Econ674

Economics of Natural Resources and the Environment

Session 11

Technological Dimensions in Natural Resource Use

There have been numerous previous references to the role of technology in natural resource use. We already have noted the fundamental role of the laws of thermodynamics in shaping the choice of technology. We now turn to applications of natural resources through a review of specific technologies.

There are two broad categories of technologies we wish to consider. First is those technologies that convert an existing natural resource into useful energy. Second, is the examination of alternative storage and conversion technologies.

We consider these technologies in terms of their operational dimensions as well as in terms of the underlying economics that shapes the selection of any particular technology.

A useful way of understanding the role of technology is to look at the evolution of natural resource use over time. The evolution of natural resource use is a function of the state of knowledge from which economically useful extractions can be made of natural resources, along with the relative abundance of these resources in nature, and for which pricing mechanisms assist in the selection of one resource over another.

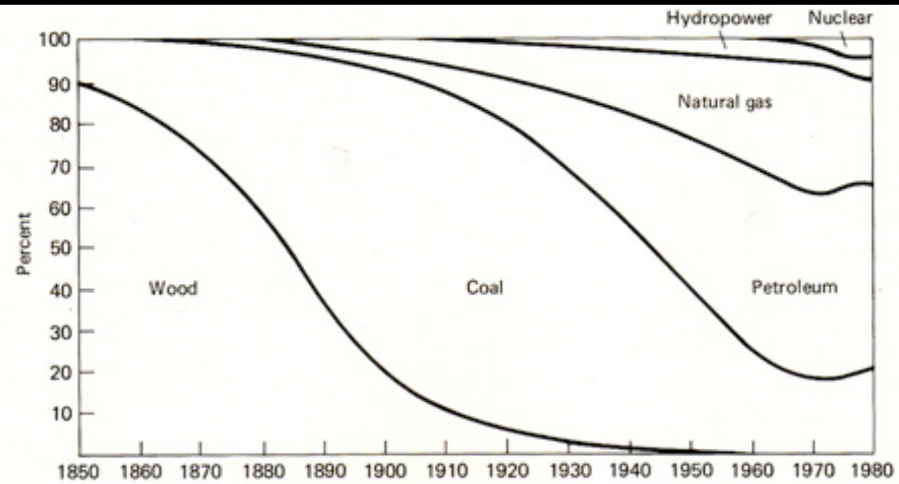

Figure 2.1. Distribution of U.S. Gross Energy Consumption by Type of Resource, 1850–1980. Data from Schurr and Netschert, *Energy in the American Economy*; and Department of Energy, Energy Information Administration, *Monthly Energy Review*, May 1981.

In terms of energy resources, Figure 2.1 illustrates the shift in resource use for an economy such as the U.S, but which provides a roadmap for what is likely to be the case for other economies in the future.

First is the initial dependence on wood natural resources - for cooking, building, and heating. Over time, deforestation has occurred with many forest stocks, leading to resource substitution - initially toward coal, followed by petroleum, natural gas, nuclear energy, and finally renewable technologies.

Wood is, of course, a renewable natural resource, just as are wind and solar energy. Recent advances point to an increasing shift in resource use away from wood toward wind and solar alternatives, as numerous technological innovations now coming to the market attest, e.g. wind farms to generate commercial electricity, solar panels to produce decentralized electricity.

Regardless of the form of natural resource use, energy and materials consumption per capita increase with the level of income. As this occurs, economies experience rising levels of environmental pollution, and is likely do so at an accelerated pace as long as population growth rates exceed depreciation rates of energy-using capital stocks.

While population and income growth may determine projected levels of energy use and environmental emissions, as the capital stocks of energy-using technologies depreciate, they tend to be replaced by higher energy efficient technologies.

Whether the predicted energy transition in the figure above will take place in all economies depends on the relative pricing of natural resources in the first instance, and in the second, on whether environmental pollution externalities have been accounted for.

At this point it is useful to examine briefly what kinds of energy-using technologies are now used in an economy, and how their conversion rates affect natural resource use and the environment. We do so by first looking at fossil fuel technologies, followed by nuclear technologies, after which we examine renewable natural resources.

Fossil Fuel Technologies: Petroleum Resources

Fossil fuels consist of petroleum, natural gas, and coal. They constitute the principal source of energy consumption in many economies. Once discovered and extracted, crude oil is refined into the various forms suitable to end use. The diagram below illustrates the flows through a typical petroleum refinery.

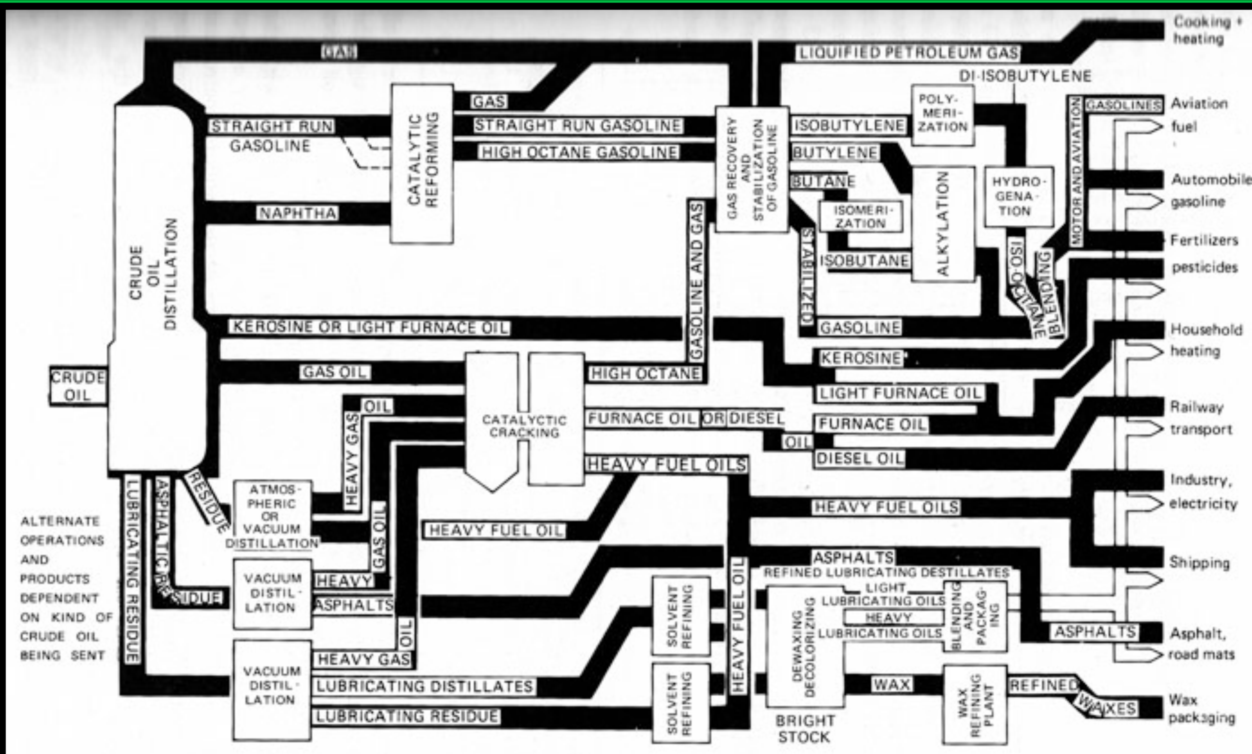

Figure 5.1. Petroleum Flows through a Modern Refinery. Adapted from Olin T. Mouzon, *Resources and Industries of the United States* (New York: Appleton-Century-Crofts, 1966).

Petroleum Refining

Without energy and chemical additives, ordinary distillation may not generate the proportions of useful end-use petroleum products demanded in the economy. Along with crude oil availability and refining capacity, this is one factor that affects seasonal variations in the pricing of refined petroleum products.

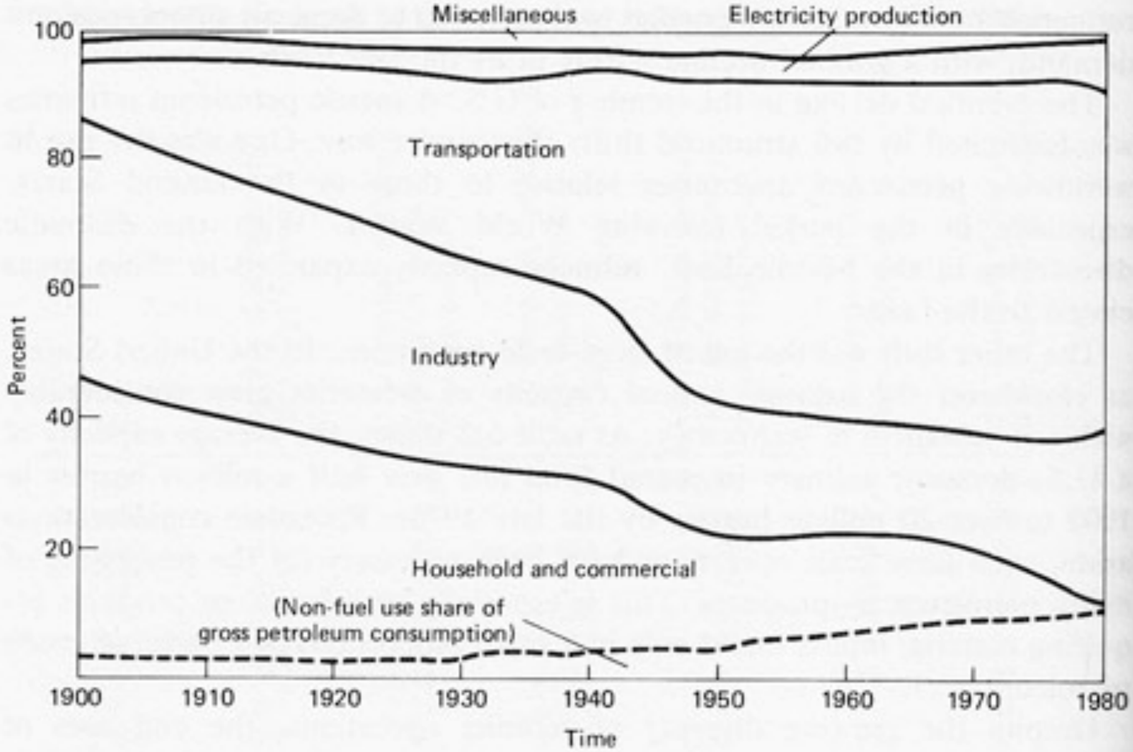

Figure 5.3. Sector Distribution of U.S. Petroleum Consumption, 1900–1980. Data from Department of Energy, Energy Information Administration, *Monthly Energy Review*, 1974–80; Department of the Interior, *Energy Perspectives 2*; and Department of Commerce, Bureau of the Census, *Historical Statistics, Colonial Times to 1970*, vol. 1.

Natural Gas Resources

For many end-uses, natural gas is a close substitute for petroleum. In the industrial and commercial sectors, the elasticity of substitution may be one or greater, for example.

Natural gas is often a discovered byproduct of petroleum exploration, even though some exploration results in one or the other type of deposit. While refined petroleum products can be distributed through pipelines, storage tanks, and in terms of delivered containers, natural gas may required pressurization into a liquefied natural gas form for an economical distribution system.

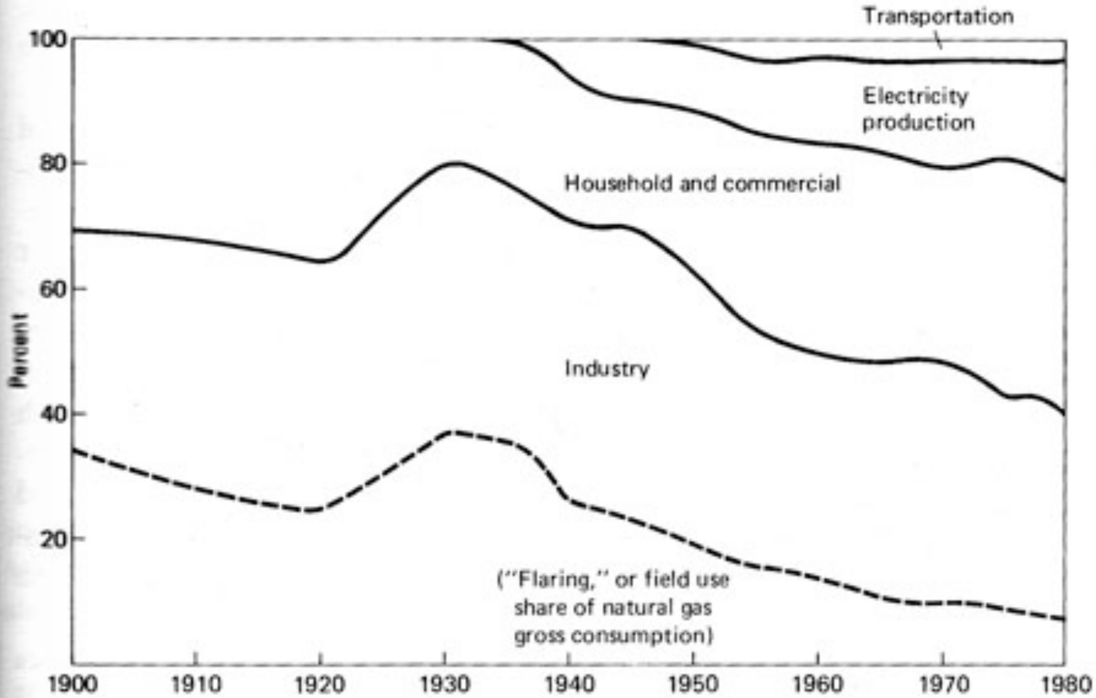

Figure 5.4. Sector Distribution of U.S. Natural Gas Consumption, 1900–1980. "Flaring" includes pumping, extraction, field losses, and plant fuel uses. Data from Department of Energy, Energy Information Administration, *Monthly Energy Review*, 1974–80; Department of the Interior, *Energy Perspectives 2*; and Department of Commerce, Bureau of the Census, *Historical Statistics, Colonial Times to 1970*, vol. 1.

Natural Gas Resources

Natural gas is used primarily in industrial processes as well as in commercial and residential heating and cooking. Although liquefied natural gas technologies have enabled some applications in transportation, notably in urban mass transit bus systems, it generally has not found widespread use as a substitute for refined gasoline and diesel fuels for trucks and individual automobiles. It does compete economically with refined petroleum in electricity generation, but both refined petroleum fuel and natural gas tend to be more expensive in comparison to coal, and, in several cases, in comparison to selected renewable energy technologies.

Coal Resources

Coal is a relatively more abundant natural resource. However, in its naturally mined state it often contains concentrations of sulfur and other particulates that add considerably to environmental pollution. As a result, it has generally not functioned widely as a source of household heating and cooking energy as it once did, and since in its solid form, it has but limited use in several manufacturing processes (notably as a primary natural resource in steel refining), it has been used increasingly as a primary resource in the generation of electricity, especially in rapidly growing economies such as China and India.

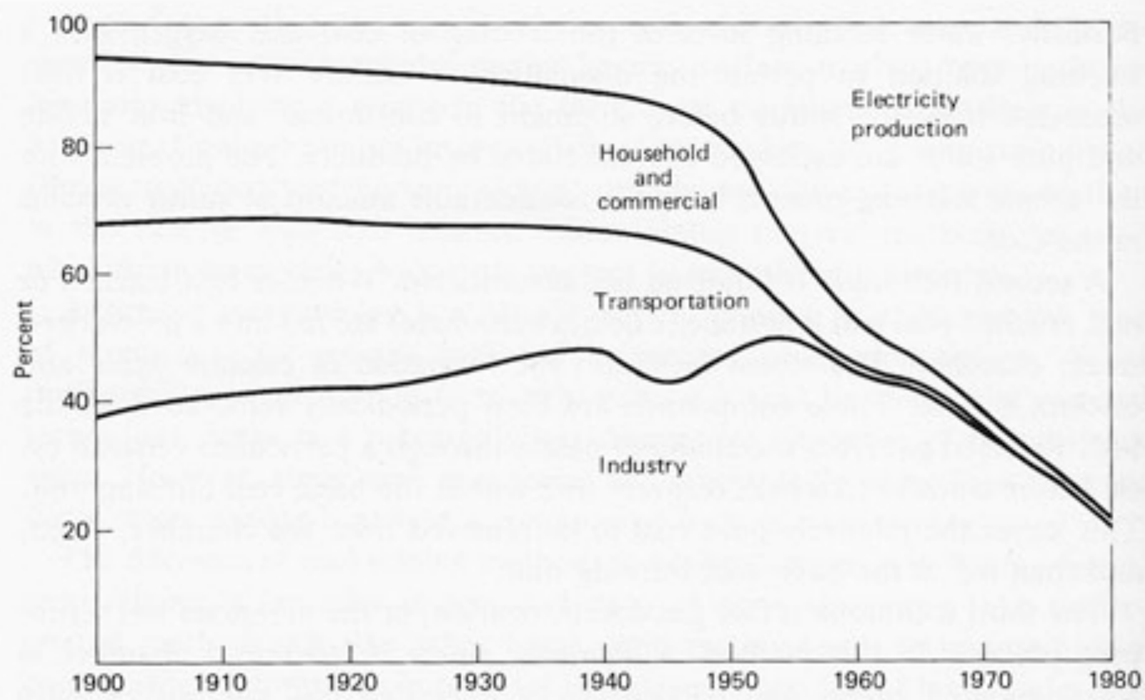

Figure 5.6. Sector Distribution of U.S. Coal Consumption, 1900–1980. Data from Department of Energy, Energy Information Administration, *Monthly Energy Review*, 1974–80; Department of the Interior, *Energy Perspectives 2*; and Department of Commerce, Bureau of the Census, *Historical Statistics, Colonial Times to 1970*, vol. 1.

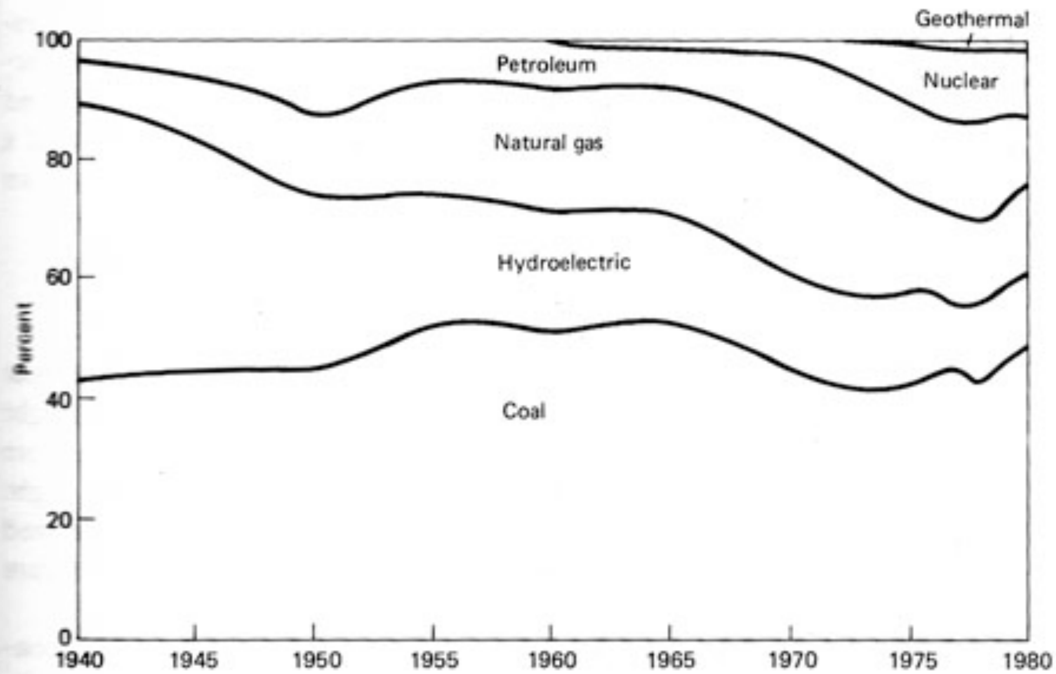

Figure 6.3. Frequency of Primary Energy Inputs in U.S. Electricity Production, 1940–80. Data from Federal Power Commission, *Consumption of Fuel for Production of Electric Energy* (Washington, D.C.: U.S. Government Printing Office, selected years); Department of Energy, Energy Information Administration, *Annual Report to Congress III* (1980); idem, *Monthly Energy Review*, September 1981; Department of the Interior, *Energy Perspectives 2*.

Fossil Fuel Conversion Technologies

Coal is a relatively more abundant natural resource. However, in its naturally mined state it often contains concentrations of sulfur and other particulates that add considerably to environmental pollution. As a result, it has generally not functioned widely as a source of household heating and cooking energy as it once did, and since in its solid form, it has but limited use in several manufacturing processes (notably as a primary natural resource in steel refining), it has been used increasingly as a primary resource in the generation of electricity, especially in rapidly growing economies such as China and India.

Coal Liquefaction and Gasification

To compete more effectively with refined petroleum and natural gas, technologies exist to convert coal into a liquid or gas form. Considerable energy is used in the conversion process with the result that the net energy efficiency tends to be less than that available through scarce primary petroleum or natural gas resources.

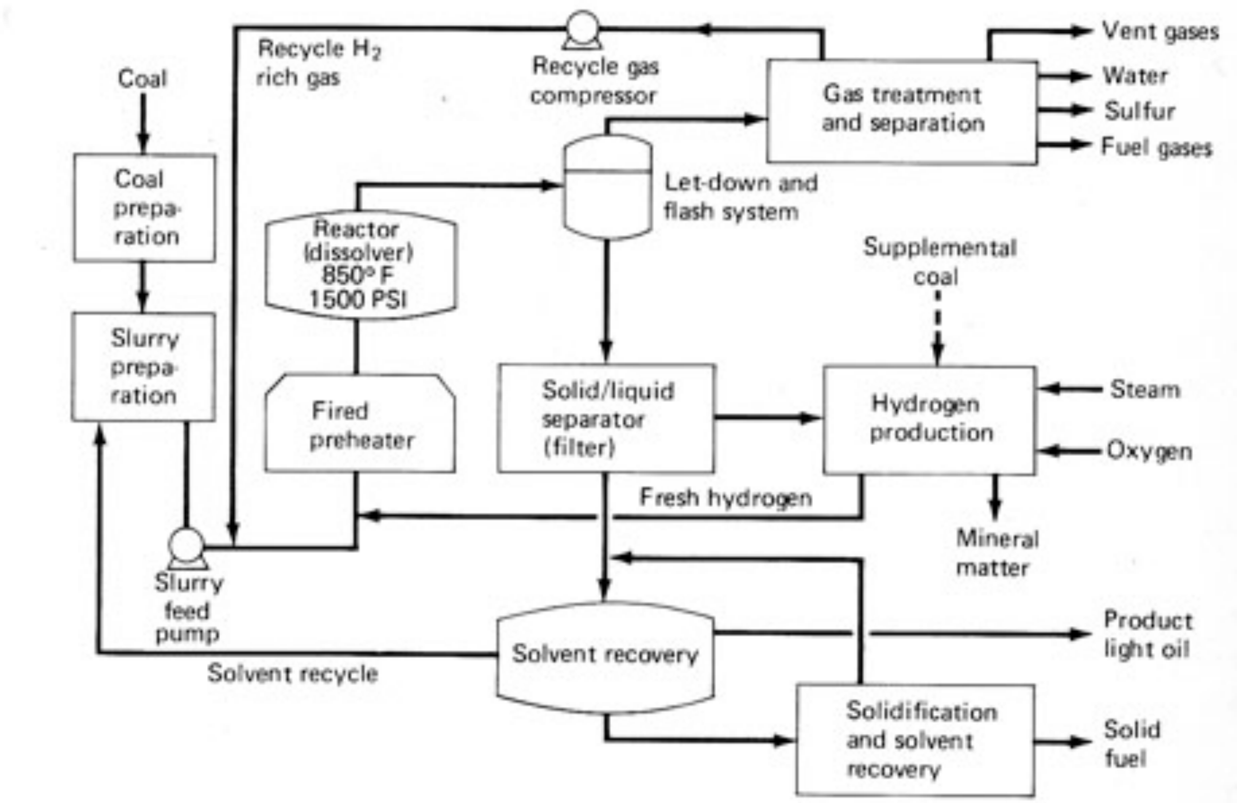

Figure 5.7. Solvent-Refined Coal Liquefaction Technology. Adapted from President's Commission on Coal, *Coal Data Book* (Washington, D.C.: U.S. Government Printing Office, February 1980), p. 181.

Shale Oil Resources

One fossil fuel resource that exists in relative abundance in nature is shale oil. Crude oil is embedded in shale rock deposits and in order to extract usable fuel, some form of separation must first be undertaken prior to refining of the residual crude oil. The figure below illustrates the general technology of how this is accomplished.

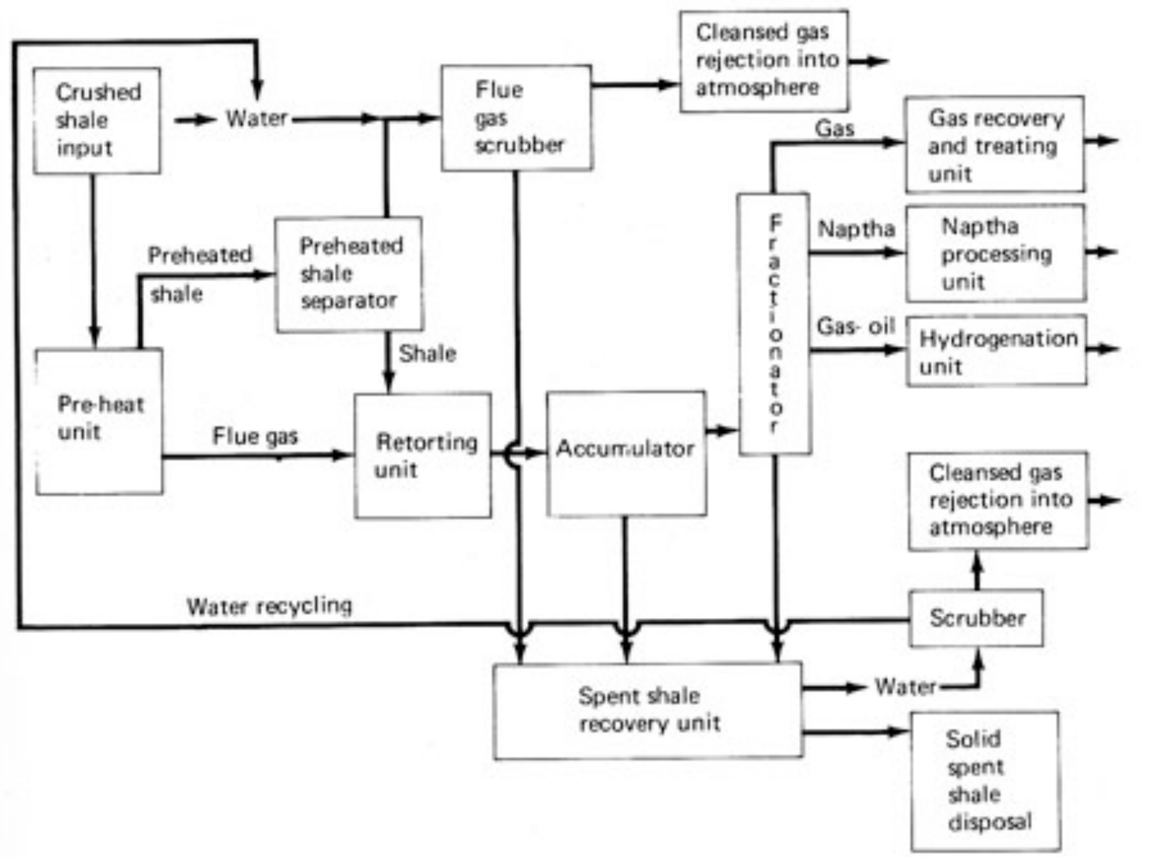

Figure 5.8. Shale Oil Basic Conversion Technology. Adapted from T. F. Yen, *Science and Technology of Oil Shale* (Ann Arbor: Ann Arbor Science Publishers, 1976), p. 48; and T. Healy, *Energy and Society* (San Francisco: Boyd and Fraser Publishing Co., 1976), p. 109.

Fossil Fuel Reserves

From this brief overview of fossil fuel resources and technologies, let us now take stock of known and ultimate reserves in the world. As can be seen in the figure below, present proven reserves represent less than one percent (0.22%) of ultimately recoverable reserves. As world consumption of lower entropy resources such as petroleum, natural gas, and coal proceed, the economic value of such naturally more abundant resources as shale oil will increase. However, whether in fact such a transformation occurs depends on the relative competitiveness of non-fossil natural resources such as nuclear and renewable natural resources, and on the technical efficiency of energy conversion technologies.

Known Recoverable Reserves

	Standard Units	Quads	Btu Distribution
Petroleum	566.0	3,225	9.47%
Natural Gas	2,230.0	2,299	6.75%
NGL	363.0	1,456	4.28%
bitumens	26.7	108	0.32%
Coal	651.7	14,858	43.65%
Shale Oil	8,612.0	10,352	30.41%
Tar Sands	300.0	1,740	5.11%
Total		34,038	

Ultimately Recoverable Reserves

	Standard Units	Quads	Btu Distribution
Petroleum	2,000.0	11,600	0.07%
Natural Gas	13,000.0	13,403	0.08%
NGL	2,120.0	8,503	0.05%
bitumens	160.2	643	0.00%
Coal	11,850.0	270,186	1.71%
Shale Oil	2,676,011.0	15,520,863	98.06%
Tar Sands	600.0	3,480	0.02%
Total		15,828,678	

Source: P. LeBel, *Energy Economics and Technology* (Baltimore, Md.: The Johns Hopkins University Press, 1982), pp. 132-133.

Nuclear Energy Resources

Commercial nuclear energy first emerged from the discovery of nuclear fission that was used to produce the first atomic weapons during the Second World War. During the 1950's, the United States began a program of developing commercial applications of nuclear technology, the principal form of which has been the use of refined uranium to produce commercial electricity. (It also has been applied as a generating source of electricity for submarines, cruisers, and aircraft carriers in various navies around the world).

The key to nuclear energy resources is found in the curve of binding energy, which portrays the density of potential energy in natural elements as a function of the underlying stability. If an element contains relatively high concentrations of useful energy, then the process of fission can release sufficient heat energy to generate steam that is used to produce electricity. The curve of binding energy is illustrated below.

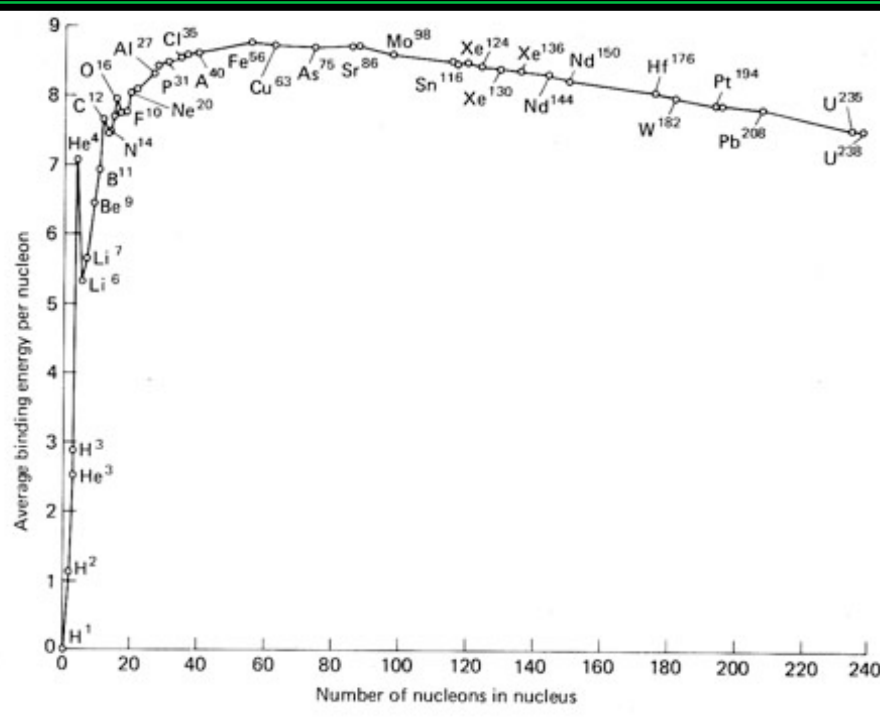

Figure 6.1. The Curve of Binding Energy. Adapted from Richard Wilson and William J. Jones, *Energy, Ecology, and the Environment* (New York: Academic Press, 1974), p. 146.

The Nuclear Fuel Cycle

Like coal, uranium exists as a mineral that is mined. In some countries such as Niger, it is found in sufficient quantities as to be able to supply a major proportion of the primary fuel used in the nuclear fuel cycle for a country such as France. (France generates over 80 percent of all of its electricity consumption through commercial nuclear reactors, and most of the natural uranium is imported form such countries as Niger).

There are several steps involved in uranium refining, as illustrated below. One problem is that the nuclear fuel cycle can be readily adapted for the production of nuclear weapons, the difference being the degree of concentration of fissile material used in weapons as opposed to a commercial nuclear reactor. This is one reason why the International Energy Agency (IEA) has been created, as an instrument to help monitor stocks and flows of the nuclear fuel cycle in various countries. It has not, however, solved the problem of nuclear proliferation, except by multinational agreements on both arms reductions, by controls universally agreed to over the nuclear fuel cycle, and by adoption of a nuclear fuel cycle inspection system. (Some countries such as South Africa and Libya have pursued nuclear processing technology but have since abandoned efforts to do so while other countries such as North Korea and Iran have continued efforts to establish domestic capacity for complete nuclear fuel cycle processing capacity).

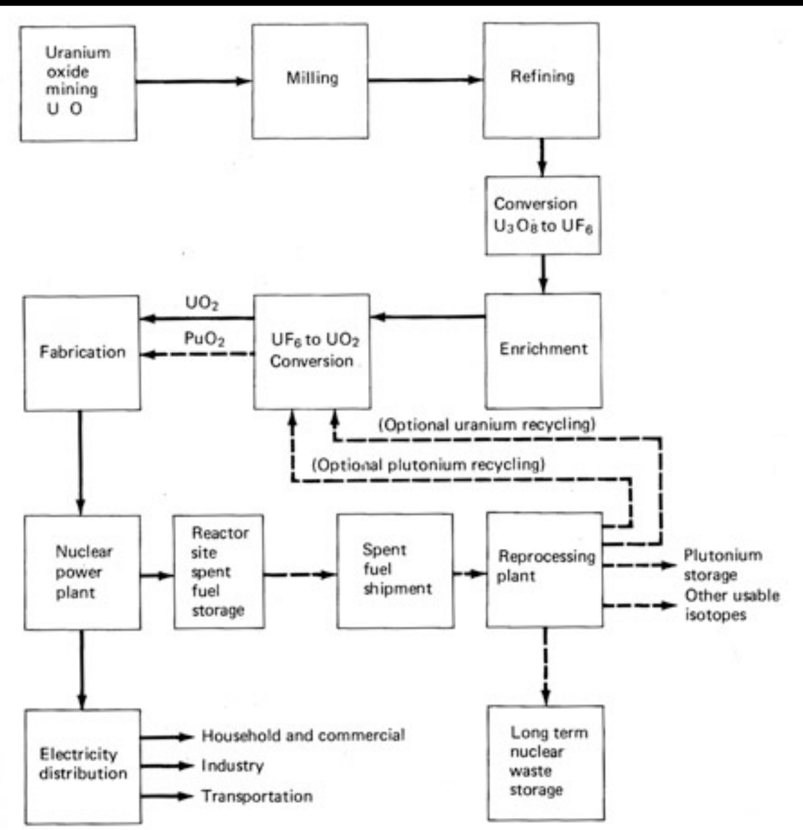

Figure 6.2. The Nuclear Fuel Cycle. Adapted from S. S. Penner, ed., *Energy and Energy Policies*, vol. 3 (Reading, Mass.: Addison-Wesley Publishing Co., 1976), p. 81.

Commercial Nuclear Reactors

All commercial nuclear reactors operate through the insertion of enriched fuel rods into a core and through whose controlled rates generate heat that generates sufficient steam to operate an electric generator turbine. There are several varieties of commercial nuclear reactors shown below: light water reactors, gas cooled reactors, heavy water reactors, and breeder reactors.

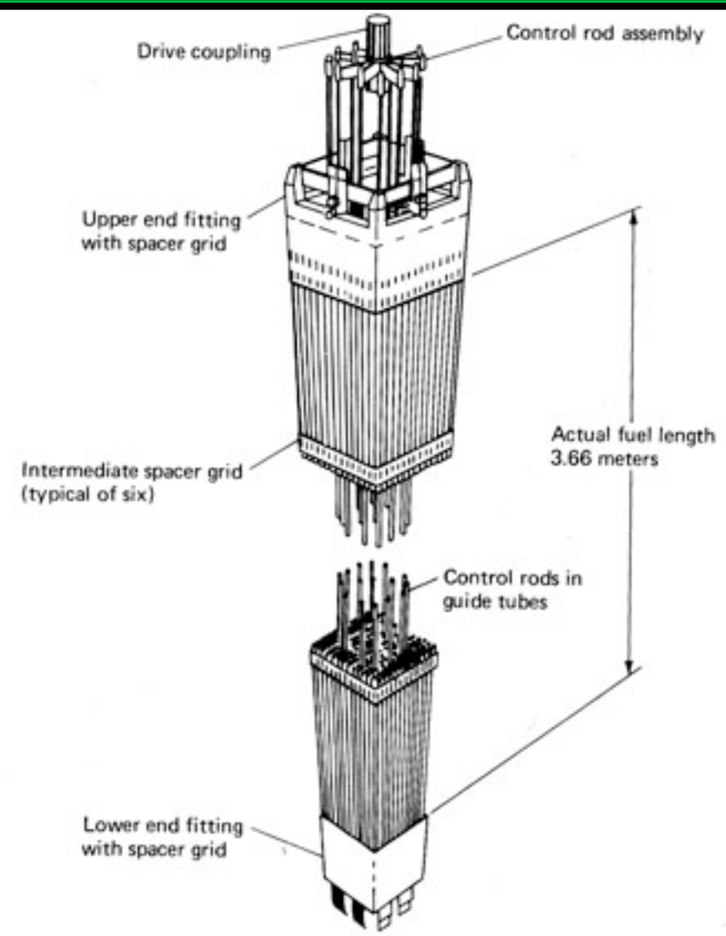

Figure 6.5. The Structure of a Nuclear Assembly Core. A single fuel rod may contain around 250 fuel pellets. Forty-nine fuel rods constitute an assembly, and several hundred assemblies are joined to form the reactor core. A typical 1,000-megawatt reactor may contain as much as a ton of fuel in some 8 million fuel pellets joined in 30,000–40,000 fuel rods. Adapted from *The Environmental Impact of Electric Power Generation: Nuclear and Fossil* (Harrisburg, Pa.: Pennsylvania Department of Education, 1973), reproduced in J. M. Fowler, *Energy and the Environment* (New York: McGraw-Hill, 1975), p. 277.

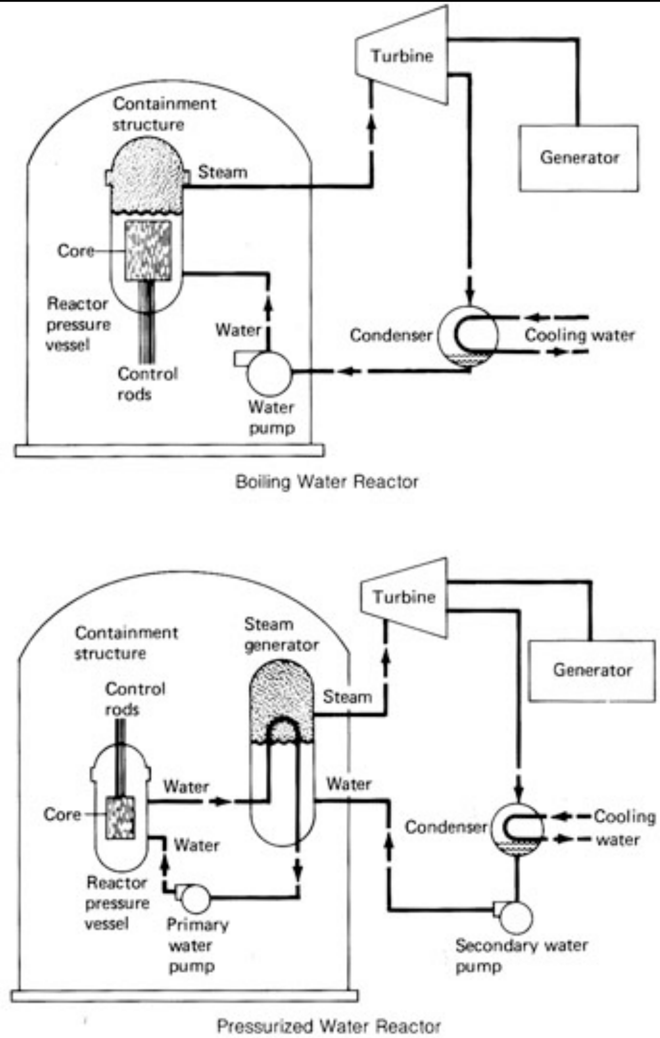

Figure 6.6. The Structure of a Light Water Reactor. *Top*, the boiling water reactor power system; *bottom*, the pressurized water reactor power system. Adapted from Spurgeon M. Keeny, Jr., *Nuclear Power Issues and Choices*, Report of the Nuclear Energy Policy Study Group (Cambridge, Mass.: Ballinger Publishing Co., 1977), pp. 394–95.

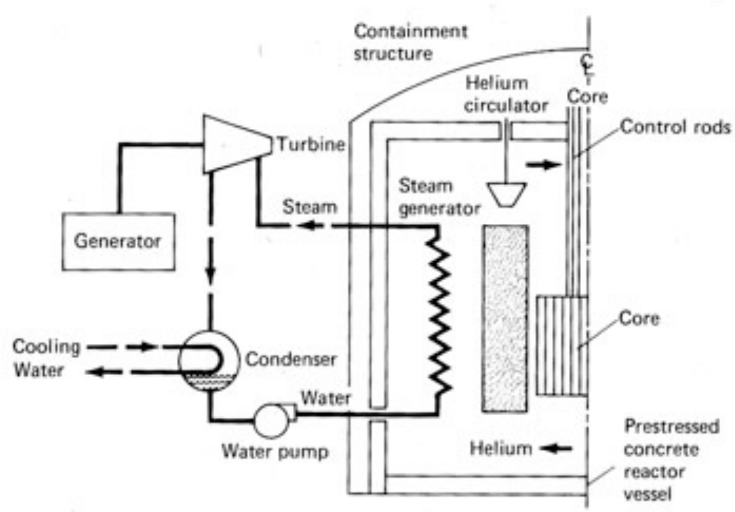

Figure 6.7. The Structure of a High-Temperature Gas-Cooled Reactor. Adapted from Keeny, *Nuclear Power Issues and Choices*, p. 397.

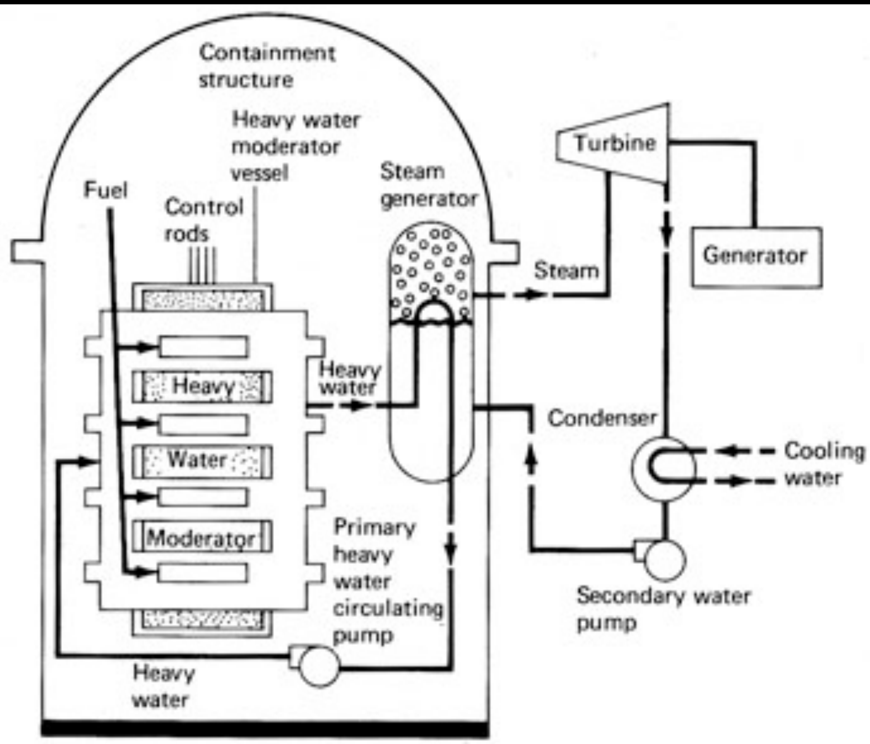

Figure 6.8. The Structure of a Heavy Water Reactor. Adapted from Keeny, *Nuclear Power Issues and Choices*, p. 396.

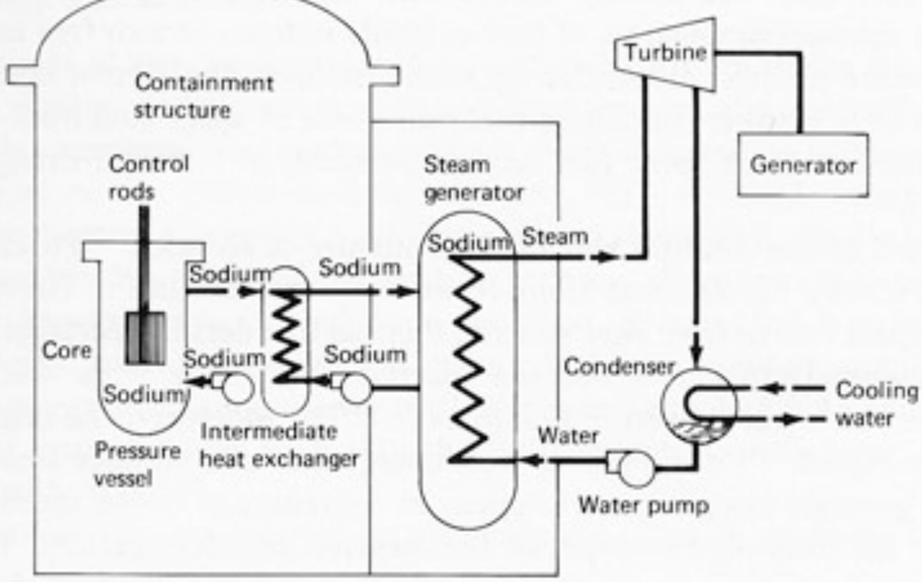

Figure 6.9. The Structure of a Liquid-Metal Fast Breeder Reactor. Adapted from Keeny, *Nuclear Power Issues and Choices*, p. 398.

Environmental Dimensions of Exhaustible Natural Resource Use

Exhaustible resource transformations into usable end forms carry inevitable consequences on the environment. We look at some of the ways they take place, which constitutes the foundation for incorporating shadow price estimates into the evaluation of alternative investment choices.

Beyond wastage in extraction and refining, one major source of environmental emissions is in central electricity generation technologies, shown here in the figure below, followed by estimates of various types of environmental impact estimates.

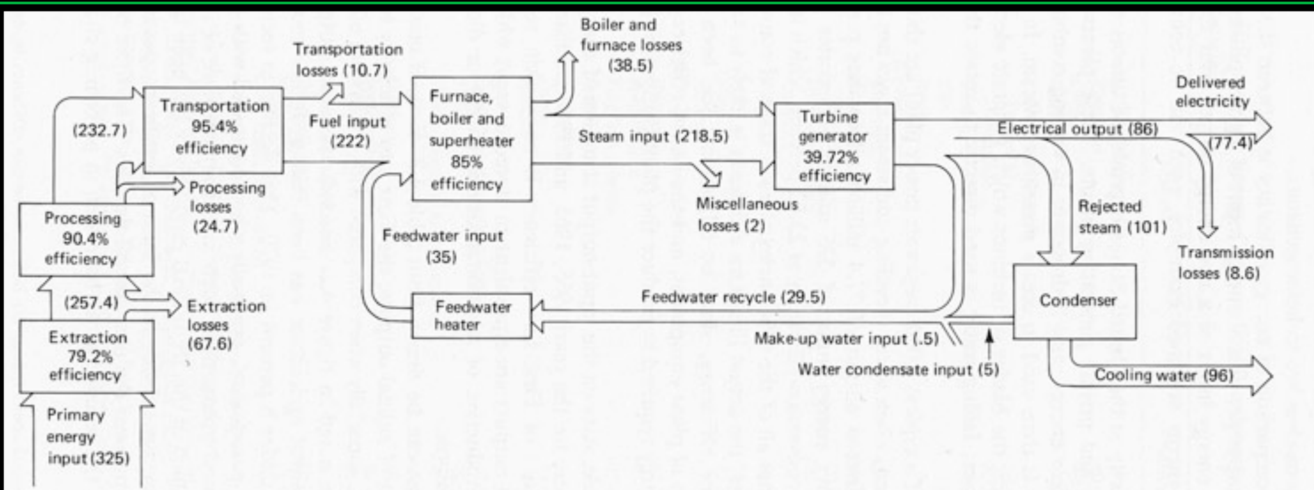

Figure 4.2. The Input-Output Structure of Large-Scale Electrical Power Generation. The figure is based on a modern, 1,000-megawatt coal-fired plant. All energy flows are shown in millions of kilocalories per hour. Adapted from Earl Cook, *Man, Energy, Society* (San Francisco: W. H. Freeman and Co., 1976), p. 37.

Table 6.3. Comparative Environmental Impact of 1,000-Megawatt Electric Energy Systems

	Air Emissions			Water Discharges				Solid Waste			Land Use		Occupational Health	
System[a]	Tons (× 10^3)	Curies (× 10^3)	Severity[b]	Tons (× 10^3)	Curies (× 10^3)	Btu's (× 10^{13})	Severity[b]	Tons (× 10^3)	Curies (× 10^3)	Severity[b]	Acres (× 10^3)	Severity[b]	Deaths	Workdays lost (× 10^3)
Coal														
Deep-mined	383.0	—	5	7.33	—	3.05	5	602	—	3	29.4	3	4.00	8.77
Surface-mined	383.0	—	5	40.50	—	3.05	5	3,267	—	5	34.3	5	2.64	3.09
Oil														
Onshore	158.4	—	3	5.99	—	3.05	3	—	—	1	20.7	2	0.35	3.61
Offshore	158.4	—	3	6.07	—	3.05	4	—	—	1	17.8	1	0.35	3.61
Imports	70.6	—	2	2.52	—	3.05	4	—	—	1	17.4	1	0.06	0.69
Natural gas	24.1	—	1	0.81	—	3.05	2	—	—	0	20.8	2	0.20	1.99
Nuclear	—	489	1	21.30	2.68	5.29	3	2,620	1.4	4	19.1	2	0.15	0.27

Source: Council on Environmental Quality, *Energy and the Environment* (Washington, D.C.: U.S. Government Printing Office, 1974), p. 14.
[a]Operating at a 0.75 load factor with low levels of environmental control or with generally prevailing controls
[b]0 = none, 1 = negligible, 2 = small, 3 = moderate, 4 = significant, 5 = serious

Environmental Dimensions of Nuclear Energy Consumption

Table 6.4. Fission-Product Radioisotopes

Element	Atomic Number	Half-life	Radiation Emitted[a]
Iodine-129	53	17,000,000 yrs.	β, γ
Technetium-99	43	500,000 yrs.[b]	e^-, $\gamma \rightarrow \beta$
Plutonium-239	94	24,300 yrs.	α, β, γ
Carbon-14	20	5,580 yrs.	β
Cesium-137	55	30 yrs.	β,γ
Strontium-90	38	29 yrs.	β
Plutonium-241	94	13 yrs.	α, β, γ
Krypton-85	36	9.4 yrs.[c]	e^-, β, $\gamma \rightarrow \beta$, γ
Promethium-147	61	2.3 yrs.	β
Cerium-144	58	1.6 yrs.	β, γ
Ruthenium-106	44	1.0 yr.	β
Zirconium-95	44	65 days	β, γ
Strontium-89	38	54 days	β
Ruthenium-103	44	39.8 days	β, γ
Niobium-95	41	35 days[d]	$e^- \rightarrow \beta$, γ
Tellurium-129	52	34 days[e]	β, γ
Cerium-141	58	32.5 days	β, γ
Praseodynium-143	59	13.8 days	β, γ
Barium-140	56	12.8 days	β, γ
Iodine-131	53	8 days	β, γ
Zenon-133	54	5.3 days[f]	e^-, $\beta \rightarrow \beta$, γ
Lanthanum-140	57	40 hrs.	β, γ
Rhodium-103	45	57 mins.	e^-
Praseodynium-144	59	17 mins.	β
Rhodium-106	45	30 secs.	β, γ

Source: Adapted from Clark Goodman, "Science and Technology of the Environment" (Houston: University of Houston, 1972), reprinted in John M. Fowler, *Energy and the Environment* (New York: McGraw-Hill, 1975), p. 479.

[a] e^- = internal electron conversion; α = alpha particles, for elements with atomic number ≥ 82; β = beta particles, or fast electrons; γ = gamma rays

[b] Preceded by 5.9 hours of isomeric internal transition

[c] Preceded by 4.4 hours of isomeric internal transition

[c] Preceded by 90 hours of isomeric internal transition

[e] Isomeric internal transition, followed by a 72-minute half-life

[f] Preceded by 2.3 days of isomeric internal transition

Table 6.5. Estimates of Annual Whole-Body Dose Rates in the United States, 1970

Source of Radiation	Average Dose Rate[a] (millirems per year)
Natural	
Environmental	
Cosmic radiation	45.0 (30.0–130.0)
Terrestrial radiation	60.0 (30.0–115.0)[b]
Internal radioactive isotopes	25.0
Subtotal	130.0 (61.9%)
Man-made	
Environmental	
Global fallout	4.0
Nuclear power	0.003[c]
Medical	
Diagnostic	72.0
Radiopharmaceuticals	1.0
Occupational	0.8
Miscellaneous	2.0
Subtotal	80.0 (38.1%)
Total	210

Sources: Spurgeon M. Keeny, Jr., *Nuclear Power Issues and Choices*, Report of the Nuclear Energy Policy Study Group (Cambridge, Mass.: Ballinger Publishing Co., 1977), p. 163; National Academy of Sciences, "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation," Report of the Advisory Committee on the Biological Effects of Ionizing (Washington, D.C.: NAS, 1972); and Klement et al., "Estimates of Ionizing Radiation Doses in the United States, 1960–2000," U.S. Environmental Protection Agency (Washington, D.C.: U.S. Government Printing Office, 1972).

Note: Values in parentheses indicate the range over which average levels for different states vary with elevation.

[a] The dose rate is the annual amount of radiation due to all preceding nuclear power generation activities; the dose commitment is the total amount of radiation eventually delivered, over an assigned period of time, due to a given amount of electricity generated by nuclear means

[b] The range of variation is attributable largely to geographic difference in the content of potassium-40, radium, thorium, and uranium in the earth's crust

[c] This figure rose to about 0.023 millirems per year in 1975

Conclusions

Whether fossil or nuclear, exhaustible resources generally have low entropy levels relative to many renewable resource alternatives.

Higher energy conversion efficiencies can be achieved with new capital designs, but none can eliminate entirely environmental emissions.

Market prices and prevailing positive rates of discount create a bias in favor of exhaustible natural resources over renewable ones.

Correcting for various forms of market failure arising from negative externalities can narrow the competitive gap between exhaustible and renewable resources. Yet market-based discount rates still leave a significant gap in terms of potentially more rapid transition to new forms of renewable resource technologies.

The choice of an appropriate rate of discount for natural resource technologies inevitably raises the question of sustainability in the management of natural resources, leaving open various paths for each society to determine what is socially optimal.