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World Oil Resources: Their Assessment and Potential for the 21st Century

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Oil has acquired a dominant position with respect to the world energy supply. This is not due to its long term abundance prospects. It is because of the outstanding ease of its utilization, and also because of an *exceptional* low cost of production owing to *exceptional* geological and political conditions. In fact, these conditions, which led to the post-World War II oil boom, were restricted to a small region (2 percent of the world's surface area) and to a mere decade, the 1960s: an instant in human history.

So the reality looks like this: our civilization depends heavily on oil. Because of the difficulties and the time needed to shift to other energy sources, it is of the utmost importance that we assess how long the oil era will or *can* last. This paper expresses a few thoughts on the subject.

Before analyzing oil resources assessments and potential for the 21st Century, we would like to put forthcoming estimates in a special perspective: How much oil or liquid fuels will, or would, we need? This is indeed not an easy question. In trying to answer it, we are confronted with a great many uncertainties. First of all, we should know how many people will be on Earth 50 or 100 years from now, and what their life-style will be like. Although the whole problem is a fascinating one, we are in fact concerned here mainly with the specific aspect mentioned above: How much oil, or liquid fuels, could be needed? Basic assumptions which we have made at IIASA in order to attempt to give a preliminary answer are: first, that the world population will be stabilized (say, at *less* than 12 billion people or 3 times the present level; possibly between 7 and 9 billion people); second, that energy needs also be stabilized, or increasing very slowly (this is in contrast with some other forecasts of ever increasing energy demand); and third, that oil and other liquid fuels will be reserved for transportation (there will be a limit to the number of cars and potential mileage), petrochemicals (but other raw materials, such as coal or biomass, will compete), and development phase of the Less Developed Countries.

It is often mentioned that "oil must be reserved for transportation and petrochemicals." In fact, with a progressive shift to the supply of heavier crudes, it is not clear what the maximum yield of light or intermediate products could be.

All in all, we came to a consumption figure of between 3 and 5 billion tons of oil per year. This seems a reasonable value. However, more of other liquid fuels (synfuels) could be produced and consumed because of their convenience or preference for them. Curiously, this consumption figure is also an often quoted maximum for world oil production supposed to occur in the 1990's (the Central Intelligence Agency of the United States, the Workshop on Alternative Energy Strategies) and in most oil companies' studies as shown in figure 1.

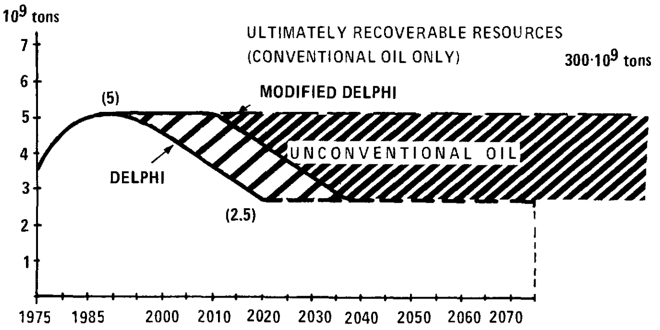

Figure 1 Potential world oil production curve, in billions of tons.

Our point of view for looking at the oil resources and (or) liquid fuels is thus to consider how long resources could allow a plateau of oil production and consumption to continue (fig. 1) and, in view of potential resources, what should possibly be done to maintain such a level of production. In other words, we challenge the bell-shaped production curve shown in figure 1.

ASSESSMENTS OF CONVENTIONAL WORLD OIL RESOURCES

We do not have good tools with which to tackle our problems. Unfortunately, world oil resources are very poorly known. Because so many important energy policy decisions are founded on so fragile a basis, it is important to understand why and, hopefully, to aim to correct this uncomfortable situation to make the poorly known well-known.

We have emphasized, as shown in figure 2, some of the differences between reserves and resources that can help us to understand better why we know so little about resources. Generally, the interest in reserves has been very great, but there was, until recently, little or no interest in resources. The time horizon for reserves is between 10 and

[1] Part of this work has been performed with the support of the Electric Power Research Institute.

	RESERVES	RESOURCES
Interest in	Great	None in the past, now emerging
Time horizon	10–30 years	Long or very long term
Economic aspect	Must be profitable	Non-profitable today, "science-fiction" technology
Estimated by	Industry	Member of industry *or* government (institutions)
Data	More or less reliable, conservative, "proprietary," and exploitation-oriented	Uncertain or speculative, but scientifically oriented
Methods	Industrial work (expensive): exploration, drilling, and measurements	Paper or computer work: "geological", "historical"

Figure 2 Reserves compared to resources.

30 years, and for resources it is long or very long term. What we, at IIASA, call the long or very long term is at least from 20 to 50 years after the year 2000, say until the year 2050 or even later, clearly into the 21st Century.

From the economic point of view, reserves must be "profitable". This is a very important point because, in fact, we have not redefined, since the oil crisis of 1973, the meaning of the word "profitable". Is a reserve "profitable for industry" (which was essentially the case up to now)? Is a reserve "profitable for a country"? This question can have a big influence on the revision of our estimates of reserves and (or) resources. Traditionally and by definition, resources are either not profitable or are unknown, and estimates even sometimes rely on what industry calls "science-fiction technology," that is, technologies still to be developed and matured. However, the border line between reserves and resources is sometimes very thin. For instance, if the British Government were to change its taxation policy only slightly and find it "profitable" to do so, so-called "marginal reserves" (currently in the 50 to 100 million barrels range) would become commercially producible.

Estimates of reserves are generally made by industry (they are its daily bread). Estimates of resources have been made by members of the industry (most often on a hobby basis, because it is not their main occupation) or by government or scientific institutions. It follows that estimates of reserves are more or less reliable, conservative, proprietary, and exploitation oriented. Methods of obtaining these data are expensive and include exploration and drilling. On the other hand, resource estimates are uncertain or speculative, more theoretically oriented, and based on paper work, now also on computer work.

If we look at these many differences, I think that we already understand why the reserves are much better known than the resources. Starting from this point of view, we at IIASA have devoted much attention to the various world oil resources assessments and have tried to understand them better. A summary of our studies was first presented at the meeting of the American Association of Petroleum Geologists in Houston, Texas, April 1–4, 1979.

Some lists of world oil resources assessments during the past 25 or 30 years have been published. We have also made our own list of these mostly well-known estimates (fig. 3). We have listed only the results we have been able to find in published papers, because sometimes reference is made to an estimate we are not able to document. Our tabulation gives the name of the estimator and his company, which is an often underestimated factor. Where applicable, we have also put the estimate for the United States. When two values are given with a slash it is because the estimator himself has given two values. For instance, Weeks has generally calculated two values, for "primary"

ESTIMATOR, AFFILIATION, AND YEAR	ESTIMATE OF TOTAL BARRELS	U.S. PART OF TOTAL	U.S. PART OF PERCENT
Duce (ARAMCO, 1946)	500	100	20
Pogue (N.A., 1946)	615	---	--
Weeks (JERSEY, 1948)	617	---	--
Levorsen (STANFORD, 1949)	1,635	---	--
Weeks (JERSEY, 1949)	1,015	---	--
Weeks (JERSEY, 1958)	1,500/3,000*	240	16
Weeks (N.A., 1959)	2,000/3,500*	270/460*	14
Hendricks (USGS, 1965)	1,984/2,480*	320/400*	16
Weeks (WEEKS, 1968)	2,200/3,550*	---	--
Hubbert (USGS, 1969)	(1,350–2,000)**	---	--
Moody (MOBIL, 1970)	1,800	---	--
Warman (B.P., 1971)	(1,200–2,000)**	---	--
Weeks (WEEKS, 1971)	2,290/3,490*	---	--
Jodry (SUN, 1972)	1,952	190	10
Odell (UNIV, 1973)	4,000	---	---
Kirby, Adams (B.P., 1974)	(1,600–2,000)**	---	--
Moody (MOODY, 1975)	(1,705–2,030–2,505)** 95 percent 5 percent	242	12
Grossling (USGS, 1976)	(1,960–2,200–3,000–5,600)**	182–250**	8
Klemme (WEEKS, 1976)	1,600	---	--
Parent, Linden (Institute of Gas Technology, 1977)	2,000	---	--
DELPHI (Desprairies) (Institut français du Petrole, 1977)	2,200/2,500**	---	--
Moody (MOODY, 1978)	2,030	300	15
Nehring (RAND [CIA], 1979)	(1,700–2,300)**	---	--

* Estimator gives primary, then secondary values.
** Estimator gives range, sometimes with a mean value.

Figure 3 Major published estimates of world oil resources. (Barrels are calculated in billions.)

and "secondary" recovery respectively. Values in brackets correspond to a range of values, sometimes with a mean value. Altogether, there have been about two dozen estimates since 1946.

Some experts have used similar tables to analyze potential trends of world oil resources estimates. Odell (1973) for instance, has made a curve, which is well-known, of the linear regression of the estimates, and has shown that the estimates generally increased with time. In addition, it is possible to see from such graphs, even adding the most recent estimates, that the uncertainty or, one might say, the spreading of the estimates did *not* decrease with time. In fact, if we take all the values listed in figure 3, the picture appears as shown in figure 4. Even if many values tend to increase, it is in fact difficult to draw a regression line through the estimates. At best, there appears to be a magic line or "magic figure" of 2,000 billion barrels, at which many of the estimates are "knocking."

Analyzing these various estimates after a careful reading of the documents, we can summarize thus:

In 1947, there was the introduction of estimates of offshore oil which first boosted the estimates (Pratt, 1947; Levorsen, 1949).

In 1958, Weeks introduced the first estimate of broad regional distribution.

In 1962, Hubbert introduced the first "estimate of estimates."

In 1965, Hendricks estimated "discoverable" oil in-place.

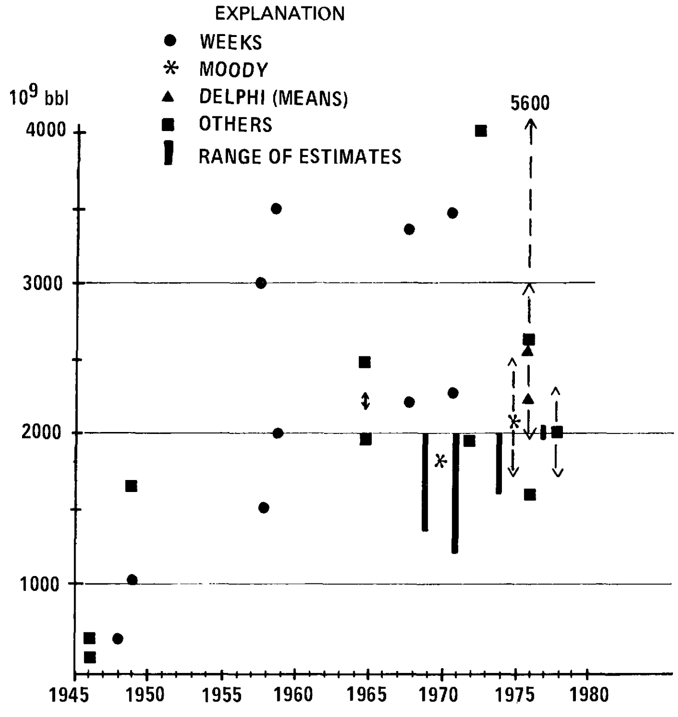

Figure 4 Evolution of estimates of ultimate world oil resources. (Barrels are calculated in billions.)

In 1969, analyzing previous estimates, Hubbert stated that the uncertainty of world estimates was between 1,350 and 2,000 billion barrels.

In 1970, Moody stressed the importance of giant and supergiant fields.

In 1975, Moody published what remains one of the best (and most influential) estimates, and introduced probability distribution.

In 1977, the extremely important DELPHI study was issued (Desprairies, 1977).

In 1978, Nehring was the first to disclose the method and the data used to perform an estimate.

Concerning the study by Nehring, it is worth pointing out that previous estimates were, in fact, calling mostly upon our "faith," because if the method was, at best, suggested, the data used to arrive at the estimates were never cited. Here we refer to world estimates and not estimates for the United States, for which the situation was different. This means that from the scientific point of view, it was not possible to check whether world assessments were good or not.

As a next step, it is interesting to investigate the relative independence of these various estimates. Levorsen's, for instance, is not independent because he combined those of Pogue (1946) and of Weeks (1948), and added the offshore estimate of Pratt (1947). Weeks has made a lot of estimates but, of course, they are mere revisions and are not independent of each other. Hendricks was apparently independent. Hubbert, as we mentioned, made the first "estimate of estimates." This last process has more or less continued until the present day. To cut short this long story, figure 5 summarizes, using the horizontal axis for independent estimates and arrows for connections, a thirty-year period, from 1946 to 1976, for which we have found about six independent world oil resource estimates.

Then, in 1977, the very important DELPHI study by Pierre Desprairies of the French Petroleum Institute was published. It was prepared for the Conservation Commission of the World Energy Conference held September 1977. More than forty experts were consulted: 27 answered the first set of questions, 22 of them confirmed or revised their answers in the second round. We can, however, question, by referring to the above, whether all of these 22 estimates are really complete, independent estimates.

Figure 6 summarizes the main findings of the DELPHI study. Ultimate world oil resources remaining to be produced (to which must be added 300 billion barrels of past cumulative production, to make these figures comparable with others given previously) would be 1,900 billion barrels, excluding deep offshore and polar areas, and 2,200 billion barrels if these are included, assuming the recovery rate were raised from today's average 25 percent to about 40 percent at the end of the century. (In fact, the

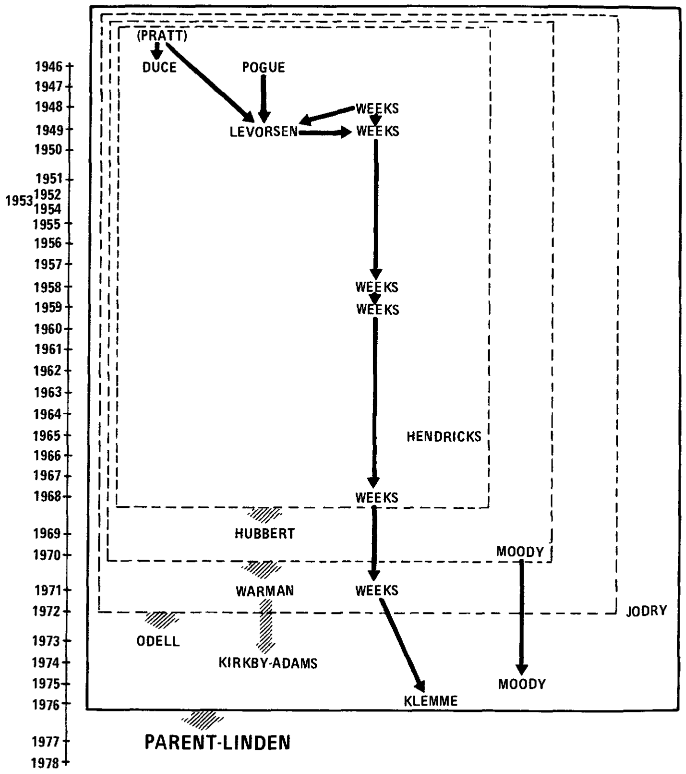

Figure 5 Source relationships between oil resources estimates.

• Ultimate world oil resources remaining to be produced ("consensus")	:	1.900×10^9 bbl (260 Gt) or 2.200×10^9 bbl (300 Gt) including deep-offshore and polar areas

- 45 percent offshore
- Recovery increasing from present 25 percent to 40 percent in the year 2000
- Increasing contribution of enhanced recovery: 55 percent of gross increase in 2000
- slowing down of annual rate of growth of reserves: Back to 20×10^9 bbl/yr in 2000

Figure 6 Main findings of the WEC-DELPHI study published for the 1977 Conference.

limits imposed on the study were the year 2020 and a production cost of less than $20 per barrel, in 1976 dollars.) These are the values proposed by the estimator. The DELPHI study also concluded that the increasing contribution of enhanced recovery would account for 50 percent of the gross increase in the year 2000. By that year, the annual rate of growth of reserves would slow down to 20 billion barrels per year.

It is interesting to look at the degree of consensus. In the following paragraphs, we use billion metric tons of oil, which were the original units of the DELPHI study, instead of billions of barrels. In figure 7, the 27 "first" answers are plotted—each respondent number appearing on the vertical scale and his corresponding individual estimate on the horizontal scale. It may be seen that the answers, in fact, cover a broad range, from about 170 billion to 750 billion tons (the latter is an average for the 550 to 950-billion-ton range). It is interesting to remark that, even when extreme estimates are eliminated, the estimates of the consensus group (fig. 7), show some appreciable disagreement on the potential future role of deep offshore and polar areas. Figure 8 shows another way of presenting the same results.

Finally, in relation to our IIASA studies to assess potential future world oil production, it is interesting to try to establish values on regional distributions of world oil resources according to the DELPHI study experts. Figure 9 shows, in a similar fashion to figure 8, the answers for North America. We find the known phenomenon of the broad ranges of estimates (answers re-converted to billion barrels in figures 8 and 9). And figure 10 shows for major regions the minimum estimates, the maximum estimates and the averages for the totality of answers from the experts, or only for the answers of the "consensus" in the global range of 200 to 300 billion tons. The 1975 Moody values and the 1978 Nehring values fall into the same ranges, and more especially into the consensus ranges. However, this no longer applies to the range of estimates, generally and understandably much broader if all the answers are taken into account. But even in the consensus range, and although agreement on the global value is plus or minus 20 percent, there is no clear convergence of estimates at the regional level. The ratios between higher and lower values in the 200 to 300 Gt range vary from 2 to 4. Estimates of socialist countries, which do not publish statistics, are difficult to evaluate. For the Middle East, the factor of 2 represents a very big difference of 80 billion tons, which is roughly equivalent to present known world reserves. The highest disagreement of opinion among the experts is related to deep offshore and polar areas. It is fair to say that the DELPHI study in fact occurred about at the turning point: concerning deep offshore, the original optimism of the mid-1970s has now been succeeded by an (exaggerated?) pessimism.

This is where we stand with regional estimates for world oil resources and the material with which we are working. It seems appropriate to say that, from the scientific point of view, our knowledge is very, very poor.

ASSESSMENTS OF WORLD UNCONVENTIONAL OIL RESOURCES

We can assess estimates of unconventional oil resources in the world by saying that the situation is still much worse than for conventional oil resources.

True, there are some very large deposits, more or less well known—and curiously, located on the "oil ring" described by Nehring (1978) (Athabasca Tar Sands, Colorado Oil Shales, Orinoco Heavy Crudes). The aggregate in-the-ground resources of these very large deposits are considerable, at least 800 billion tons, of which about 150

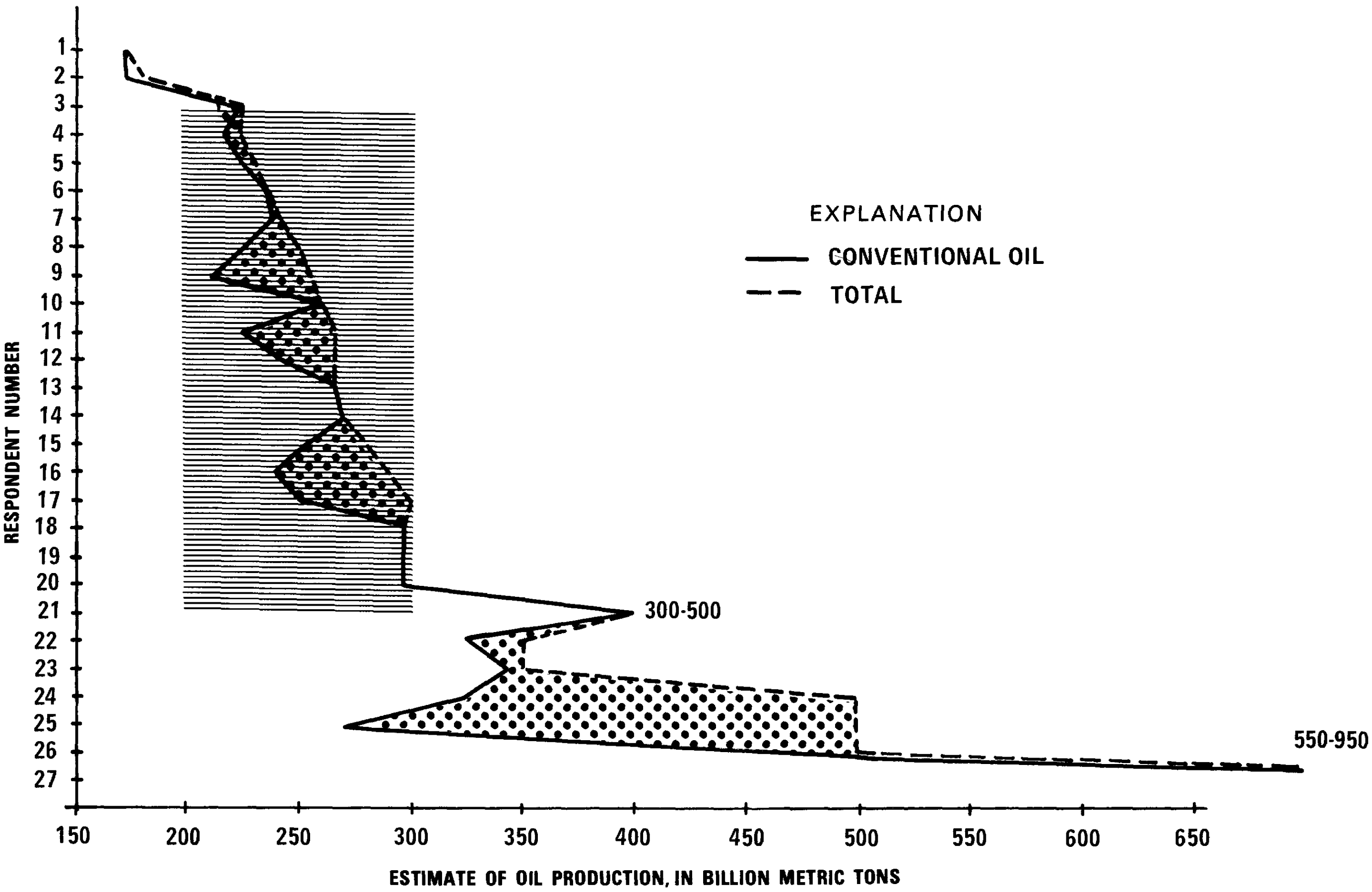

Figure 7 Analysis of answers to DELPHI questions. Shaded area: 18 answers regarded by Desprairies (1977) as representing a consensus. Values on the left are figures without polar and offshore areas, where applicable; values on the right include polar and offshore areas.

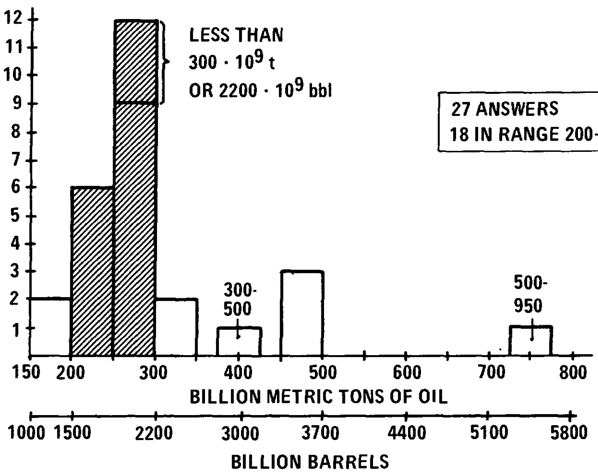

Figure 8 World oil resources remaining to be produced (DELPHI study). Vertical scale: number of answers for the various ranges of the horizontal scale; shaded area: 18 answers regarded by Desprairies (1977) as representing a consensus.

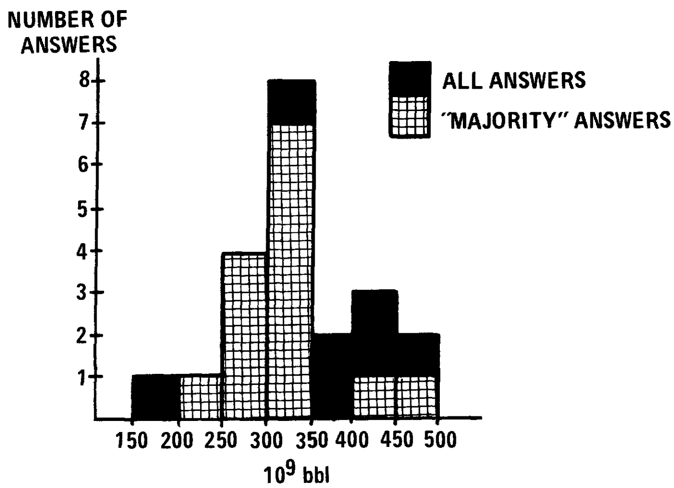

Figure 9 Ultimate oil recovery in United States and Canada (DELPHI study). (Estimates are calculated in billions of barrels.)

billion tons are presently considered to be recoverable (fig. 11), which has to be compared to the 900 billion tons of conventional oil originally in place, if we accept the DELPHI values. But our main concern is to answer this question: what may possibly exist at a global level beyond these huge deposits; that is, what is the potential regional

	RANGE PROJECTED IN ALL VALUES			VALUES "IN CONSENSUS" 200-300 Gt RANGE*		
	MINI-MUM	MAXI-MUM	AVER-AGE	MINI-MUM	MAXI-MUM	AVER-AGE
Socialist countries	27.3	96.3	54.9	40.3	83	54.9
U.S.A. and Canada	6.2	50	28.5	15.6	45	26.1
Middle East and North Africa	54.8	300	109.1	76	156	101.9
Africa South of Sahara	2.7	40	11.3	4	13.4	8.8
Western Europe	5	22	11.2	5	22	11.1
Latin America	7.9	55	22.9	12.5	36.9	20.9
East and South Asia (includes Japan, Australia, and New Zealand)	5.5	30	15.1	6	25	13.6
Deep offshore and polar regions	0	230	38.7	0	50	21.2

*Of the 18 values in the 200 to 300 Gt Range, four do not give details by regions.

Figure 10 Regional distribution of DELPHI estimates. (Figures are calculated in gigatons.)

distribution of these unconventional oil resources? Because of a lack of economic interest until now (let us recall: reserves must be profitable), very little effort has been made to assess these unconventional resources in most countries.

As we showed at our 1976 IIASA-UNITAR Conference on the "Future Supply of Nature-Made Petroleum and Gas", sources of global data are generally very few and very old (Barnea and others, 1977). Contrary to what was expected, the first United Nations sponsored Conference on Heavy Crudes and Tar Sands held at Edmonton, Alberta in 1979 (United Nations Institute for Training and Research, 1981) did not really improve the data situation. Most improvements were related to Canada and, to a lesser extent, to the United States and Venezuela. Many of us, in the energy community, had expected that a serious reassessment would get started after the 1973–74 oil crisis. Apparently (we will come back to this matter later) and unfortunately, this did not happen, except in the three abovementioned countries plus, possibly, in a very few other places.

That is why the International Institute for Applied Systems Analysis has launched its own survey of unconventional oil resources, through questionnaires and interviews. Our study is about midway so that it is premature to present final results and (or) conclusions. However, some of our progress will be reported.

Heavy Crudes and Tar Sands

At the already-mentioned international conference in Edmonton, Meyer and Dietzman of the U.S. Geological Survey presented a global estimate of resources and possibly recoverable reserves of heavy crudes and tar sands (fig. 12). Recovery rates for tar sands were generally very conservatively estimated at 10 percent or less (paper given in June 1979).

We, at IIASA, consider these figures somewhat misleading inasmuch as they aggregate rather good data—for Canada, the U.S.A., and Central America (essentially Venezuela)—with poor to very poor data for the other regions.

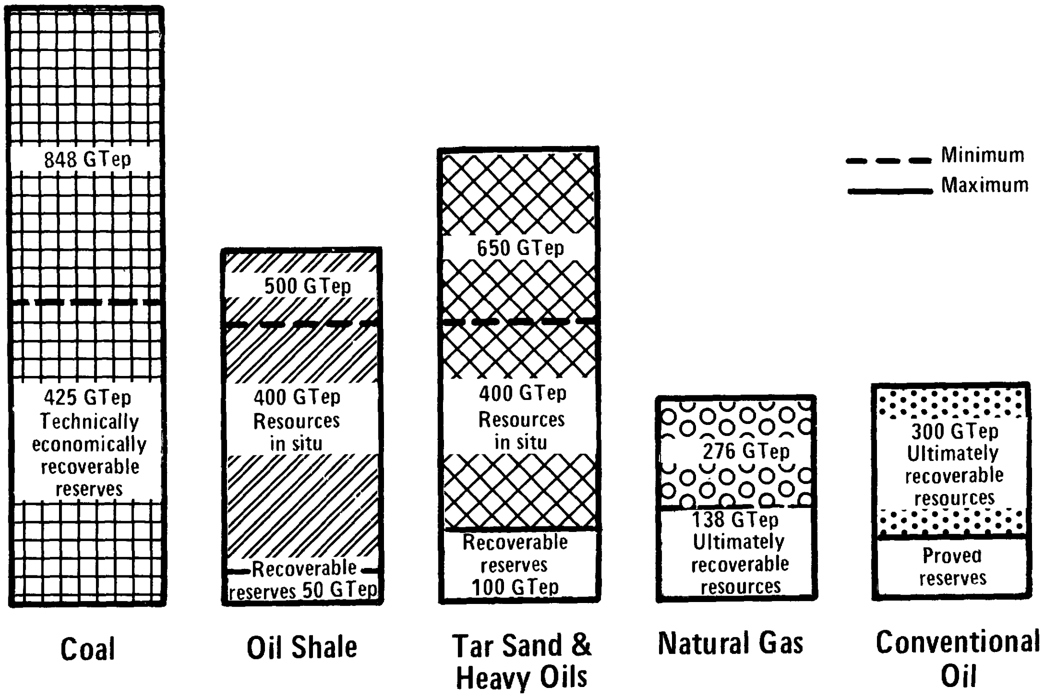

Figure 11 Fossil fuel reserves and resources. (Estimates are given in billions of tons; GTep = gigatonnes (billions of tons) of oil equivalent.)

	MEDIUM CRUDE OILS 20≤ °API≤25	HEAVY CRUDE OILS °API<20	DEPOSITS*	TOTAL
Canada	119	69	333,010	333,198
U.S.A.	2,271	2,254	2,512	7,057
Middle America	108	331	______	439
South America	8,376	5,654	100,012	114,033
Europe	154	734	______	6
Africa	4,197	89	175	4,461
Middle East	32,759	3,528	______	36,287
USSR/Asia	660	97	16	773
Total	48,664	12,747	435,731	497,122

*In this table Meyer uses the word "deposits" to refer to crude oil which does not occur in conventional reservoirs.

Figure 12 Estimate of heavy crude and tar sand reserves (10^6 barrels) (from Meyer and Dietzman, 1979).

It is interesting to point out that, in known areas and the ones, in fact, where knowledge has increased further, there has generally been an increase in the estimates.

Athabasca tar sands: 627 billion barrels estimated in 1976 (Canada, Ministry of Energy, Mines, and Resources, 1977); 869 billion barrels estimated in 1979 by Mossop and others (Alberta Research Council) who referred to a 1978 study by Outtrim and Evans.

Lloydminster (Alberta) heavy crudes: Two probabilistic estimates, one for 1976 and one for 1979, are shown in figure 13. See also McCrossan and others (1979).

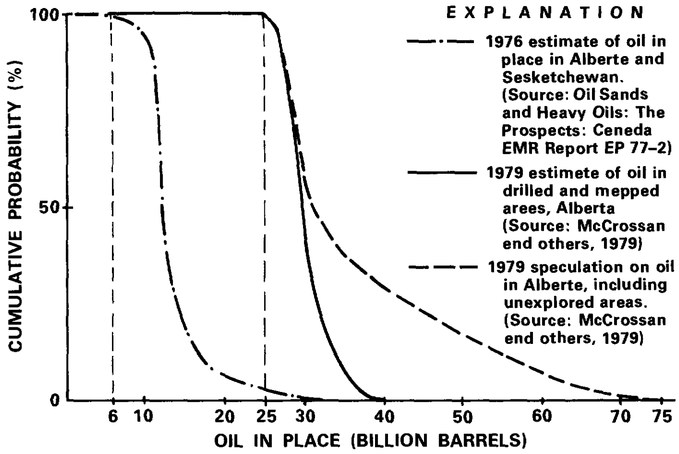

Figure 13 Lloydminster-area heavy oils.

California tar sands: Estimates have increased from 270–323 million barrels in 1965 (Ball Associates, Monograph 12) to 966 million barrels in 1979 (Hallmark paper given at International Conference, Edmonton) through the addition of new deposits, not including two large but conjectural deposits.

Utah tar sands: Estimates have grown from 2.0–4.3 billion barrels in 1965 (Ball Associates, Monograph 12) to 22.4–29.2 billion barrels in 1979 (Ritzma, 1974 and 1979).

An important question is, of course: Can this upward revising be expected to be a general phenomenon? That is, were deposits very conservatively estimated in the past (sometimes, a long time ago, as much as a few decades) and will more recent and better assessments upgrade them? It is premature, and unfortunately not possible, to give a definite answer to this question. However, three examples outside North America, among the few we have at hand, give some preliminary information.

In Madagascar, an unpublished 1954 British Petroleum study (Kent, 1954) that was used in Meyer and Dietzman's 1979 assessment had estimated tar sand resources at 1.79 billion barrels; but a 1962 survey by Andrianasolo and others for the Malagasy Oil Company arrived at a possible estimate of 22 billion barrels or 3 billion tons.

For Italy, the 1979 Meyer and Dietzman estimate referred to 50 million tons (about 360 million barrels) of recoverable heavy oil. The most recent Azienda Generale Italiana Petroli (AGIP) assessment by Dalla Casa and others mentions 350 million tons of heavy oil originally in place in developed fields and 1,200 million tons in discovered but not yet developed fields. Assuming a low-recovery factor of 10 percent because of technical difficulties, this represents about 155 million tons or 1,100 billion barrels of recoverable oil.

For Peru, based on previous estimates, Meyer and Dietzman reported 60 million barrels of recoverable reserves. But at the Edmonton International Conference, A. A. Pardo (Petroleos del Peru) mentioned that in-place reserves of heavy crudes for the Maranon Basin are estimated at 1,500 million barrels. A low 10 percent recovery rate would yield 150 million barrels.

The few examples cited above illustrate, if at all necessary, the difficulties but also the potential for evolution of such reserves and resources estimates of heavy crudes and tar sands.

Oil Shales

World oil-shale resources were given by J. R. Donnell (1977) at the 1976 IIASA-UNITAR Conference, as shown in figures 14 and 15. In fact, most of these data originate from the excellent 1965 U.S. Geological Survey Circular 523 by Duncan and Swanson, itself a collection of old to very old data. The various tables by Meyer, Duncan,

CONTINENTS	RECOVERABLE UNDER PRESENT CONDITIONS	MARGINAL AND SUBMARGINAL
Africa	10	90
Asia	24	84
Australia and New Zealand	___	1
Europe	30	46
North America	80	2,120
South America	50	750
Total	190	3,091

Source: By J. R. Donnell; modified from Duncan and Swanson.

Figure 14 Known oil shale resources of the world land areas (billions of barrels).

SMALL RESOURCES

	$10^6 m^3$	10^6 barrels
Chile	3	18.9
Israel	3	18.9
Jordan	7	44.0
Tasmania	3	18.9
Turkey	3	18.9
	10^6 tons	10^6 barrels
Austria	1	8
Malagasy	4	32
Poland	6	48

MEDIUM RESOURCES

	$10^6 m^3$	10^6 barrels
South Africa	20	125.8
Argentina	60	377.4
Australia	40	251.6
Bulgaria	20	125.8
Spain	40	251.6
France	70	440.3
Luxembourg	110	691.9
New Zealand	40	251.6
Thailand	130	817.7
Yugoslavia	30	188.7
	10^6 tons	10^6 barrels
Morocco	74	592

LARGE RESOURCES

	$10^6 m^3$	10^6 barrels
West Germany	320	2,012.8
Burma	320	2,012.8
Brazil	127,320	800,842.8
Canada	7,000	44,030.0
People's Republic of China	4,430	27,864.7
Zaire Kinshasa	16,000	100,640.0
U.S.A.	250,000	2,000,220.0
Great Britain	160	1,006.4
Italy (Sicily)	5,600	35,224.0
Sweden	400	2,516.0
USSR	17,000	112,591.0

Figure 15 Estimates of oil shale resources by country.

Swanson, Donnell, and others are, in fact, the first tentative assessments of the global existence and (or) availability of unconventional oil.

Our IIASA survey permits an additional perspective; continuing again with a few examples:

In France, in 1954 there were 440 million barrels of known oil shale resources according to J. R. Donnell (1977). A three-year study (1974–1978) by R. Breton and others (1978) included 35 core drillings over a broad area east of Paris plus 10 core drillings in a selected area within that broad area. The broad area survey indicated about seven billion barrels, and the intensive survey of the smaller area identified more than 400 million barrels with contents between 40 and 100 liters of oil per ton of rock (restricted to an overburden ratio of about 2).

In Morocco, Duncan and Swanson (1965) gave no oil shale estimate; but in 1974, A. K. Matveyev estimated about 600 million barrels. Today, known resources are estimated at 1.6 billion barrels and total resources can possibly reach 5 billion barrels, according to recent IIASA survey findings.

In contrast to these two important upward revisions, our survey has also revealed downward revisions, such as for Italy, the United Kingdom, and New Zealand. The final figure for Italy is not yet known, but it is foreseen, on the basis of the IIASA survey, that it will be lower than the previous figure of 35 billion barrels. For Great Britain, where data are most uncertain, and interest is very low, a pilot study in the Kimmeridge Clay apparently downgrades occurrences. For New Zealand, no figures are available, but a statement, based on 20 core drillings, reports that resources are smaller than previously estimated and are of no economic importance (personal commun., IIASA Survey).

Most studies indicate that at present there is little or no interest in oil shale resources. In fact, it is clear that most if not all the deposits are relatively smaller and of a lesser oil content than the Colorado oil shale deposits, and that probably no effort will be made elsewhere before the United States really begins to exploit their huge oil shale reserves, apart maybe from the special case of Brazil.

THE THREE PATHS TO COSTLY OIL

There is no doubt that the cost of oil (we are not speaking here of its sale price!) shows a rising trend regardless of what production route is followed. We summarize this in figure 16.

The first path is the historical one: the oil industry, especially onshore, shifts production progressively from supergiant and giant fields to medium-size fields and, finally, to small fields. The supergiants or fields larger

GIANT FIELD → MEDIUM FIELDS → SMALL FIELDS

(5 · 10^9 bbl) (700 · 10^6 t) — (500 · 10^6 bbl) (70 · 10^6 t) — 50 · 10^6 bbl) (7 · 10^6 t) — (5 · 10^6 bbl) (0,7 · 10^6 t)

ON-SHORE → OFF-SHORE → DEEP-OFFSHORE

"GOOD" OIL (80–25° API) → DIFFICULT OIL (25–10° API) → "BAD" OIL (10–7° API, TAR SANDS) KEROGEN, OIL SHALES)

Figure 16 The three paths to costly oil.

U.S.A.	2,219	Venezuela	41	Burma	20	Japan	14
Canada	241	India	40	Abu Dhabi	19	Malaysia	13
Mexico	174	United Kingdom	34	Peru	19	Turkey	13
Algeria	101	Iraq	29	Trinidad	19	Italy	12
Argentina	73	Libya	28	Nigeria	18	Austria	11
Indonesia	61	Germany	25	Netherlands	17	Australia	10
Brazil	54	Saudi Arabia	24	Syria	17	Colombia	10
Iran	53	Yugoslavia	22	Egypt	15	Pakistan	10

Figure 17 Summary of world rig activity in 1978 (excluding socialist areas), given as number of rigs by country. Besides the 3,456 rigs listed, another 30 countries have from 1 to 9 rigs, for a total of 120.

Oil rigs by region	Number operating	Prospective Areas in square miles by Grossling (1976)	by Ivanhoe
North America [1]	2,460	4,421,400	———
Latin America	402	4,804,600	1,819,300
Europe	142	1,394,000	———
Middle East	193	1,344,800	———
Africa	182	5,034,590	———
Asia	186	———	———
South Pacific	13	———	———
Total	3,578		

[1] Includes United States and Canada but not Mexico. Total number of rigs by region does not necessarily agree with enumeration by country.

Figure 18 Number of rigs by regions and by estimated size.

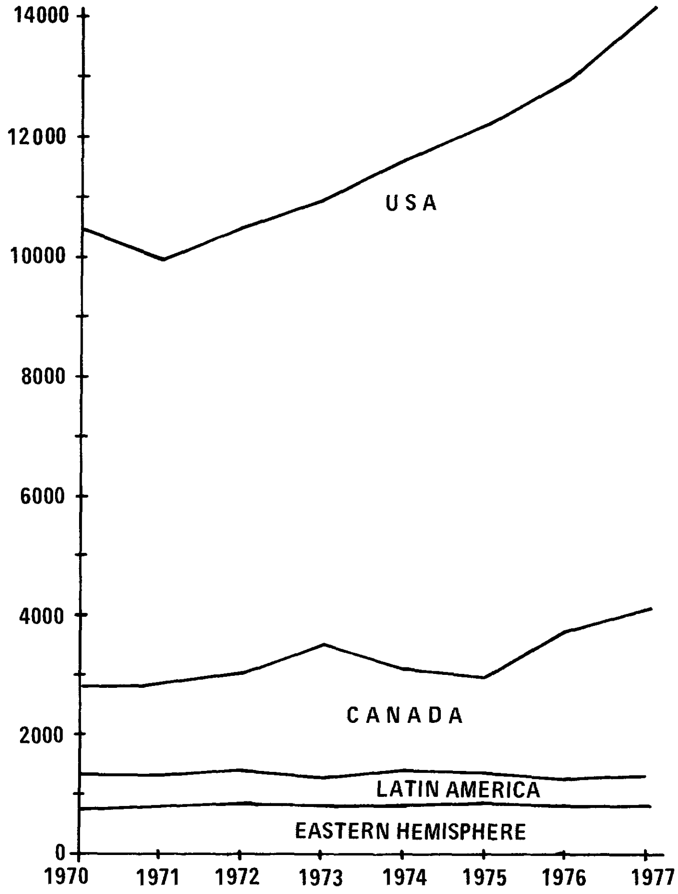

Figure 19 Free world total exploratory well completions.

than 700 million tons or 5 billion barrels were eagerly searched for all over the world and the giants, those larger than 70 million tons or 500 million barrels, were both the most profitable, and still account for more than 70 percent of world oil production.

Small fields already account for 15 percent of United States production. It is sometimes argued that this could only happen in the United States because of the special situation where the wealth underground belongs to the owner of the surface: thousands and thousands of farmers have taken the risk; a few became millionaires. This only means that in other countries – if the same result is to be achieved – other or new types of incentives will have to be found. We are confident that, since it will take a long time before a substitute for oil is found, these incentives will indeed be developed. Nationalized oil companies will probably be the first to benefit from them.

A review of world petroleum history makes clear that there is an enormous variation in the size of drilling efforts, as brilliantly shown by B. F. Grossling in his article, "Window on Oil" (1976). Regarding the prospects for finding more oil, we at IIASA agree qualitatively with Grossling, but not "quantitatively" in the sense that we find him somewhat optimistic. But we are convinced that there is still a lot of oil to be found.

Curiously, it is interesting – but somewhat disappointing – to see how the Western World has reacted to the 1973–74 crisis. This is illustrated by the data for rig activity (figs. 17 and 18) and for exploratory drilling completions (fig. 19). Two conclusions can be drawn: (1) There is a continuous – and even increasing – difference between drilling by the United States and Canada on the one hand and the rest of the Western World on the other hand: and (2) only the United States and Canada have dramatically increased their search for oil and gas since the oil crisis.

From the DELPHI study, a tentative supply curve can be drawn for the 300 billion tons of oil remaining to be produced (fig. 20). Incidentally, a similar curve was mentioned by Shell representatives in a May 9, 1979 lecture by K. R. Williams. This means that a good part, about two-thirds of these 300 billion tons of oil, was considered to be producible at less than $12 per barrel (in 1976 dollars), with corresponding investments of less than $10,000 per barrel per day capacity. Let us recall that the greater part of oil today (in 1979) is still produced at costs probably not higher than $2 per barrel per day.

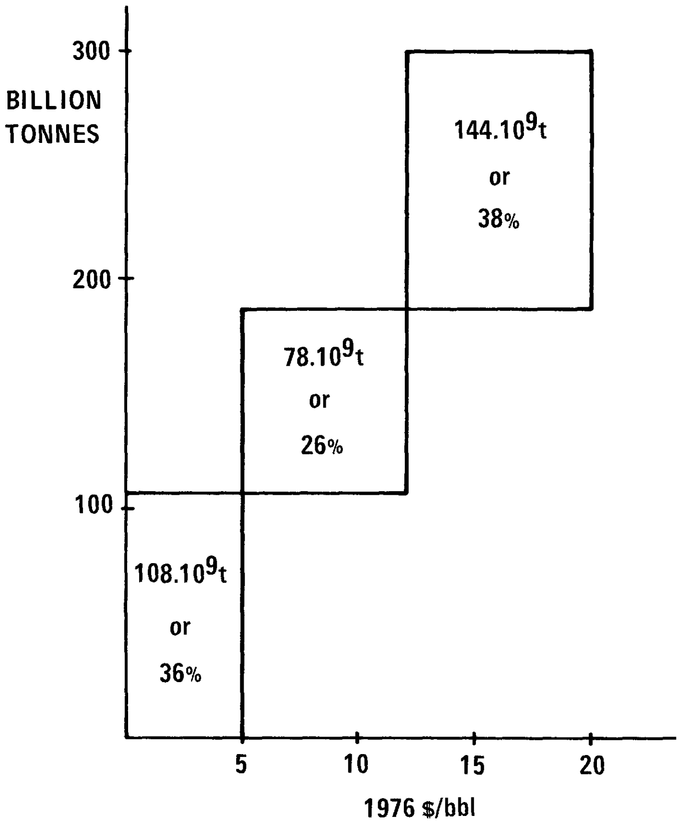

Figure 20 World oil supply curve, according to DELPHI study (1977).

For these reasons, we think that, on a global basis, this path will remain the preferred one in coming decades, and will probably be used reasonably far into the 21st Century. It can provide sufficient time—taking into account that world consumption and (or) production of oil will increase much slower than previously forecast—for a timely penetration of unconventional oil into the market, provided a few countries pave the way; for example, the United States with the Synfuel program and Canada with tar sands.

The second, or offshore path, began with a technological extension of onshore exploration and production, and was further encouraged for political reasons. The North Sea was especially suitable for offshore development because of its highly appealing political stability. Here the most impressive technological progress has been achieved. Unfortunately, the progress has been accompanied by parallel and dramatic cost increases ($10,000 to $12,000 per barrel per day capacity). Moreover, there is some disappointment with U.S. Atlantic offshore explorations, for instance with regard to the Baltimore Canyon. This, together with discouraging results up to now in deep offshore areas, has somewhat slowed down the race to deeper and deeper water, and has led some experts to revise downward their previous hopes for deep offshore potential. Higher and higher costs are obvious, but the resources—if any—are elusive. Curiously, this path is counter to the first: because of increasing costs, unfortunately, going deeper and deeper obliges oil operators to concentrate only on the biggest deposits. That means that giant fields are needed for normal offshore production (as mentioned above for North Sea "marginal" fields) and probably that supergiants are needed for deep offshore production, unless new production methods are developed.

The third path would be from "good oil" to "bad oil" (oil shales) passing through "difficult oil" (heavy crudes and tar sands). Such a production evolution is highly technology-dependent and will really occur—if it occurs at all—as a result of a political determination and only in a few countries at first. These few countries, including presumably Canada and the United States, have the double incentive of high oil consumption *and* imports and of owning the largest deposits presently known. They also have the advantage of possessing oil producers competent at the highest technological levels. A problem whose solution is not yet clear, but which could be highly important at the world level, is to understand whether path 3 will resemble path 1 or path 2 as far as sizes of deposits are concerned. Because of the immature state of development of the technology of "difficult" and "bad" oil, it is hard to anticipate whether only large to very large deposits will be producible or whether small deposits will also be producible, possibly through different methods. With our present knowledge, investments for path 3 are the highest among the various steps of the three paths: for example, $25,000 to $30,000 per barrel per day capacity for new tar sand projects in Alberta.

These very high capital costs (for production from tar sands, deep offshore, oil shales, etc.) and the huge size of deposits and (or) production facilities point to a necessary and permanent role for major oil companies, with the hope that the necessary steps will be taken to encourage them, or simply to keep them alive.

CONCLUSION

We are hopeful that the necessary amounts of liquid fuels can be produced, according to our curve proposed in figure 1, with a progressive—and well-planned—penetration of unconventional oil. (We do not underestimate the possible role of liquids from coal, but this question is outside the scope of this paper.)

Two final comments by way of conclusion:

1. The three paths that lead to costly oil also lead, in fact, to a new dimension in oil history, because of the dramatic increases not only in costs in monetary value but also in costs of natural (and human) resources. Impacts on, and requirements for, other

natural (and human) resources will become greater and greater for producing these new sources of energy. So much so, in fact, that energy resources can no longer be considered in isolation from other resources such as water, land, materials, and manpower, these same resources being discussed during this U.S. Geological Survey Centennial Symposium. To understand these systems aspects better, we have developed the WELMM approach (Water, Energy, Land, Materials and Manpower) at IIASA and summarized our opinion in the slogan: Man does not consume energy, but WELMMITE. A lot remains to be done to achieve a better understanding in this direction.

2. Much will depend on what will happen in the next decade in North America. If the North Americans are successful, their efforts will open the way to new resources, not only for North America, but all over the world. It is with some melancholy that I must confess that Western Europe, the region depending the most on oil and, unfortunately, on imported oil, has restricted itself to a wait-and-see position.

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