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FORMATION AND CONSUMPTION RATES OF MAJOR ENERGY SOURCES

by

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Report No. 77CRD005 March 1977

TECHNICAL INFORMATION SERIES

CLASS 1

GENERAL ELECTRIC

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General Electric Company
Corporate Research and Development
Schenectady, New York

TECHNICAL INFORMATION SERIES

AUTHOR Wentorf, RH, Jr	SUBJECT energy sources and uses	NO. 77CRD005 DATE March 1977
TITLE Formation and Consumption Rates of Major Energy Sources		GE CLASS 1 NO. PAGES 10
ORIGINATING COMPONENT Power Systems Laboratory		CORPORATE RESEARCH AND DEVELOPMENT SCHENECTADY, N.Y.

SUMMARY

Many sources of useful energy are available to mankind. Estimates of the rates of production and consumption of energy resources are presented. The carbonaceous fossil fuels are being used faster than they are being formed. Of the renewable sources, wood and water are already fairly well utilized and should not be expected to make a major contribution to future sources. Geothermal, wave, and tidal power sources are relatively small and localized. A wind-powered electrical network could be a significant contributor, but improvements in windmills to use high winds are needed. Direct sunshine could supply significant energy for space heating. Coal, oil shale, and uranium are sufficiently abundant to warrant strong development programs for these sources. The increasing cost of energy will probably force changes in life styles. The current number of people is probably not too small.

KEY WORDS

energy, wind, solar, hydroelectric, geothermal, fuels, coal, gas, oil, shale, uranium, wood, population

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FORMATION AND CONSUMPTION RATES OF MAJOR ENERGY SOURCES

R.H. Wentorf, Jr.

I. INTRODUCTION

The estimates made in this report were prepared as part of an invited talk on energy given at Mount Holyoke College on November 3, 1976. The talk also contained some discussion of entropy as well as likely changes in life styles forced by higher costs for available energy.

A summary of the estimates appears in Tables I through IV. Production and consumption rates are expressed in megawatts (MW), with thermal energy considered the equal of mechanical energy. (It is not nature's fault if men burn fuel to make the same mechanical work that wind and water can provide.) "Production" means new material created on the earth, not pumping or digging out what already exists. "Consumption" means what is dug, pumped, or harvested from the earth and deliberately used by mankind in processes which involve active participation by humans. Therefore, not counted in "consumption" are certain passive processes such as lying in the sunshine, ordinary greenhouses, etc. which go on anyway simply because these things are outside. However, the special collection and storage of solar heat for buildings would be considered "consumption."

In parentheses under the major consumption figures are the percentages which the particular sources supply of the total consumption from all sources, excluding direct sunlight.

Tables I through III also give resource lives or periods of use in years, based on current consumption rates for that resource, and also at rates needed for the particular resource to supply one-third of total current energy resource consumption. The aim is to get some idea of how long we can count on a particular resource at a particular rate. For a fossil fuel, the life is the deposit divided by the consumption rate. For a dynamic source like wind, the life is indefinitely long, but only so much wind is available each year. For a steady-state source like biogas, the production rate does not permit it to supply one-third of current consumption--only about 2%.

An annual fractional increase of f in consumption rate C means that the total resource R will be consumed in n years according to the expression for the sum of a power series:

$$R = C[(1+f)^n - 1]/f.$$

Some people express f in percent and call it a growth rate.

Table V lists values of n for selected values of R/C and f. Thus, for example, what one would consider a 50-year resource at today's rate would last 28 years at a 4% growth rate, which is considered typical for energy consumption growth these days. Doubling the size of the resource (to 100 years at today's rate) extends the time to depletion by 13 years, to 41 years. (The doubling time at 4% growth is ln 2/ln 1.04 = 17.7 years = 0.7/0.04.) Evidently the process of exponential growth of material things ultimately ceases.

We note the following relationships:

1 Btu/sec = 1.055 kW
1 year = 3.156×10^7 sec
10^{15} Btu/year $= \dfrac{10^{15} \cdot 1.055}{3.15 \times 10^7 \times 10^3} = 3.34 \times 10^4$ MW
1 bbl oil = 42x142,000 = 6×10^6 Btu
1 ton coal = 2000x12,000 = 24×10^6 Btu
1 g ^{238}U = 7.78×10^7 Btu (in reactor)
= 7.8×10^4 MW-s
1 kcal = 1.163×10^{-3} kW-hr = 3.968 Btu
1 lb of wood = 7000 Btu

II. CALCULATION OF ESTIMATED QUANTITIES AND NOTES THEREON

A. Sunlight on Land, 60°N to 60°S

Land area of earth	148.85×10^6 km^2 (29%)
Ocean area of earth	361.25×10^6 km^2 (71%)
Average radius of earth	6371 km
Area of disk	$\pi r^2 = 127,516,118$ km^2
Consider 0.80 of this as	60°N-60°S
Effective land area thus	$\sim 0.8 \times 0.29 \times 6371^2 \pi$
	$= 29.6 \times 10^6$ km^2

Average cloud cover is 52%; clear solar input is 880 W/m^2; cloudy, 120 W/m^2.

Average	500 W/m^2 or 500 MW/km^2

Total solar input to earth's habitable land thus is approximately:

$500 \times 29.6 \times 10^6 = \underline{14.8 \times 10^9 \text{ MW}}$

U.S. 48 Continental states	8×10^6 km^2
Ratio of disk/sphere is	$\pi/4\pi = 1/4$
24-hour effective area	2×10^6 km^2 at 500 MW/km^2
U.S. insolation	$2 \times 10^6 \times 500 = \underline{10^9 \text{ MW}}$

In 1975 there were 135 solar-heated houses in the U.S. If each one absorbed the equivalent of 10 bbl oil or 60×10^6 Btu, for a grand total of 8.1×10^9 Btu, this is 2.7×10^{-2} MW. Triple this to account for backyard

Manuscript received December 20, 1976.

TABLE I

	PRODUCTION (MW)		CONSUMPTION (MW)		RESOURCE LIFE AT CURRENT CONSUMPTION OF THAT RESOURCE		RESOURCE LIFE, TO SUPPLY 1/3 CURRENT TOTAL ENERGY RESOURCE CONSUMPTION	
	WORLD	USA	WORLD	USA	WORLD	USA	WORLD	USA
Sunlight on Land 60°N - 60°S	$15x10^{9}$	$1.0x10^{9}$	$<10^{2}$ (unnatural use)	<10	∞	∞	∞	∞
Carbohydrate, Cellulose, etc. on Land	$2-7x10^{7}$	$1-4x10^{6}$	$2.2x10^{6}$ (20%)	10^{5} (3%)	1-∞	∞	∿20% max	∞
Food	$1.5x10^{6}$	$3.7x10^{5}$	$1.5x10^{6}$	$3.5x10^{5}$	0.1-0.2	0.2-1	NA	NA
Biogas	$\sim 8x10^{5}$	$\sim 4x10^{4}$	$\sim 10^{4}$?	$\sim 10^{3}$?	∞	∞	∿2% max	∿2% max
Wind (land)	$>2x10^{7}$	$>10^{6}$	∿10	∿1	∞	∞	∞	∞

TABLE II

	PRODUCTION (MW)		CONSUMPTION (MW)		RESOURCE LIFE AT CURRENT CONSUMPTION OF THAT RESOURCE		RESOURCE LIFE, TO SUPPLY 1/3 CURRENT TOTAL ENERGY RESOURCE CONSUMPTION	
	WORLD	USA	WORLD	USA	WORLD	USA	WORLD	USA
Coal	80?	4?	$17x10^{5}$ (15%)	$5.3x10^{5}$ (18.5%)	4000	1300	2000	650
Petroleum	4.4	1	$4.1x10^{6}$ (37%)	$1.24x10^{6}$ (43.5)	50	11-15	50	15-20
Oil Shale Tar Sands	1	0.1	4? (<1%)	2? (<1%)	$187x10^{6}$	$46x10^{6}$	50-200	100
Gas	5	1	$2.1x10^{6}$ (18.7)	$8.3x10^{5}$ (29.5)	30-150	10-45	17-85	9-40

TABLE III

	PRODUCTION (MW)		CONSUMPTION (MW)		RESOURCE LIFE AT CURRENT CONSUMPTION OF THAT RESOURCE		RESOURCE LIFE, TO SUPPLY 1/3 CURRENT TOTAL ENERGY RESOURCE CONSUMPTION	
	WORLD	USA	WORLD	USA	WORLD	USA	WORLD	USA
Hydroelectric	$\sim 10^{6}$ (E)	$\sim 10^{5}$ (E)	$4x10^{5}$ (3%)	$2.8x10^{4}$ (1%)	100	100	∿4% max	∿4% max
Wave, Tide	$\sim 10^{5}$	$\sim 3x10^{3}$	500 (<1%)	∿0			0.1% max	0.1% max
Geothermal	$7x10^{6}$	$<3.8x10^{5}$	$2x10^{3}$ (<1%)	10^{3} (<1%)	100	100	1.5% max	1.5% max
Radiation U, Th, K	$<7x10^{6}$	$3.8x10^{5}$	$2x10^{5}$ (E) (2%)	10^{5} (E) (2%)	∿187	∿187	∿20 Depends on Ore	∿20
Pu (man-made)	$\sim 7x10^{4}$	$3.5x10^{4}$	$\sim 2x10^{4}$	$\sim 10^{4}$	$\sim 10^{4}$	10^{4}	∿1000	∿1000

TABLE IV

	TOTAL PRODUCTION MW (Excluding Direct Sunlight)		TOTAL CONSUMPTION MW (Excluding Direct Sunlight)	
	World	USA	World	USA
	$49\text{-}89\text{x}10^6$	$2.4\text{x}10^6$	$11.2\text{x}10^6$	$2.8\text{x}10^6$
KW Per Person	12-22	∿10	2.8	12
Entropy Rate Per Person			9.3	40 watt/°K

TABLE V

Values of n in $R = C[(1+f)^n-1]/f$

	f				
R/C	0.02	0.03	0.04	0.05	0.06
10	9.2	8.2	8.6	8.3	8.1
20	17	15.9	15.0	14.2	13.5
50	35	31	28	25.7	23.8
100	55.5	46.9	41	36.7	33.4
200	81.3	65.8	56	49.1	44
500	121	93.8	77.8	66.8	58.9
1000	153	116	94.7	81	70.6

experimenters, and triple it again for drying raisins, prunes, etc., to arrive at ~0.3 MW. So, <10 MW is probably close enough for the U.S.A. For the entire world we might multiply the U.S. figure by 17 on the basis of land area, 136/8 = 17 (omitting Antarctica, $12.5\text{x}10^6$ km^2), or population,

$$\frac{4\text{x}10^9}{2.25\text{x}10^8} = 17.8,$$

and arrive at an estimate of $\leq 10^2$ for deliberate solar energy use world-wide.

Obviously this resource will last indefinitely, either at the going rate or when supplying one-third of the total energy consumptions, which work out to be about $2.8\text{x}10^6$ MW for the U.S. and $11.2\text{x}10^6$ MW for the entire world. Presumably this one-third of consumption would be primarily for low-temperature heat for buildings, water, etc. Photovoltaic devices based on Si, etc. appear to be too expensive for large-scale electric power, but perhaps their costs (energy and monetary) can be made reasonably low.

B. Carbohydrate, Cellulose, etc.

This is essentially the net photosynthetic rate of land-based organisms and does not include ocean production, which one may take equal to that on land, although estimates of ocean production vary by tenfold, from half to five times that on land [Ref.: The Earth as a Planet, ed. by G. Kuiper, University of Chicago Press (1954), p. 380].

In the above reference, the net C fixed by world land photosynthesis is $15.1\text{x}10^{15}$ g/year which corresponds to using the atmospheric CO_2 once every 8.4 years. We shall see that human-related food production is about 10% of the total. The heat of combustion of glucose, $C_6H_{12}O_6$, is 673 kcal/g-mol or 673/72 = 9.35 kcal/gC (note for plain carbon, heat of combustion is 94/12 = 7.82). Thus, energy stored by photosynthesis becomes

$$\frac{1.055\text{x}9.35\text{x}15.1\text{x}10^{15}\text{x}3.968}{3.15\text{x}10^{10}} = \underline{18\text{x}10^6\ \text{MW}}.$$

Another estimate by Chancellor and Goss [Science 192, 213 (1976)] gives $534\text{x}10^{15}$ kcal/year for human use or

$$\frac{53.6\text{x}10^{15} \text{ x } 1.055 \text{ x } 3.968}{3.15\text{x}10^{10}} = \underline{71\text{x}10^6\ \text{MW}}.$$

In Energy Primer, Portola Institute, Menlo Park, Calif. (1974), p. 111, one finds $117\text{x}10^9$ tons/year or $52\text{x}10^6$ MW. Another estimate is based on a photosynthetic efficiency of 0.1% or 0.5 MW/km^2 on half the land area (not counting Antarctica, $12.5\text{x}10^6$ km^2)

$$0.5 \text{ x } 68\text{x}10^6 = \underline{34\text{x}10^6\ \text{MW}}.$$

(0.1% efficiency is typical for forest and grass not intensively cultivated.)

For the U.S.A., with 1/17 of the land area, the photosynthetic production would probably lie between 10^6 and $4\text{x}10^6$ MW. P.H. Kydd (General Electric TIS Report 72CRD190) estimates potentially recoverable photosynthetic fuel at $5\text{x}10^{16}$ Btu/year in the U.S.A. which is $1.68\text{x}10^6$ MW.

For the consumption of photosynthetic products, excluding food, we consider mainly wood used for lumber, paper, and fuel with small amounts of other crop residues such as sugar cane bagasse, beet pulp, corncobs, straw, etc. P.H. Kydd (72CRD190) and I.S. Goldstein [Science, 189, 847 (1975)] estimate the wood used for pulp in the U.S.A. at $100\text{x}10^6$ tons in 1970. Lumber was estimated at $50\text{x}10^6$ tons with scrap and sawdust amounting to about $15\text{x}10^6$ tons. This total of $165\text{x}10^6$ tons is $7.5\text{x}10^4$ MW.

On the other hand, the "Statistical Abstract of the United States, 1975," gives 62 ft^3 of wood consumed per capita, 34 for lumber, 23 for pulp, and only 2.4 ft^3 for firewood. At 30 lb/ft^3 average dry weight and $220\text{x}10^6$ people and 7000 Btu per lb, the wood consumption would be

$$\frac{62 \times 30 \times 220\times10^6 \times 7000}{3.15\times10^{10}} = 9\times10^4 \text{ MW.}$$

Cotton and rayon production was about 7.4x10^9 lb (Chem. Eng. News, April 16, 1973), which comes to

$$\frac{7.4\times10^9 \times 7000}{3.15\times10^{10}} = 1.65\times10^3 \text{ MW.}$$

Other miscellaneous uses of bagasse, beet pulp, etc. probably account for 3x10^3 MW.

Thus, one might estimate the total nonfood use of photosynthetic products at about 10^5 MW for the U. S. A., or ~3% of its annual energy consumption.

For the entire world, one could multiply the U. S. estimate by about 17 or 18 to arrive at about 2x10^6 MW, except that the rest of the world probably uses more firewood per capita. The 1975 world wood fuel consumption is estimated at 1.2x10^9 m^3 (Energy Primer, p. 160) which works out to be about 5x10^5 MW, or 25% of the estimated total vs 4% of the total for the United States. Thus one might raise the world estimate total to about 2.2x10^6 MW -- 20% of consumption.

C. Food Production

A crude world estimate is 4x10^9 people at 2700 kcal/day, including food animals, for

$$\frac{9\times10^9 \times 2.7\times10^3 \times 365 \times 3.968}{3.15\times10^{10}} = 5.0\times10^5 \text{ MW.}$$

Another estimate follows from reported world grain production of wheat, corn, and rice of about 2.2x10^{12} lb

$$\frac{2.2\times10^{12} \times 7\times10^3}{3.15\times10^{10}} = 4.9\times10^5 \text{ MW.}$$

If this is two-thirds of the total, the total would be about 7.4x10^5 MW.

To this we might add another 7.4x10^5 MW to account for animal fodder, bedding, etc., for a grand total of about 1.5x10^6 MW.

The U. S. production of food, including sorghum and hay and animal feed, was about 727x10^9 lb in 1974 (Statistical Abstract of the United States, 1975) with the principal contributors being corn, hay, and wheat:

$$\frac{727\times10^9 \times 7000}{3.15\times10^{10}} = 2.30\times10^5 \text{ MW.}$$

To this we could add pasture of ~600x10^6 acres at ~0.5 ton dry matter per acre-year for another

$$\frac{600\times10^6 \times 1000 \times 7000}{3.15\times10^{10}} = 1.33\times10^5 \text{ MW.}$$

Finally, straw and other bedding material for ~10^7 milk cows and other animals at ~1 ton each per year uses

$$\frac{10^7 \times 2000 \times 7000}{3.15\times10^{10}} = 0.45\times10^4 \text{ MW.}$$

Therefore, the grand total of green material used in the U. S. for human food, directly or indirectly, is about

$$3.67 \times 10^5 \text{ MW.}$$

The real total may be slightly larger because of local unrecorded growing of vegetables and fodder (e. g., what does a small farmer with a few cows care about reporting his harvest to the USDA?).

A big difference between U. S. agriculture and that practiced by most people in the world is that most U. S. bovines (14x10^7) eat grain and are grown to be eaten, while in the rest of the world most bovines or other draft animals eat grass and are grown to work, with human muscle supplying much of the rest of the power.

The world consumption of food is just about in balance with production, but the U. S. was a net exporter of about 103 million tons of agricultural items in 1974 or

$$\frac{103\times10^6 \times 10^3 \times 7000}{3.15\times10^{10}} = 2.3\times10^4 \text{ MW}$$

so that U. S. net consumption was about

$$3.7\times10^5 - 0.23\times10^5 = 3.5\times10^5 \text{ MW.}$$

We have considerable reserves of food, but the rest of the world is not so fortunate.

D. Biogas

The conversion of cellulose to methane + CO$_2$ proceeds with a thermal efficiency of about 77%. About 140 million tons of organic waste could be readily collected in the U. S. each year (Energy Primer, p. 112). Many times this amount is actually generated by photosynthesis; but part of it is necessary for continuing fertility of the soil and part of it is simply too diffuse to be worth collecting. Useful energy is required to collect the waste and process it, and return the sludge to the land, so that the net overall thermal efficiency could be around 50%.

$$\frac{140\times10^6 \times 0.5 \times 2000 \times 7000}{3\times10\times10^{10}} = 4\times10^4 \text{ MW}$$

Estimated world production would be about 17 to 20 times this, or about 8x10^5 MW.

Some sewage treatment plants and many farmers use biogas for heating, etc. already, but the attention and investment required to operate the process effectively limit its use, so that less than 10% of its potential is realized, and very approximate estimates of consumption are ~10^4 MW for the world and ~10^3 MW for the U. S.

Obviously, biogas would not be a large-scale source of fuel, but it can certainly be valuable in local or special situations.

E. Wind

Wind is a widespread, dilute energy resource. Accurate figures for the wind energy available in most locations are not available, but renewed interest in wind power is spurring the collection of more complete data (R. L. Thomas, NASA TM X-71890). Sørensen [Science 189, 255 (1975)] reports average wind energies over flat land in Denmark of 200 to 400 W per vertical m^2 (like a picture on a wall). The wind returns to its normal state 2 km beyond a mill 50 m high, so that about 0.025 of the land area is available for windmill area. A perfect mill would extract 59% of the wind energy and reduce the wind velocity to one-third original (Energy Primer, p. 77). The overall efficiency of real mills is about 33% (Sørensen; Energy Primer).

Heronemus writes (ChemTech, August 1976, p. 498) that the land areas of the world could support a practical wind energy system of 2×10^7 MW. This corresponds to a power density of about

$$\frac{2 \times 10^7}{1.30 \times 10^6} = 0.15\ \mathrm{MW/km^2} \text{ or } 0.15\ \mathrm{W/m^2}.$$

In Denmark the maximum practical power density using 33% mill efficiency, a mill/land area ratio of 0.020, and 200 W/m^2 wind energy would be

$$200 \times 0.020 \times 0.33 = 1.32\ \mathrm{W/m^2}.$$

The arithmetic average yearly winds at Dayton, Ohio, are about 10.7 mph or 4.8 m/s (Energy Primer, p. 78). Analysis of the data to find the average energy flux, which goes as the cube of the speed, indicates that the energy flux average wind speed is about 13 mph or 5.83 m/s. With an air density of 1.3 kg/m^3 the average flux becomes

$$0.5 \times 1.3 \times 5.83^3 = 129\ \mathrm{W/m^2}.$$

Most wind data are gathered at weather stations that are frequently located at airports. The wind velocities at airports are likely to be lower than those for good windpower sites, and 129 W/m^2 is probably a conservative estimate for an average useful flux in the 48 states. At 129 W/m^2, 33% mill efficiency and a mill/land area ratio of 0.020, the maximum usable power density would be

$$129 \times 0.33 \times 0.020 = 0.85\ \mathrm{W/m^2} \text{ or } 0.85\ \mathrm{MW/km^2}.$$

Thus, the entire 48 states equipped with windmills could extract about $8 \times 10^6 \times 0.85 = 6.8 \times 10^6$ MW of electric power. This is to be compared with an installed generating capacity of about 500,000 MW and an average electricity consumption of about 220,000 MW. Apparently the potential is about 30 times the consumption.

One wonders what would happen to the winds if -- say, 300,000 MW -- were extracted. Consider the dissipation of wind energy in trees. Assume that an average tree is 15 m high, 5 m wide, with an effective area vs the wind of about 50 m^2. Assume that trees are 80% permeable on the average, so that 20% of the air is stopped. Assume that such trees are spaced 50 m apart or 400 trees/km^2, that only one-eighth of the U. S. has such trees in the wind, and that the average wind is 5 m/s for energy flux purposes. Then total energy dissipation by wind in trees is about

$$50 \times 400 \times 8 \times 10^6 \times 0.125 \times 0.2 \times 0.5 \times 1.3 \times 5^3 \times 10^{-6} = 324{,}000\ \mathrm{MW}.$$

This estimate could be in error by about a factor of 2 either way but it supports one's intuitive feeling that it would be quite difficult to really bother the wind using 50 m windmills on a 2 km spacing.

The insolation heating on the U. S. surface is about 10^9 MW, but at least 10^8 MW is absorbed by the atmosphere and helps to drive the winds. In a sense, the winds form an engine running between about 200 °K and 300 °K and 5 °K as solar energy is absorbed and radiated. Heronemus points out that wind energy tends to flow from the upper air toward the surfaces on earth, where it is being dissipated, as one may note on gusty days -- the gusts result from vertical mixing. So the net effect of extracting, say, 300,000 MW of energy from the wind would be to reduce the wind dissipation in trees, etc. immediately downstream of the windmills. The overall effect would probably be environmentally benign since very few living things benefit from high winds. Of course, there would be no SO_2, CO_2, ash, etc. from windmills.

Windmills of about 1.5 MW are estimated to be the most economical (Thomas) with blade diameters of 60 to 70 m. On good sites one would expect average fluxes of at least 500 W/m^2, similar to good sites in Denmark (Sørensen). The average output for a 60 m mill would then be about

$$30^2\pi \times 0.33 \times 500 \times 10^{-6} = 0.46\ \mathrm{MW}.$$

To deliver 220,000 MW on demand would require about 470,000 such windmills, interconnected to send power to where the winds were temporarily inadequate. The transmission distances would be comparable with the radii of weather systems: about 200 miles. Some energy storage would also be valuable. Hilly terrain favors both good wind and water storage. If each mill cost $\$7 \times 10^5$ (Thomas) and 30,000 were built each year, the annual cost would be $\$21 \times 10^9$ or less than 20% of the defense budget. Imported oil at \$10/bbl and 2.1×10^9 bbl/year costs us $\$21 \times 10^9$/year today.

The main technical obstacles to the wider use of wind power are the development of mills which can use high winds and endure ice, snow, etc., and the selection of suitable sites.

F. Coal

Probably coal is being formed in several places in the world today, beginning as peat in colder climates where vegetable matter in the soil does not decay rapidly, or in various anaerobic mucks. Presumably most of the coal began to form about 290 million years ago in the Mississippian Period.

The world reserves of coal are estimated to be about 192×10^{18} Btu according to M. K. Hubbert [see W. Häfele, American Scientist 62, 438 (1974)]. The U. S. reserves are about 32×10^{18} Btu, which shows how extraordinarily lucky we are. If we assume that the real reserves are twice this size and that they formed at a fairly uniform rate for the past 150 million years only, so as to be four times conservative, we arrive at a current rate of formation of about

$$\frac{384\times10^{18}}{150\times10^{6}\times 3.15\times10^{10}} = 80\ \text{MW}$$

for the world and on the basis of area, about 5 MW for the U. S. A.

Currently coal is being burned in the U. S. A. at a rate of about 700×10^{6} tons per year. At 24×10^{6} Btu/ton, this is about

$$\frac{700\times 24\times10^{12}}{3.15\times10^{10}} = 5.3\times10^{5}\ \text{MW or } 18.5\%$$

of the total U. S. energy consumption. Total world coal consumption in 1971 was about 1860×10^{6} short tons or

$$\frac{1860\times10^{6}\times 24\times10^{6}}{3.15\times10^{10}} = 14\times10^{5}\ \text{MW}.$$

Assuming about 4% annual growth since 1971, current world consumption would be about 17×10^{5} MW, about 15% of the total.

At current rates of consumption, world coal reserves would have a useful life of about

$$\frac{192\times10^{18}}{24\times10^{6}\times 22\times10^{8}} = 4000\ \text{years}$$

and U. S. reserves at 10^{9} tons/year use, which seems like a probable value in the next several years ("Outlook: 1975 and Beyond," Continental Oil Co., May 13, 1975) would last

$$\frac{32\times10^{18}}{24\times10^{6}\times 10^{9}} = 1330\ \text{years}.$$

Currently coal supplies about 15% of world energy requirements. If it supplied 33%, the useful life of the reserves would be approximately halved to around 2000 years. In the U. S., using coal for 33% of our energy instead of 18.5% would shrink the useful life to something around 650 years at zero-growth consumption rates.

G. Petroleum

The estimated recoverable reserves of petroleum in the world are about 1.1×10^{12} bbl or 6.6×10^{18} Btu, according to a number of experts [A. A. Meyerhof, American Scientist 64, 536 (1976)]. The estimates of what remains to be found range between 0.9 and 1.3×10^{12} bbl for a total of about 2.3×10^{12} bbl or 13.5×10^{18} Btu of ultimately recoverable petroleum.

Presumably this petroleum began forming when life began on the earth in the Cambrian Period, 550×10^{6} years ago and it is still forming today in new sediments. To estimate today's recoverable formation rate, we can be conservative and take 200×10^{6} years as the formation period and assume the experts have overlooked half of the world's petroleum, so that the world production rate becomes

$$\frac{27\times10^{18}}{200\times10^{6}\times 3.15\times10^{10}} = 4.4\ \text{MW}$$

(this is about 20,000 bbl per year). The U. S. production rate would be about 6% of this but we can be optimistic and call it 1 MW.

The world consumption of petroleum (which oil people call "production") is about 20.5×10^{9} bbl/year (Meyerhof, loc. cit.) or 4.1×10^{6} MW, just about 10^{6} the estimated production rate. This is about 37% of all energy consumed. The U. S. consumes about 17×10^{6} bbl/day or a rate of about 1.24×10^{6} MW, 43% or its total energy consumption.

The world reserves of 10^{12} bbl at 2×10^{10} bbl/year would last about 50 years. The U. S. probable reserve of 65×10^{9} bbl (Meyerhof, loc. cit.) at 6×10^{9} bbl/year would last about 11 years, but maybe we will find a little more. If U. S. petroleum had to supply only one-third of the U. S. energy consumption instead of 43.5%, it would last 15 to 20 years at current rates.

Usually over half of the petroleum remains in the underground deposit after conventional extraction methods are completed. So-called secondary and tertiary recovery methods aim to extract part of this residue from the porous rock by use of solvents, water, heat, etc. However, these operations naturally increase the price of the extracted oil, and eventually the energy yield from these operations falls to zero.

H. Oil Shale and Tar Sands

Oil shale reserves seem to be larger than tar sand hydrocarbons; but extraction of oil from shale is regarded as being more difficult, so that the recoverable reserves of each could be regarded as roughly equal, 1 to 2×10^{18} Btu (Häfele, loc. cit.) each, about 0.1 that of petroleum. Hence their current production rates must be about 0.1 that of petroleum, of the order of 1 MW for the world and 0.1 MW for the U. S.

Both tar sands and oil shale are being extracted on a small scale in the U. S. and Canada, at rates of a few thousand bbl/day, or 2 to 4 MW. At this rate the reserves will last a very long time, of the order of 1000 years.

Some estimates of western U. S. oil shale reserves put them up to world petroleum reserves of 12×10^{18} Btu (15 gallons or more oil per ton). (See Chem. Eng. News, p. 36, October 18, 1976.) Eastern U. S. oil shale is not as rich, but is easier to treat and occurs in large amounts, probably at least equivalent to the western deposits. If these large reserves were to prove useful, the U. S. A. could use oil shale for one-third of its energy needs for 100 years at current rates.

The U. S. is not the only country with oil shale, and probably deposits similar in quantity exist elsewhere, so that one-third of world energy consumption could be provided by oil shale and tar sands for 50 to 200 years.

I. Gas

World gas recoverable reserves are estimated to be about half of those of petroleum or about $3.2x10^{18}$ Btu (Meyerhof, loc. cit.). United States probable reserves are about $1.2x10^{18}$ Btu (Continental Oil Co., May 13, 1975, Presentation to Security Analysts: "Outlook: 1975 and Beyond"). Assuming that they formed concurrently with petroleum and coal, but that only about half the gas formed is actually trapped, gives estimates of formation rates of about 5 MW for the world and 1 MW for the U. S. This does not include biogas. In any case, the world and U. S. consumptions are far larger than production, at about $2.1x10^{6}$ MW (19% of total energy) and $8.3x10^{5}$ MW (29%) of total energy, respectively (Chem. Eng. News, April 16, 1972, "The World Chemical Economy").

The world gas reserves would last about 30 to 150 years at current rates, depending on prices and luck, and 17 to 85 years if they supplied one-third of the world's energy. The U. S. reserves would last 10 to 45 years at current rates, or 9 to 40 years if they supplied one-third the energy. The spread in the figures results from uncertainties in proven and estimated reserves, which depend on prices, which depend on politics. The well owners would rather understate their reserves than be "caught short."

J. Hydroelectric Power

In 1970, world hydroelectricity consumption averaged about $1.4x10^{5}$ MW, according to the Encyclopedia Britannica. This would be about 1.3% of total world consumption excluding direct sunshine. The world's potential hydroelectric output is probably less than about 10^{6} MW electric, or about 4% of total use.

In the U. S. A., hydroelectricity consumption was about $2.8x10^{4}$ MW, about 1% of the total consumption. The U. S. potential hydroelectric capacity is said by various experts to be pretty well exploited, and so we can take it to be at most about 10^{5} MW or 4% of total use.

The lifetime of this resource is estimated to average about 100 years because of the silting-up of reservoirs. Good soil conservation practices have several benefits! Note that pumping out the silt only works for the lowest reservoir in the river.

K. Wave and Tide

One tidal power station of 500 MW operates on the Rance River in France. There are possibly 100 sites in the world which are suitable for extracting tidal power, for a possible total of $5x10^{4}$ MW.

Wave power is more elusive to estimate. When a wave is used, the water is calmed and a reach of wind is needed to form waves again. Thus one must consider primarily shoreline length. English proponents claim that 600 miles of coast could provide half of England's electric power or about $60x10^{3}$ MW. Skeptics think $6x10^{3}$ MW is closer to reality.

Since bigger waves are more widely spaced, we might take as useful a 3-foot wave every 3 seconds. One kilowatt is about 800 ft-lb/s or 13 ft^{3} of water per second or about 10 linear feet, and one might thus expect about 500 kW/mile, on the average. If the world coastline is about 120,000 miles, we arrive at $6x10^{4}$ MW. Potential world tide and wave together is thus estimated to be about 10^{5} MW, or about 0.1% of total use.

For the U. S., with about 3000 miles of effective coast, wave power might yield 1500 MW and tidal power a like amount, total about $3x10^{3}$ MW, again about 0.1% of total use.

Power from ocean temperature differences is not considered here because the engineering difficulties involved in using it on a large scale seem insurmountable. The relatively small temperature differences mean that enormous volumes of water would have to be pumped through large devices which would be very expensive and subject to failure by storms, barnacles, whales, weeds, etc. The alterations in ocean current temperature and flow resulting from any large-scale extraction of power could produce undesirable climatic or marine changes. It would be better to practice on the warm-water effluent from nuclear reactors, especially in cold weather.

L. Geothermal

If the earth's crust contained no radioactive materials, the earth would have cooled off in about 30 million years instead of staying hot for 4 to 5 billion years. The decompositions of K, Th, U, Ra, etc. produce a world surface heat flow of about $6x10^{12}$ cal/s, very small compared with sunshine. On land, then, the heat flow is about 29% of this or $7x10^{6}$ MW, and the U. S. share of this is at most $3.8x10^{5}$ MW.

The average increase in temperature with depth is about 20 °C to 30 °C per km; but generally speaking it does not pay to drill a deep hole for heat because the thermal conductivity and heat capacity of rock are not high enough. For example, the thermal conductivity of granite is about $1.88\ \text{W m}^{-1}\,°\text{C}^{-1}$, and its heat capacity is about $2.24x10^{6}\ \text{W-s/m}^{3}\,°\text{C}$.

A proposal by D. W. Brown of Los Alamos (LA-UR-73-1075) suggested that the hot rock (300 °C) in the western U. S. be used to generate electric power. In the proposed method, a hole about 5 km deep is drilled down to the hot rock, and then the rock is split in a vertical plane by injecting water at high pressure. (The split would naturally tend to begin and propagate along the bore-hole.) In this way a large, approximately circular area would become available in the hot rock for heating high-pressure water, which would in turn drive a powerplant on the earth's surface. A 50 MW plant is described which uses 270 MW of hot water at 280 °C. However, the author did not estimate the useful life of the heat source.

One may get an idea of the size of the heat source required by a simplified analysis which assumes that the heat comes from the opposed end faces of two circular cylinders infinitely long, of cross-sectional area A. The heat is assumed to be extracted across the end faces (along the axes) of the cylinders. To be optimistic, let us assume that the rock cylinders are initially at a uniform temperature of 300 °C, that the face temperature (fluid temperature) is 270 °C, and that the heat flow is uniform over the face. Then the problem is a well-known one in the theory of heat flow. From Ingersoll, Zobel, and Ingersoll, Heat Conduction, University of Wisconsin Press, Madison (1954), p. 90, one finds for the total heat flux w,

$$w = \frac{Ak\,(T_S - T_0)}{\pi\alpha t}$$

where k is thermal conductivity

T_S is temperature of the plane at $x=0$;

T_0 is original uniform temperature of the body;

$\alpha C = k$, where C is volumetric heat capacity;

t is time.

If we consider the situation after extracting heat from the rock for one year, at which time we are still extracting 270 MW, we find A from:

$$270 \times 10^6 = \frac{A \times 1.88 \times 30}{\pi \times 0.839 \times 10^{-6} \times 3.15 \times 10^7}$$

so that $A = 43.6 \times 10^6\ \mathrm{m}^2$.

If this area is represented by 2 disks of radius r, then

$$r = 2.63 \times 10^3\ \mathrm{m}.$$

Or, the diameter of the circular crack in the rock is 5.2 km, slightly larger than the depth of the hole! The thermal characteristics of other rocks are not much different from those of granite. The two longest holes ever drilled went down about 8 km.

Brown suggests that the cooled rock might fracture and expose more hotter rock surface. However, he does not indicate how deep the new fractures will penetrate into the original faces, nor does he mention the enhanced plasticity of rock at high pressures and moderate temperatures.

One may estimate how closely spaced the fractures should be, and how deep the fractures should penetrate to be effective, by assuming that the temperature gradient in the rock varies with distance x as

$$\frac{(T_0 - T_S)}{\pi\alpha t} = \exp\,(-x^2/4\,\alpha t).$$

(Ingersoll et al., p. 90).

Where $x^2 = 4\alpha t$, the gradient has fallen to 1/e of its surface value and a crack which reaches this far would help heat transfer; i.e., a characteristic length x_0 of the system is $2\ \alpha t$. For one year in granite, $x_0 = 2\ \ 26.4 = 10.26$ m. So to increase the heat transfer rate by a factor of e after one year, one would need cracks perpendicular to the original face which were about 10 m deep and occurred about every 20 m on the original face. Then the heat transfer fluid (water) would have to flow freely into the full depth of the cracks without taking the shorter, easier route along the original face.

The prospects for extracting appreciable amounts of heat from subterranean hot rocks do not appear very favorable in view of the unalterable natural obstacles. Some ERDA estimates of geothermal heat appear to contain large amounts of heat of this kind which in reality are not readily available.

In addition, one should consider the seismic consequences of pressurizing deep rock with water because the local reduction of shear resistance is known to lead to earth tremors.

In certain spots such as the Geysers area of California or in parts of Italy or New Zealand, subterranean water flows past large volumes of hot rock, and hot water or steam can be obtained. The Geysers field in California is expected to produce about 10^3 MW when fully developed in a few more years. [See G. R. Robson, Science 184, 371 (1974).] The total world output is about 2×10^3 MW. These resources are expected to be useful for about 100 years, but they can supply only a small fraction of the world or U. S. energy consumption.

M. Radiation

The natural radioactivity in the earth's crust provides the bulk of the geothermal heat. In a sense, the production of radioactive K, Th, U, Ra, etc. is steadily declining as these atoms decay into stable daughter elements. When gathered together in nuclear reactors, isotopes of U and Th can be induced to change more rapidly by being bombarded with daughter neutrons.

The world fission reactor output is about 2×10^5 MW; in the U. S., the energy from fission reactors is about 10^5 MW. This furnishes about 2% of the total energy consumed.

Known reserves of uranium and thorium and planned use of fission reactors indicate that conventional nonbreeding reactors could be fueled for about 50 years, but only for about 20 years if they are asked to provide one-third of the energy consumption. The reserves depend strongly on the cost of U ore: its richness and the development of improved chemical and isotope separation techniques. In effect, the current technology is based on ^{235}U, since it provides most of the neutrons that promote fission.

Fusion power is not considered in this report because no net power production from this process has so far been demonstrated.

N. Plutonium

Isotopes of Pu are produced by neutron irradiation of ^{238}U. These Pu isotopes can be used as fuel for fission reactors since they decay by emitting neutrons which incite decay in other Pu atoms. In an ordinary light water reactor, whose primary fuel is ^{235}U, about a third of the energy is produced by the decay of Pu generated in the ^{238}U present in the fuel; but not as much new Pu is produced as ^{235}U is consumed. However, it is possible to build a breeder reactor in which enough Pu is produced that the energy content of the fuel increases with time. In this way the large amounts of energy in the ^{238}U isotope become available to mankind, and the energy reserves for fission power increase from about 50 years to about 1500 years, depending upon ore richness, etc. Indeed, the development of fission power on a commercial scale would be a relatively short-lived, futile exercise without the possibility of using ^{238}U in a Pu cycle.

The current production of Pu isotopes occurs mainly in commercial power reactors. A typical 1000 MW reactor uses 10^5 kg UO_2 every 3 years, enriched to about 3.2% ^{235}U. About 0.7 of the ^{235}U ends up as Pu in the spent fuel. So per MW-year, $10^5 \times 3.2 \times 10^{-2} \times 0.7/3 \times 10^7 = 0.75$ kg Pu (figures courtesy of D. W. Lillie). The U. S. has about 25,000 MW nuclear capacity which operates at a load factor of about 0.6, so that the annual U. S. production of Pu is at least $0.75 \times 25{,}000 \times 0.6 = 11{,}000$ kg/year. Military Pu production is probably one-quarter of this. The energy from 1 gram of Pu is slightly larger than from 1 gram of U, about 2.5×10^3 MW-s used in a reactor. In 14,000 kg of Pu are $\sim 3.5 \times 10^4$ MW-years. So the U. S. Pu production is about 3.5×10^4 MW. World Pu production is about twice this, or 7×10^4 MW. About one-third of the power in a conventional reactor comes from Pu, so the actual use of Pu is about 10^4 MW in the U. S. and 2×10^4 MW world-wide.

Natural Th can be used with ^{233}U in a similar cycle to increase potential reserves even more, but ^{233}U has some special problems which make it more difficult to use than Pu.

Various objections to the safety of nuclear fission power have been evaluated by B. Cohen in American Scientist 64, 552 (1976). In view of the widespread use of cigarettes, living in cities, obesity, or not using seat belts in automobiles, the hazards of nuclear power appear to be relatively tiny, and objections to it must be based on other factors such as cost, politics, aesthetics, thermal pollution, etc.

O. Totals

Excluding direct sunlight, the world production of energy is about 49 to 89×10^6 MW, the greatest uncertainty being carbohydrate production. With 4 billion people, the per capita production comes to about 12 to 22 kW. World consumption is about 11.2×10^6 MW, 2.8 kW per person. However, this consumption is far from uniform, as the figures for the U. S. A. indicate.

The U. S. A. produces about 2.4×10^6 MW or about 10 kW per person, but consumes about 2.8×10^6 MW or 12 kW per person. What is produced is mostly carbohydrate, but what is consumed is mostly oil, coal, and gas.

The entropy rate per person is estimated by assuming that in most cases the heat is supplied at 2500 °K to 5000 °K (combustion or solar temperatures) and rejected at about 300 °K. Thus the main term contains 300 °K in the divisor, and 2.8 and 12 kW per person become 9.3 and 40 W/°K, respectively. Generally speaking, one always pays a price for a high rate of entropy production since the minimization of this rate provides one with more options for the future. Entropy production also correlates well with "gross national product."

P. Where Is All the Carbon Hiding?

Most people who have studied the question believe that all the oxygen in the earth's atmosphere was made by photosynthesis, and that not all of this oxygen is still in the atmosphere owing to oxidation of primeval inorganic material (e. g., FeS) or to escape from the earth. Air, molecular weight 29, is about 21% oxygen and weighs about 10^3 g/cm^2 on the earth's surface, 510×10^{16} cm^2. Thus our cargo of oxygen is

$$\frac{0.21}{29} \times 10^3 \times 510 \times 10^{16} = 3.7 \times 10^{19} \text{ g-mol.}$$

Recoverable world coal reserves not too hard to dig out are estimated at 192×10^{18} Btu. If we take this to be pure carbon, this is about

$$\frac{192 \times 10^{18}}{4 \times 94} = 5.1 \times 10^{17} \text{ g-mol.}$$

To burn this would use 5.1×1^{17} g-mol of oxygen -- about 1.4% of the world's supply.

If we multiply the coal reserves by 10 to allow for small, unrecoverable, or undiscovered deposits, we come up to 14% of the oxygen.

Average estimates of oil and gas energy reserves run about 12% of the recoverable coal. If we multiply these by 10 to account for pessimism, unrecoverable, and undiscovered material, we add $1.2 \times 1.4 = 1.7\%$ of the oxygen as fixed carbon.

Living biomass on the earth plus old tires and newspapers would scarcely cover the land to an average depth of 0.3 m at an average density of 1 to amount to $148 \times 10^6 \times 10^6 \times 300 \times 7 = 3.1 \times 10^{17}$ Btu, negligible compared with coal reserves. If the oceans contain three times as much as the land, we reach about 10^{18} Btu -- still negligible.

The sulfate, pyrite, etc. reduced by previously fixed photosynthetic carbon is negligible compared with coal.

One must also bear in mind that some of the earth's fixed carbcn is primeval, in that it came with the cosmic dust from which the earth formed. (The oldest meteorites contain tar, etc., and graphite is found in many meteorites.) Some of this hydrocarbon may have contributed to petroleum.

Much low-grade oil shale is known to underlie large areas of the Eastern U.S. Probably similar deposits associated with sedimentary rocks exist in other countries. It is difficult at this time to estimate the fixed carbon in such deposits. Potential Western U.S. oil shale deposits at 15 gal/ton are reported to be about 2×10^{12} bbl or 12×10^{18} Btu. If we estimate that the Eastern U.S. shales contain ten times as much oil and that the world reserves of oil shale are ten times that of the U.S., then we arrive at something like 1200×10^{18} Btu, which would account for about 8.8% of the atmospheric oxygen.

So the grand total of conventional carbonaceous materials could account for about 14+1.7+8.8 = 24.5% of the oxygen. Thus the remaining three-quarters of the world's fixed carbon could be very dilute and widely dispersed. The most likely reservoirs seem to be very low grade oil shales -- one could account for a large amount of fixed carbon by multiplying a huge volume of sedimentary rock by a low but plausible carbon content. And perhaps large amounts of fixed carbon remain to be discovered.

However, things are not all that rosy. Using 1% of the earth's oxygen for fuel would mean an equivalent amount of CO_2 dumped into the atmosphere. Considerable CO_2 is absorbed in the oceans, but it takes time. The change in ocean pH could affect marine life and weather, and the rise in atmospheric CO_2 would probably affect climate. The subject is not thoroughly understood so far, and it would be stupid to mess around on a global scale with things we do not understand very well. It would probably be wise to limit CO_2 formation by combustion to something less than about 10^7 MW; i.e., a half or third of the photosynthesis rate, which is just about what we are doing now, world-wide.

III. CONCLUDING REMARKS

Were world and U.S. populations half or quarter their present sizes, then energy, environmental, and food problems would be eased considerably. A considerable part of the growth in energy consumption is simply the result of more consumers. High levels of food production are becoming increasingly dependent on energy supplies; Chancellor and Goss [Science <u>192</u>, 213 (1976)] have discussed this difficulty and concluded that population limitation is necessary now. The hope is for a gradual transition rather than a catastrophe, for eventually the limits of a finite earth will rule; growth cannot go on forever.

Looking over the list of energy sources, it is apparent that many of them are insignificant, except perhaps locally, and others are too short-lived to be worth developing. The sources which seem to be the best ones to work on are:

- Wind for electric power
- Solar heat for buildings and homes
- Concentrated solar heat for low-temperature processes and air conditioning
- Photovoltaic solar electricity
- Coal mining and utilization
- Oil shale development
- Breeder reactor
- Energy storage.

A high consumption of fossil fuels, while they last, may produce severe environmental problems in the areas of air and water pollution, local thermal overloads, and general climatic changes which affect food supplies. However, it appears from the energy per capita figures that even the present swollen human population could get by tolerably well if only renewable energy sources were used. For example, wind could furnish most of the electric power required for home, industry, and major transport. Muscle could supply minor transportation. Improved communications systems would obviate much travel. Liquid fuels for off-highway uses, particularly agriculture, could be obtained from carbohydrates. Most building heat and air conditioning could be done with solar energy. Some of the investments needed to use renewable energy sources are large, but they are essentially one-time investments, worth building well for a long working life.

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Report No. 77CRD005 FORMATION AND CONSUMPTION RATES OF MAJOR ENERGY SOURCES
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