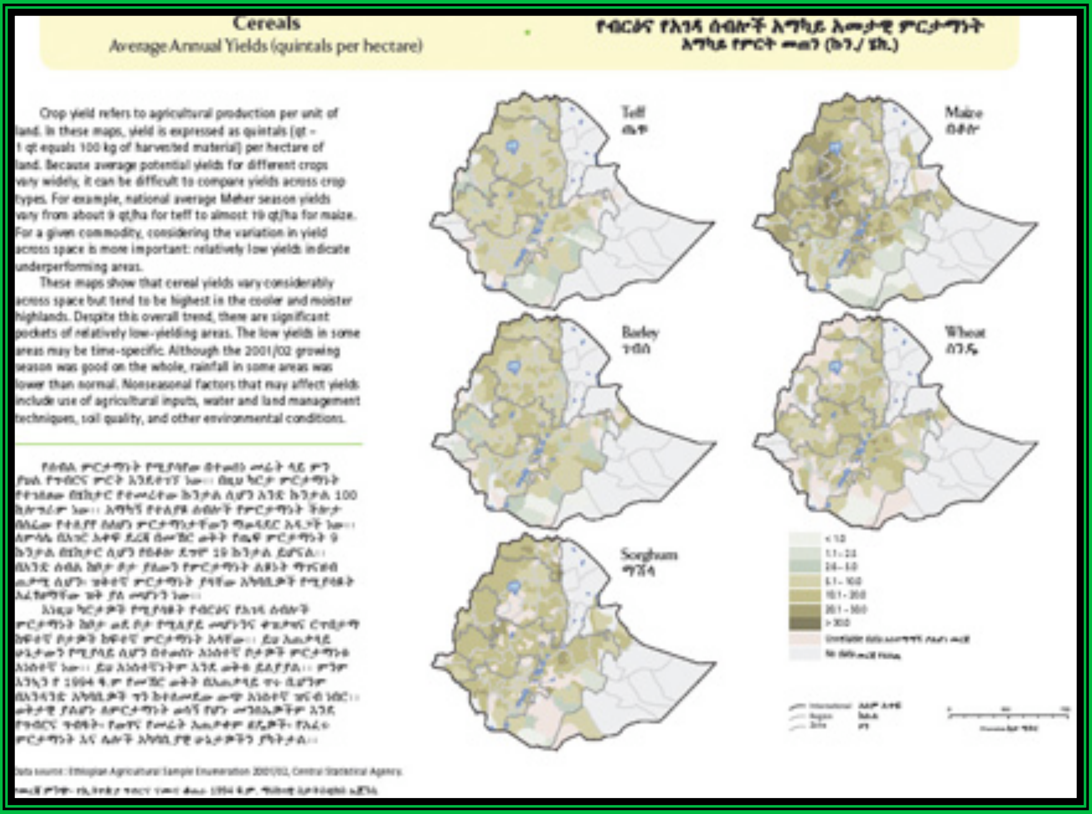


Selected Country Groundnut Yields,

in Hg per Hectare

Source: FAO, *Production Yearbook*, selected years

Cereal Yields in Ethiopia



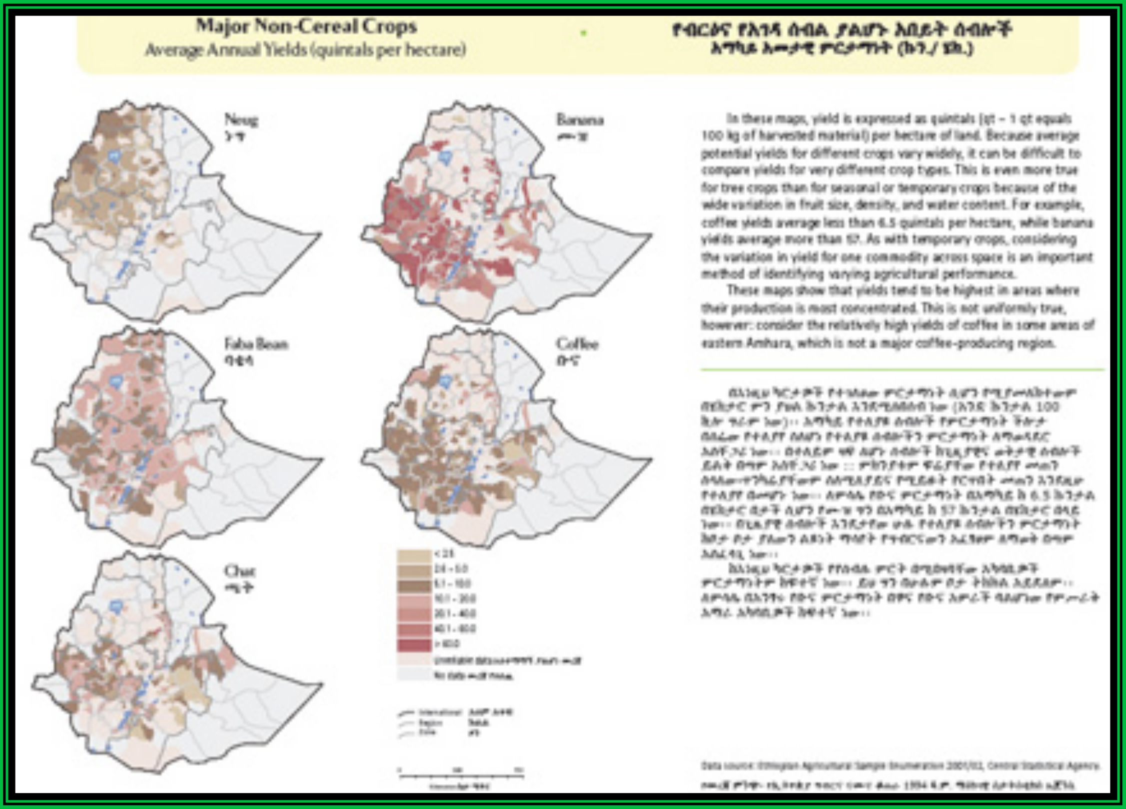
Cereals

Average Annual Yields (quintals per hectare)

Crop yield refers to agricultural production per unit of land. In these maps, yield is expressed as quintals (qt – 1 qt equals 100 kg of harvested material) per hectare of land. Because average potential yields for different crops vary widely, it can be difficult to compare yields across crop types. For example, national average Meher season yields vary from about 9 qt/ha for teff to almost 19 qt/ha for maize. For a given commodity, considering the variation in yield across space is more important: relatively low yields indicate underperforming areas.

These maps show that cereal yields vary considerably across space but tend to be highest in the cooler and moister highlands. Despite this overall trend, there are significant pockets of relatively low-yielding areas. The low yields in some areas may be time-specific. Although the 2001/02 growing season was good on the whole, rainfall in some areas was lower than normal. Nonseasonal factors that may affect yields include use of agricultural inputs, water and land management techniques, soil quality, and other environmental conditions.

Data source: Ethiopian Agricultural Sample Enumeration 2001/02, Central Statistical Agency.



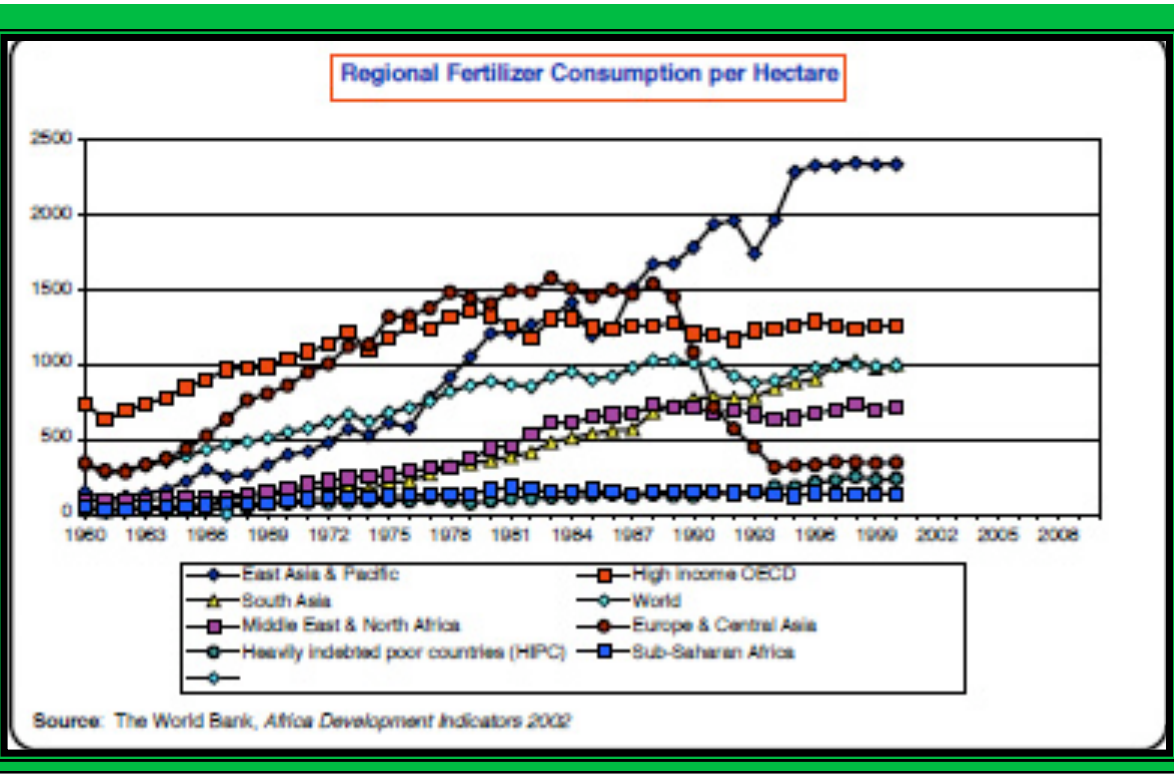
Major Non-Cereal Crops

Average Annual Yields (quintals per hectare)

In these maps, yield is expressed as quintals (qt – 1 qt equals 100 kg of harvested material) per hectare of land. Because average potential yields for different crops vary widely, it can be difficult to compare yields for very different crop types. This is even more true for tree crops than for seasonal or temporary crops because of the wide variation in fruit size, density, and water content. For example, coffee yields average less than 6.5 quintals per hectare, while banana yields average more than 57. As with temporary crops, considering the variation in yield for one commodity across space is an important method of identifying varying agricultural performance.

These maps show that yields tend to be highest in areas where their production is most concentrated. This is not uniformly true, however: consider the relatively high yields of coffee in some areas of eastern Amhara, which is not a major coffee-producing region.

Data source: Ethiopian Agricultural Sample Enumeration 2001/02, Central Statistical Agency.


Regional Fertilizer Consumption per Hectare

Source: The World Bank, *Africa Development Indicators 2002*

Hydropower Technology

Beyond agriculture, water resources also are an alternative to the use of exhaustible fossil and nuclear resources in the generation of electricity. The potential of hydropower is determined by variations in the elevation of land over which water passes, how concentrated into rivers are those flows, and the density and variability of annual rainfall.

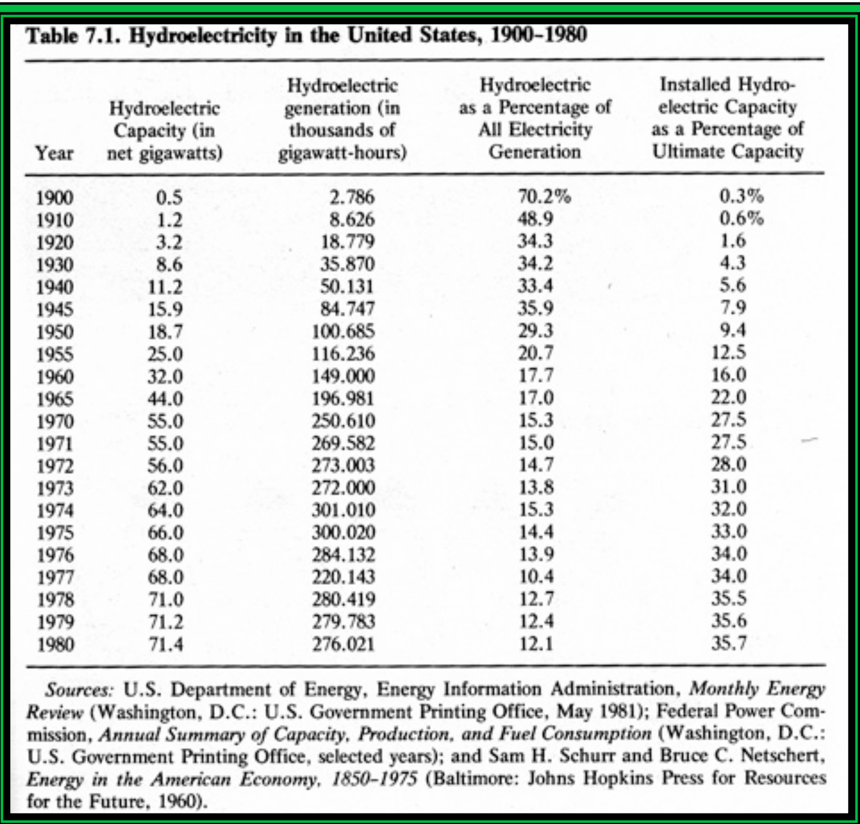


Table 7.1. Hydroelectricity in the United States, 1900–1980

Year	Hydroelectric Capacity (in net gigawatts)	Hydroelectric generation (in thousands of gigawatt-hours)	Hydroelectric as a Percentage of All Electricity Generation	Installed Hydro-electric Capacity as a Percentage of Ultimate Capacity
1900	0.5	2.786	70.2%	0.3%
1910	1.2	8.626	48.9	0.6%
1920	3.2	18.779	34.3	1.6
1930	8.6	35.870	34.2	4.3
1940	11.2	50.131	33.4	5.6
1945	15.9	84.747	35.9	7.9
1950	18.7	100.685	29.3	9.4
1955	25.0	116.236	20.7	12.5
1960	32.0	149.000	17.7	16.0
1965	44.0	196.981	17.0	22.0
1970	55.0	250.610	15.3	27.5
1971	55.0	269.582	15.0	27.5
1972	56.0	273.003	14.7	28.0
1973	62.0	272.000	13.8	31.0
1974	64.0	301.010	15.3	32.0
1975	66.0	300.020	14.4	33.0
1976	68.0	284.132	13.9	34.0
1977	68.0	220.143	10.4	34.0
1978	71.0	280.419	12.7	35.5
1979	71.2	279.783	12.4	35.6
1980	71.4	276.021	12.1	35.7

Sources: U.S. Department of Energy, Energy Information Administration, *Monthly Energy Review* (Washington, D.C.: U.S. Government Printing Office, May 1981); Federal Power Commission, *Annual Summary of Capacity, Production, and Fuel Consumption* (Washington, D.C.: U.S. Government Printing Office, selected years); and Sam H. Schurr and Bruce C. Netschert, *Energy in the American Economy, 1850–1975* (Baltimore: Johns Hopkins Press for Resources for the Future, 1960).

Solar Energy Technology

Solar energy technology utilizes direct radiation from the sun to provide space heating, the generation of steam that can be used to operate an electrical generating unit, or direct conversion of solar radiation into electricity. For the latter, much depends on the energy efficiency of semi-conductor materials used in the collection, concentration, and conversion of solar radiation into electrical charges.

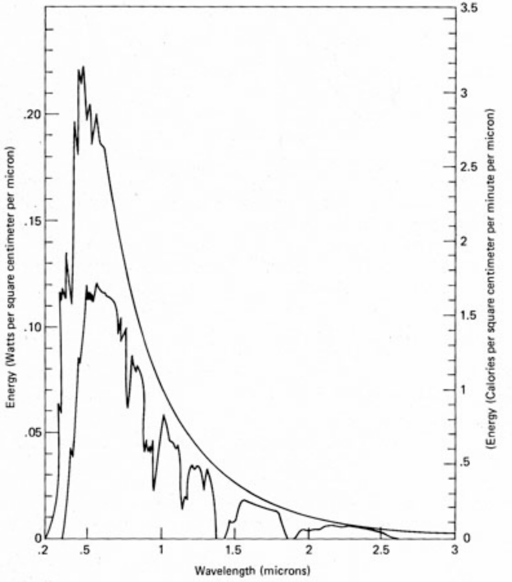


Figure 7.3. The Earth's Spectral Distribution of Solar Radiation. The outer distribution refers to solar radiation reaching the earth at the top of its atmosphere. The inner distribution refers to solar radiation reaching the ground, and takes into account the absorbing effects of water vapor, carbon dioxide, oxygen, nitrogen, ozone, and particles of dust. Data are based on a solar constant of 1.95 calories per square centimeter per minute. Adapted from D. M. Gates, "The Flow of Energy in the Biosphere," in *Energy and Power*, edited by the editors of *Scientific American* (San Francisco: W. H. Freeman and Co., 1971), p. 47; Farrington Daniels, *Direct Use of the Sun's Energy* (New York: Ballantine Books, 1974); and M. P. Thekaekara, "Data on Incident Solar Radiation," in *Solar Cells*, ed. Charles E. Backus (New York: IEEE Press, 1976), p. 3.

Calculating Solar Energy Potential

The potential level of solar energy in a given environment depends on the angle of the surface relative to the sun, and on the intensity of radiation as a function of latitude. For the United States, aggregate solar radiation arrives at an approximate rate of 1650×10^{12} watts. Allowing for seasonal and nocturnal variations, if solar radiation is released t this rate for only half of any average year, then the annual flow would provide the following total amount of energy:

$$E = 1650 \times 10^{12} \text{ watts} \times 8760 \text{ hours per year}/2$$
$$= 7.227 \times 10^{18} \text{ watt-hours.}$$

Since one watt-hour is equal to 3.413 Btu's, the theoretically available solar energy in the United States amounts to 2.4666×10^{19} Btu's, or 24,700 quads. This is over 300 times the amount of energy consumed from existing fossil, nuclear, and hydropower resources. For developing countries in more tropical climate zones, the ratio would be much higher.

Calculating Solar Heating Collector Requirements

Consider the storage capacity of a hot water tank. At 400 C, it can store up to1.67 x 10^5 joules (158.48 Btu's) of energy per kilogram. For a typical 140 square meter (1,500 square foot) residential structure, around 800 million joules (759,200 Btu's) of energy per day for space and water heating. If the residence uses a solar collector with an efficiency of 500 watts per square meter, then over the course of a seven-hour day, the energy per square meter of collector space would be be 3,500 watt-hours, or 12.6x10^6 joules. The collector space needed to sustain 100 percent of daily space and water heating is thus:

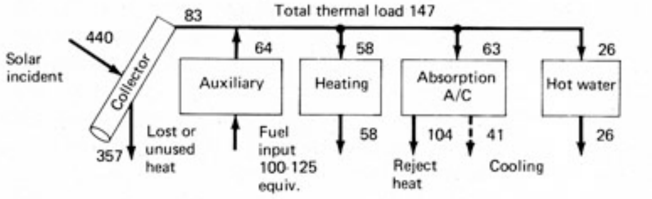
A = (8x10^8 joules of daily consumption)/(12.6x10^6joules/m^2/day)
= 63.49 m^2

The volume of water necessary to sustain daily energy consumption is obtained by dividing daily consumption b the thermal capacity of water. In the present case, the necessary water storage volume is:

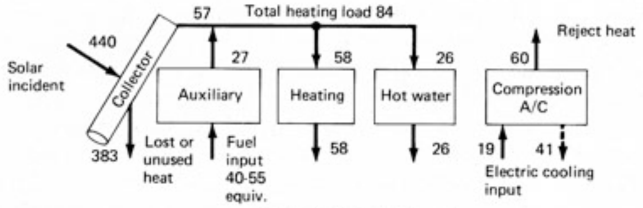
V = (8x10^8 joules of daily energy consumption)/(1.67x10^5 joules/kg of water storage)
= 4,790 kg = 4.79 cubic meters of water = 1,264 gallons of water.

The preceding can be expanded to allow for the infrequency of cloud-free sunny days, based on the underlying climate regime.

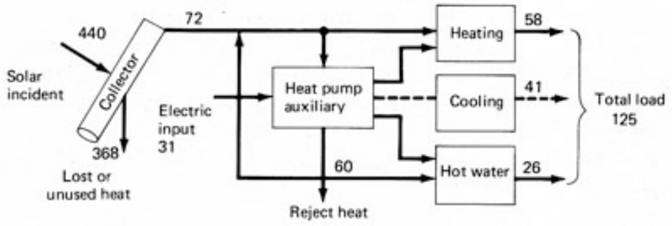
Three variations of solar systems are illustrated below.



System 1. Heating and cooling



System 2. Solar heating only



System 3. Solar assisted heat pump

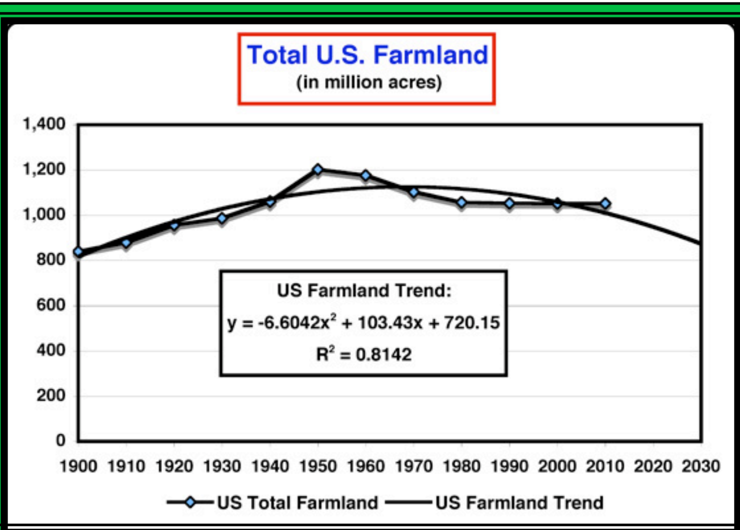
Figure 7.5. Residential Solar Energy Systems. The figure is based on an 800-square-foot collector. Numbers are in millions of Btu's per year. From Albert Weinstein, "Technical and Economic Considerations for Solar Heating and Cooling of Buildings: A Report by Westinghouse Heating Electric Corporation," in Iachetta, *Proceedings of the Workshop on Solar Heating and Cooling of Buildings*, p. 37.

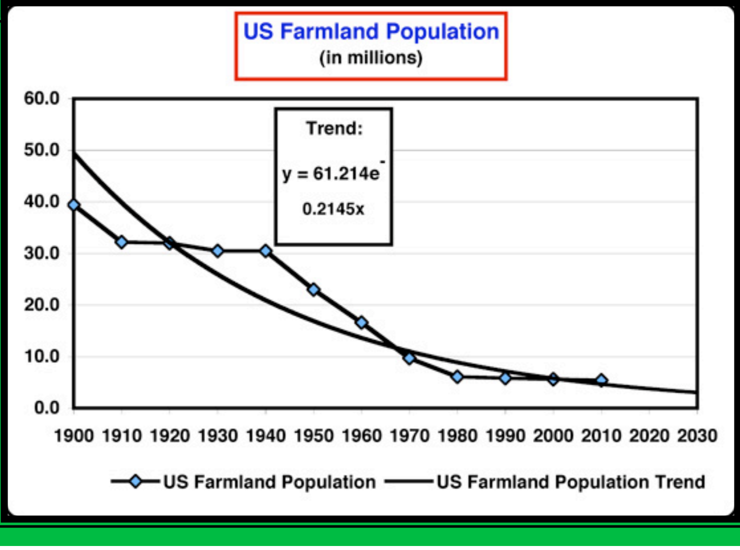
Biomass and Biofuel Natural Resources

While solar technologies can provide substitution possibilities for reliance on traditional and enhanced fossil and nuclear fuel technologies. Biomass resources include cellulose and charcoal based wood, bio-digested gas from organic wastes, as well as recycled solid waste for use as fuel in cooking. We illustrate here some variations of these resources.

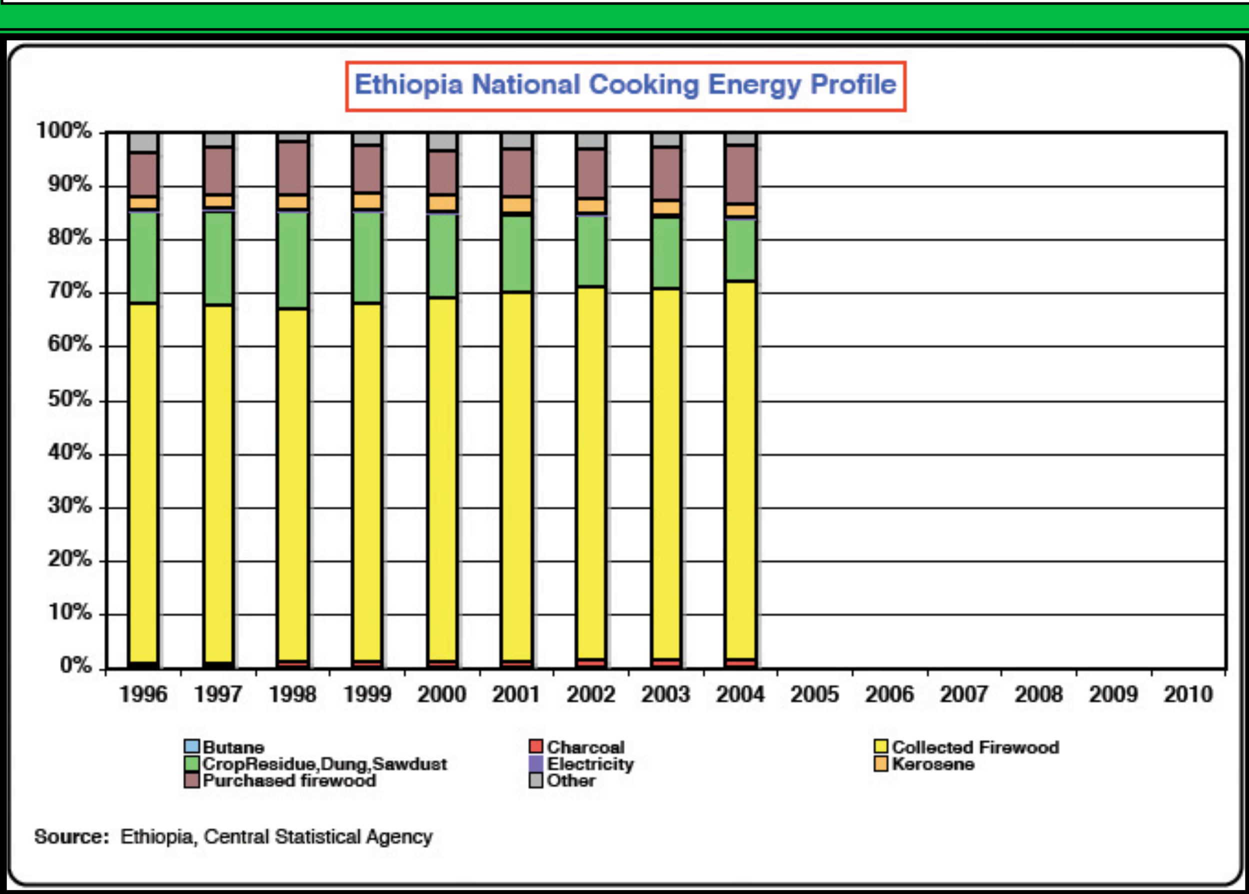
For some economies such as the U.S., continued application of energy in the form of fertilizers, and in energy-saving capital equipment has permitted a reduction in the amount of farmland as well as in the size of the farm population, even though total agricultural production has increased. This has enabled the U.S. to consider not only self-sufficiency in major food crops, but also to consider the production of non-food biomass resources such as ethanol, which functions as a substitute for refined gasoline, and is now widely used throughout the U.S.

For developing economies, food self-sufficiency often does not exist, nor is domestic food production typically sufficient to reach daily kilocaloric intake levels consistent with maximization of life expectancy. As a result, biomass fuel production is more problematic than elsewhere.





Residential Primary Energy Fuels in Ethiopian Cooking and Heating

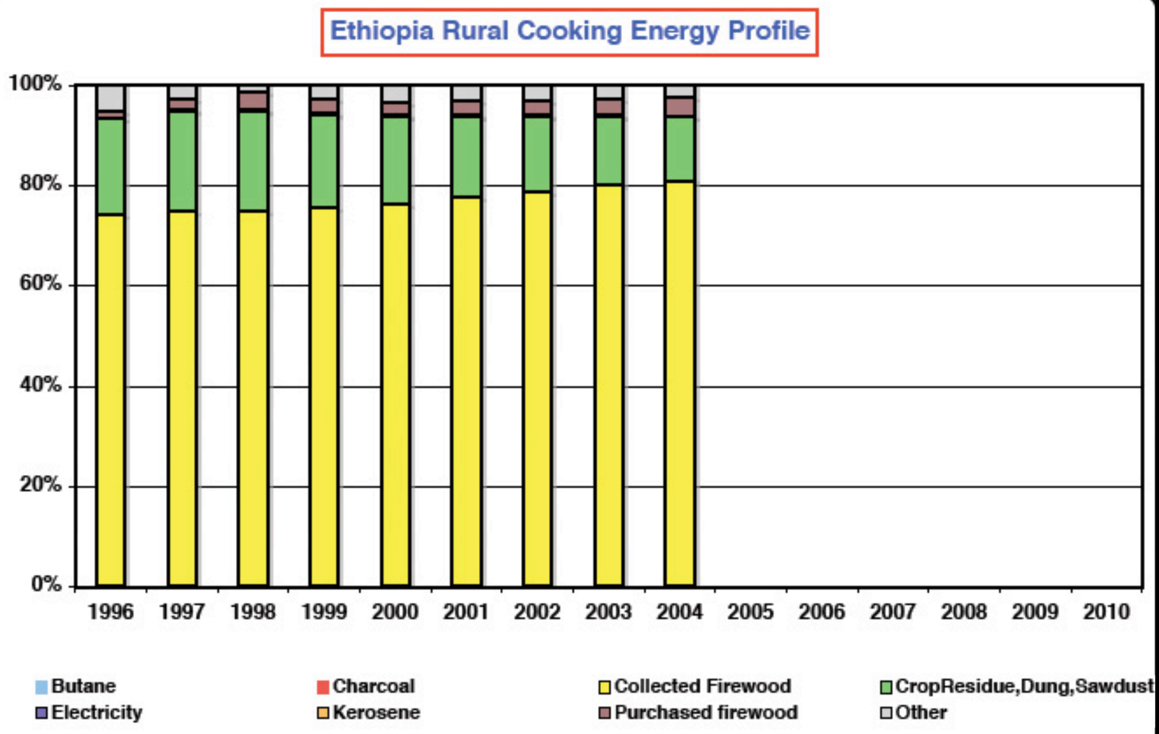


Source: Ethiopia, Central Statistical Agency

Ethiopia relies more on wood energy resources for household cooking and heating than countries with a higher level of per capita income such as China or India. Because a substantial proportion of fuelwood consumed is collected rather than purchased, there is less incentive to consume fuelwood efficiently through the use of stove technologies, while at the same time, it leads to accelerated deforestation, especially in the absence of well-defined property rights.

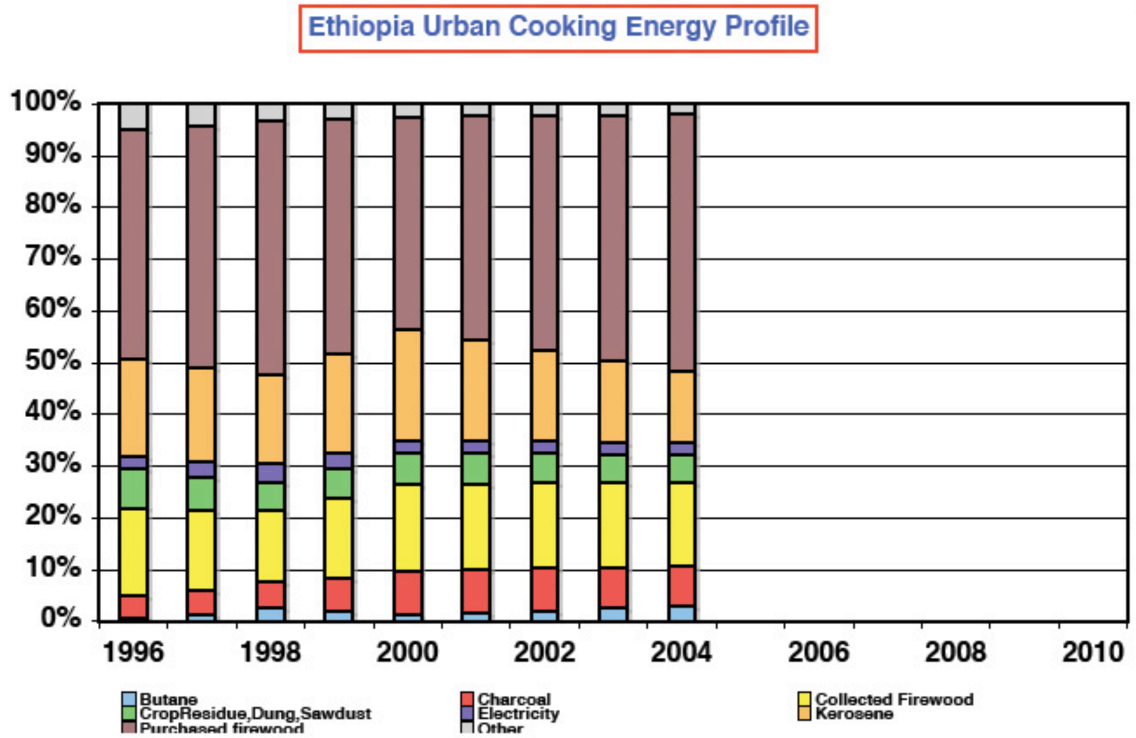
When broken into rural and urban samples, however, urban consumers purchase a much higher share of their fuelwood than do rural consumers, pointing to the costs of transportation, as well as to a mechanism whereby fuelwood may be priced more closely to its opportunity cost in the future as urbanization proceeds.

Rural-Urban Differences in Residential Primary Energy Fuels in Ethiopian Cooking and Heating



Ethiopia Rural Cooking Energy Profile

Source: Ethiopia. Central Statistical Agency



Ethiopia Urban Cooking Energy Profile

Source: Ethiopia, Central Statistical Agency

Comparative Differences in Energy Consumption in Developing Countries

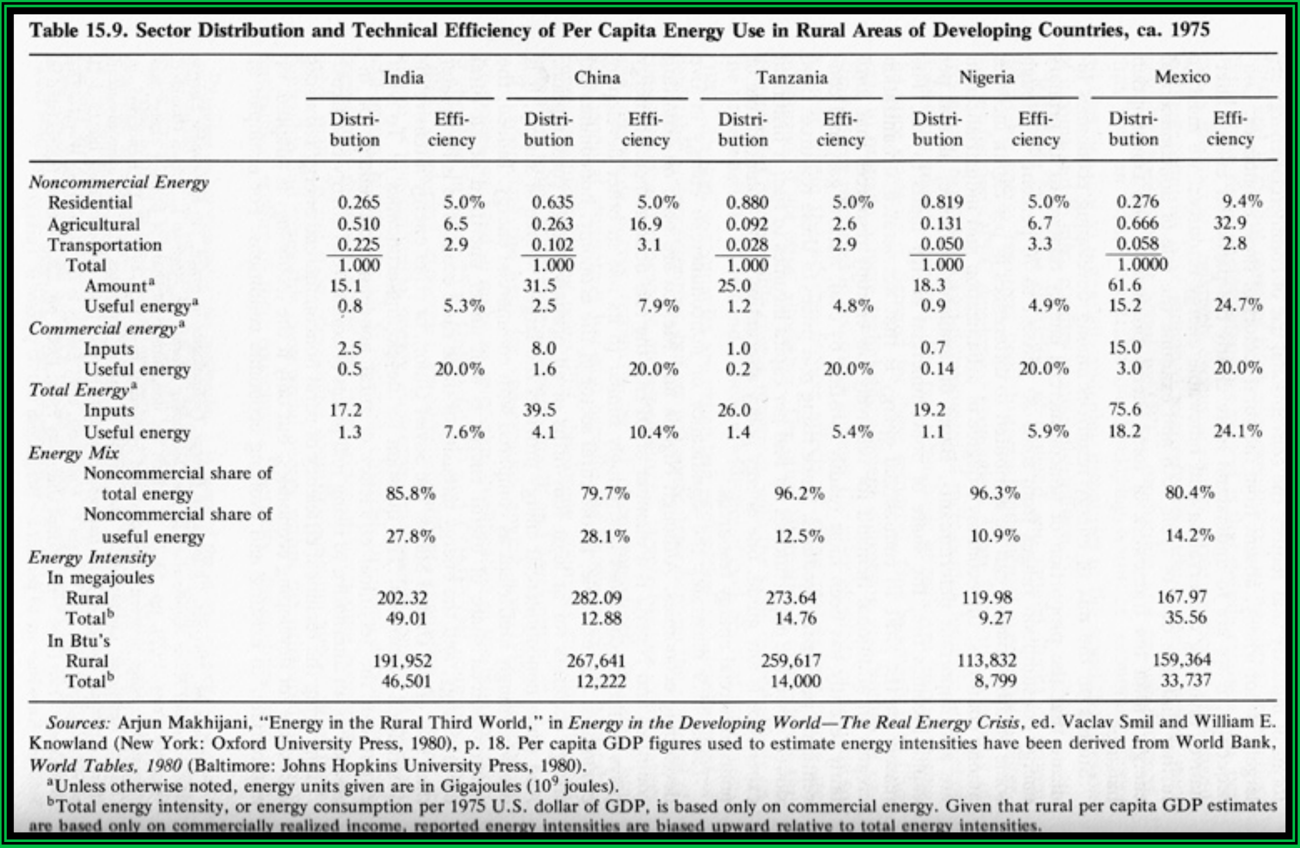


Table 15.9. Sector Distribution and Technical Efficiency of Per Capita Energy Use in Rural Areas of Developing Countries, ca. 1975

	India		China		Tanzania		Nigeria		Mexico	
	Distribution	Efficiency	Distribution	Efficiency	Distribution	Efficiency	Distribution	Efficiency	Distribution	Efficiency
Noncommercial Energy										
Residential	0.265	5.0%	0.635	5.0%	0.880	5.0%	0.819	5.0%	0.276	9.4%
Agricultural	0.510	6.5	0.263	16.9	0.092	2.6	0.131	6.7	0.666	32.9
Transportation	0.225	2.9	0.102	3.1	0.028	2.9	0.050	3.3	0.058	2.8
Total	1.000		1.000		1.000		1.000		1.0000	
Amount[a]	15.1		31.5		25.0		18.3		61.6	
Useful energy[a]	0.8	5.3%	2.5	7.9%	1.2	4.8%	0.9	4.9%	15.2	24.7%
Commercial energy[a]										
Inputs	2.5		8.0		1.0		0.7		15.0	
Useful energy	0.5	20.0%	1.6	20.0%	0.2	20.0%	0.14	20.0%	3.0	20.0%
Total Energy[a]										
Inputs	17.2		39.5		26.0		19.2		75.6	
Useful energy	1.3	7.6%	4.1	10.4%	1.4	5.4%	1.1	5.9%	18.2	24.1%
Energy Mix										
Noncommercial share of total energy	85.8%		79.7%		96.2%		96.3%		80.4%	
Noncommercial share of useful energy	27.8%		28.1%		12.5%		10.9%		14.2%	
Energy Intensity										
In megajoules										
Rural	202.32		282.09		273.64		119.98		167.97	
Total[b]	49.01		12.88		14.76		9.27		35.56	
In Btu's										
Rural	191,952		267,641		259,617		113,832		159,364	
Total[b]	46,501		12,222		14,000		8,799		33,737	

Sources: Arjun Makhijani, "Energy in the Rural Third World," in *Energy in the Developing World—The Real Energy Crisis*, ed. Vaclav Smil and William E. Knowland (New York: Oxford University Press, 1980), p. 18. Per capita GDP figures used to estimate energy intensities have been derived from World Bank, *World Tables, 1980* (Baltimore: Johns Hopkins University Press, 1980).

[a] Unless otherwise noted, energy units given are in Gigajoules (10^9 joules).

[b] Total energy intensity, or energy consumption per 1975 U.S. dollar of GDP, is based only on commercial energy. Given that rural per capita GDP estimates are based only on commercially realized income, reported energy intensities are biased upward relative to total energy intensities.

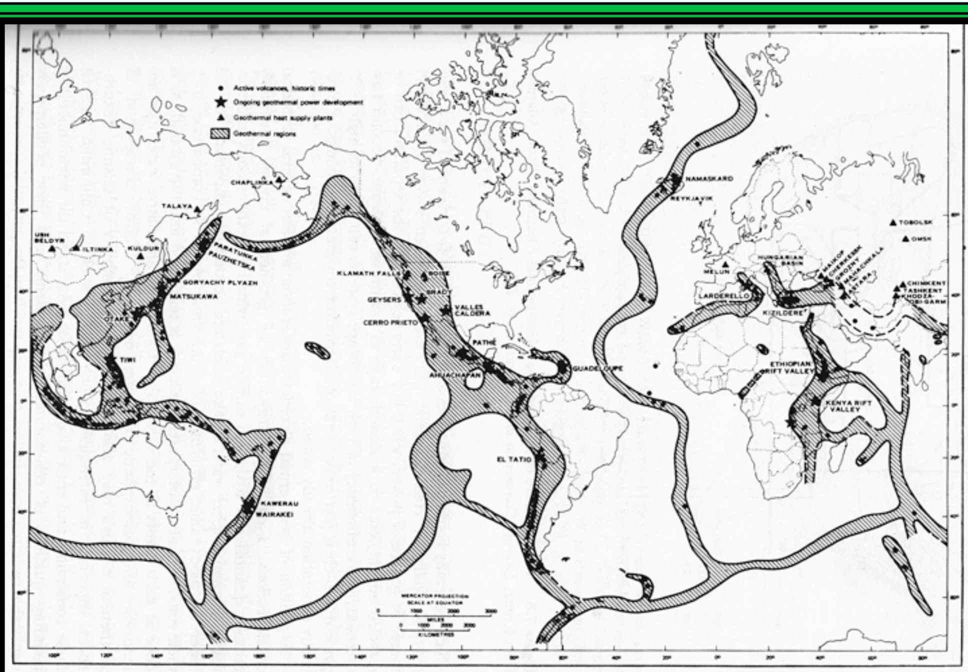
Comparative studies on energy use patterns vary significantly across countries. The higher is the level of per capita income, the higher is the share of commercial energy.

In addition, the higher is the level of per capita income, the higher is the end use energy efficiency. This reflects to some extent differences in the age and vintage of energy-using capital stocks.

Finally, the higher is the level of per capita income, the lower is the level of aggregate energy intensity. This difference provide a further reflection of the impact of energy-conserving capital stocks.

Geothermal Energy Technology

Countries as disparate as Iceland, Italy, and Ethiopia are endowed with significant potential for geothermal energy. The natural release of hot air and gases from fissures in the earth's surface plates can be tapped to generate steam for the operation of commercial electric generating stations. Shown below is a geographic distribution of geothermal sites, followed by an illustration of basic geothermal steam generation technology.



SOURCE: GEONOMICS, INC. (HEMPSTEAD, NEW YORK, 1974).

Figure 7.7. Geothermal Regions of the World. From the Futures Group, *A Technology Assessment of Geothermal Energy Resource Development* (Washington, D.C.: National Science Foundation, 15 April 1975), p. 220.

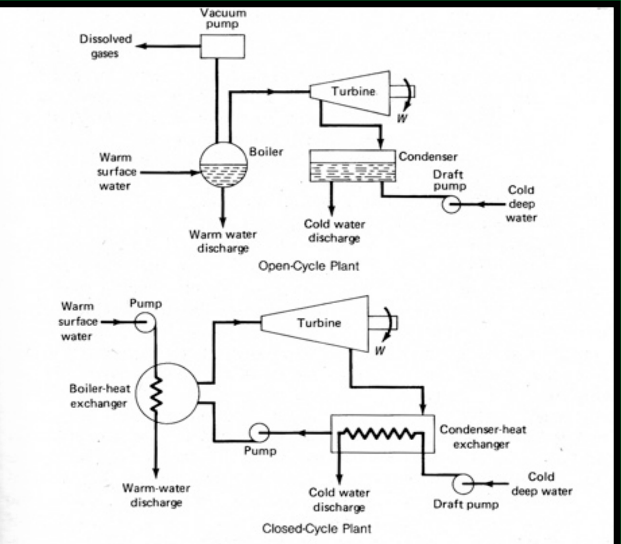


Figure 7.6. The Structure of a Hydrothermal Electricity Plant. *Top*, an open-cycle plant; *bottom*, a closed-cycle plant. Adapted from Jerrold H. Krenz, *Energy: Conversion and Utilization* (Boston: Allyn and Bacon, 1976), pp. 273, 275.

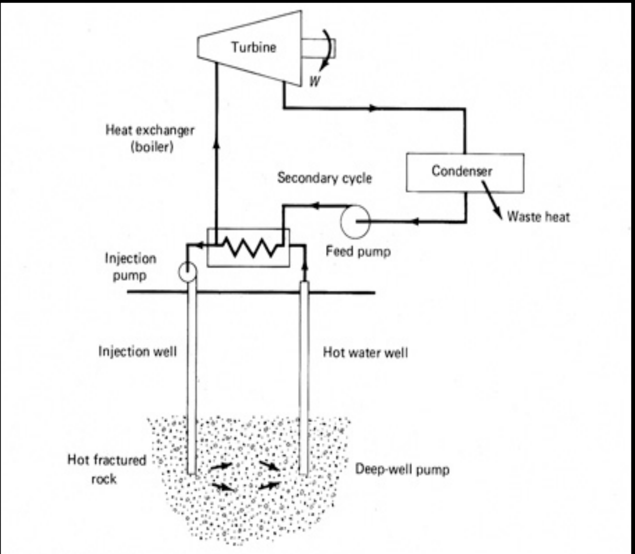


Figure 7.8. The Structure of a Closed-Cycle Geothermal Electricity Plant. Adapted from Krenz, *Energy: Conversion and Utilization*, p. 291.

Wind Energy Technology

Wind energy potential is significant for many countries, including many developing countries such as Ethiopia. Wind energy has long been used to empty flooded regions, as in Holland centuries ago, and to lift water from boreholes in arid climates, as in the southwestern United States and in the Sahel of West Africa.

More recently, windmill technology has been refined to be able to generate electricity from large scale windmill grids. This already exists in California in the U.S., in Denmark, the U.K., Germany, and France in Europe, and is now an option for developing countries seeking to install generating capacity with fewer adverse effects on the environment in comparison with traditional fossil fuel or nuclear technologies.

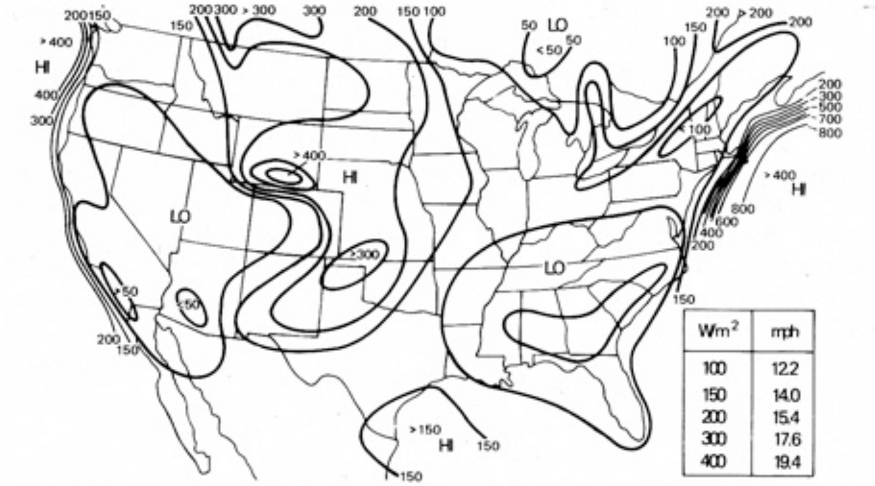
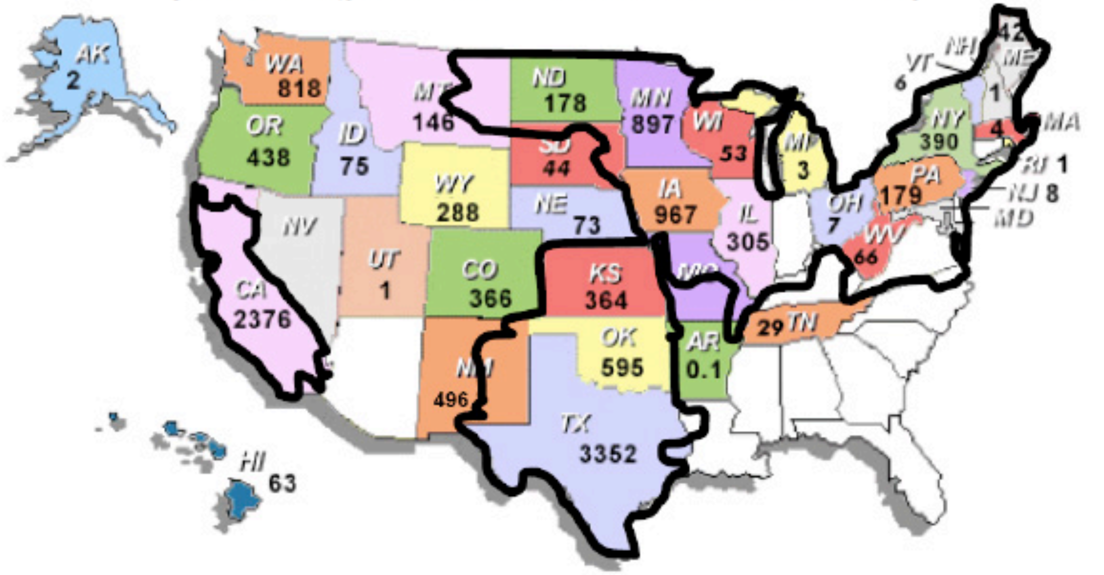


Figure 7.9. The Distribution of Wind Energy Potential in the United States. From J. W. Reed, "Wind Climatology," in *Second Workshop on Wind Energy Conversion Systems*, ed. F. R. Eldridge, NSF-RA-N-75-050 (Washington, D.C.: National Science Foundation, 1975), pp. 319, 325, reprinted in David R. Inglis, *Wind Power and Other Energy Options* (Ann Arbor: University of Michigan Press, 1978), p. 50.

Total Installed U.S. Wind Energy Capacity (MW in each state as of June 2007)
(Border of regions in RTOs is shown in bold black outline)



Source: http://www.awea.org/utility/wind_overview.html (total wind capacity = 12,634 MW as of June 30, 2007)
http://www.ferc.gov/industries/electric/indus-act/rto/rto-map.asp (RTOs as of September 2007)

Calibrating Wind Energy Technology Requirements

The kinetic energy from a windmill can be calculated as follows:
$E = (.5)\rho V^2$ joules per cubic meter, where ρ is the density of air, that is, its kilogram unit mass divided by its cubic-meter volume. V^2 is the square of the meters-per-second velocity of air. In turn, when a volume of air moves one meter, we can derive the available power per square meter of air as:

$P = EV$
$= (.5)\rho V^3$ watts per square meter.

Not all air flows can be converted to power. Moreover, in the case of rotary windmills, power can not be expressed in simple cubic-meter blocks. To adjust for efficiency, we restate the above as follows:

$P = 2\pi r^2 \rho V^3 a(1-a)^2$, where:

$\pi\rho^2$ is the cylindrical volume of air, in cubic meters;
ρ is the density of air, V^3 is the cube of the velocity of entering air; and
a is the axial interference of the mindmill rotors, defined by the pitch of the blades, as well as their number, width, and thickness.

When the rate of change in power is computed as a function of axial interference, it is possible to determine the most efficient degree of axial interference needed to obtain the maximum power from a given windflow. It turns out that this occurs when the coefficient, a, has a value of .33, which when inserted into the preceding equation yields:

$P_{max} = 2\pi r^2 \rho V^3 (.333)(1-.333)^{2.}$

$= (8/27)\pi r^2 \rho V^3$

The theoretical net efficiency of a given wind machine is then defined as the ratio of the maximum output to its actual output, i.e,:

$\Pi = [(8/27)\pi r^2 \rho V^3]/[.5\pi r^2 \rho V^3]$

$= (16/27) = .5926 = 59.3$ percent.

In practice, there are may possible configurations of wind energy technologies. Illustrated here are some of those alternatives.

Alternative Wind Energy Configurations

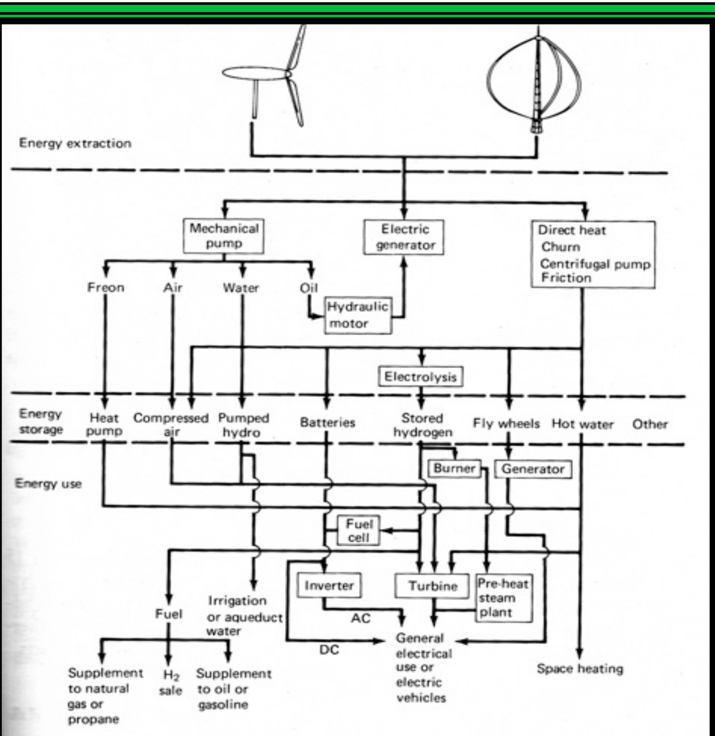


Figure 7.11. Wind Energy Alternative Applications. From National Science Foundation, Division of Advanced Energy and Resources Research and Technology, *Wind Machines*, p. 34.

U.S. Annual Gross Renewable Energy Potential

For the U.S. alone, the annual gross renewable energy potential is over eight times the presently known stocks of recoverable fossil fuel resources and is 127 times the presently known stock of nuclear energy reserves using conventional fission technology. Yet substitution requires ultimately consideration of relative life cycle costs relative to the level of aggregate energy demand by end use. Such comparisons apply equally to developing economies as well.

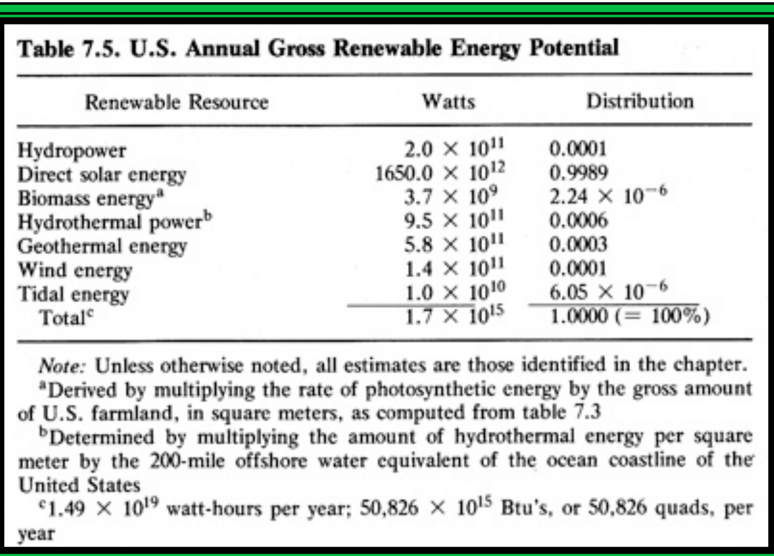


Table 7.5. U.S. Annual Gross Renewable Energy Potential

Renewable Resource	Watts	Distribution
Hydropower	2.0×10^{11}	0.0001
Direct solar energy	1650.0×10^{12}	0.9989
Biomass energy[a]	3.7×10^{9}	2.24×10^{-6}
Hydrothermal power[b]	9.5×10^{11}	0.0006
Geothermal energy	5.8×10^{11}	0.0003
Wind energy	1.4×10^{11}	0.0001
Tidal energy	1.0×10^{10}	6.05×10^{-6}
Total[c]	1.7×10^{15}	1.0000 (= 100%)

Note: Unless otherwise noted, all estimates are those identified in the chapter.

[a] Derived by multiplying the rate of photosynthetic energy by the gross amount of U.S. farmland, in square meters, as computed from table 7.3

[b] Determined by multiplying the amount of hydrothermal energy per square meter by the 200-mile offshore water equivalent of the ocean coastline of the United States

[c] 1.49×10^{19} watt-hours per year; $50,826 \times 10^{15}$ Btu's, or 50,826 quads, per year

Alternative Energy Storage and Conversion Technologies

One issue in any shift from exhaustible to renewable energy resources is the capacity for energy storage and conversion. Energy can be stored through air compression, through flywheel technology, through batteries, and through hydrogen. Without examining in detail how each of these technologies works here, we illustrate in the table below the various levels of maximum energy storage density associated with these alternative technologies. The economic competitiveness of any one of these depends on the level of production, the costs of production, and on relative prices in each potential end-use sector. Common end use storage technologies include batteries used in computer laptops, pda's, cellphones, hybrid and all-electric vehicles, as well as in storage-backup systems for central electricity generation.

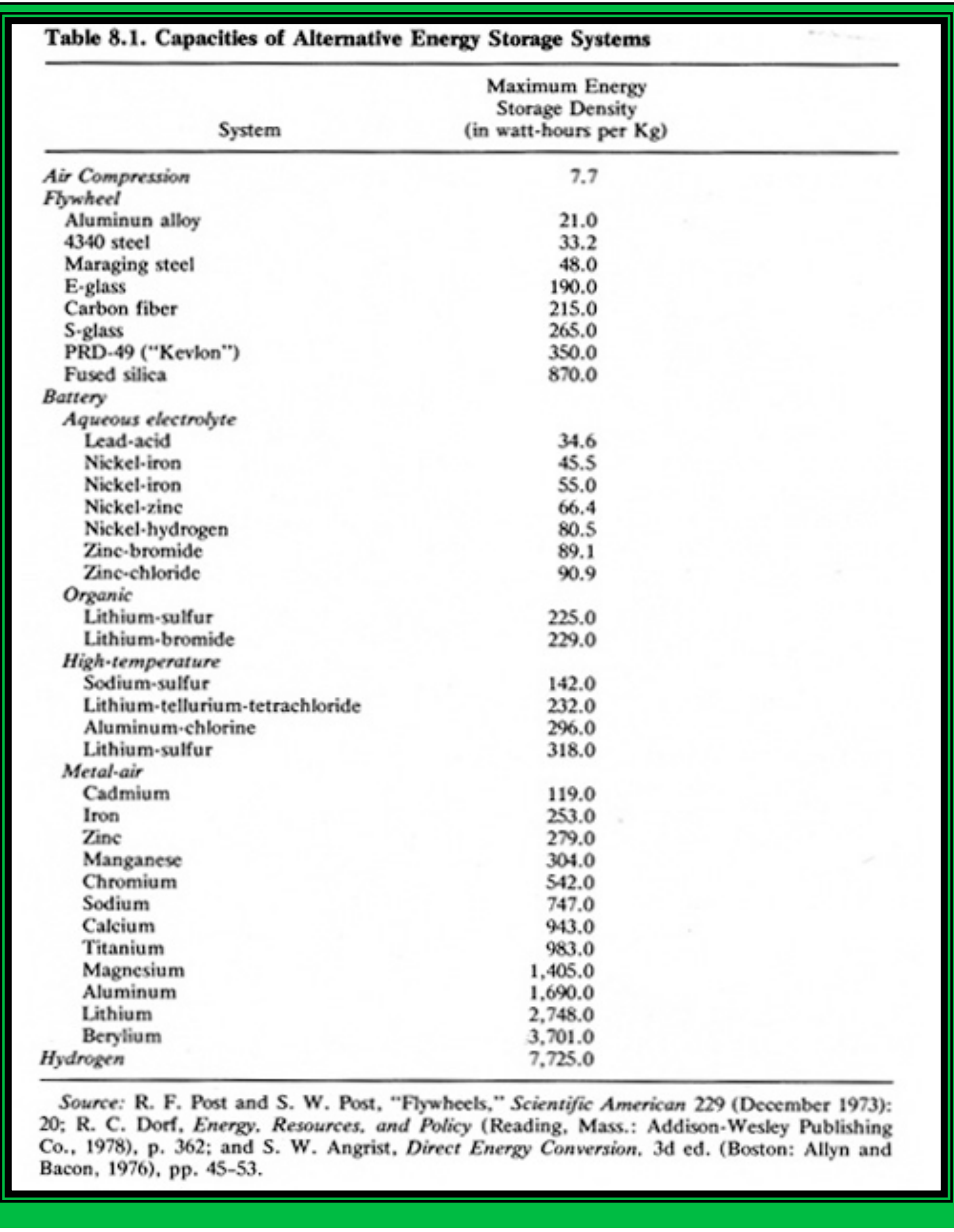


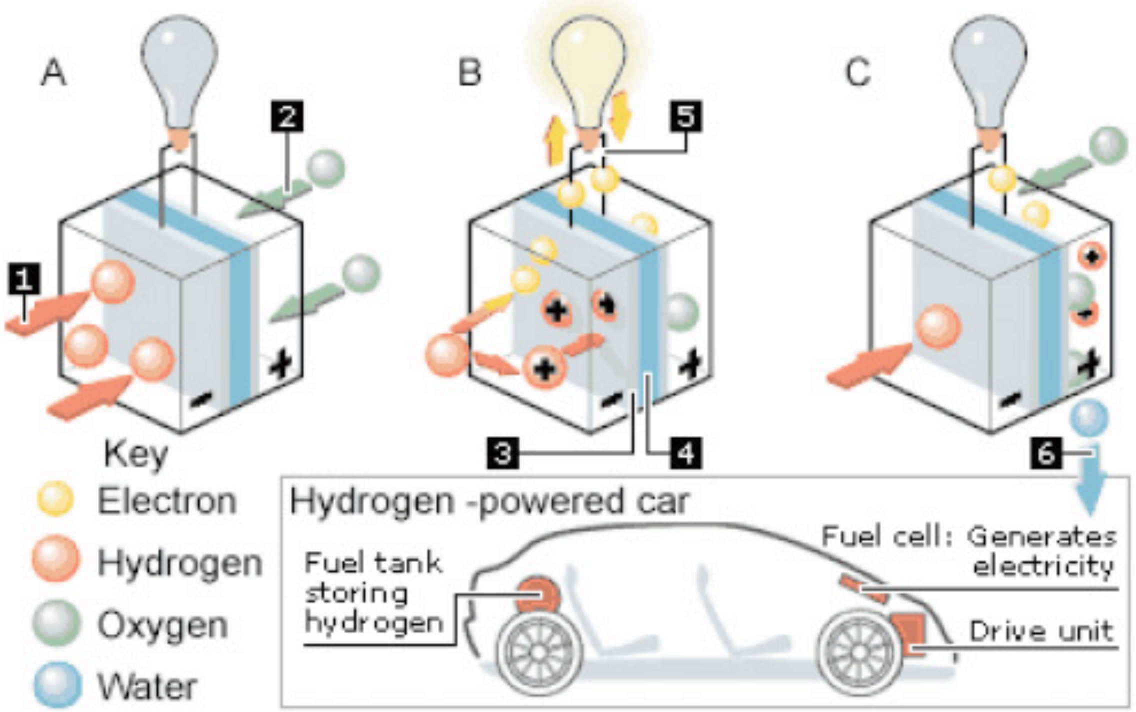
Table 8.1. Capacities of Alternative Energy Storage Systems

System	Maximum Energy Storage Density (in watt-hours per Kg)
Air Compression	7.7
Flywheel	
Aluminun alloy	21.0
4340 steel	33.2
Maraging steel	48.0
E-glass	190.0
Carbon fiber	215.0
S-glass	265.0
PRD-49 ("Kevlon")	350.0
Fused silica	870.0
Battery	
Aqueous electrolyte	
Lead-acid	34.6
Nickel-iron	45.5
Nickel-iron	55.0
Nickel-zinc	66.4
Nickel-hydrogen	80.5
Zinc-bromide	89.1
Zinc-chloride	90.9
Organic	
Lithium-sulfur	225.0
Lithium-bromide	229.0
High-temperature	
Sodium-sulfur	142.0
Lithium-tellurium-tetrachloride	232.0
Aluminum-chlorine	296.0
Lithium-sulfur	318.0
Metal-air	
Cadmium	119.0
Iron	253.0
Zinc	279.0
Manganese	304.0
Chromium	542.0
Sodium	747.0
Calcium	943.0
Titanium	983.0
Magnesium	1,405.0
Aluminum	1,690.0
Lithium	2,748.0
Berylium	3,701.0
Hydrogen	7,725.0

Source: R. F. Post and S. W. Post, "Flywheels," *Scientific American* 229 (December 1973): 20; R. C. Dorf, *Energy, Resources, and Policy* (Reading, Mass.: Addison-Wesley Publishing Co., 1978), p. 362; and S. W. Angrist, *Direct Energy Conversion*, 3d ed. (Boston: Allyn and Bacon, 1976), pp. 45-53.

Hydrogen Powered Vehicles

How a Hydrogen (Proton Exchange) Fuel Cell Works



1 Hydrogen: Constantly pumped in at negative terminal
2 Oxygen: Pumped in at opposite positive terminal
3 Catalyst: Helps electrons break free from hydrogen atoms
4 Membrane: Allows hydrogen ions through but blocks electrons
5 Circuit: Electrons flow through circuit to positive terminal
6 Electrons and hydrogen ions combine with oxygen, forming water

Fuel cell technology now competes with hybrid electric and all electric vehicle technology. The basic technology of fuel cells is illustrated above, and shows that vehicles can use fuel cells to generate electricity to provide energy to vehicles, and the only exhaust emission is water. The problem with hydrogen energy technology is that it requires a primary energy source to produce, and must be compressed if it is to substitute for traditional gasoline and diesel powered vehicles.

Organic Natural Resources and Recycling Technologies

Given the relative inefficiencies of various traditional and hybrid technologies, environmental conservation may be as well served by adoption of recycling,and organic technologies, including biogas. We illustrate here the potential of these technologies, which may be of more immediate practical import to developing economies.

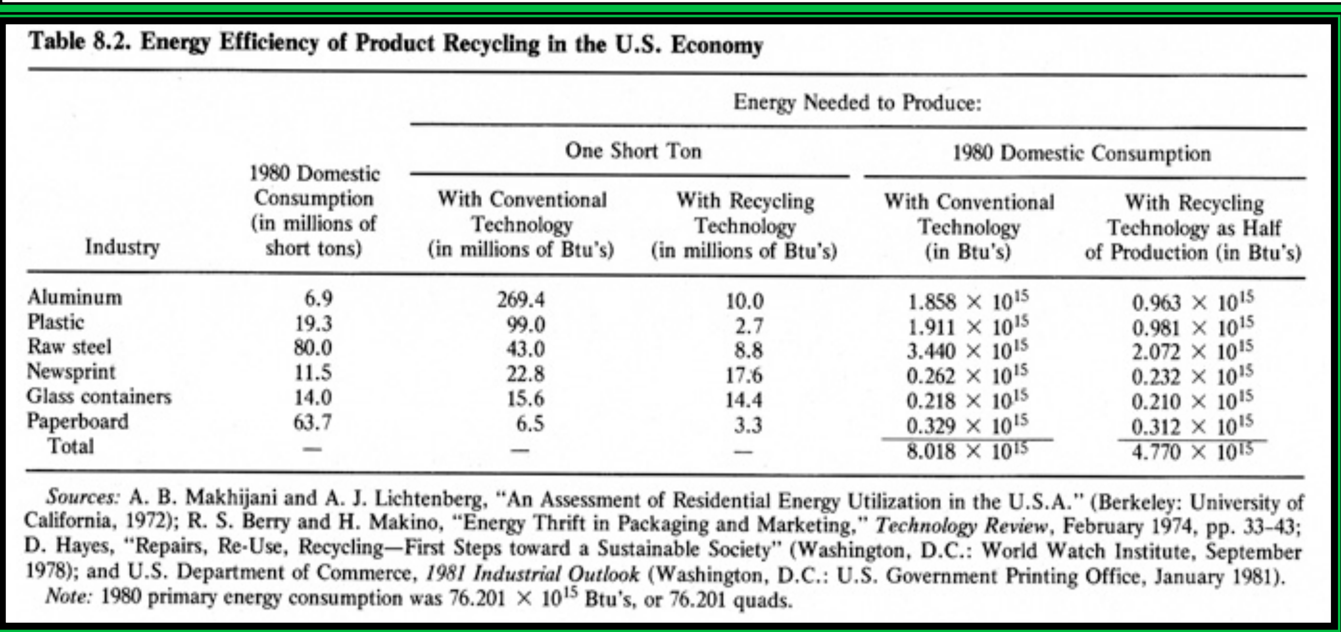


Table 8.2. Energy Efficiency of Product Recycling in the U.S. Economy

Industry	1980 Domestic Consumption (in millions of short tons)	Energy Needed to Produce: One Short Ton: With Conventional Technology (in millions of Btu's)	Energy Needed to Produce: One Short Ton: With Recycling Technology (in millions of Btu's)	Energy Needed to Produce: 1980 Domestic Consumption: With Conventional Technology (in Btu's)	Energy Needed to Produce: 1980 Domestic Consumption: With Recycling Technology as Half of Production (in Btu's)
Aluminum	6.9	269.4	10.0	1.858×10^{15}	0.963×10^{15}
Plastic	19.3	99.0	2.7	1.911×10^{15}	0.981×10^{15}
Raw steel	80.0	43.0	8.8	3.440×10^{15}	2.072×10^{15}
Newsprint	11.5	22.8	17.6	0.262×10^{15}	0.232×10^{15}
Glass containers	14.0	15.6	14.4	0.218×10^{15}	0.210×10^{15}
Paperboard	63.7	6.5	3.3	0.329×10^{15}	0.312×10^{15}
Total	—	—	—	8.018×10^{15}	4.770×10^{15}

Sources: A. B. Makhijani and A. J. Lichtenberg, "An Assessment of Residential Energy Utilization in the U.S.A." (Berkeley: University of California, 1972); R. S. Berry and H. Makino, "Energy Thrift in Packaging and Marketing," *Technology Review*, February 1974, pp. 33–43; D. Hayes, "Repairs, Re-Use, Recycling—First Steps toward a Sustainable Society" (Washington, D.C.: World Watch Institute, September 1978); and U.S. Department of Commerce, *1981 Industrial Outlook* (Washington, D.C.: U.S. Government Printing Office, January 1981).

Note: 1980 primary energy consumption was 76.201×10^{15} Btu's, or 76.201 quads.

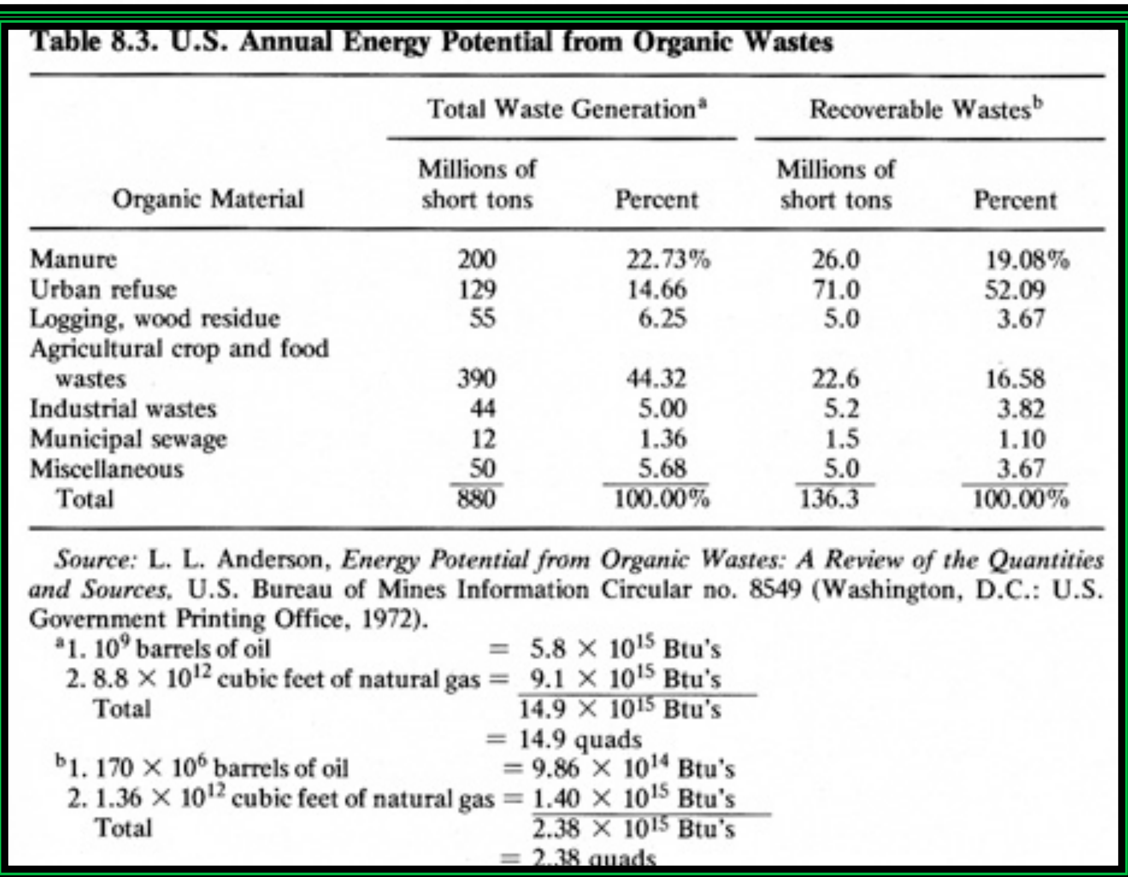


Table 8.3. U.S. Annual Energy Potential from Organic Wastes

Organic Material	Total Waste Generation[a]: Millions of short tons	Total Waste Generation[a]: Percent	Recoverable Wastes[b]: Millions of short tons	Recoverable Wastes[b]: Percent
Manure	200	22.73%	26.0	19.08%
Urban refuse	129	14.66	71.0	52.09
Logging, wood residue	55	6.25	5.0	3.67
Agricultural crop and food wastes	390	44.32	22.6	16.58
Industrial wastes	44	5.00	5.2	3.82
Municipal sewage	12	1.36	1.5	1.10
Miscellaneous	50	5.68	5.0	3.67
Total	880	100.00%	136.3	100.00%

Source: L. L. Anderson, *Energy Potential from Organic Wastes: A Review of the Quantities and Sources*, U.S. Bureau of Mines Information Circular no. 8549 (Washington, D.C.: U.S. Government Printing Office, 1972).

[a] 1. 10^9 barrels of oil = 5.8×10^{15} Btu's
2. 8.8×10^{12} cubic feet of natural gas = 9.1×10^{15} Btu's
Total 14.9×10^{15} Btu's
= 14.9 quads

[b] 1. 170×10^6 barrels of oil = 9.86×10^{14} Btu's
2. 1.36×10^{12} cubic feet of natural gas = 1.40×10^{15} Btu's
Total 2.38×10^{15} Btu's
= 2.38 quads

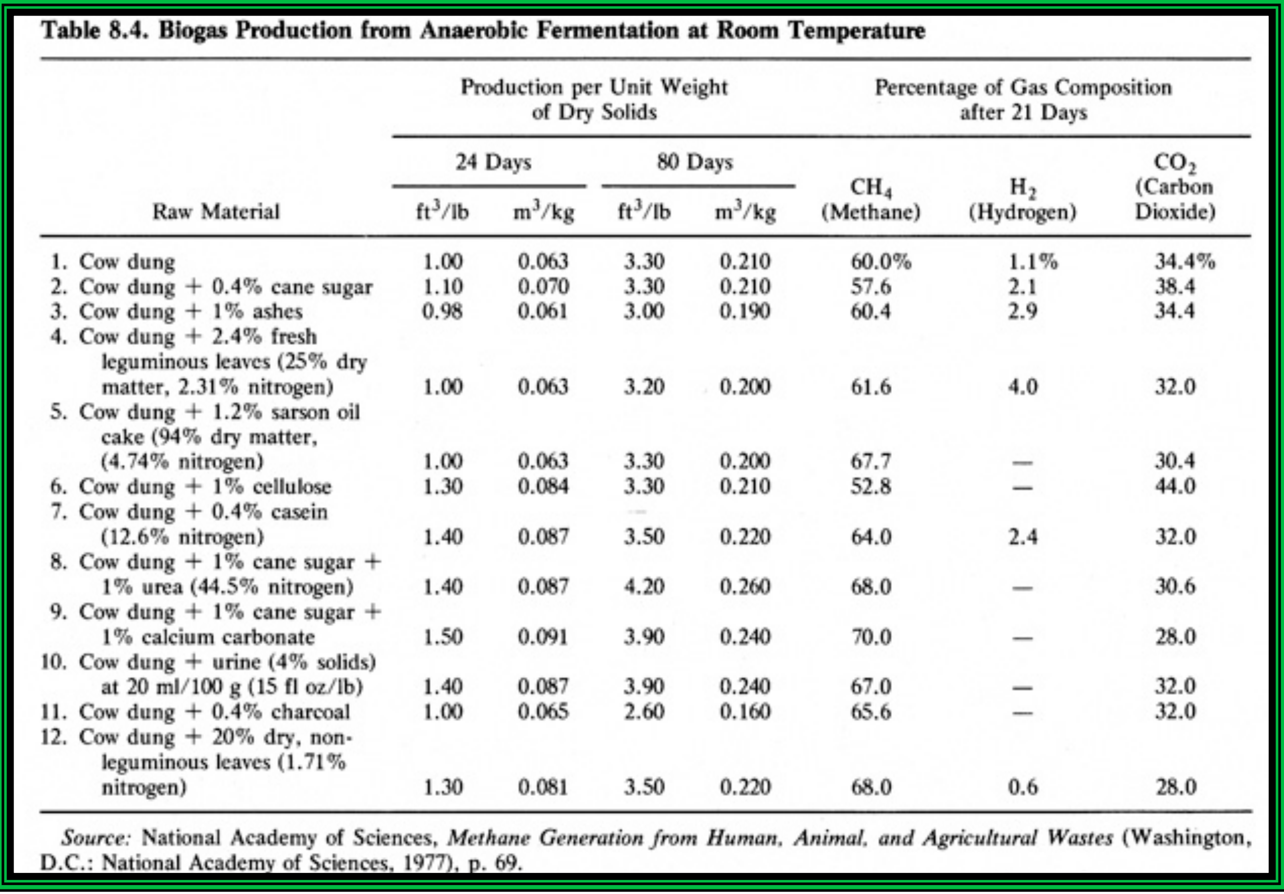


Table 8.4. Biogas Production from Anaerobic Fermentation at Room Temperature

Raw Material	Production per Unit Weight of Dry Solids: 24 Days ft^3/lb	24 Days m^3/kg	80 Days ft^3/lb	80 Days m^3/kg	Percentage of Gas Composition after 21 Days: CH_4 (Methane)	H_2 (Hydrogen)	CO_2 (Carbon Dioxide)
1. Cow dung	1.00	0.063	3.30	0.210	60.0%	1.1%	34.4%
2. Cow dung + 0.4% cane sugar	1.10	0.070	3.30	0.210	57.6	2.1	38.4
3. Cow dung + 1% ashes	0.98	0.061	3.00	0.190	60.4	2.9	34.4
4. Cow dung + 2.4% fresh leguminous leaves (25% dry matter, 2.31% nitrogen)	1.00	0.063	3.20	0.200	61.6	4.0	32.0
5. Cow dung + 1.2% sarson oil cake (94% dry matter, (4.74% nitrogen)	1.00	0.063	3.30	0.200	67.7	—	30.4
6. Cow dung + 1% cellulose	1.30	0.084	3.30	0.210	52.8	—	44.0
7. Cow dung + 0.4% casein (12.6% nitrogen)	1.40	0.087	3.50	0.220	64.0	2.4	32.0
8. Cow dung + 1% cane sugar + 1% urea (44.5% nitrogen)	1.40	0.087	4.20	0.260	68.0	—	30.6
9. Cow dung + 1% cane sugar + 1% calcium carbonate	1.50	0.091	3.90	0.240	70.0	—	28.0
10. Cow dung + urine (4% solids) at 20 ml/100 g (15 fl oz/lb)	1.40	0.087	3.90	0.240	67.0	—	32.0
11. Cow dung + 0.4% charcoal	1.00	0.065	2.60	0.160	65.6	—	32.0
12. Cow dung + 20% dry, non-leguminous leaves (1.71% nitrogen)	1.30	0.081	3.50	0.220	68.0	0.6	28.0

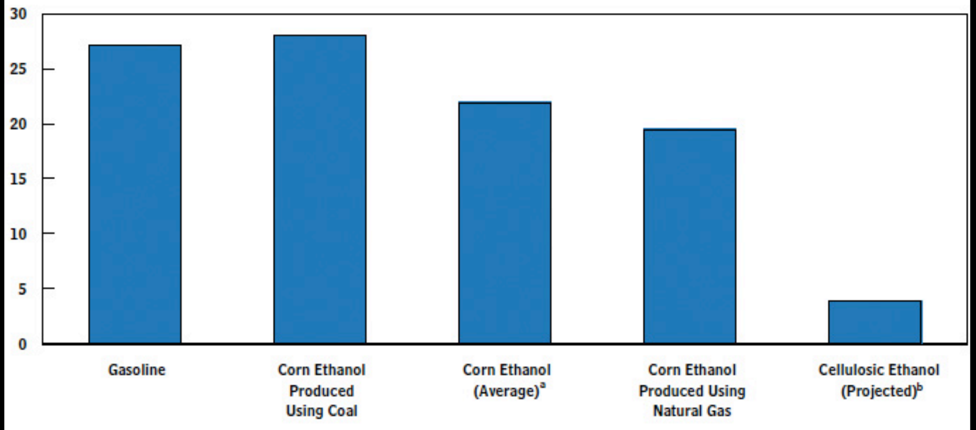
Source: National Academy of Sciences, *Methane Generation from Human, Animal, and Agricultural Wastes* (Washington, D.C.: National Academy of Sciences, 1977), p. 69.

Environmental Effects of Biofuels

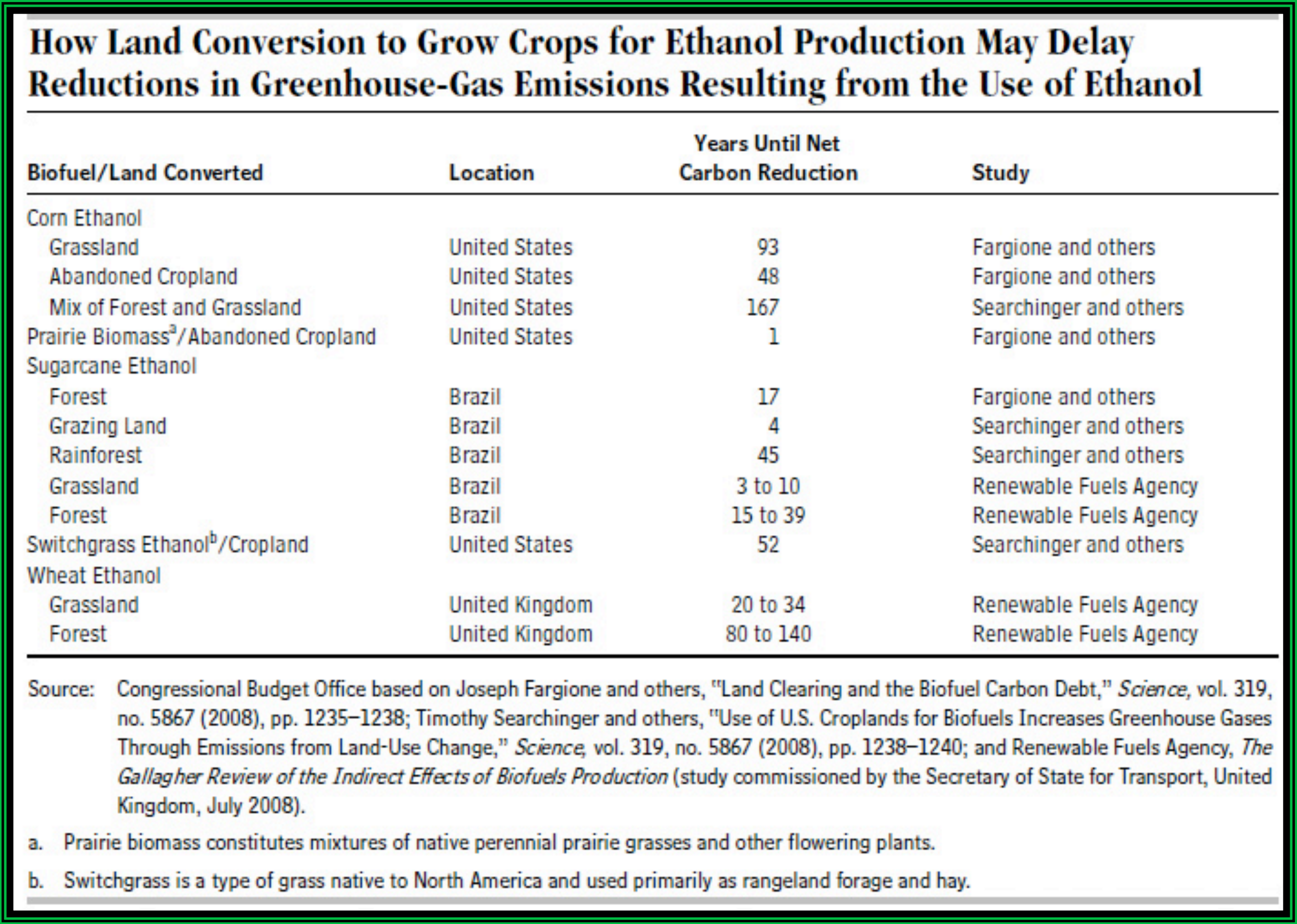
Biofuels have the appeal of substitutability for traditional gasoline fuel. There are, however, limits to the substitutability. Among them are the energy efficiency of ethanol, the principal biofuel grown from corn or sugarcane, and secondly, environmental emissions from the conversion of biofuels into end uses. Finally, biofuels may compete with food production at some point, thus raising the cost of food beyond what it would be otherwise.

Life-Cycle Greenhouse-Gas Emissions from Selected Fuels

(Pounds of CO_2e per energy-equivalent gallon of gasoline)



Source: Congressional Budget Office based on Michael Wang, May Wu, and Hong Huo, "Life-Cycle Energy and Greenhouse Gas Emission Impacts of Different Corn Ethanol Plant Types," *Environmental Research Letters*, vol. 2, no. 2 (2007).



How Land Conversion to Grow Crops for Ethanol Production May Delay Reductions in Greenhouse-Gas Emissions Resulting from the Use of Ethanol

Biofuel/Land Converted	Location	Years Until Net Carbon Reduction	Study
Corn Ethanol			
Grassland	United States	93	Fargione and others
Abandoned Cropland	United States	48	Fargione and others
Mix of Forest and Grassland	United States	167	Searchinger and others
Prairie Biomass[a]/Abandoned Cropland	United States	1	Fargione and others
Sugarcane Ethanol			
Forest	Brazil	17	Fargione and others
Grazing Land	Brazil	4	Searchinger and others
Rainforest	Brazil	45	Searchinger and others
Grassland	Brazil	3 to 10	Renewable Fuels Agency
Forest	Brazil	15 to 39	Renewable Fuels Agency
Switchgrass Ethanol[b]/Cropland	United States	52	Searchinger and others
Wheat Ethanol			
Grassland	United Kingdom	20 to 34	Renewable Fuels Agency
Forest	United Kingdom	80 to 140	Renewable Fuels Agency

Source: Congressional Budget Office based on Joseph Fargione and others, "Land Clearing and the Biofuel Carbon Debt," *Science*, vol. 319, no. 5867 (2008), pp. 1235–1238; Timothy Searchinger and others, "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change," *Science*, vol. 319, no. 5867 (2008), pp. 1238–1240; and Renewable Fuels Agency, *The Gallagher Review of the Indirect Effects of Biofuels Production* (study commissioned by the Secretary of State for Transport, United Kingdom, July 2008).

[a] Prairie biomass constitutes mixtures of native perennial prairie grasses and other flowering plants.

[b] Switchgrass is a type of grass native to North America and used primarily as rangeland forage and hay.

Conclusions

The adoption of any of the various renewable, and alternative storage and conversion technologies depends not just on the underlying compatibility with existing forms of energy use, but also on relative prices. What remains fairly clear is that rising concern over carbon emissions from the combustion of fossil fuels places growing pressure on increasing the efficiency of energy conversion processes, the adoption of lower carbon emission technologies, and selecting choices that are as compatible as possible with existing economic patterns of production and consumption of goods and services.

How this is to be accomplished depends on the pricing of energy and natural resources. From an economic perspective, this means taking into account all forms of market failure, and finding mechanisms to minimize the adverse effects of natural resource use in ways that are consistent with achieving rising standards of living, some form of sustainability in the use of natural resources, and mechanisms to contain the adverse effects of global climate change.