

United States and World Resources of Energy^{1/}

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Abstract

Energy resources must be viewed as a range extending from reserves in known deposits minable at present prices to resources that may become usable in the future through further exploration and technologic advance. Appraised in this framework, domestic resources of the fossil fuels of the types now considered usable contain 5.5 to more than 130 Q (i.e., 10^{16} Btu), and if very low grade organic-rich deposits are included, the potential may be more than 1,600 Q. World resources contain about 23 to more than 475 Q, and if very low grade resources are considered the potential may be more than 20,000 Q.

The energy potential of uranium resources in the United States ranges from about 0.16 to more than 280,000 Q, the larger figure depending not only on the use of low-grade ore but also on the successful development of the breeding process. The energy potential of world uranium resources similarly ranges upward from 0.34 Q to an order of magnitude of 5 million Q. The energy potential of thorium resources of the United States ranges from 7 to 420,000 Q, and of the world from 48 to about 7 million Q. If nuclear fusion can be controlled for power generation, the potential energy from resources of deuterium and lithium⁶ are orders of magnitude larger than the fissionable mineral resources. Deuterium alone contains potential energy of 7.5 billion Q. Water power, geothermal energy, solar energy, and tidal power also represent large potential sources.

The almost staggering contrast between the magnitude of known reserves minable at present prices and potential resources minable only at higher prices or more advanced technology underscores the critical importance of research, exploration, and development in meeting future needs.

Introduction

Most energy source materials lie hidden beneath the earth's surface and their extent is difficult to determine. Compounding the problem of appraising the magnitude of energy resources is the fact that the kinds of materials usable as energy sources are constantly changing as the advance of technology permits us to recover energy from materials that were once too low grade or too inaccessible to mine, and to utilize materials that were not previously visualized as economical sources of energy.

These factors, of course, combine to enlarge our usable supplies of mineral fuels. Development of geophysical techniques for petroleum exploration, expansion of geologic knowledge concerning the habitat of oil, improvement in drilling techniques, and development of methods of secondary recovery are among the scientific and technologic advances that have made it possible to find and recover a far larger amount of oil than was thought to exist a few decades ago. Similarly, technologic advances in transportation have made possible widespread and quantitatively important use of natural gas, whereas the great bulk of it was discarded before. Uranium and other nuclear materials were not even thought of as commercial sources 25 years ago, and oil shale and other organic-rich shales, not yet used as energy sources except on an insignificant scale, almost certainly will become important in the future.

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The concept that supplies of usable minerals are extended by the advance of scientific knowledge forces three important conclusions pertinent to preparation of resource estimates: 1) even though searching estimates are prepared, they can never represent a final inventory of resources of the commodity in question, but are at best a quotation reflecting the status of knowledge of resources at the time the estimates are made; 2) in making and interpreting estimates of mineral resources it is necessary to differentiate between deposits that are known and closely appraised and those that are either not closely appraised or are as yet undiscovered but are believed to exist, on the basis of geologic evidence; and 3) it is necessary to distinguish between deposits that are minable or recoverable at present costs and those that cannot be mined now but might be recovered under more favorable economic or technologic conditions. To appraise the future availability of energy supplies, therefore, several categories of resources are examined:

- 1) Known recoverable reserves--deposits whose location and general magnitude are established and that are recoverable at or close to present prices and with established technology. Generally, the figures include estimates of other authors described as measured, indicated and inferred, or proved, possible, and probable reserves [For definitions, see F. Blondel and S. G. Lasky, Mineral reserves and mineral resources: Econ. Geol. v. 51, 1956, p. 686-697].
- 2) Undiscovered recoverable resources--deposits whose specific location is unknown but whose presence and character are indicated by geologic evidence.
- 3) Known marginal and submarginal resources--deposits whose location and general magnitude are established and that may become recoverable as technology advances or economic conditions change, but cannot be recovered now.
- 4) Undiscovered marginal and submarginal resources--deposits whose specific location is unknown but whose presence and character are indicated by geologic evidence.

Estimates of reserves and resources depend upon the methods utilized, the assumptions adopted, and the basic information available. Wide divergence in estimates prepared by different observers is therefore not uncommon. Over the past few years, for example, estimates of crude oil "reserves" have ranged from 31 to 590 billion barrels. Some of these are estimates of reserves in known recoverable deposits only, and some include resources that may eventually be found and recovered as technology advances. Some are projections based on existing knowledge or economic conditions, and others assume that technologic or economic changes will take place. And some may be purely statistical projections of the past and present rates of discovery, while others take account of geologic concepts of origin and accumulation.

Knowledge of resources is best represented by estimates that reflect a range in values and assumptions, which is accomplished by the four definitions above and by the estimates given in subsequent tables. The totals presented here are generally larger than those published previously, mainly because the estimates here take more account of undiscovered and marginal resources. Seen in this perspective, the differences in estimates of recent years are not so large as might first appear. For example, the estimate of known recoverable reserves of petroleum in table 1 corresponds to the minimum estimates of recent years; those of undiscovered recoverable resources correspond approximately to estimates of "ultimate" reserves that allow for new discoveries but not much change in technologic or economic conditions. The estimates of undiscovered marginal and submarginal resources represent resources of potential value that are commonly excluded from other resource estimates.

Most of the estimates here were prepared first to serve the needs of the Natural Resources Committee of the Federal Council for Science and Technology [Federal

Council for Science and Technology, Committee on Natural Resources, 1963, Research and development on natural resources: Washington, D. C., U. S. Govt. Printing Office, 134 p.], and with some modifications in coverage they have been used for other recent studies undertaken within the Federal Government [see also U. S. Dept. Interior, Energy Policy Staff, 1963, Supplies, costs, and uses of the fossil fuels: Washington, D. C., 34 p. 2 figs.]. They are provisional, not only in the sense that all resource estimates are provisional, but also in the sense that they will be replaced shortly by new estimates currently in preparation by members of the U. S. Geological Survey.

Fossil fuels

The energy content of known domestic reserves of fossil fuels recoverable at or close to present prices and with established technology is about 5.5 Q (quintillion or 10^{18} Btu), and that of undiscovered and/or marginal and submarginal resources, minable under changed conditions or higher prices, is a little more than 124 Q (table 1). These amounts are respectively equivalent to about 0.2 and 4.8 trillion tons of coal, measured in terms of the standard equivalent of 26 million Btu per ton of bituminous coal. Of the presently minable deposits, coal contains nearly 84 percent of the total energy and most of the remainder is about equally divided among petroleum and natural gas liquids, natural gas, and shale oil. Oil shale deposits contain about 28 percent of the marginal and submarginal resources; shales, not included in the above estimates, containing 10 percent or more organic matter, hold an energy potential of 220 Q, and those with 5-10 percent organic matter have a potential of about 1,600 Q.

The energy content of known recoverable world reserves of fossil fuels is about 23 Q. Undiscovered and/or marginal and submarginal resources contain about 452 Q (table 2). Shales with more than 5 percent organic matter probably have an energy potential of more than 20,000 Q.

Nuclear fuels

Known United States reserves of uranium minable at a price of \$5-\$10 per pound of U_3O_8 are about 142,000 tons, and 181,000 tons additional have already been delivered to the Atomic Energy Commission (table 3). Assuming complete burn-up of contained U^{235} , the energy equivalent of delivered and minable uranium is 0.16 Q; assuming complete burn-up of U^{235} and U^{238} (possible only with breeding), the energy equivalent is about 22 Q. Unappraised and undiscovered resources of the same quality as those being mined probably contain energy equivalents of 0.35-54 Q (depending on burn-up). Lower-grade uraniferous deposits, which with present technology would cost up to \$100 or more a pound of U_3O_8 to mine, contain energy equivalents of 2,000-280,000 Q (depending on burn-up). World uranium reserves minable at \$5-\$10 a pound are about 700,000 tons, with an energy equivalent of 0.34-48 Q, and may be far larger (table 4).

Thorium will be available as an energy source only when the breeder reactor is practicable, and because it has not been in much demand its resources are not as well known as those of uranium. Known domestic recoverable reserves minable at \$5-\$10 a pound of U_3O_8 are 100,000 tons, with an energy equivalent of 7 Q, assuming complete burn-up (table 5). Unappraised and undiscovered resources of the same and lower quality probably contain the energy equivalent of more than 420,000 Q. World reserves minable at \$10 a pound or less contain the energy equivalent of 48 Q and the energy equivalent in lower grade resources are far larger (table 6).

The fusion reaction now yields only explosion energy. If it can be sustained and controlled for the production of electric power, the natural fuels would be deuterium and lithium⁶. According to Friedman and others [Friedman, I., Redfield, A. P., Schoen, B., and Harris J., 1964, The variation of the deuterium content of natural waters in the hydrologic cycle: Rev. Geophysics, v. 2, p. 177-224], the oceans contain about 2.5×10^{13} short tons of deuterium, the energy equivalent of which is about 7.5 billion Q.

Table 1. Provisional estimates of United States resources of fossil fuels 1/
(Energy equivalent in 10^{18} Btu shown in parenthesis)

	Known recoverable reserves 2/	Undiscovered recoverable resources	Known marginal and submarginal resources	Known marginal and submarginal resources
Coal (short tons)	220×10^9 (4.6)	Not estimated	$1,400 \times 10^9$ (29)	$2,600 \times 10^9$ (55)
Petroleum (barrels)	47×10^9 (0.272)	200×10^9 (1.16)	40×10^9 (0.23)	300×10^9 (1.74)
Natural gas (cu. ft.)	276×10^9 (0.285)	$1,200 \times 10^{12}$ (1.24)	Not estimated	850×10^{12} (0.88)
Natural gas liquids (barrels)	7.7×10^9 (0.035)	30×10^9 (0.140)	Not estimated	60×10^9 (0.28)
Oil in bituminous rock (barrels)	1.3×10^9 (0.008)	Not estimated	Not estimated	10×10^9 (0.058)
Shale oil (barrels)	50×10^9 (0.29)	Not estimated	$2,000 \times 10^9$ (11.6)	$4,000 \times 10^9$ (23.2)
Total (rounded) energy	(5.5)	(2.6)	(41)	(81)
Grand (rounded) total, all classes	(130)			

Energy equivalents: 1 short ton of coal = 21×10^6 Btu; 1 barrel petroleum, oil from bituminous rock, or shale oil = 5.8×10^6 Btu; 1 barrel natural gas liquids = 4.62×10^6 Btu; 1 cubic foot natural gas = 1,035 Btu.

1/ Compiled by D. C. Duncan and V. E. McKelvey, U. S. Geological Survey. Explanation, definitions, and sources of data are on the following pages.

2/ As defined here, this category includes measured, indicated, and inferred reserves. Estimates of indicated and inferred reserves of oil, gas, and natural gas liquids are not available, however, the estimates shown for them are proved (i.e., measured) reserves and therefore not wholly comparable to the estimates shown for coal, oil in bituminous rocks, and shale oil.

Explanation of resource estimates

Coal. Known recoverable reserves are those in thick coal beds lying at depths less than 1,000 feet, and assume 50 percent recovery of coal in place. The minimum thickness for beds of bituminous and higher rank coal included in the estimate is 3.5 feet and that of subbituminous and lower rank coal is 10 feet.

Known marginal and submarginal resources include coal left in first mining of known recoverable reserves, coal in thin beds at shallow depth, and coal lying at depths between 1,000 and 3,000 feet below surface. The estimate refers to coal in place, and includes coal in the measured, indicated, and inferred categories of P. Averitt, U. S. Geol. Survey Bull. 1136 (with additional data reported by H. Beikman, et al., Washington Division of Mines and Geol. Bull. 47), less that reported here in the known recoverable class, rounded to two significant figures.

Undiscovered marginal and submarginal resources refer to coal believed to be in place to depths of 6,000 feet. No separate estimate has been prepared of undiscovered thick coal at shallow depths. Compiled from estimates by M. R. Campbell, Coal Resources of the World, 1913, less the sum of known reserves and known marginal and submarginal resources, rounded to two significant figures.

Petroleum. Known recoverable reserves include proved reserves of American Petroleum Institute (31 billion barrels as of Dec. 31, 1963) plus reserves economically recoverable by established secondary-recovery methods in practice (16 billion barrels) as estimated by Interstate Oil Compact Commission as of January 1, 1962. The API estimate includes primary reserves plus those secondary reserves recoverable by methods already in practice in each field. The IOCC estimates refer to oil recoverable by established methods but not yet in practice in all fields.

Known marginal and submarginal resources include additional oil in known deposits considered to be physically recoverable by newer secondary-recovery methods but possibly at increased costs. The original oil in place in known deposits is estimated by IOCC to be 346 billion barrels. Production of 73 billion barrels to January 1963, plus primary and secondary reserves of the above estimates total 160 billion barrels or 46 percent of the estimated oil in place. A somewhat larger recovery, as much as 65 percent of the oil in place, is considered possible eventually with future improvements in recovery techniques; hence the known marginal and submarginal resources might be as much as 110 billion barrels.

Undiscovered recoverable resources include oil in possible extensions of known field and in undiscovered fields thought to be discoverable under present conditions. Both estimates are based on unpublished estimates of A. D. Zapp, U. S. Geological Survey, who derived them from analysis of extent of favorable ground compared with total footage of exploratory drilling completed thus far. For outline of method, see A. D. Zapp, U. S. Geol. Survey Bull. 1142-H.

Undiscovered marginal and submarginal resources include petroleum accumulations thought to be present in less favorable areas, at greater depths, and in less productive accumulations than those considered commercially usable under present conditions.

Natural gas. Known recoverable reserves include proved reserves as of the close of 1963, from American Gas Association and American Petroleum Institute. No estimate has been prepared of known marginal and submarginal gas resources.

Estimates of undiscovered recoverable resources are based on a ratio of 6,000 feet of gas discovered per barrel of oil. Recent estimates of this ratio range from 6,000 to 8,000 cu. ft. of gas per barrel of oil, and hence the undiscovered recoverable resources of gas may be as high as 1,500 or 1,600 x 10¹² cu. ft.

Undiscovered marginal and submarginal resources are Zapp's unpublished estimates of resources not economic now. Because a larger fraction of natural gas in subsurface reservoirs is recoverable than oil under present circumstances, the estimate of submarginal resources of gas is less generous than that for oil.

Deep drilling, however, might produce much larger quantities, for experience already indicates that there is some increase in concentration of natural gas with depth. The estimate does not include possible large sources, such as many known unproduced natural gas accumulations reported as "shows" that were considered uneconomic when found, pore-space gas in coal and black shale, or synthetic gas from black shale or coal. For example: the Chattanooga shale and its stratigraphic equivalents probably contain about 8×10^{15} cu. ft. of gas equivalent if processed by hydrogenolysis. The four trillion tons of coal in the United States may also contain as much as 8×10^{15} cu. ft. of entrapped methane gas, some fraction of which might be recoverable in the future. The carbonaceous shales associated with coal might contain an additional 4×10^{15} cu. ft. of gas and some marine black shales such as the Chattanooga and equivalents, may contain comparable or larger amounts of such gas in pore space.

Natural gas liquids. Known recoverable reserves are rounded from API-AGA estimates for the close of 1963 which indicate a ratio of about 25 barrels of liquids economically recoverable per million cubic feet of gas. Undiscovered recoverable resources are based on the same ratio of natural gas to natural-gas-liquids. Undiscovered marginal and submarginal resources are Zapp's unpublished estimate which assumes more complete recovery and greater quantities of natural-gas-liquids in the deeper gas accumulations.

Oil in bituminous rock. Known recoverable resources include minimal estimates of some deposits for which ready data are at hand; assumed recovery is 50 percent of the oil in place. An estimate of 10 billion barrels from L. G. Weeks, 1960, Geotimes, v. 5, no. 1, p. 20, is the basis for the figure on undiscovered marginal and submarginal resources; it includes a number of known deposits that are unappraised.

Shale oil. Known recoverable reserves include oil recoverable from higher grade oil shale in Colorado and Utah in beds 25 feet or more thick, yielding about 30 gallons of oil per ton of rock, and lying at depths less than 1,000 feet below surface. Assumed recovery is 50 percent of the oil content of the shale. Known marginal and submarginal resources include shale left in first mining of the known recoverable reserves, estimates of the full oil content of similar higher grade deposits at depths greater than 1,000 feet below surface, and estimates of thin and low-grade oil shale, with minimum yield of 10 gallons of oil per ton and minimum thickness of 5 feet and to depths as much as 10,000 feet below surface.

Undiscovered marginal and submarginal resources include a speculative estimate of equivalent oil in possible extensions of some major known oil shale deposits, yielding 10 gallons or more oil per ton to depths as much as 20,000 feet. A much larger amount of incompletely appraised shale is known and inferred. Shales not included in the estimates shown on the table but containing 10 percent or more organic matter probably contain about 9 trillion tons of organic matter with a potential energy content of 220 Q. Shale containing 5 to 10 percent organic matter probably contains an energy equivalent of 1,600 Q.

Table 2. Provisional estimates of world resources of the fossil fuels
(Energy equivalent in 10^{18} Btu shown in parenthesis)

	<u>Known recoverable reserves</u>	<u>Undiscovered and/or marginal and submarginal resources</u>
Coal (short tons) <u>1/</u>	850×10^9 (18)	$15,150 \times 10^9$ (320)
Petroleum (barrels) <u>2/</u>	300×10^9 (1.7)	$4,000 \times 10^9$ (23)
Natural gas (cu. ft.) <u>3/</u>	$1,800 \times 10^{12}$ (1.9)	$19,000 \times 10^{12}$ (20)
Natural gas liquids (barrels) <u>4/</u>	45×10^9 (0.21)	700×10^9 (3.2)
Oil in bituminous rocks (barrels) <u>5/</u>	40×10^9 (0.23)	$1,060 \times 10^9$ (6.1)
Shale oil (barrels) <u>6/</u>	150×10^9 (0.87)	$13,600 \times 10^9$ (79)
Total (rounded) energy in fossil fuels (10^{18} Btu)	23	452

1/ Known recoverable reserves consist of half of the measured reserves of coal and lignite reported by Parker (World Power Conference Survey of energy resources, 1962: Central Office World Power Conference, London, p. 10), adjusted to make U. S. reserves conform with those shown in table 1, and to incorporate a different approximation of minable reserves in the U.S.S.R. The latter is based on the 1956 estimated quoted by J. A. Hodgkins (Soviet power, energy resources, production and potential: Prentice Hall, 1961) that 2.09 trillion metric tons of coal in the U.S.S.R. lie above a depth of 300 meters; it is assumed that the distribution of these beds by thickness is similar to that in the U. S., so that 30 percent of the total, or 695,000 short tons, is in thick beds, half of which is recoverable.

Undiscovered or marginal resources are those reported by Parker, adjusted to make U. S. reserves conform with those shown in table 1 and to incorporate the 1956 estimate of U.S.S.R. coal and lignite above a depth of 1,800 meters (9.6 trillion tons), less known recoverable reserves

2/ Recoverable reserves are taken as the U. S. figure from table 1, plus proved reserves in remainder of world (Oil and Gas Jour., v. 60, no. 53, p. 85, 1962). Undiscovered or marginal and submarginal resources are the undiscovered recoverable, known marginal, and undiscovered marginal and submarginal resources for the other areas; the latter are based on an extrapolation of U. S. estimates to the remainder of the world according to area of sedimentary rocks and to the geologic favorability factors derived from L. G. Weeks, 1959, Where will energy come from in 2059?: Petroleum Engineer, v. 31, no. 9, p. A24-31).

3/ There are no available estimates of proved world gas reserves. Hence, known recoverable reserves are estimated on the basis that 6,000 cu. ft. of gas are expectable per barrel of oil. Estimates of undiscovered and marginal and submarginal resources are unpublished ones of Zapp and allow a somewhat lower gas-oil ratio for marginal resources.

4/ There are no available estimates of proved world reserves of natural gas liquids. Known recoverable reserves are estimated on the basis that natural gas contains about 24 barrels of natural gas liquids per million cubic feet of gas as in the U. S. Estimates of undiscovered and marginal and submarginal resources are unpublished ones of Zapp and allow a somewhat larger ratio between liquids and gas in marginal and submarginal resources.

- 5/ Estimates of known recoverable reserves include only deposits in U. S. and Canada. Canadian reserves of 37.9×10^9 barrels have been calculated by H. L. Berryhill, Jr., from information on extent of deposits now obtainable by open-pit mining methods reported by Oil and Gas Jour., v. 59, July 31, 1961, p. 253, and August 14, 1961, p. 79, and on the assumption that 75 percent of the oil in place is recoverable. Undiscovered and marginal and submarginal resources are from L. G. Weeks (less known reserves), op. cit., 1960.
- 6/ From unpublished estimates of D. C. Duncan. Known recoverable reserves generally are limited to those deposits yielding more than 25 gallons of oil per ton, in zones 25 feet or more thick, and lying less than 1,000 feet below the surface, and assume 50 percent recovery in mining. In certain foreign areas, however, where an oil shale industry is already established, deposits of the grades and thicknesses currently mined are considered recoverable under certain conditions; in some places deposits containing as little as 12 gallons per ton are mined by open-pit methods. Marginal and submarginal oil shale deposits are those yielding 10 gallons or more per ton and includes possible major extensions of known deposits. Other unappraised organic-rich-shale deposits extending to depths of 20,000 feet, and containing 10 percent or more organic matter, probably contain energy equivalent of about 4,000 Q; deposits containing 5 to 10 percent organic matter probably contain an energy equivalent of about 20,000 Q. These unappraised deposits are not included in the estimates shown on the table.

Table 3. Provisional estimates of United States resources of uranium ^{1/}
 (Short tons of U. Energy equivalent to 10^{18} Btu shown in
 parenthesis) ^{2/}

Present cost (dollars per pound of U) ^{3/}	Known deposits	Unappraised and undiscovered resources
5 - 10 ^{4/}	142,000 (0.07 - 10)	770,000 (0.38 - 54)
10 - 30 ^{5/}	140,000 (0.07 - 10)	500,000 (0.24 - 35)
30 - 100 ^{6/}	21,300,000 (6 - 860)	20,000,000 (10 - 1,400)
100 - 500 ^{7/}	--	4,000,000,000 (1,969 - 280,000)

- ^{1/} Estimates of known deposits recoverable at a cost of \$5-10 per pound are by the Atomic Energy Commission; most other estimates prepared by the U. S. Geological Survey.
- ^{2/} The minimum energy equivalent is that contained in U^{235} and assumes complete burn-up. The maximum is the total contained in U^{235} as well as U^{238} . Conversion factor: 1 short ton U = 7×10^{13} Btu.
- ^{3/} Based on specific estimates by AEC of mining and processing costs of various types of deposits, assuming present economic and technologic conditions.
- ^{4/} Uranium already mined and delivered to AEC totals 181,000 tons and should be added to known reserves to represent uranium available under present conditions. Known reserves, estimated by AEC, include 135,000 tons in western sandstone deposits averaging about 0.21 percent U, and 7,000 tons in western vein deposits averaging about 0.21 percent U. Undiscovered resources estimated by A. P. Butler, Jr. (unpublished data), include approximately 700,000 tons in sandstone deposits in the Colorado Plateau and adjacent areas and 60,000 tons in vein deposits in the western states.
- ^{5/} Known deposits include a) about 23,000 tons recoverable as by-product from the manufacture of triple superphosphate and similar products, taken as 15 percent (the proportion of total phosphate production currently treated by such methods) of the 90,000 tons estimated by V. E. McKelvey (unpublished data, 1952) to occur in beds 3 feet or more thick, and containing more than 30 percent P_2O_5 and lying 1,000 feet below entry level in the western phosphate field and of the 65,000 tons estimated by J. B. Cathcart (unpublished data, 1951) to occur in currently recoverable phosphate concentrates in the Florida field; b) about 8,000 tons in western sandstone deposits and 1,000 tons in vein deposits containing more than 0.1 percent U but not considered by AEC to be minable at present prices; c) 95,000 tons in sandstone deposits containing 0.04 to 0.1 percent U, estimated by A. P. Butler, Jr. from the fact that assay data show such materials to be present in amounts equal to about two-thirds of the higher grade ore; and d) 12,000 tons in uranium-bearing pyrochlore in potassic syenite in the Bearpaw Mountains (W. T. Pecora, unpublished data). Unappraised and undiscovered resources include a) 30,000 tons in by-product recovery from the 200,000 tons estimated by J. B. Cathcart (unpublished data) in potential resources in the North Carolina phosphate field; b) 460,000 tons in low-grade western sandstone deposits; and c) 20,000 tons in uranium-bearing pyrochlore deposits.
- ^{6/} Known resources include a) about 130,000 tons in the remainder of the known phosphate resources mentioned above (assumed to be recoverable as a principal product in this cost range; b) about 65,000 tons in phosphate concentrates in the Bone Valley formation of Florida; c) about 100,000 tons in aluminum phosphates in the Bone Valley leached zone; d) 6,000,000 tons estimated by Andrew Brown in the Chattanooga shale of Tennessee and adjacent states (averaging about 0.006 percent U); and e) 6,000,000 tons estimated by A. P. Butler, Jr., in the Conway alkalic granite, N. H., to a depth of 1,000 feet. Unappraised resources include

a) 600,000 tons in high-grade phosphate rock in the western field lying more than 1,000 feet below entry level; b) 1,300,000 tons in phosphate containing about 0.0008 percent U and more than 24 percent P_2O_5 in the western field; c) 200,000 tons estimated by A. P. Butler, Jr., (from data of G. H. Espenshade) to occur in phosphate in northern Florida; d) 1,000,000 tons in phosphate nodules, averaging about 0.005 percent, in the Hawthorne formation of Florida; e) 170,000 tons in the North Carolina phosphates; and f) 16,000,000 tons estimated by V. E. Swanson to occur in the Chattanooga shale in beds containing 0.004 percent or more U.

7/ Includes a) 2 billion tons estimated by V. E. Swanson to occur in the Chattanooga shale and equivalents in central United States in beds averaging about 0.003 percent U; b) 2 billion tons in large granitic bodies (Pikes Peak, Marquette Co., Michigan, Wisconsin, Minnesota, Idaho batholith, California batholith, S. California batholith, N. California batholith, N. Washington batholith, Appalachians, and New England), containing about 4 ppm U above a depth of 1,500 feet (estimated by AEC).

Table 4. Provisional estimates of world uranium reserves ^{1/}
 (Energy equivalent to 10^{18} Btu shown in parenthesis ^{2/})

Country	Short tons
United States	142,000 (0.07 - 10)
Canada	236,000 (0.11 - 16)
South Africa	127,000 (0.06 - 9)
France	34,000 (0.02 - 2.4)
Australia	13,700 (0.007 - 0.96)
Sino-Soviet Bloc	110,000 - 400,000 (0.05 - 0.2; 7.7 - 28)
Other ^{3/}	<u>21,000 (0.01 - 1.5)</u>
Total (rounded) non Communist world	575,000 (0.28 - 40)
Total (rounded) world ^{4/}	685,000 - 1,085,000 (0.34 - 0.53; 48 - 76)

- ^{1/} Known deposits minable at \$5-10 per pound; those for the United States, Canada and South Africa represent material minable at \$8 per pound or less. Estimates of reserves in Sino-Soviet Bloc from the McKinney Staff, Report to the Joint Committee on Atomic Energy, Congress of the United States, 1960, v. 4, p. 1613. Estimates on all other countries supplied by R. D. Nininger, U. S. Atomic Energy Commission.
- ^{2/} The minimum energy equivalent is that contained in U^{235} and assumes complete burn-up. The maximum is the total contained in U^{235} and U^{238} . Conversion factor: 1 short ton U = 7×10^{13} Btu.
- ^{3/} Argentina, Congo, Germany, India, Japan, Mexico, Portugal, and Spain.
- ^{4/} Undiscovered deposits of the same quality are estimated to be 770,000 tons (see table 3); data are not available for similar country by country estimates, but the relation between crustal abundance of the elements and their minable resources suggests that potential world resources in deposits of this quality are of the order of 45 million tons (see V. E. McKelvey, Am. Jour. Sci., v. 258A, p. 234-241, 1960). Despite the lack of quantitative estimates of total marginal or submarginal resources, several examples indicate that their potential is enormous. The alum black shale of Sweden contains about 850,000 tons U in known deposits averaging 0.03 percent U_3O_8 , and another 1.7 million tons in known deposits averaging about 0.02 percent; unappraised resources may be of the order of 10 million tons. North African phosphorites contain about 2 million tons U (R. D. Nininger and C. J. Gardner, U. S. Atomic Energy Commission TID-8207, p. 3, 1960). Each of the major types of low-grade resources is known qualitatively in other parts of the world and an estimate of potential world resources based on an extrapolation of those listed in table 3 to the rest of the world on the basis of the proportionately larger area involved--say 4 billion tons x 17.3--about 70 billion tons (approximately 5 million Q)--is probably of the right order of magnitude.

Table 5. Provisional estimates of United States resources of thorium ^{1/}
 (Short tons of Th. Energy equivalent to 10^{18} Btu shown in parenthesis) ^{2/}

Present cost (dollars per pound ThO ₂ ^{3/})	Known deposits	Unappraised and undiscovered resources
5 - 10 ^{4/}	100,000 (7)	800,000 (56)
10 - 30 ^{5/}	100,000 (7)	1,700,000 (120)
30 - 100 ^{6/}	---	30,000,000 (2,100)
100 - 500 ^{7/}	---	6,000,000,000 (420,000)

^{1/} Estimates of thorium in known deposits in the \$5-10 cost range prepared by the AEC; most other estimates prepared by the U. S. Geological Survey.

^{2/} Assumes complete recovery. Conversion factor: 1 short ton Th = 7×10^{13} Btu.

^{3/} Based on specific estimates by AEC of mining and processing costs of various types of deposits, assuming present economic and technological conditions.

^{4/} Known deposits include about 88,000 tons in vein deposits in the Lemhi Pass area of Idaho (B. J. Sharp, D. L. Hetland, and A. E. Granger, AEC, unpublished data); about 4,000 tons in Idaho and Carolina monazite placers (AEC estimate); and about 16,000 tons in the Goodrich quartzite, Michigan (R. C. Vickers, U. S. Geol. Survey Bull. 1030-F). The estimate of unappraised and undiscovered resources is a speculative one by J. C. Olson, U.S.G.S., that includes 300,000 tons of potential resources in the Lemhi Pass district estimated by Sharp, et al. as well as potential resources in veins in about 20 other promising districts.

^{5/} Known deposits include 53,000 tons in Carolina placers (W. C. Overstreet, P. K. Theobald, and J. W. Whitlow, Am. Inst. Mining Eng. Trans., v. 214, p. 709-714, (1959) and 50,000 tons in the Goodrich quartzite. Unappraised and undiscovered resources include 150,000 tons in the Goodrich quartzite; 10,000 tons in Idaho and Montana placers (D. E. Eilertson and F. D. Lamb, U. S. Bur. Mines RME-3140, U. S. Atomic Energy Comm. Tech. Info. Service, Oak Ridge, Tenn.); 120,000 tons in a monazite placer off the mouth of the Apalachicola River, Florida (W. F. Tanner, A. Mullins, and J. D. Bates, Econ. Geol., v. 56, p. 1079-1087, 1961); 8,000 tons in Arkansas bauxite (estimated by Olson from data of J. A. S. Adams, and C. E. Weaver, Am. Assoc. Petroleum Geologists Bull., v. 42, p. 387-430, 1958); 14,000 tons in quartz bostonites in Colorado to a depth of 1,000 feet (G. Phair, U.S.G.S. unpublished data, 1962); 1,000,000 tons in hornblende-albite syenite, Wet Mountains, Colo., to a depth of 1,000 feet (M. R. Brock, U.S.G.S. unpublished data, 1962); 180, tons in shonkinite, Mountain Pass, Calif., to a depth of 1,000 feet (J. C. Olson, U.S.G.S. unpublished data, 1962); 4,500 tons in gneiss, Mass., to a depth of 1,000 feet (D. H. Johnson, U. S. Geol. Survey TEI-69, U. S. Atomic Energy Comm. Tech. Info. Service, Oak Ridge, Tenn.); 10,000 tons in thorium-bearing veins, Wet Mountain, Colo., to a depth of 50 feet (M. R. Brock, U.S.G.S. unpublished data, 1962); 17,000 tons in Cretaceous black sand deposits in the western states (V. T. Dow, J. V. Beatty, U. S. Bur. Mines Rept. Inv. 5860); and a speculative estimate by J. C. Olson of 200,000 tons in thorium-bearing veins containing 0.03-0.3 percent Th to depths of 1,000 feet in the Wet Mountains, Colo., and elsewhere.

^{6/} Conway granite, N. H., to depth of 1,000 feet. In addition, the Silver Plume granite and Pikes Peak granite, Colo., probably contain 50,000 tons and 100,000,

respectively, to depth of 1,000 feet, in rocks with thorium contents of 90 and 50 ppm (G. Phair, U.S.G.S. unpublished data).

- 7/ Large granitic bodies containing 12-30 ppm Th to depth of 1,500 feet, including Pikes Peak granite, Marquette County, Mich., Wisconsin, Minnesota, Idaho batholith, California batholith, S. California batholith, N. California batholith, N. Washington batholith, Appalachians, and New England. Estimated by AEC.

Table 6. Provisional estimates of world thorium reserves, minable at \$10 per pound or less^{1/} (Energy equivalent to 10^{18} Btu shown in parenthesis; assumes complete burn-up)

<u>Area</u>	<u>Short tons</u>
United States	100,000 (7)
Canada	175,000 (12)
Brazil	25,000 (2)
Africa	45,000 (2)
India, Ceylon, Afghanistan, Nepal, Pakistan ^{2/}	220,000 (15)
Sino-Soviet Bloc	90,000 (6)
Australia	45,000 (3)
Total ^{3/}	700,000 (48)

- ^{1/} Estimates for the United States from table 10. Estimate for Australia from Bowie, S. H. U., 1959, The uranium and thorium resources of the Commonwealth: Royal Soc. Arts Jour., v. 107, p. 706; those for other areas from McKinney report, op. cit., p. 1612-1613.
- ^{2/} An additional 250,000 tons is possible in the inland placers of Bihar and West Bengal, which have not been thoroughly explored.
- ^{3/} Undiscovered resources of the same quality are potentially much larger. On the basis of a comparison between thorium reserves and the known areal extent of metamorphic and igneous rocks (to which thorium deposits are genetically related), world resources would be expected to be 3-6 million tons, taking the United States and the base for extrapolation; or, taking India as the base, 6-12 million tons (J. C. Olson, U.S.G.S., unpublished data). Using the relation between reserves and crustal abundance, world thorium resources would be expected to be of the order of 20 to 200 million tons (McKelvey, op. cit.). Low-grade resources have been little explored, but data from specific deposits show that their ratio to high-grade resources over the world may be similar to that in the United States and known examples indicate their large magnitude. Thus, the Kaffo riebeckite granite of Nigeria contains 70 tons of uranium, at least 140 tons of thorium, and about 1,840 tons of $(\text{Nb}, \text{Ta})_2\text{O}_5$ per foot of depth and is only one of several known in Nigeria to be highly radioactive (R. A. Mackay and K. E. Beer, Geol. Survey of Great Britain Rept. 9SM (AED.95). Carbonatite averaging 0.07 percent ThO_2 at Araxa, Brazil contains 110,000 tons above a depth of 475 feet (D. Guimaraes, Div. de Fomento da Producao Mineral Belo Horizonte, Bull. 103) and carbonatites at Palabora in the Transvaal and in Kenya, averaging about 0.02-0.05 percent ThO_2 , contain tonnages of the same order of magnitude at shallow depths. As with uranium, an extrapolation from the United States to the rest of the world on the basis of proportionality of areas -- 17.3×6 billion tons -- about 100 billion tons (7 million Q) -- probably supplies an estimate of potential resources valid as to general order of magnitude.

Lithium is not in great demand and hence its resources have been little explored. Li^6 in known minable deposits in the United States probably totals about 73,000 tons, with an energy equivalent of 21 Q (table 7). World minable reserves probably contain about 230,000 tons of Li^6 , with an energy equivalent of 70 Q (table 8). Low-grade deposits are little known but should be of about the same magnitude as those of uranium. The Li^6 content of the ocean is 20 billion tons, with an energy equivalent of 6 million Q (table 8).

Water power, geothermal energy, and other energy sources

The installed capacity of water-power plants of the United States is about 38,600 megawatts, and the 1962 output was 168 million megawatt hours. The potential at mean flow is about 121,000 MW, equivalent to an annual production of 1 billion MW hours. The installed capacity over the world is about 180,000 MW, and the potential at the mean flow is about 2,700,000 MW (table 9).

According to D. E. White (U. S. Geol. Survey, unpublished data), present world utilization of geothermal energy is in the order of 1,000 MW, and this can probably be increased 10-100 times for at least 50 years. Stored energy to a depth of 3 km that might be recoverable at or near present costs are estimated to be 0.12 Q. Of the total resources of geothermal energy, probably 5 to 10 percent occurs in the United States.

Other sources of energy include tidal power and various forms of solar energy, including direct radiation, wind power, and ocean heat. These are potentially enormous (for example, the solar radiation striking the earth's surface amounts to 3,200 Q per year, and of this 90 Q is converted into wind), but no estimates have been made of the fractions that might be recovered at various costs.

Conclusions

Known supplies of coal minable at or below present prices are more than adequate for foreseeable needs through the 20th century. Large additional resources exist, and if the research needed to advance technology is pressed, low cost supplies should be available for many more decades at prices comparable to those prevailing now. Proved reserves of oil and gas are sufficient for only a decade or so but substantial additional resources can be developed through continued exploration and improvement of secondary recovery practices. Resources of oil shale and related deposits are enormous.

Mining reserves of uranium are large and much larger tonnages in deposits of the same quality will be discovered on further exploration. At present low rates of reactor efficiency, the energy available from these sources is small, although it is ample to support a budding nuclear power industry for a few decades, provided the exploration for concealed deposits is pursued successfully.

If breeder technology is developed for commercial use, energy from U^{238} and Th will be available for millenia to come from low-grade resources--phosphorites, shales, and igneous rocks.

If control of fusion becomes economical, enormous energy resources will be available from lithium in relatively shallow parts of the earth's crust, and especially from lithium and deuterium in the ocean.

The contrast between the energy that is available in known sources available at present prices and established technology, and that potentially available through successful exploration and process development is almost staggering, and underscores the critical importance of research, exploration and development in meeting future needs.

Table 7. United States lithium reserves
(In short tons Li_2O . Estimated by J. J. Norton, U. S. Geological Survey)

Locality	Measured and indicated reserves		Inferred reserves
	Major operating mines	Other deposits	
Foote Mineral Co. mine, Kings Mountain, N. C.	317,000	240,000	
Other deposits in the Kings Mountain district, N. C.	--	490,000	
Black Hills, S. Dak.	--	12,000	
Searles Lake, Calif.	--	90,000	
Total (rounded)		<u>1,000,000</u>	<u>1,000,000</u> ^{1/}
Li^6 (energy equivalent in 10^{18} Btu in parenthesis)			<u>73,000</u> (22)

^{1/} Mainly in the Kings Mountain district. Further exploration undoubtedly will reveal additional reserves of high-grade ore (the relation between reserves and abundance suggests that the tonnage of lithium may be at least 6 and perhaps 60 million tons, or 0.42-4.2 million tons of lithium-6; see McKelvey, op. cit.) and far larger tonnages of lithium-6 in various classes of resources are about the same as or slightly larger than those of uranium.

Table 8. World reserves of lithium^{1/}
 (In short tons LiO₂. Estimated by J. J. Norton, U. S. Geological Survey)

<u>Area</u>	<u>Measured and indicated reserves</u>	<u>Inferred reserves</u>
United States	1,000,000	1,000,000
Canada	400,000	2,000,000
Africa	200,000	2,000,000
	<u>1,700,000</u>	<u>5,000,000</u>
Li ⁶ (energy equivalent in 10 ¹⁸ Btu in parenthesis)	230,000 (70)	
Li ⁶ content of the ocean (energy equivalent in 10 ¹⁸ Btu)	20 x 10 ⁹ (6,000,000)	

^{1/} Known world reserves of lithium are limited to a few areas; reserves at the four main producing localities -- Kings Mountain, N.C., Searles Lake, Calif.; Barraute, Quebec; and Bekita, southern Rhodesia -- account for the bulk of the 1.7 million tons of measured and indicated reserves of LiO₂. Unquestionably, the estimate of 6.7 million tons in deposits of minable quality is conservative. In addition, low grade deposits may be expected in about the same abundance as those of uranium.

Table 9. Installed capacity and potential waterpower of the United States and world^{1/}
 (In megawatts)

	<u>Gross theoretical power, at 100 percent efficiency and flows</u>			<u>Developed sites</u>	
	<u>At flows available 95 percent of the time</u>	<u>At flows available 50 percent of the time</u>	<u>Mean flow</u>	<u>Number of sites</u>	<u>Installed capacity of waterpower plants</u>
United States	33,800	72,000	121,300	1,398	38,600
World	--	--	2,724,000	--	180,900

^{1/} Based on estimates by L. L. Young, 1964, U. S. Geol. Survey Circ. 483.