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2Da-II. UNITED STATES AND WORLD RESOURCES OF ENERGY[1]

by

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Submitted by the Government of the United States of America

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 950 billion to more than 22 trillion barrels of oil equivalent, and if very low grade organic-rich deposits are included, the potential may be nearly 350 trillion barrels of oil equivalent. World resources contain about 3.9 trillion to more than 80 trillion barrels of oil equivalent, and if very low grade resources are considered the potential may be about 4.3 quadrillion.

The energy potential of uranium resources in the United States ranges from about 35 billion to more than 48 quadrillion barrels of oil equivalent, 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 58 billion to an order of magnitude of about 850 quadrillion barrels of oil equivalent. The energy potential of thorium resources of the United States ranges from 1.2 trillion to 72 quadrillion barrels of oil equivalent, and of the world from 8.3 trillion to about 1.2 quintillion barrels. If nuclear fusion can be controlled for power generation, the potential energy from resources of deuterium and lithium[6] are orders of magnitude larger than the fissionable mineral resources. Deuterium alone contains potential energy of 1.3 sextillion barrels of oil equivalent. 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

World consumption of energy in 1963 was about 23.3 billion barrels of oil equivalent, of which about 47 per cent was supplied by oil and gas. Per capita consumption in the countries over the world ranged from about 0.03 to 42 barrels of oil equivalent, and averaged about 7.2 barrels. The world average rate of increase in energy consumption during recent years has been about 4.9 per cent per year, although it has been as much as 15 per cent per year in a number of rapidly industrializing nations.

At the recent average rate of increase, by the year 2,000 world energy consumption would reach an annual level of about 137 billion barrels of oil equivalent, about 19.6—22.8 barrels per capita for a world population of 6—7 billion people. Cumulative consumption from 1964 through 2,000 would be about 2,400 billion barrels of oil equivalent—3 times the total used in all previous history. Projections over such long periods are risky, of course, and this one is not intended to be a forecast. Most of the forecasts that have been made assume that the rate of increase will start to taper off within a couple of decades and hence that the annual consumption at the end of the century will be somewhat lower than a projection based on recent trends. In view of the fact that the projected world per capita consumption would still be far lower than even present North American levels, however, it is desirable to aim at an even higher rate of growth for the world at large. The above projection, therefore, may be taken as a goal that we hope will be much exceeded.

How will these growing future demands be met? How long can oil and gas maintain their dominance in the future world energy market? These questions are of special significance to ECAFE countries, for they include on the one hand a substantial part of the world population with below average consumption, and if their economies and levels of living are to attain desired standards they must have access to steadily increasing supplies of energy. On the other hand, some ECAFE countries are currently large producers of oil and gas, and they are concerned about the magnitude of both world markets and competing sources of energy.

To give at least partial answers to these questions, it is pertinent to examine the extent of world energy

[1] From ECAFE document I&NR/PR.3/127.

resources, not only of oil and gas, but other present and potential sources as well. Estimates of United States resources, which are somewhat better known than those in many other parts of the world, are included for comparison.

Most of the estimates that follow 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.

Meaning and Classification of Resource Estimates

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.

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 favourable 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 of 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.

Fossil fuels

The energy content of known United States reserves of fossil fuels recoverable at or close to present prices and with established technology is about 950 billion (950×10^9) barrels of oil equivalent, and that of undiscovered and/or marginal and submarginal resources, minable under changed conditions or higher prices, is a little more than 21 trillion (21×10^{12}) barrels. Of the presently minable deposits, coal contains nearly 84 per cent 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 per cent of the marginal and submarginal resources; shales, not included in the above estimates, containing 10 per cent or more organic matter, hold an energy potential of 38 trillion barrels and those with 5-10 per cent organic matter have a potential of about 275 trillion barrels.

The energy content of known recoverable world reserves of fossil fuels is about 3.9 trillion barrels of oil equivalent. Undiscovered and/or marginal and submarginal resources contain about 78 trillion barrels of oil equivalent (table 2). Shales with more than 5 per cent organic matter probably have an energy potential of nearly 4.3 quadrillion (4.3×10^{15}) barrels.

Nuclear fuels

Known United States reserves of uranium minable at a price of $5-$10 per pound of U_3O_8 are about 166,000 tons, and 244,000 tons additional have already been delivered to the Atomic Energy Commission (table 3). Assuming complete burn-up of contained U^{235}, delivered and minable uranium contains about 35 billion barrels of oil equivalent; assuming complete burn-up of U^{235} and U^{238} (possible only with breeding), the oil equivalent is about 5 trillion barrels. Unappraised and undiscovered resources of the same quality as those being mined probably contain oil equivalents of 65 billion to 9.3 trillion barrels (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 340 trillion to 48 quadrillion barrels (depending on burn-up). World uranium reserves minable at $5-$10 a pound are at least 710,000 tons, with an oil equivalent of 60 billion to 8.6 trillion barrels, and may be far larger (table 4). About 260,000 tons have already been delivered to the United States and other countries of the non-Communist world and should be added to these reserves to indicate the amount available under present conditions. Low-grade resources are enormous. The ocean alone contains nearly 4.2 billion tons of uranium; recent studies indicate that it may be recovered from sea water at a cost of $13-$26 a pound. Uranium in other low-grade sources is probably of the order of 70 billion tons.

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 ThO_2 are 100,000 tons, with an oil equivalent of 1.2 trillion barrels, assuming complete burn-up (table 5). Unappraised and undiscovered resources of the same and lower quality probably contain the oil equivalent of more than 72 quadrillion barrels. World reserves minable at $10 a pound or less contain the energy equivalent of 8.3 trillion barrels 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 lithium[6]. According to Friedman and other [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. 177 244], the oceans contain about 2.5×10^{13} short tons of deuterium, the energy equivalent of which is about 1.3 sextillion (1.3×10^{21}) barrels.

2Da-II. Table 1. PROVISIONAL ESTIMATES OF UNITED STATES RESOURCES OF FOSSIL FUELS[a]

(Energy in 10^9 barrels of oil equivalent shown in parenthesis)

	Known recoverable reserves[b]	*Undiscovered recoverable resources*	*Known marginal and submarginal resources*	*Undiscovered marginal and submarginal resources*
Coal (short tons)	220×10^9 (795)	Not estimated	$1{,}400 \times 10^9$ (5,000)	$2{,}600 \times 10^9$ (9,500)
Crude oil (barrels)	47×10^9	200×10^9	40×10^9	300×10^9
Natural gas (cu. ft.)	276×10^{12} (49)	$1{,}200 \times 10^{12}$ (215)	Not estimated	850×10^{12} (150)
Natural gas liquids (barrels)	7.7×10^9 (6)	30×10^9 (24)	Not estimated	60×10^9 (48)
Oil in bituminous rock (barrels)	1.3×10^9	Not estimated	Not estimated	10×10^9
Shale oil (barrels)	50×10^9	Not estimated	$2{,}000 \times 10^9$	$4{,}000 \times 10^9$
Total (rounded) energy	(950)	(440)	(7,000)	(14,000)
Grand (rounded) total, all classes	(22,400)			

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

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

[b] 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 or more. 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.

Campbell's estimate of 1913 included coal 14 inches or more thick, extending to depths as much as 6,000 feet below surface, and totalled about 4.2 trillion short tons in place. The estimate included substantial tonnages of coal that is now known to be more than 6,000 feet below surface in some fields. This estimate, which was based on limiting criteria more nearly comparable to those used for world coal resource estimates of the World Power Conferences (30 cm minimum thickness, 1200 m maximum depth for high rank coal and 500 m maximum depth for lignite), is substantially larger than the more recent restrictive estimates of U.S. coal reserves which exclude thin low-rank coal, all coal more than 3000 feet below surface, and most of the undiscovered and incompletely appraised coal. New estimates that are presently being prepared by the U.S. Geological Survey will be somewhat smaller, due in part to the exclusion of thin low-rank coal, and some very deeply buried coal.

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 Interestate 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 fields 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. An extension of these studies by the U.S. Geological Survey suggests that the ultimately recoverable crude oil may be more than originally estimated by Zapp. A more conservative estimate of ultimate crude oil reserves of the United States by M. King Hubbert (Nat. Acad. of Sci., Pub. 1000-D, 1962), totals 175 to 225 billion barrels. Hubbert's estimate included past production and was based largely on projections of past production and proved reserves.

Undiscovered marginal and submarginal resources include oil 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 6,000 ft. of gas per barrel of oil, and hence the undiscovered recoverable resources of gas may be as high as 1,500 or $1{,}600 \times 10^{12}$ 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 more to 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 38 trillion barrels of oil equivalent. Shale containing 5 to 10 percent organic matter probably contain an energy equivalent of about 275 trillion barrels of oil.

2Da-II Table 2. PROVISIONAL ESTIMATES OF WORLD RESOURCES OF THE FOSSIL FUELS

(Energy in 10^9 barrels of oil equivalent shown in parenthesis)

	Known recoverable reserves		*Undiscovered and/or marginal and submarginal resources*	
Coal (short tons)[a]	850×10^9	(3,000)	$15{,}150 \times 10^9$	(55,200)
Crude oil (barrels)[b]	300×10^9		$4{,}000 \times 10^9$	
Natural gas (cu.ft.)[c]	$1{,}800 \times 10^{12}$	(330)	$19{,}000 \times 10^{12}$	(3,450)
Natural gas liquids (barrels)[d]	45×10^9	(36)	700×10^9	(550)
Oil in bituminous rocks (barrels)[e]	40×10^9		$1{,}060 \times 10^9$	
Shale oil (barrels)[f]	150×10^9	———	$13{,}600 \times 10^9$	———
Total (rounded) energy in fossil fuels		(3,900)		(77,800)

[a] 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 estimate 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.

[b] 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).

[c] 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 expected 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. L. G. Weeks (1958, Habitat of oil, p.58) estimated about 65 quadrillion cubic feet of hydrocarbon gas are contained in solution in waters of porous sandstone in the world sedimentary basins. Rocks such as coal and organic-rich shale perhaps contain a few hundred quadrillion cubic feet of natural gas entrapped in pore space. The potential energy of such low-grade hydrocarbon gas resources may be several tens-of-trillions barrels of oil equivalent. Part of their energy potential is included with the estimate for organic-rich-shale deposits in footnote f.

[d] 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 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.

[e] 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 1, 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. Estimates of the size of deposits in Canada and Venezuela have been increased recently. About 700 billion barrels of tar and viscous oil in place are reported in deposits of Alberta, Canada (Oil and Gas Journal, December 16, 1963, p.54), and about 200 billion barrels are reported in deposits of eastern Venezuela (Oil and Gas Journal, July 13, 1964, p.66). The tar and viscous oil in these deposits alone contain an energy potential of about 900 billion barrels of oil equivalent.

[f] 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 is mining. In certain foreign areas, however, where an oil shale industry is already established, deposits of the grade 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 include 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 an oil equivalent of about 7 quadrillion barrels; deposits containing 5 to 10 percent organic matter probably contain an oil equivalent of about 35 quadrillion barrels. These unappraised deposits are not included in the estimates shown on the table.

2Da-II. Table 3. Provisional estimates of United States resources of uranium[a]

(Short tons of U. Energy in 10^9 barrels of oil equivalent shown in parenthesis)[b]

Present cost (dollars per pound of U_3O_8)[c]	*Known deposits*	*Unappraised and undiscovered resources*
5 – 10[d]	166,000 (14 – 2,100)	770,000 (65 – 9,300)
10 – 30[e]	140,000 (12 – 1,700)	500,000 (41 – 6,000)
30 – 100[f]	12,300,000 (1,000 – 148,000)	20,000,000 (1,700 – 240,000)
100 – 500[g]	——	4,000,000,000 (340,000 – 48,000,000)

[a] 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.

[b] 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 $U = 7 \times 10^{13}$ Btu.

[c] Based on specific estimates by AEC of mining and processing costs various types of deposits, assuming present economic and technologic conditions.

[d] Uranium already mined and delivered to AEC totals 244,000 tons and should be added to known reserves to represent uranium available under present conditions. Known reserves, estimated by AEC as of Jan. 1, 1965, include 142,000 tons in western sandstone deposits averaging about 0.21 percent U; about 7,000 tons in western vein deposits averaging about 0.21 percent U; and about 17,000 tons available as a by-product of phosphate fertilizer production through the year 2,000. 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.

[e] 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 20,000 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.

[f] 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 hgih-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 0.008 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.

[g] 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).

2Da-II. Table 4. Provisional estimates of world *uranium reserves*[a]

(Energy in 10^9 barrels of oil equivalent shown in parenthesis)[b]

Country	*Short tons*
United States	166,000 (14 – 2,100)
Canada	236,000 (19 – 2,800)
South Africa	127,000 (10 – 1,500)
France	34,000 (3 – 410)
Australia	13,700 (1 – 16)
Sino-Soviet Bloc	110,000 – 400,000 (9 – 35; 1,300 – 4,800)
Other[c]	21,000 (2 – 260)
Total (rounded) non Communist world	600,000 (52 – 7,200)
Total (rounded) world[d]	710,000 – 1,110,000 (60 – 95; 8,600 – 13,000)
U content of the ocean[e]	4,160,000,000 (350,000 – 50,000,000)

[a] Except for uranium in the ocean (see below), the estimates are for known deposits minable at $5-10 per pound of U_3O_8. 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. Uranium already mined and delivered to the United States and other countries of the non-communist world is of the order of 260,000 tons and should be added to known reserves to represent uranium available under present conditions.

[b] 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 $U = 7 \times 10^{13}$ Btu.

[c] Argentina, Congo, Germany, India, Japan, Mexico, Portugal, and Spain.

[d] 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 areas involved — say 4 billion tons × 17.3 = about 70 billion tons — is probably of the right order of magnitude.

[e] From R. V. Davies and others, Nature, v. 203, no. 4950, p. 1110, who estimate that uranium can be recovered from sea water at a cost of $13-26 a pound.

2Da-II. Table 5. PROVISIONAL ESTIMATES OF UNITED STATES RESOURCES OF THORIUM[a]

(Short tons of Th. Energy in 10^9 barrels of oil equivalent shown in parenthesis)[b]

Present cost (dollars per pound ThO_2)[c]	Known deposits	Unappraised and undiscovered resources
5 – 10[d]	100,000 (1,200)	800,000 (9,600)
10 – 30[e]	100,000 (1,200)	1,700,000 (21,000)
30 – 100[f]	——	30,000,000 (360,000)
100 – 500[g]	——	6,000,000,000 (72,000,000)

[a] 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.

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

[c] Based on specific estimates by AEC of mining and processing costs of various types of deposits assuming present economic and technological conditions.

[d] 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.

[e] Known deposits include 53,00 tons in Crolina placers (W.C. Overstreet, P. K. Theolbald, 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 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); 180,000 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.

[f] 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).

[g] 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.

2Da-II. Table 6. PROVISIONAL ESTIMATES OF WORLD THORIUM RESERVES, MINABLE AT $10 PER POUND OR LESS[a]

(Energy in 10^9 barrels of oil equivalent shown in parenthesis; assumes complete burn-up)

Area	Short tons
United States	100,000 (1,200)
Canada	175,000 (2,100)
Brazil	25,000 (340)
Africa	45,000 (340)
India, Ceylon, Afghanistan, Nepal, Pakistan[b]	220,000 (2,600)
Sino-Soviet Bloc	90,000 (1,000)
Australia	45,000 (520)
TOTAL[c]	700,000 (8,300)

[a] 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.

[b] An additional 250,000 tons is possible in the inland placers of Bihar and West Bengal, which have not been thoroughly explored.

[c] 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 as the base for extrapolation; or, taking India as the base, 6-12 million tons (J. C. Olson and W. C Overstreet, U.S.G.S. Bull. 1204, p.45). 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 $(Nb,Ta)_2O_5$ 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 area — 17.3×6 billion tons = about 100 billion tons — 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 oil equivalent of 3.6 trillion barrels (table 7): World minable reserves probably contain about 230,000 tons of Li^6, with an oil equivalent of 12 trillion barrels (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 oil equivalent of 1 quintillion (1×10^{18}) barrels (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 120×10^{15} Btu (an oil equivalent of about 20 billion barrels).

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 3.2×10^{21} Btu per year, and of this 90×10^{18} Btu 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.

Minable 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.

2Da-II. Table 7. United States lithium reserves

(In short tons LiO_2. Estimated by J. J. Norton, U. S. Geological Survey)

Locality	Measured and indicated reserves: Major operating mines	Measured and indicated reserves: Other deposits	Inferred reserves
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)	1,000,000		1,000,000[a]
Li^6 (oil equivalent in 10^9 barrels shown in parenthesis)			73,000 (3,600)

[a] 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.

2Da-II. Table 8. World reserves of lithium[a]

(In short tons LiO_2. Estimated by J. J. Norton, U. S. Geological Survey)

Area	Measured and indicated reserves	Inferred reserves
United States	1,000,000	1,000,000
Canada	400,000	2,000,000
Africa	200,000	2,000,000
	1,700,000	5,000,000
Li^6 (energy equivalent in 10^9 barrels of oil in parenthesis)	230,000 (1,200)	
Li^6 content of the ocean (energy equivalent 10^9 barrels of oil)	20×10^9 (1,000,000,000)	

[a] 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 LiO_2. 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.

2Da-II. Table 9. Installed capacity and potential waterpower of the United States and world[a]

(In megawatts)

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

[a] Based on estimates by L. L. Young, 1964, U. S. Geol. Survey Circ. 483.