Kirk-Othmer Encyclopedia of Chemical Technology.

PETROLEUM RESOURCES

Petroleum resources are distributed widely in the earth's crust as gases, liquids, and solids. The products derived from these naturally occurring resources are used principally as energy sources, although substantial volumes serve as feedstocks in the chemical, plastics, and other industries (see Feedstocks). Petroleum resources are found as natural gas, as a variety of liquids that are usually classified as normal or heavy crude oils, and as semisolid and solid substances such as asphalt (qv), tar, pitch, gilsonite, and many others. The petroleum resources considered here are those liquid crude oils that can be produced through a conventional wellbore by current primary, secondary, or tertiary (enhanced recovery) production techniques and those unconventional crude oils that may be captured and converted into conventional sources of crude petroleum by advancing production technologies.

No method has been devised to estimate with complete accuracy the amount of crude petroleum that ultimately will be produced from the world's conventional oil and gas fields. Degrees of uncertainty, therefore, should be attached to all such estimates. These uncertainties can be expressed in several ways, the most important of which is achieved by dividing a resource into various categories. Several petroleum resources classifications have been proposed, and a comprehensive discussion of them (1), as well as the definition used in the assessment of the undiscovered resources of the United States (2), have been provided. Seven commonly used categories of resources are given here.

Resources represent the total amount (including reserves) of petroleum that exists in a form and amount such that economic extraction is currently or potentially feasible.

Reserves constitute the petroleum that has been discovered and can be produced at the prices and with the technology that exist when the estimate is made.

Proved reserves are estimates of petroleum reserves contained primarily in the drilled portion of fields.

Indicated reserves constitute known petroleum that is currently producible but cannot be estimated accurately enough to qualify as proved.

Inferred reserves are producible, but the assumption of their presence is based on limited physical evidence and considerable geologic extrapolation. This places them on the borderline of being considered undiscovered, and the accuracy of the estimate is very poor.

Subeconomic resources constitute the petroleum in the ground that cannot be produced at present prices and technology but may become producible at some future date at higher prices or by improved technology.

Undiscovered resources are estimated totally by geological reasoning; no evidence through drilling is available.

To various degrees, the conventional petroleum resources in many parts of the world have been classified according to such a system. In certain regions, only estimates of proved reserves are made routinely, whereas in the United States, Canada, and certain other regions, estimates are made of volumes of petroleum in each of these categories. In the United States and Canada, estimates for several of these categories (in particular, proved reserves) are made each year by governmental agencies (3). For other categories, eg, undiscovered U.S. resources, many estimates have been prepared by various agencies, committees, panels, and companies (4–6).

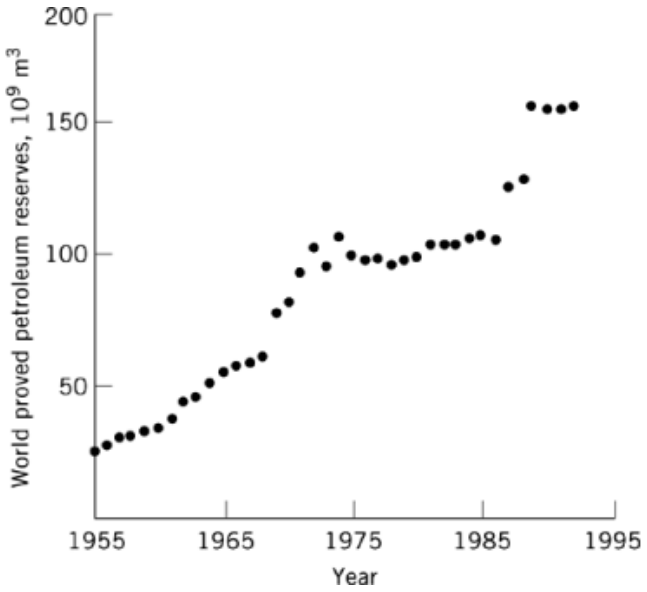

Fig. 1. Growth of world's reserves of conventional petroleum. To convert m^3 to bbl, multiply by 6.29.

In a similar manner, estimates for several resource categories have been made for most other countries and for the world as a whole (7–9).

1. World Reserves

Most of the large volume of crude petroleum consumed in the world is extracted from only a small fraction of the total number of oil fields discovered. The concentration of crude petroleum in a few large fields is a consequence of the interaction of the geologic processes that create and trap petroleum. Even though commercial quantities of petroleum have been discovered in many localities around the world, there are enormous volume differences in fields present in a single region and in the total volume of petroleum present in different regions.

By far the largest known concentrations of conventional petroleum reserves are in the Middle East, particularly in Saudi Arabia, the United Arab Emirates, and Kuwait (Table 1). The largest concentration of reserves is in the Burgan field (10.2×10^9 m^3 (64.2×10^9 bbl)) in Kuwait (10), which contains about 68% of that country's reserves. The second largest concentration of reserves is in the Ghawar field (7.4×10^9 m^3 (46.5×10^9 bbl)) in Saudi Arabia (10), which is about 18% of that country's reserves. In some regions, a large portion of the reserves may not be contained in the largest field. However, the largest field usually contains more than 10% of the total reserves of a region. More than 20,000 petroleum fields have been discovered worldwide, and more than half of the world's proved reserves of 160.1×10^9 m^3(1006.8×10^9 bbl) of petroleum are contained in only the 51 largest fields (10).

The world's reserves of conventional petroleum have increased from 91.7×10^9 m^3 (577×10^9 bbl) in 1978 to 160.1×10^9 m^3 (1006.8×10^9 bbl) in 1991 (Fig. 1). This growth of 68.4×10^9 m^3 (430.2×10^9 bbl) in 13 years did not take place uniformly from region to region nor from year to year. Most of this increase took place during two years, 1987 and 1989 (Fig. 1). These increases are the result of recording of additional reserves in known fields as well as some new field discoveries, principally in the Middle East.

Table 1. World Reserves and Production of Petroleum[a,b]

Country	Reserves[c]		Production, 10^6 m^3[d]	
	Volume, 10^6 m^3[d]	Percentage of world	1978	1992
United States	5,103	3.2	611	514
Canada	1,208	0.8	90	120
Mexico	8,156	5.1	70	183
Total North America	*14,467*	*9.0*	*771*	*817*
Argentina	254	0.2	26	31
Brazil	477	0.3	9	40
Venezuela	9,952	6.2	126	145
others	843	0.5	45	64
Total South America	*11,526*	*7.2*	*206*	*280*
Total Western Hemisphere	*25,993*	*16.2*	*977*	*1,097*
Norway	1,399	0.9	21	126
United Kingdom	652	0.4	63	113
others	461	0.3	19	34
Total Western Europe	*2,512*	*1.6*	*103*	*273*
Iran	14,769	9.2	302	200
Iraq	15,898	9.9	153	28
Kuwait	14,944	9.3	108	53
neutral zone[e]	795	0.5	27	19
Saudi Arabia	40,986	25.6	495	507
United Arab Emirates	16,184	10.1	106	173
others	1,638	1.0	62	82
Total Middle East	*105,214*	*65.7*	*1,253*	*1,062*
Algeria	1,463	0.9	71	77
Libya	3,625	2.3	116	88
Nigeria	2,846	1.8	111	107
others	1,908	1.2	58	129
Total Africa	*9,842*	*6.1*	*356*	*401*
Australia/New Zealand	318	0.2	26	34
China	3,816	2.4	116	165
Brunei/Malaysia	795	0.5	26	49
former Soviet Union	9,062	5.7	651	527
India	954	0.6	15	34
Indonesia	922	0.6	95	89
other	636	0.4	25	35
Total Asia	*16,503*	*10.3*	*954*	*933*
Total Eastern Hemisphere	*134,071*	*83.8*	*2,666*	*2,669*
Total World	*160,064*	*100.0*	*3,643*	*3,766*

[a] Ref. 7.
[b] Includes crude oil, shale oil, oil sands, and where known, natural gas liquids.
[c] January 1992.
[d] To convert m^3 to bbl, multiply by 6.29.
[e] Neutral zone is produced jointly by Saudi Arabia and Kuwait.

The U.S. proved reserves of crude petroleum and natural gas liquids (NGL) together are 5.1×10^9 m^3 (32.1×10^9 bbl) and constituted 3.2% of the world's proved reserves in 1991. The U.S. position in proved reserves has fallen since 1978, when it reported 5.4×10^9 m^3 (34×10^9 bbl) and constituted 6% of the world's proved reserves. Canada's proved reserves declined slightly between 1978 and 1991, whereas Mexico reported a large increase in crude petroleum reserves development over the same period,

Table 2. Estimates of Proved Petroleum Reserves in Parts of Western Europe

Country	Volume, 10^6 m^3[a]
Denmark	116.1
Italy	110.1
Germany	43.2
former Yugoslavia	29.7
Spain	2.9
Austria, Greece, the Netherlands, and France	69.2
Total	*371.2*

[a]To convert m^3 to bbl, multiply by 6.29.

from 4.5×10^9 m^3 (28.3×10^9 bbl) to 8.2×10^9 m^3 (51.6×10^9 bbl), thereby surpassing the United States and becoming the country with the largest proved reserves in North America (see Table 1).

In South America, Venezuela continues to dominate in the proved reserve and the production categories. Since 1978, reserves of crude petroleum in Venezuela have increased from 2.9×10^9 m^3 (18.2×10^9 bbl) to 10.0×10^9 m^3 (62.6×10^9 bbl), nearly doubling its share of the world's proved reserves from 3.2 to 6.2%. Venezuela has extra large deposits of heavy oils in the East Venezuela Basin, the further development of which may expand its position in proved petroleum reserves.

The 1991 petroleum resources of Western Europe were almost identical to what they were in 1978 (2.5×10^9 m^3 (16.1×10^9 bbl) vs 2.6×10^9 m^3 (15.8×10^9 bbl)). During that period, the net decline in reserves in the United Kingdom from 1.6×10^9 m^3 (10.2×10^9 bbl) to 0.7×10^9 m^3 (4.1×10^9 bbl) was offset by the net increase in reserves in Norway from 0.7×10^9 m^3 (4.1×10^9 bbl) to 1.4×10^9 m^3 (8.8×10^9 bbl). The reserves of the rest of Western Europe are insignificant (Table 2).

At the end of 1991, the reserves of crude petroleum in Africa were 9.8×10^9 m^3 (61.9×10^9 bbl), or only slightly higher than those in 1978, when they were 8.9×10^9 m^3 (56.3×10^9 bbl). Algeria, Libya, and Nigeria account for over 80% of these reserves and over 65% of the production from Africa.

The reserves of crude petroleum in Asia stood at 16.5×10^9 m^3 (103.8×10^9 bbl) in 1991. This is an increase of 10% since 1978; most of this increase was accounted for by China, India, and Brunei/Malaysia. Levels of proved reserves fell during this period in Australia/New Zealand, Indonesia, and several other Asian countries. In the countries that formerly composed the Soviet Union, reserves decreased slightly (2.5%) between 1978 and 1991, whereas annual production decreased 19%. For many years, the Soviet Union had been the leading producer of crude petroleum in the world, a position it still held in 1991, when it produced 527×10^6 m^3 (3.3×10^9 bbl). This level is only slightly higher than production levels in the United States (514×10^6 m^3 (3.2×10^9 bbl) and Saudi Arabia (507×10^6 m^3 (3.2×10^9 bbl).

The proved reserves and levels of production for Japan, Myanmar (formerly Burma), Pakistan, Taiwan, and Thailand are insignificant by world standards. In 1979, the Philippines established the first commercial production in the small offshore South Nido field. This success came after more than 75 years of wildcat drilling in the Philippines. After several additional discoveries, production rose to 0.3×10^6 m^3 (1.7×10^6 bbl) in 1991.

2. U.S. Reserves

Between 1978 and 1991, U.S. proved reserves of crude petroleum decreased by 21.3% from 5.0×10^9 m^3 (31.4×10^9 bbl) to 3.9×10^9 m^3 (24.7×10^9 bbl), as listed in Table 3. During this same period, NGL reserves increased by 33% from 0.9×10^9 m^3 (5.9×10^9 bbl) to 1.2×10^9 m^3 (7.5×10^9 bbl). The data in Table 3 show that despite small net additions in several U.S. states, eg, Colorado and New Mexico, the con-

Table 3. Estimates of Proved Reserves and Production of Crude Petroleum in the United States, 10^6 m^3[a,b]

States	Proved reserves		1978–1991	
	End 1978[d]	End 1991[d]	Net additions to reserves	Cumulative production[c]
Alabama	11.7	6.8	-4.9	41.9
Alaska	1491.9	967.1	-524.8	1329.7
Arkansas	17.6	11.1	-6.5	31.4
California	790.8	795.2	+4.4	844.5
Colorado	30.8	52.3	+21.5	63.4
Florida	26.7	5.9	-20.8	39.8
Illinois	25.1	20.3	-4.8	48.4
Indiana	4.6	2.5	-2.1	8.6
Kansas	48.2	47.7	-0.5	138.3
Kentucky	6.4	4.9	-1.5	10.0
Louisiana	548.2	390.1	-158.1	963.1
Michigan	35.0	18.9	-16.1	56.8
Mississippi	39.7	30.8	-8.9	67.3
Montana	25.1	32.0	+6.9	55.8
Nebraska	4.8	4.1	-0.7	87.5
New Mexico	92.1	114.6	+22.5	154.4
North Dakota	25.8	36.9	+11.1	87.5
Ohio	11.0	10.5	-0.5	23.4
Oklahoma	155.6	111.3	-44.3	295.7
Pennsylvania	4.3	2.4	-1.9	5.1
Texas	1416.7	1090.1	-326.6	1759.0
Utah	29.9	37.0	+7.1	63.7
West Virginia	4.8	4.1	-0.7	6.2
Wyoming	134.3	120.3	-14.0	246.4
miscellaneous[e]	3.8	6.7	+2.9	10.9
Total	*4984.9*	*3923.6*	*-1061.3*	*6438.8*

[a] Ref. 3.
[b] To convert m^3 to bbl, multiply by 6.29.
[c] Includes lease condensates.
[d] December 31.
[e] Includes Arizona, Maryland, Missouri, Nevada, New York, South Dakota, Tennessee, and Virginia.

ventional crude petroleum reserves of the United States were depleted rapidly between 1978 and 1991. Even with this decline in proved reserves, the United States was the second largest producer of crude petroleum in the world in 1992 after the former Soviet Union (see Table 1). Although much crude petroleum in the United States in recent years has been credited to the proved inventory through the extension and revision development processes, many of the newer discoveries of conventional hydrocarbon have been natural gas (see Gas, natural).

3. Ultimate Petroleum Resources of the World

Since the late 1960s, the ultimate amount of crude petroleum in the world that is producible through conventional production techniques has been estimated to be about 350×10^9 m^3 (2.2×10^{12} bbl) (9,11–13). By the end of 1991, cumulative world production was 103.8×10^9 m^3 (652.9×10^9 bbl)(14), and world proved reserves were estimated to be 160.1×10^9 m^3 (1006.8×10^9 bbl) (see Table 1). Thus, by the end of 1991,

Table 4. World Petroleum Statistics, 1992, 10^3 m^3/d[a,b]

Area	Consumption	Production[c]	Refinery capacity[d]
North America	2,847	1,735	2,732
Latin America	829	1,269	1,211
Total Western Hemisphere	*3,676*	*3,004*	*3,943*
OECD Europe	2,169	747	2,226
non-OECD Europe[e]	1,250	1,485	2,044
Middle East	560	2,909	781
Africa	322	1,100	465
Asia/Australia	2,419	1,076	2,308
Total Eastern Hemisphere	*6,720*	*7,317*	*7,824*
Total World	*10,396*[f]	10,321[f]	*11,767*

[a] Ref. 7.
[b] To convert m^3 to bbl, multiply by 6.29.
[c] Includes U.S. natural gas liquids.
[d] On December 31, 1992.
[e] Includes the former Soviet Union, the former Czechoslovakia, Hungary, Poland, and other former Eastern Bloc countries.
[f] Differences between production and consumption are accounted for by stock change and unknown military liftings.

263.9×10^9 m^3 (1659.7×10^9 bbl) of crude petroleum had been discovered, which is more than 75% of the estimated 350×10^9 m^3 (2200.0×10^9 bbl) of conventional crude petroleum estimated to be ultimately recoverable.

4. World Petroleum Supply and Consumption

As shown in Table 4, the 1992 world consumption of petroleum was nearly 10.4×10^6 m^3/d (65.4×10^6 bbl/d) (8), which is slightly higher, at 3.6%, than in 1978. In most of the regions shown in Table 4, consumption and production levels are not in balance. The one exception is the group of non-OECD European countries, ie, the former Soviet Union, the former Czechoslovakia, Hungary, Poland, and other former Eastern Bloc countries, where production was nearly in balance with consumption at about 19% above consumption in 1992.

Consumption in North America in 1992 (2.8×10^6 m^3/d (17.9×10^6 bbl/d)), although lower than that of 1978 (3.2×10^6 m^3/d (20.1×10^6 bbl/d)), nonetheless exceeded production in the region by 64%. In Latin America, consumption rose to 829.0×10^3 m^3/d (5.2×10^6 bbl/d) in 1992, up from 666.0×10^3 m^3/d (4.2×10^6 bbl/d) in 1978, or an increase of 24%; production in this region increased by 61% from 789.0×10^3 m^3/d (5.0×10^6 bbl/d) in 1978 to 1269.0×10^3 m^3/d (8.0×10^6 bbl/d) in 1992. Much of this increase in production is from fields discovered in the 1980s in Brazil and Colombia.

Historically, the world's petroleum production pattern can be related to geologic, economic, and political factors. In the past, many countries have had large excesses in production capacity, whereas in the 1990s, only countries in the Middle East, such as Saudi Arabia, Kuwait, Iraq, and the United Arab Emirates, have, in the short run, enough excess capacity to expand production of conventional crude petroleum in any significant manner. In the Middle East, production of petroleum is over five times the region's consumption (see Table 4). On a much smaller scale, Africa produces far more petroleum than it consumes (3.4 times).

In terms of consumption in the Eastern vs the Western Hemisphere, the data in Table 4 show that not only is most of the world's petroleum produced in the Eastern Hemisphere (71%), but it is also consumed largely in that region (65%), with 8.5% in Japan alone. The surplus production in the Eastern Hemisphere (597×10^3 m^3/d (3.8×10^6 bbl/d)) is consumed in the Western Hemisphere, mostly in North America. The

Western Hemisphere thereby produces 29% of the world's total production, or about 82% of the petroleum that it consumes.

For some time, annual production and reserves of conventional petroleum have remained nearly level or have been declining in a number of countries, eg, the United States, Canada, the United Kingdom, Algeria, Australia/New Zealand, the former Soviet Union, Indonesia, and a number of other, smaller producers. Unless substantial new reserves can be discovered in these countries, the production rates will continue to decline. The rate of these declines will be determined by the physical quality of the existing reservoirs. Some anticipated decline in production levels in these countries may be prevented in the short run by more intense reservoir development, eg, in-field drilling and application of enhanced recovery technology. Reserves in several Middle Eastern countries are large enough to support substantially increased production, as are reserves in Venezuela, Colombia, Norway, and several other countries.

Perhaps the most striking feature shown in Table 4 is the large imbalance between regional production and consumption in the Middle East as compared to OECD Europe. In 1992, the Middle East produced five times more crude petroleum than it consumed, and OECD Europe consumed about three times more crude petroleum than it produced; that is, in 1992, the Middle East exported about 81% of its production of crude petroleum, whereas OECD Europe imported about 66% of the crude petroleum that it consumed. In the Asia/Australia region, 2419×10^3 m^3/d (15.2×10^6 bbl/d), or 23.3% of the world's total, was consumed in 1992. In the United States, production of crude petroleum peaked in 1971 and has declined since then so that only 54.5% of the U.S. crude petroleum consumed in 1992 was produced domestically. In Latin America, production of crude petroleum stood at about 150% of consumption, whereas in 1978, production and consumption were about equal.

5. Outlook

Petroleum displaced coal (qv) as the principal source of energy in the United States by 1948 and in the world by 1965 (15). In 1992, petroleum satisfied over 40% of the world's energy needs, while coal filled only 28% of needs, barely ahead of natural gas at 23%. The spectacular growth in consumption of crude petroleum in the world during the middle and late twentieth century is directly attributable to the ease with which petroleum can be discovered, produced, transported, processed, and utilized (see Petroleum, enhanced oil recovery). This growth has been so rapid that as much crude petroleum (55.5×10^9 m^3 (349.4×10^9 bbl)) was taken from the ground between 1976 and 1992 as was produced during the entire previous 119-yr period (1857–1975). This rapid rate of expansion in production and consumption, coupled with the finiteness of the conventional petroleum resource base, has from time to time led some analysts to conclude that world petroleum production will peak in the near future (16, 17). Other analysts who examine such data forecast impending global crisis as crude petroleum consumption declines and coal reclaims its former position as the principal source of fossil energy (18, 19).

The key factor influencing the varying interpretations is that although there is an enormous volume of petroleum resources in the ground throughout the world, it is found in deposits that differ in quality and quantity from country to country. Only a small fraction of these resources are conventional petroleum resources (160.1×10^9 m^3 (1006.8×10^9 bbl)) and are in the category of proved reserves. An additional 93×10^9 m^3 (585×10^9 bbl) of conventional petroleum is estimated to be undiscovered in the world. This estimate is of undiscovered petroleum resources that are economic to produce by means of normal production technology.

Although the world is not running out of petroleum, it is difficult to sum up how much is available in the short run, as well as in the longer run, in light of various possible future political and economic developments. The effect of a variety of sociopolitical forces now at work will be to reduce the world's consumption of energy, in particular of petroleum; such forces include clean-air regulations in the United States and the ever-increasing

rate of taxation of petroleum use in many countries in order to raise general revenues. Countervailing forces, such as the advancement of exploration and production technology, can be counted on to expand the discovery and development of additional conventional petroleum resources in deep-water offshore regions and in hostile arctic climates. Also, advancements in technology, eg, in three-dimensional seismic surveys and horizontal drilling, will increase the inventory of proved reserves through the process of field extensions. Over the next several decades, many billions of cubic meters of conventional petroleum will be credited to the reserves inventory through this field-growth process.

Perhaps the biggest contribution that technological advancement in petroleum production will make is bringing large volumes of unconventional petroleum resources, eg, heavy oil and tar sands, into a viable economic realm by lowering the unit cost of production. Compared to the inventory of conventional petroleum reserves and undiscovered resources, the physical inventories of such unconventional petroleum resources are extremely large; for example, the Athabasca tar sands in Alberta, Canada, are estimated to contain 360×10^9 m^3 (2250×10^9 bbl) of in-place petroleum (19). This volume is equivalent to the total inventory, ie, the combined cumulative production, reserves, and undiscovered resources, of world conventional crude petroleum. In 1992, however, only about 10% of total in-place petroleum resources was technically recoverable (20).

Large unconventional resources of petroleum also occur as extra heavy crude oils in the Orinoco belt, Venezuela, and in oil shale in the western United States. Petroleum resources in the unconventional category, such as tar sands, heavy crude oils, and oil shales, are located mostly in the Western Hemisphere, as opposed to the conventional resources, which are located mostly in the Middle East. Also, the in-place resources of these unconventional resources are about twice as large as the in-place resources of conventional crude petroleum. Although the recovery rates from these resources are low, improving technology may capture increasing volumes of these unconventional petroleum resources, thereby converting them into conventional petroleum resources.

The irony underlying the current perceptions of the world's petroleum resource situation is that the world is not running out of combined petroleum resources. However, the bulk of the world's conventional petroleum resources that are inexpensive to produce are concentrated in the Middle East, whereas the much larger volume of higher cost unconventional petroleum resources, such as tar sands and heavy oils, are located in Venezuela, western Canada, and the western United States. The uneven distribution of the conventional resources thus causes concern that in the short run political unrest in the Middle East could cause a catastrophic interruption of supply.

However, the general pessimism about a perceived threat to the world economy that existed at the time of the Arab oil embargoes in the 1970s has been dispelled. At the core of this concern was the idea that the well-being of modern society was totally dependent on the ever-expanding use of cheap energy, especially crude petroleum. Since that time, the world has consumed petroleum at the nearly steady rate of 3.5×10^9 m^3/yr (22×10^9 bbl/yr) even as the world economy has continued to expand. This ending of growth in consumption is the result of the price rises caused by the Arab oil embargoes in 1970s, which have prompted the world's economic agents to turn to conservation, technology, and in some situations interfuel substitution, eg, alcohol for gasoline, and coal for petroleum in electric power generation (qv). Perhaps the most surprising response to the increasing price of petroleum was the speed with which the world downsized its fleet of private automobiles, thereby lowering the demand for petroleum in that sector.

The world will never "run out" of petroleum, simply because there is so much of it in the ground in so many different forms. However, the resources of conventional crude petroleum are finite. These are the petroleum resources that are very inexpensive to produce because they flow to the wellbore either directly or by pumping after the application of standard well completion methods. There is a more or less general agreement among analysts that the size of the inventory of these resources is about 350×10^9 m^3 (2200×10^9 bbl); the world is consuming these resources at about 1%/yr. The primary question that faces the world is, "Has the pattern of exponential growth in consumption of petroleum that took place between the end of World War II and 1973 become a relic of the past, or could growth resume as world population continues to expand?" Analysis of the

pattern of world energy consumption shows that the world consumption of crude petroleum may gradually increase even with increased efficiency in the use of energy, simply as a result of population growth. However, these developments could be dramatically altered by an increase in the price of energy (21).

Another consideration of petroleum assessment analysts is whether, and to what degree, the vast resources of unconventional petroleum in the world can be captured by advances in petroleum production technologies, thereby converting them into conventional sources of petroleum. It is a simple fact that the in-place resources of petroleum in tar sands, heavy oils, and oil shale can guarantee the future supply of petroleum for hundreds of years at the current rate of consumption, provided they can be produced at competitive costs.

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