Working Paper

An Assessment of World Hydrocarbon Resources

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WP-96-56
May 1996

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1 Energy Reserves and Resources

1.1 Motivation and Definitions

Our current knowledge of energy resource availability and recovery costs inevitably shapes our perspectives of future energy system development. Knowledge and resource recovery economics, however, are continuously changing due to advances in geosciences, technical progress in the upstream production operations, rates of current production and future energy demand expectations. As a result, it is impossible to encapsulate energy resources or production economics by simple measures or single numbers. Because of the numerous uncertainties entering the analysis, energy resource assessment is "the effort of estimating the economic portion of an unknown total" (Adelman 1992). Government bureaus and industry attempt to rise to the challenge of presenting up-to-date estimates of the economically available crude oil, natural gas, coal and uranium resources. Usually, these assessments comprise elements along a continuum of three dimensions: *geological knowledge, economics*, and *technology*. Another important dimension, and perhaps from the perspective of society the most important, is the level of future resource extraction and use. The fact that these different dimensions do not evolve independently from each other, adds to the already complex task of energy resource assessments, especially if the temporal scope of the assessment extends beyond traditional energy sector planning horizons.

Traditionally, energy resource assessments have focussed on the immediate to short-term accessibility of oil, gas, coal and uranium, usually in terms of annual reserve additions relative to current production. From the perspective of the primary industrial sector in general and the resource industries in particular, this focus on the exact delineation of economically accessible resources is inevitable. Private sector investments in exploration, development and production capacities need to be balanced against the resource economics of the day and provide for an adequate rate of return. Longer-term outlooks serve as a guide primarily with respect to potential resource depletion rates and expected market price movements as well as geo-political developments, contractual arrangements, concessions and taxation. The time horizon of these outlooks rarely exceeds one decade or two. The most prominent guide lines for the industry are the so-called *reserve-to-production ratios* which contrast the presently known reserves to current production and thus represent a measure for the temporal reach of exhaustible energy sources. Typically, these ratios fluctuate between 20 to 40 years for the sources most in demand. As will be argued in the following paragraphs, the notion of *reserve-to-production ratios* is seriously flawed and, in the past, has led to aberrant conclusions (MacKenzie 1996). The most erroneous conclusion is that the world will be running out of resources by the point in time suggested by reserve-to-production ratios. Viewed through the lens of economics, however, there are no depletable resources really. Even in the event of "the cessation, once and for all, of technological progress" (Boserup 1979) in the hydrocarbon upstream sector, the cost of replenishing depleted production capacity would eventually make investments in this resource uneconomical compared to alternatives. Investors would simply stop investing in this resource and the remaining occurrences remain in the Earth's crust untapped.

In the study "Long-term Energy Perspectives to 2050 and Beyond" (IIASA-WEC 1995) conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC), the temporal scope of the analyses extends out to the year 2100—a daunting task. Inevitably, numerous assumptions enter such an analysis. One of the most critical premises concerns future rates of technology change and productivity gains. Technology advances in the hydrocarbon upstream sectors have an immediate impact of long-term fossil energy resource availability. Because resource availability and resource costs play a central role in long-term energy analyses, the IIASA-WEC Study devised several alternative images of future rates of technology progress and fossil resource availability ranging from conservative to accelerated advances. The premise of cessation of technical progress, however, was rejected.

A study looking more than 100 years ahead necessarily involves an assessment of resources as well as an evaluation of their recoverability which extends far beyond conventional reserve analyses. In this context, the word assessment carries the connotation of inventory while recoverability refers to both technically recoverable and economically recoverable resources. Uncertainty is a common element to inventory and to recoverability, i.e., uncertainty with respect to geological assurance and techno-economic feasibility of resources. The IIASA-WEC Study first assessed the occurrence of fossil resources in the broadest dimensions possible without immediate reference to recoverability. In a second step, the assessed occurrences were categorized into estimated ranges of potential future production costs. A modified "McKelvey box" approach was used for the resource categorization and techno-economic feasibility estimates.

McKelvey (1972) proposed a diagram with a matrix structure for the classification of mineral resources along two dimensions: decreasing geological assurance of occurrence and decreasing economic recoverability. In the case of fossil energy, the notion "occurrence" or "in-place" represents all types and forms of hydrocarbon deposits in the Earth's crust (Fettweis 1973). Global occurrences are usually assessed by mass-balance calculations on the basis of geophysical and geochemical information. At the regional level, analogy is the basic concept for a first-order assessment of hydrocarbon occurrences. Geological properties of one particularly well explored area are applied to geologically similar areas. The resource characteristics of the reference site in terms of in-place accumulation, distribution, etc., are then assumed to be similar to the characteristics of undiscovered resources within the unexplored area of interest (Grossling 1976).

The McKelvey box then adds the dimensions of uncertainty and techno-economic recoverability to the analogy concept. For example, *measured* occurrences have the highest geological assurance, followed by *indicated*, *inferred* and *undiscovered* or *speculative* occurrences. *Indicated* occurrences are resources located in known reservoirs that can be extracted through the application of additional or improved recovery techniques. *Inferred* occurrences are identified resources that can be recovered by additional drilling in the extensions of known fields. Also included in the *inferred* category are newly discovered pay zones and net upward revisions of previous estimates (Dolton *et al.* 1993). Taken together the *measured, indicated and inferred* occurrences are often referred to as *Proved Reserves* or *Reserves*. In short, *Reserves* are those occurrences that are identified, measured and at the same time known to be technically and economically recoverable. Thus, reserve estimates

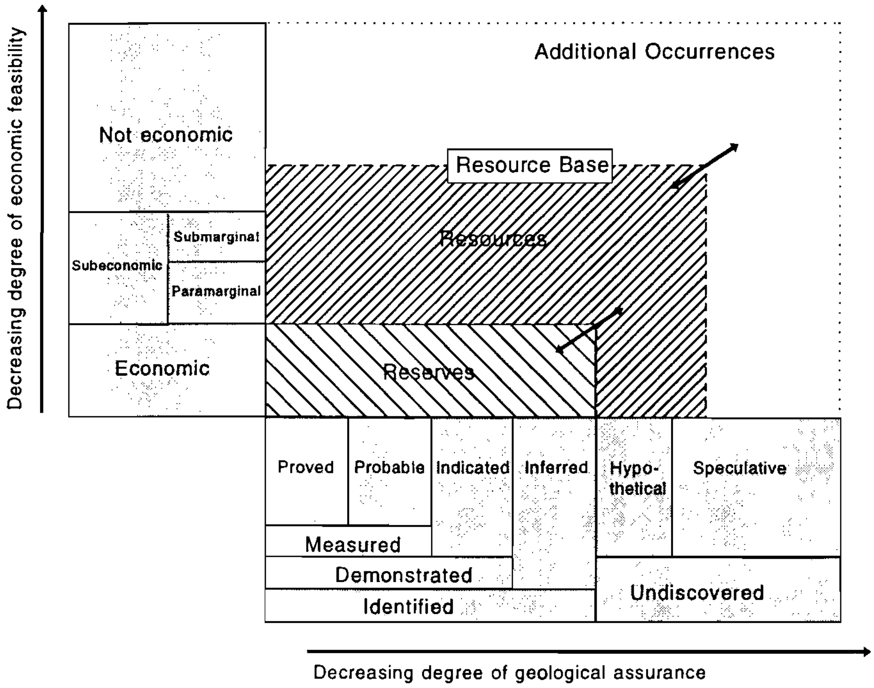


Figure 1: Classification of energy reserves and resources. Source: Modified from McKelvey (1972).

inherently depend on the state-of-the-art of present exploration and production technologies as well as on the prevailing and anticipated market prices.

Resources then are occurrences with less certain geological assurance and/or doubtful economic feasibility. The boundary between occurrences and resources is fuzzy and usually drawn "by practice" in inventory assessments. Together, reserves and resources form the so-called *resource base*[1]. Additional quantities with unknown degrees of assurance and/or with unknown or without economic significance are referred to as "*undiscovered*" or "*additional occurrences*," respectively. For example, additional occurrences include methane clathrates, known to exist in enormous quantities. To date, however, there is little knowledge as to their actual resource potential and the eventual techno-economic feasibility of their extraction.

As helpful as the McKelvey diagram is for an organized and internally consistent presentation of reserves and resources, the underlying concept seems to have escaped the attention of most energy resource analysts who fail to recognize the dynamic nature of the diagram. Instead, the diagram is viewed as an ironclad matrix structure with fixed quantities in each rectangle. In this case, energy reserves and resources appear to be ultimately determined by present knowledge, technological and economic conditions. The result are those widely publicized reserve-to-production ratios which convey as a definite sense of imminent finiteness. Reality, however, proves the opposite.

[1]The resource base estimates include reserves, and potentially recoverable resources of coal, conventional oil and natural gas, but also of unconventional oil (oil shale, tar sands, and heavy crude) and natural gas resources (gas in Devonian shales, tight sand formations, geopressured aquifers, and coal seams).

In response to the energy service needs of a growing world population, improved geological knowledge, both scientific and experimental (e.g., reservoir theories and exploration techniques), technical progress, and innovation have continuously expanded the fossil energy resource base. In fact, over the past 150 years the additions to reserves have regularly outpaced consumption. Market prices or price expectations, the latter often raised by the static concept of energy reserves which inherently fuels a "running-out-of-reserve" perception, contribute indirectly to the steadily growing resource base. Fluctuating prices impact resource availability in two ways. First, increasing prices render previously marginal or even uneconomic resources profitable. Higher market prices increase the technical recoverability of known and even of depleted deposits (e.g., enhanced oil recovery can double the extraction from some reservoirs). Higher prices also accelerate exploration and induce technology change. Improved exploration and extraction technologies help identify and access quantities that were previously only inferred or beyond technical reach, and result in the reclassification of resources to reserves. Finally, technology improvements can further reduce the production costs of currently operating fields.

After a period of large additions to the resource base, in general, and reserves, in particular, price expectations tend to decline. Exploration activities are streamlined and concentrate on the most promising projects. Likewise, exotic technology development is abandoned. In the short run, the net effect is an increase in exploration and production productivity and, consequently, also in the resource base. This will further suppress price expectations and eventually exploration activity bottoms out. The resource base stagnates and even begins to shrink. Periodical reserve estimates display declining reserves-to-production ratios which raise future price expectations; and the cycle begins anew.

Obviously, energy resource estimates based on, and responding to, short-term business cycle dominated events in the market place are inadequate for any long-term evaluation of energy resources and their techno-economic availability. In retrospective over the last century, technology has probably had a more profound and lasting impact on prices than prices on technology. Energy prices matter in the short run when infrastructures are essentially locked-in. They also matter in that rising prices tend to spark price-induced change (in technology and behaviour). Their long-run impact, however, is rather opaque. Energy price volatility may have caused many economic windfall profits or losses but history has been shaped by technology. Figure 2 illustrates the impact of technological progress on resource accessibility and thus on production costs: A two-fold increase in reserves at constant costs or a substantial cost reduction for a fixed reserve quantity.

Consequently, a dynamic concept must be applied which factors anticipated rates of technical change into the resource evaluation. Moreover, people demand and buy energy services, not primary energy reserves or resources. Consequently, the quality and cost of the service matters. The energy component in the service costs, however, varies with technology and infrastructure availability. The technology component at the level of energy services has become more and more complex and capital intensive. Hence, technology change in the broadest sense, i.e., ranging from exploration to management technologies, will determine future energy resource accessibility.

To know the true extent of geological occurrences is intriguing and, theoretically can be derived from integral (i.e., since the genesis of the planet) mass, energy and entropy balances for carbon, hydrogen, oxygen, solar radiation, etc. But in the final analysis such knowledge is irrelevant. In the long run the marginal costs of replacing depleted fossil energy sources will be evaluated against the package consisting of convenience, quality and costs associated with the supply of energy services.

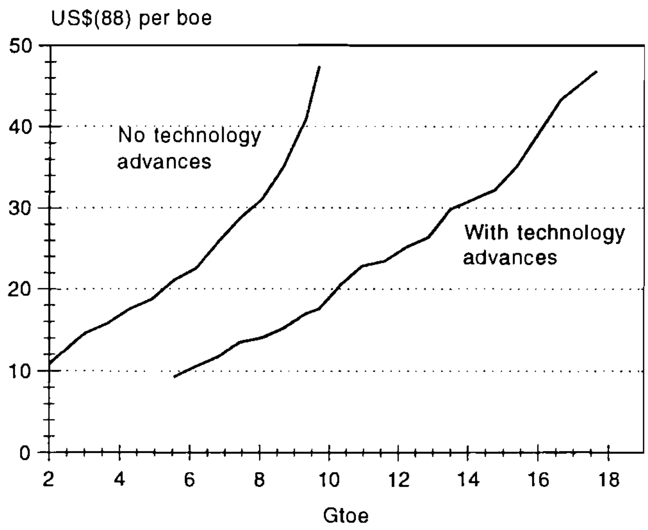


Figure 2: The impact of technological progress and natural gas resource availability and production cost in the United States (lower 48 states). Source: Modified form GRI (1990).

At a certain level of non-renewable resource replacement costs, renewable based energy services become competitive. Given the rate of technical change for all energy technologies but in particular for those technologies which have yet to reach the level of commercialization, it is reasonable to expect that a significant share of fossil energy occurrences will remain in the ground untapped. Moreover, concerns regarding the quality and stability of the climate system are likely to restrain the unrestricted use of carbon containing energy sources. One should note, however, fossil resource depletion appears less likely to become the major force that will help curb carbon emission to the atmosphere before the 21st century draws to an end.

2 Classification

This assessment of non-renewable energy resources, prepared as an input to the joint IIASA-WEC Study, was structured to reflect, in spirit, the McKelvey diagram. Unfortunately, resource estimates published in the literature rarely report their findings according to that scheme. In particular, the dimension of economic feasibility of the estimated resource quantities is hardly delineated. The majority of estimates include economically viable reserves of the day only. For example, reserve estimates of conventional crude oil are based on the current knowledge of world oil resources, and "emphasize how much oil has already been found, where we have found it and where we have failed to find it, and when we found it" (Nehring 1982).

The literature on resource assessments reveals far reaching differences in the interpretation of otherwise quite similar formal definitions. While a Proved Reserve in some countries, especially in the United States, "has the specific meaning of describing a quantity of petroleum that is technically ready to be commercially produced" (Masters *et al.* 1994), the same notion in the BP Statistical Review of World Energy reads "Proved Reserves of Oil are generally taken to be those quantities which geological and engineering information indicate with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions " (BP 1995). When these definitions are applied individually to the same geographic area, reserve estimates may differ by a factor of more than four (Masters *et al.* 1994). Such differences can, at least partly, be explained by the underlying concepts of the dynamics of knowledge and readiness. The US definition includes time or readiness for production in an immediate sense while BP uses an integral approach to readiness, i.e., the estimates include those known quantities that can be developed if so required. With reference to the McKelvey diagram, the BP Proved Reserve notion corresponds approximately to the "Demonstrated" by "Economic" rectangle in Figure 1.

The lesson learned from this discussion is the apparent difficulty to incorporate future development efforts, technology change and uncertainty into reserve assessments. The short term implications of these differences are not so important but will definitely influence any long-term energy demand and supply analysis. If a long-term energy analysis with a study horizon of 50 or 100 years into the future incorporates an oil and gas resource availability based on current reserve-to-production ratios of 45 to 60 years, a running-out-of-resources future is hard-wired into the study findings. Therefore, a resource concept reflecting the overall hydrocarbon occurrences as wells as future dynamics of technology change needs to be applied, i.e., a series of "McKelvey boxes" as a function of time and technology change.

2.1 Resource Categories

Estimates of global conventional and, to a lesser extent, unconventional oil and natural gas occurrences are routinely published by many organizations (BP 1995; Masters *et al.* 1994; Oil and Gas Journal 1973-1995; WEC 1995; BGR 1995). Unfortunately, it is impossible to put these reserve and resource estimates at face value into the format suggested by the McKelvey box. The respective industries and institutions tend to report their quantities using quite different terminologies, concepts and boundaries. As shown above, the same terminology may carry a distinctly different meaning between countries. Because of these difficulties an attempt was made to reconcile the individual estimates with the help of the McKelvey box. One drawback of such an attempt is the difficulty to compare the resulting resource quantities with the original industry classifications and reporting structures.

Altogether, the resource assessment for the joint IIASA-WEC Study distinguishes eight resource categories for the *in-situ* occurrences of crude oil and natural gas, ten for coal and five for uranium. The selection of a finite number of resource categories is a compromise between data availability and the necessity to reflect uncertainty. For data availability, the number of categories make maximum use of the information supported in the literature. For uncertainty, sufficient categories allow the simulation of different future innovation rates and energy market conditions, i.e., the higher the resource category, the larger the geological uncertainty and cost of recovery ranges.

Conventional oil and gas resources are organized across the first three resource categories (see Table 1). By and large Category I corresponds to "Measured Reserves" of the McKelvey box. The definition used by both Masters *et al.* (1994) and the USGS (1995) extends to include a

Table 1: Fossil reserve and resource categories of the IIASA-WEC study

Crude oil and natural gas

	Conventional reserves and resources				Unconventional reserves and resources			
	Proved recoverable reserves	Estimated additional reserves	Additional speculative resources	Enhanced recovery[a]	Recoverable reserves	Resources	Additional occurrences	
Category	I	II	III	IV	V	VI	VII	VIII

Hard and brown coal

	Proved recoverable reserves	Additional recoverable resources	Additional identified reserves	Additional resources	
Grade	A	B	C	D	E

[a] from conventional reserves and resources, i.e., Categories I to III.

share of the indicated reserves as well. The boundaries of the BP and WEC estimates which use the concept of proved recoverability are somewhat narrower than the Identified Reserves of Masters *et al.* More important than the reconciliation of these estimates is the fact that Category I serves as the point of departure for many energy related economic, political and environmental considerations. For example, the commonly reported "reserve-to-production ratios" are based on Category I-type reserves. Obviously, proved recoverable reserves is a very limiting and potentially dangerous concept for any long-term business planning or policy analyses.

Category II represents occurrences with a reasonable geological probability of discovery of to date undiscovered but presumed to exist conventional oil and gas resources. In due course, Category II resource volumes will come to bear as exploration and development efforts expand as a function of the eventually declining oil and gas of Category I. From the perspective of the consumer, Category II resources will replenish Category I reserves and will become themselves Category I type reserves. WEC (estimated additional reserves) and Masters *et al.* (mode or 50 percent probability of discovery) assess Category II resources. In terms of the McKelvey box, Category II overlaps with the inferred and, to a lesser extent, undiscovered hypothetical sections (see Figure 1).

Category III is of a more speculative nature and corresponds to the right hand side of the McKelvey box in terms of geological assurance, primarily, and to a lesser extent in terms of technical recoverability. Only Masters *et al.* assess and quantify low probability estimates. In this assessment, Category III reflects the difference between Masters *et al.* five percent and fifty percent probability estimates of undiscovered oil and gas occurrences.

Categories I to III encompass conventional oil and natural gas quantities that can be delineated with present development practice and are amenable to the application of existing recovery technology. Uncertainty with respect to their eventual discovery, i.e., the horizontal dimension in the McKelvey box, is the principal characteristic between these categories. The remaining categories IV through VIII now increasingly add technological and economic uncertainty to decreasing geological assurance.

Category IV reflects the potential for enhanced recovery. In the past, on average only 34 percent of the in-situ oil and 70 percent of natural gas were recovered with primary (based on natural drive mechanisms from the initial reservoir pressure) or secondary (compensating for declining reservoir pressure e.g., by water or gas injection) production methods. An additional fraction of the original in-situ oil and gas can be recovered from both abandoned and existing fields with advanced production technologies. Enhanced oil recovery methods include the use of solvents that improve the viscosity of oil, especially of the heavier types, steam injection or chemical methods that modify the properties of the water which, in turn, displaces oil and thus changes the pathways of oil flows through the reservoir rock. To date there was no need to develop and deploy enhanced natural gas recovery methods. Extensive fracture stimulation comes closest to enhanced gas recovery.

In this assessment, future conventional oil and gas production from Categories I to III are assumed to utilize 40 and 80 percent of the in-situ occurrences, respectively. Since the reserve quantities are delineated for the domain of primary and secondary recovery methods, there may also arise the possibility to lever the initial quantities by enhanced recovery methods.

Categories V through VIII encompass unconventional oil and natural gas. Unconventional oil and natural gas are occurrences that, in general, cannot be tapped with conventional production methods for technical or economical reasons or both. The boundary between conventional and unconventional resources is flexible and depends on regional technology access and availability, geography, market prices, and definitions. Consequently, quantifications and statistics on reserves, resources and production of conventional and unconventional oil and natural gas may well overlap. In fact, technology progress is one of the main causes for shifts of this boundary.

Unconventional oils include oil shales, tar sands/bitumen, heavy and extra-heavy crude oils but also deep sea oil occurrences. Unconventional natural gas includes gas in Devonian shales, tight sandstone formations, geopressured aquifers, coal-bed gas, and methane in clathrate structures (gas hydrates). These resources are known to exist in large quantities but to date only minor efforts have been expended for their delineation. It should be noted that the geological formations containing unconventional gas are distinctly different from those associated with unconventional oils. The latter are usually of low-grade and often involve extraction technologies that have a larger resemblance to coal than to conventional oil. For example, estimates suggest that about 85 percent of global oil shale resources are contained in shales averaging less than 0.08 toe per tonne (Russel 1988). In contrast, unconventional natural gas requires elaborate drilling technologies, well stimulation or liquid-gas and gas-gas separation equipment. In general, the term unconventional suggests that this class of occurrences could historically not be produced using traditional development and extraction practices. Consequently, the production processes suitable for unconventional oil and gas production lack maturity. Given the large resource volumes of conventional oil and natural gas, there has been no immediate need to embark on rapid development of unconventional extraction technologies. Moreover, in the case of unconventional oil occurrences, the extraction products are less readily usable than conventional oils and require further treatment/up-grading.

Category V contains the identified reserves of unconventional oil and gas. Reserves in this context reflect those unconventional occurrences which can be produced today or in the near future at prevailing international market prices. It is important to note the difference between market price and production costs. While unconventional reserves can be produced commercially at current market prices and provide adequate returns to investors, their production costs tend to be significantly higher than those of conventional fuels, especially in the Middle East. Therefore, at present their economic viability is quite vulnerable with respect to any downward pressure on international market prices.

Categories VI and VII encompass unconventional oil and gas resource estimates while Category VIII contains all remaining occurrences of both conventional and unconventional in-situ occurrences including the quantities remaining *in-situ* after commercial production has been abandoned. The occurrences of Category VIII are reported for reasons of data completeness and are not expected to be technically recoverable or economically feasible before the end of the 21st century. Therefore, the joint IIASA-WEC Study excluded Category VIII resources from the menu of potential energy supply options.

Coal reserves and resources assessments usually distinguish between the rank of coal (e.g., lignite, sub-bituminous, bituminous, or anthracite) which is a proxy for its energetic value, depth of deposits, seam thickness and type of recovery, i.e., surface or underground mining. As in the case of oil and natural gas, assessments of coal occurrences differ greatly in their reporting structures, terminology, technology assumptions and levels of aggregation[2]. Another difference concerns the

[2]For a detailed review of coal occurrences see Fettweis (1973).

units used in the assessment documentation. For example, WEC reports coal resources in physical units, i.e. in tonnage per rank and country, plus tables of national coal characteristics stating heating values and coal composition in terms of sulphur, carbon, ash, volatile matter and moisture. These characteristic are given as ranges or averages or both. In contrast, BGR (1989) provides the estimates in terms of both natural units (tonnage) and tons of coal equivalent.

In the joint IIASA-WEC Study the two BGR ranks of hard coal and lignite were adopted. Each rank was subdivided into 5 sub-categories or Grades: (A) Recoverable Reserves, (B) Additional Identified Reserves, (C) Additional Recoverable Resources, (D) Additional Resources and (E) Remaining Occurrences. In terms of the McKelvey box, Grades A to C roughly correspond to the respective subsections of the "Demonstrated" geological assurance level, while D and E approximate the Inferred and Undiscovered fields.

Uranium resources are usually reported with reference to their production costs. For many years, the threshold limit has been US$130/kg uranium. In the past, supply has regularly exceeded the requirements and inventories have been large enough to keep uranium market prices well below US$80/kg uranium. The potential availability of uranium from the disarmament process further suppresses the short-term prospects of the uranium market. Long-term uranium requirements depend greatly on the energy effectiveness of the fuel cycle and the reactor technology used. More importantly, the future prospects of uranium resource development will hinge upon how the current controversies concerning safety, waste disposal, and proliferation are resolved. As a result of the many uncertainties revolving around the future of nuclear energy, uranium exploration and development has kept a low profile.

Uranium occurrences are immense, especially if low-concentration sources such as seawater or granite rock are considered. In this assessment, uranium occurrences are grouped into five resource categories based on the OECD Nuclear Energy Agency (OECD-NEA[3]) uranium resource classification. The uranium occurrence dimension, however, was extended beyond the OECD-NEA framework to also include highly speculative uranium occurrences with unknown production costs.

The following sections present an account of global and regional non-renewable energy sources and their recovery costs used in the IIASA-WEC Study. The account is an attempt to construct an internally consistent energy resource platform from numerous unrelated and ambiguously reported, thus difficult to compare, resource estimates and technology performance assumptions.

Throughout this review of finite energy resources, the data presented in the various tables may suggest a level of precision which, in reality, is illusory. The data were compiled, aggregated and tabulated as point estimates. It is one of the pitfalls of computer based analyses to produce estimates with many "significant" digits, creating an illusion of definitiveness. Thus, the reader should be aware that there exists a considerable uncertainty range around each of these point estimates. Hence, the data represent an indication of the order of magnitude of a particular source and not a categorical determination of quantities and costs.

Table 2 lists how the joint IIASA-WEC Study grouped the countries of the world into eleven separate regions. The main criteria for the regionalization were geography, demography, resource endowment, and a country's economic development state. The challenge then was to develop

[3] Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD)

Table 2: IIASA-WEC study regions[a].

NAM	NORTH AMERICA	LAM	LATIN AMERICA & THE CARIBBEAN
WEU	WESTERN EUROPE	EEU	CENTRAL & EASTERN EUROPE
FSU	FORMER SOVIET UNION	MEA	MIDDLE EAST & NORTH AFRICA
AFR	SUB-SAHARAN AFRICA	CPA	CENTRALLY PLANNED ASIA & CHINA
PAO	PACIFIC OECD	PAS	OTHER PACIFIC ASIA
SAS	SOUTH ASIA		

[a] For a detailed account of the regional aggregation see IIASA-WEC (1995).

energy resource quantity-cost relations for each of the eleven regions based on often very scarce and aggregate information.

2.2 Conventional Oil

Tables 3 compares the most recent WEC (1992), BP (1995) and Masters *et al.* (1994) assessments of conventional oil reserves and resources.

At present Category I global oil reserves amount to somewhere between 137 and 150 Gtoe depending on the definition applied. That the BP and WEC global estimates based on the notion of proved recoverability are somewhat lower than the Identified Reserves of Masters *et al.* is plausible. The regional differences between these estimates, however, are difficult to explain.

Category II estimates range between 61 and 77 Gtoe. The larger WEC estimate makes up, in part, for the different boundaries of the WEC and Masters *et al.* assessments with respect to their allocation to Categories I and II. In addition, WEC does not report any "Estimated Additional Reserves" for the FSU. Still, the total of the WEC and Masters assessments, 215 versus 211 Gtoe, respectively, agree quite well. The undiscovered resources with a low geological assurance, i.e., Category III, amount to 84 Gtoe. Here only Masters *et al* report estimates at this level. In summary, the total resource base estimate of conventional oil applied to this study amounts to 295 Gtoe. The total of historical production and the resource base, often referred to as the "ultimately recoverable conventional crude oil resources", amount to 385 Gtoe.

Since the 1960s the mean estimates of global ultimately recoverable resources of conventional oil have ranged between 250 and 400 Gtoe with a median value of 290 Gtoe (Hubbert 1962; Grenon 1982; Nehring 1982; BGR 1989; Masters *et al.* 1994; MacKenzie 1996). In one way or another, all estimates include caveats regarding the potential impact of technical progress on these estimates. For example, today on average 34 percent of *in-situ* oil occurrence are recovered with state-of-the-art technology. A one percentage point improvement in the recovery rate leads to a 3 to 5 percent increase in ultimately recoverable resources depending on the actually realized historical recovery rates which often ranged considerably below today's average and the economic viability of revisiting long-time abandoned oil plays (BGR 1989). The long-run recovery rate of conventional crude oil assumed for this analysis is 40 percent. Against the background of present and future technology advances, an ultimately recoverable conventional oil resource base of 385 Gtoe is plausible.

Table 3: Estimates of conventional crude oil reserves, in Gtoe.

	Category I			Category II		Category III
Region	WEC Proved recoverable reserves	BP Proved reserves	Masters *et al.* Identified reserves	Masters *et al.* Undiscovered mode	WEC Estimated additional reserves	Masters *et al.* Undiscovered at 5% probability
NAM	5.2	5.3	8.5	8.6	1.1	6.7
LAM	16.9	17.0	17.4	8.9	36.7	15.5
WEU	2.0	2.3	5.6	2.1	1.4	3.6
EEU	0.2	0.3	0.3	0.2	0.1	0.6
FSU	8.0	7.8	17.1	13.6	0.0	19.3
MEA	96.4	95.9	87.9	17.0	2.8	21.9
AFR	2.9	3.0	4.0	3.4	0.0	4.9
CPA	3.3	3.4	5.1	4.7	35.0	8.2
PAO	0.3	0.3	0.4	0.3	0.1	0.6
PAS	1.4	1.7	2.9	1.6	0.1	2.5
SAS	0.9	0.8	1.0	0.3	0.2	0.6
World[a)]	137	138	150	61	78	84

[a)] Totals may not add up due to rounding

Sources: Masters *et al.* (1994), WEC (1992), BP (1995)

Category IV reflects the potential for enhanced recovery (see Table 5). It is assumed that in addition to the present average of 34 percent another 10 percent of the original in-situ oil could possibly be recovered from existing fields with advanced production technologies. Future conventional oil production from Categories I to III is assumed to utilize 40 percent of the in-situ occurrences. The enhanced recovery potential for oil is estimated at 15 percent of the original in-situ quantities (ultimate recovery rates of 55 to 60 percent were suggested by Nehring (1982). Based on these assumptions the potential for enhanced recovery would amount to 138 Gtoe.

2.2.1 Unconventional Oil

Categories V through VIII encompass unconventional oil occurrences. Despite their presumably large resource volumes, to date only minor efforts have been expended for their delineation. Most known unconventional oil deposits are economically marginal or unattractive under present market conditions and technology availability. The technology for their exploitation is complex and capital intensive. With a few notable exceptions, unconventional oil is not exploited to contribute to liquid fuel supply. Current oil production from unconventional resources amounts to some 160 Mtoe per year (or 5% of global oil production). In the absence of considerably higher oil market prices, further technology advances are called upon to improve the economic attractiveness of unconventional oil resources. Because of this innovation-dependence, both the "oil in-place" occurrences reported in the literature and prerequisite oil market price levels vary significantly, i.e., between 875 and 4,120 Gtoe and $20 to 70 per barrel, respectively (Hiller 1995). Moreover, potentially very high environmental costs add to the already large production cost uncertainty[4]. Moreover, unconventional oils contain low carbon-to-hydrogen ratios. In order to blend with or substitute for present oil products, unconventional oils need to be upgraded by means of hydrogen addition. Because of the greater density, viscosity, molecular structure, and non-hydrocarbon content, their production, transportation, upgrading and refining processes differ greatly from those applied to conventional oil (Meyer and Duford 1988).

Oil Shales

Oil shales are sedimentary rocks containing a high proportion of kerogen formed from organic matter buried not deep enough to be transformed into oil and natural gas. Oil shale recovery may occur by way of mining (surface or underground) similar to the production of coal or by in situ techniques (retorting or chemical treatment). In general, oil shale deposits are of low-grade quality with averages yields of oil per tonne of deposit material rarely exceeding 0.1 toe. One estimate suggests that about 85 percent of global oil shale resources are contained in shales averaging less than 0.08 toe per tonne (Russel 1988). The low-grade characteristic of this hydrocarbon resource represents a particular technological challenge. A large-scale production has to meet two objectives simultaneously, i.e., economic viability and environmental compatibility.

In the past, oil shale was used as an under-boiler fuel or was refined into synthetic oil and gas. In future, this resource is expected to initially supplement and eventually substitute for conventional oil.

Oil shales account for the lion's share of unconventional oil occurrences. Oil-in-place estimates range from 450 to 2,510 Gtoe (BGR 1995). An earlier study by BGR (BGR 1989) showed a resource range of 667 to 2,512 Gtoe, i.e., the bottom end of the estimate was revised downward significantly. The IIASA-WEC Study incorporated an overall oil shale occurrence of 934 Gtoe. This resource volume is the result of a middle-of-the-road approach to the earlier BGR resource data based on a conservative interpretation of the immense resource range reported for China[5].

Most recent studies report only some 12 to 14 Gtoe as "proved reserves" (BGR 1995; WEC 1995). Proved reserves have hovered at this level for almost a decade. Therefore, 14 Gtoe appeared as a plausible datum for the IIASA-WEC Study. Estimated additional reserves span from 35 Gtoe (WEC 1995) to almost 160 Gtoe (BGR 1995). The latter estimate is somewhat higher than the 1989 assessment of 123 Gtoe. At the time of the IIASA-WEC Study, the 1995 estimates were not yet available and Table 4, therefore, shows the 1989 BGR value.

[4] Most unconventional oils contain undesirable non-hydrocarbons ranging from vanadium, nickel to sulfur, nitrogen, and oxygen (Meyer and Duford 1988).

[5] "Data from China appears to be erratic. It often appears that tons of shale oil, and barrels of shale oil may be transposed" (Russel 1988).

Table 4: Estimates of unconventional oil occurrences, in Gtoe.

	Shale oil				Tarsands						Heavy Oil			
	BGR		WEC		BGR		WEC		Meyers *et al.*		BGR		Meyers *et al.*	
Region	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves
NAM	220	3.0	217	*na*	258	5.00	26.8	0.52	368	*na*	14	0.83	23	2.57
LAM	120	9.0	19	0.4	125	0.01	24.4	0.00	1	*na*	166	33.0	215	2.29
WEU	29	4.0	2	0.2	*na*	0.04	0.3	0.03	0	*na*	1	0.07	10	1.04
EEU	3	0.3	*na*	*na*	0	0.01	0.1	0.01	0	*na*	0	0.04	0	0.02
FSU	35	2.0	42	2.0	42	0.34	19.0	*na*	65	*na*	0	0.02	23	0.95
MEA	144	20.0	79	6.3	0	0.01	0.0	0.01	0	*na*	2	*na*	76	16.0
AFR	16	*na*	0	*na*	9	1.00	0.2	0.03	5	*na*	1	0.20	2	0.41
CPA	202	80.0	*na*	1.0	1	*na*	1.7	0.25	*na*	*na*	4	0.90	9	1.26
PAO	133	3.3	102	3.7	*na*	*na*	*na*	*na*	*na*	*na*	*na*	0.01	0	0.01
PAS	18	1.0	19	0.1	*na*	0.09	0.0	0.00	*na*	*na*	1	0.13	6	0.39
SAS	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	1	*na*	1	0.10
World[a)]	920	123	479	14	436	6	72	1	440		191	35	367	25

[a)] Totals may not add up due to rounding
Sources: BGR (1989), WEC (1992), Meyer and Duford (1988), Meyer and Schenk (1985), Russel (1988).

Natural Bitumen (Tar Sands) and Heavy Crude Oil

Natural bitumen (tar sands) and heavy crude oil are closely related, i.e., they share most of the same physical and chemical characteristics. In essence, these hydrocarbons are oils that have seeped upwards from the geological "petroleum window" and near surface were oxidized or microbiologically altered (Häfele 1981). An exact distinction has yet to be determined. In general, viscosity and API gravities at reservoir conditions are used as one distinguishing characteristic. Heavy oils have 10° to 25° gravities but are less viscous than 10,000 centipoise (cP). Extra heavy oil is less than 10° API. Heavy oils above can still flow although extremely slowly, especially at the lower API range and their production often involves in situ flow and lift enhancement methods (heat, steam and polymer stimulation). Natural bitumen has a viscosity greater than 10,000 cP. At this viscosity level, bitumen differs more from conventional oil than heavy oil and its production requires more complex techniques. Tar sands and extra heavy oil have a 7° to 10° API gravity and cannot flow under normal reservoir conditions. Their extraction methods are surface mining or in-situ thermal recovery.

Worldwide resource estimates for tar sands and heavy crude oil were reported by WEC (1992), Meyer and Duford (1988), Meyer and Schenk (1985), and BGR (1989). For tar sands, the estimates span from 73 to 460 Gtoe. The lower estimate of WEC is the result of a relatively narrow resource concept which only includes occurrences meeting criteria otherwise applied to potentially recoverable reserves. All other studies arrived at a similar resource level of 436 to 460 Gtoe. Based on the availability of regional data a total resource volume of 446 Gtoe was deemed plausible. It appears that tar sand reserves were generally assessed cautiously, i.e., the reserves are very low compared to the immense resource volume. The values reported in the literature reflect the capital intensiveness of tar sand recovery and the low oil market price level of the late 1980s when these assessments were made. The maximum estimate of 6.5 Gtoe was adopted in the IIASA-WEC Study.

The 1995 study of BGR shows a somewhat different resource range, i.e., tar sands are estimated at 200 to 680 Gtoe of oil-in-place. Reserve values are considerably higher compared to earlier estimates (24 Gtoe versus 6.5 Gtoe).

Heavy crude oil reserve and resource estimates are based on the same studies as the tar sand assessments. According to these studies, resources range from 191 to 367 Gtoe while reserves vary between 25 and 35 Gtoe. The latest BGR estimate shows a much wider variation, from 135 to 930 Gtoe. Likewise, the 1995 reserves estimates exceed those of 1989 by 30 percent.

Table 4 summarizes the state-of-the-art assessments of unconventional oil reserves and resources at the time of the finalization of the IIASA-WEC Study analyses in early 1995. This study examined long-term perspectives for today's energy system relying largely on fossil fuels to progress toward a generally more sustainable energy service supply structure. Attractors and barriers were identified that could accelerate or delay a transition toward sustainability. In this context, fossil energy sources may function as attractors or as barriers or even both simultaneously. An abundant availability of a low-carbon fossil source, i.e., natural gas, could well be an attractor. Initially as a substitute for the higher carbon fossil sources coal and oil, and eventually as a staple source for hydrogen production. On the other hand, continued technology change may, in the course of half a century, mobilize a sizable portion of the carbon intensive unconventional fossil occurrences which in the short-term remain technically or economically infeasible to recover. The abundant availability of inexpensive high-carbon energy sources would probably function as a barrier to sustainability if not complemented with stringent pollution abatement measures. Therefore, in order to examine a variety of future energy scenarios postulated the inclusion into the analysis of the largest fossil occurrence figures referenced in the literature. The ultimate resource availability is a scenario characteristic by choice rather than by apriori exclusion of presently subeconomic or geologically uncertain resources.

Returning to the resource categories used in the IIASA-WEC Study, Category V, the reserves of unconventional oil, is the sum of the maximum oil shale, heavy oil and tar sand reserves shown in Table 4. This aggregation leads to a total global reserve volume of 45 Gtoe. The sum of the maximum unconventional resource figures of these three types of hydrocarbons totals to some 1,726 Gtoe oil-in-place worldwide. This total resource volume is split 20:35:45 and the allocated to Categories VI to VIII, respectively. In addition, all the oil remaining *in-situ* after commercial production is added to Category VIII. The distribution of unconventional oil resources over three categories reflects the increasing uncertainty concerning

- future rates of technical progress in recovery and upgrading technology;
- future energy economics; and
- potential inaccuracies of the estimates of yet to be discovered resources.

No matter how the future is going to unfold, it is important to consider that the heavier hydrocarbons (heavier than 17° API) which account for the bulk of unconventional oil occurrences are unlikely to approach the lower molecular weight hydrocarbons in terms of capital, energy and time intensities for their development, exploitation and refining. Their inherent hydrogen deficiency, however, may well become the largest barrier, especially in a greenhouse gas emission constrained future.

2.2.2 Summary Oil Resources

Table 5 summarizes the regional distribution of conventional and unconventional oil occurrences underlying the joint IIASA-WEC Study "Global Energy Perspectives to 2050 and Beyond". Here, Categories I to III correspond to the estimates of Masters *et al.* for conventional reserves and resources (see Table 3). The rationale and procedure for the calculations of Category IV to VIII quantities were adopted as described in the previous section. Finally, the recoverable portion of these oil occurrences will be a function of the degree of future technological progress, the overall evolution of the energy system and prevailing and anticipated energy market conditions. In a long-term energy demand and supply analysis, the maximum call on these resources becomes a critical scenario component.

Table 5: Estimates of Oil occurrences, in Gtoe.

Region	Conventional oil: Proved recoverable reserves	Conventional oil: Estimated additional reserves	Conventional oil: Additional speculative resources	Unconventional oil reserves and resources: Enhanced recovery	Unconventional oil reserves and resources (Aggregate of shale, bitumen and heavy oils): Recoverable reserves	Unconventional oil reserves and resources (Aggregate of shale, bitumen and heavy oils): Resources	Unconventional oil reserves and resources (Aggregate of shale, bitumen and heavy oils): Additional occurrences		Total
	I	II	III	IV	V	VI	VII	VIII	
NAM	8.5	8.6	6.7	15.9	7.6	98.8	172.8	287.4	606
LAM	17.4	8.9	15.5	18.9	2.6	91.5	160.1	270.8	586
WEU	5.6	2.1	3.6	5.1	1.3	7.6	13.3	34.6	73
EEU	0.3	0.2	0.6	0.7	0.0	0.5	1.0	3.8	7
FSU	17.1	13.6	19.3	23.4	3.3	19.4	34.0	125.6	256
MEA	87.9	17.0	21.9	56.2	22.3	39.6	69.3	279.0	593
AFR	4.0	3.4	4.9	5.4	1.4	5.1	8.9	29.7	63
CPA	5.1	4.7	8.2	7.4	2.3	42.2	73.8	118.7	262
PAO	0.4	0.3	0.6	0.7	3.7	25.8	45.1	60.3	137
PAS	2.9	1.6	2.5	3.4	0.6	4.8	8.3	23.0	47
SAS	1.0	0.3	0.6	0.8	0.1	0.3	0.5	3.5	7
World[a]	150	61	84	138	45	336	587	1,237	2,638

[a] Totals may not add up due to rounding

Sources: BP (1995), Masters *et al.* (1994), WEC (1992), BGR (1989), WEC (1992), Meyer and Duford (1988), Meyer and Schenk (1985), Russel (1988).

2.3 Natural Gas

2.3.1 Conventional Gas

Estimates of global conventional natural gas reserves and resources are summarized in Table 6. At present Category I global natural gas reserves are assessed at 115 and 129 Gtoe depending on the definition applied. The reasons for the differences between the WEC, BP and Masters *et al.* estimates are analogous to those for the oil assessments.

Category II estimates range between 104 and 112 Gtoe. In contrast to the oil resource estimates, the impact of different boundaries between the WEC and Masters *et al.* assessments (with respect to their allocation to Categories I and II) does not materialize in the case of natural gas. The global Masters *et al.* estimate is higher for both categories. At the regional level, however, it is impossible to find a consistent pattern between these two studies. Here differences in the anticipated technology advances and technology transfer assumptions underlying these assessments are probably a major explanatory factor for the regional resource deviations.

The undiscovered resources with a low geological assurance, i.e., Category III, are assessed at 153 Gtoe. The expected future availability of presently undiscovered conventional natural gas resources is much larger than for oil. While the undiscovered oil resources are considerably lower than the proved reserves, undiscovered natural gas resources exceed their proved counterpart. In fact, the less uncertain Category II natural gas volumes are already significantly larger than oil and almost at par with proven reserves. This divergence between speculative oil and natural gas resources reflects the differences in the maturity of the industries involved. Compared to oil, natural gas is a relative newcomer on the global energy scene. Moreover, natural gas resource assessments as well as exploration activities have been guided by the oil experience, primarily. Put differently, although the physical properties of natural gas and its chief component methane differ greatly from those of the liquid oil which has immediate consequences for the geophysical and geochemical prerequisites for their respective reservoir characteristics, natural gas resource availability has, to a large extent, been viewed through the geological and technological oil window. The larger undiscovered natural gas volume is the result of the slow but definite process of gas' liberation from oil.

In summary, the total resource base estimate of conventional natural gas underlying the IIASA-WEC Study amounts to 394 Gtoe (or 420 Gtoe if natural gas liquids, NGLs, are included). In terms of ultimately recoverable conventional resources, i.e., past production plus the resource base available for future production, for natural gas this amounts to 435 Gtoe (or 468 Gtoe including NGLs).

2.3.2 Unconventional Gas

The literature distinguishes six major categories of unconventional gas:

- Coal bed methane, i.e., gas contained in coal seams
- Tight formation gas, i.e., gas in low permeable, tight reservoirs

Table 6: Estimates of conventional natural gas and natural gas liquids (NGL) resources, in Gtoe.

	Natural gas						Natural gas liquids	
	Category I			Category II		Category III	Category I	Category II
Region	WEC Proved recoverable reserves	BP Proved reserves	Masters *et al.* Identified reserves	Masters *et al.* Undiscovered mode	WEC Estimated additional reserves	Masters *et al.* Undiscovered 5%	Masters *et al.* Identified reserves	Masters *et al.* Undiscovered mode
NAM	7.0	6.5	11.8	14.3	12.4	29.9	2.2	2.9
LAM	6.2	6.8	7.6	8.0	10.1	21.8	1.1	1.6
WEU	4.1	4.8	7.3	4.9	3.3	12.1	0.6	0.5
EEU	0.5	0.5	0.7	0.7	0.9	1.9	0.1	0.1
FSU	48.5	50.3	39.1	45.0	30.9	109.9	3.2	4.8
MEA	38.0	44.6	48.2	23.0	33.0	49.9	3.9	2.3
AFR	2.8	3.9	3.9	5.3	3.9	13.8	0.3	0.6
CPA	1.0	1.9	1.1	4.6	2.0	11.6	0.1	0.5
PAO	0.6	0.6	2.1	0.5	0.9	1.3	0.2	0.1
PAS	4.3	4.3	5.4	3.8	4.1	8.8	0.5	0.4
SAS	1.7	2.1	1.6	1.8	2.0	4.4	0.1	0.2
World[a)]	115	126	129	112	104	265	12	14

[a)] Totals may not add up due to rounding

Sources: BP (1995), Masters *et al.* (1994), WEC (1992)

- Geopressured gas, i.e., gas trapped in aquifers
- Gas hydrates, i.e., gas, primarily methane, existing in form of clathrates
- Gas from fractured shales
- Ultradeep gas

Because of the vast availability of conventional natural gas, there has been little commercial interest in the delineation of unconventional natural gas occurrences. Consequently, resource estimates of unconventional gas are very sparse and primarily initiated by academic curiosity rather than by commercial necessity. Funds have been limited, so are the data on unconventional gas occurrences. The data contained in the literature are fraught with geological uncertainty. Moreover, at present, the technology implications for the eventual production of unconventional gas are poorly understood, if at all. In summary, the data in following tables have to be taken with a large grain of salt. This is particularly the case for the regional distribution which in many cases is highly speculative.

2.3.3 Coal-bed Methane

Coal-bed gas is the gas mixture contained in predominantly bituminous and anthracite coal occurrences. The major component of coal-bed gas is methane with varying admixed quantities of heavier hydrocarbons and carbon dioxide. Coal-beds are both the source and reservoir rock for large quantities of methane (Rice *et al.* 1993). As regards the source, the gas is a product of the coalification process where organic matter is initially decomposed by microorganisms to methane in an anoxic and low temperature and pressure environment (biogenic process). As sedimentation increases both temperature and pressure, the coalification process continues and large amounts of methane and carbon dioxide are released thus enriching the coal carbon contents (thermogenic process). The quantities of methane generated during the coalification process are estimated at 150 to 200 cm^3 of gas per gram of coal (Rice, Law, and Clayton 1993).

The coal-bed serves also as the gas reservoir whereas the gas is adsorbed upon as well as absorbed within the molecular lattice structure of the coal. The actual quantities of gas stored is a function of coal rank, pressure and temperature. Because permeability is extremely low in coal, gas production requires the depressurization of the coal-bed reservoir usually via dewatering or fracturing.

The potential volume of coal-bed methane (in place) has been estimated at 85 to 367 trillion cubic meters globally (Rice, Law, and Clayton 1993; Eickhoff and Rempel 1995). As regards the regional distribution, coal-bed gas is intimately linked to the geographical distribution of anthracite and bituminous coal deposits. The wide range of the coal-bed gas estimates indicates that the delineation of coal-bed gas is in its infancy (see Table 7). There are no imminent technology barriers impeding production and the economics appear quite favourable. Still, with the exception of the USA, this resource is essentially undeveloped[6]. In the USA coal-bed gas has established itself as a commercial source of natural gas and accounts for some 4 percent of domestic natural

[6]The ventilation and use of coal-bed methane from active coal mines is common in many coal producing countries. It is a necessary precautionary measure to reduce the potential risk of underground explosions during coal production. In this context, commercial use of coal-bed gas implies that gas production is the primary if not only objective and the coal serves simply as the reservoir.

gas supply. In other countries with access to conventional natural gas deposits, coal-bed gas has yet to gain appeal.

2.3.4 Tight Formation Gas

Gas in tight reservoirs occurs in variety of rock types where the common characteristic is low in-situ permeability to gas of less than 0.1 millidarcy and reservoir pressures which deviate significantly from hydrostatic pressures (in either direction). Tight gas reservoirs are present in almost every petroleum province and occur at very shallow to very deep depths. Unlike conventional natural gas, where the gas is concentrated in structural or stratigraphic maps, tight gas is independent of the existence of such conditions (Law and Spencer 1993). Although areas of tight rock formation can be found all over the globe, exploration and production of tight formation gas has been spearheaded by the USA, primarily. Production usually requires artificial stimulation such as hydraulic fracturing which adds to production costs. Consequently, at present tight gas is produced only where local gas markets accommodate premium prices. Current annual world production amounts to some 0.04 Gtoe (Eickhoff and Rempel 1995). Technical progress and horizontal drilling are expected to improve the techno-economic access to this large source of natural gas in the near-term future.

Resources estimates of in-place and recoverable potentials of tight formation gas have yet to be conducted in a consistent manner and on a global basis. To date, most exploration has occurred in the USA, and to a lesser extent, in Europe and China. Resource estimates for the USA span a wide range, i.e., from 8 to 138 Gtoe of which 5 to 14 Gtoe have been assessed recoverable (Law and Spencer 1993). Global estimates are somewhat narrower and range from 75 to almost 190 Gtoe in-place (Kuuskraa and Meyers 1983). Because the production of tight gas is technologically more challenging than conventional gas, the upstream gas industry has had little incentive to explore and develop this resource. The global estimate of Kuuskraa and Meyers which dates back to the late 1970s therefore is probably quite conservative, especially when this global volume is put into perspective with the (higher) estimates for the USA. A recent study assesses the recoverable volume at close to 150 Gtoe (BGR 1995). However, since there is no geographic distribution available for tight formation gas occurrences and tight gas reservoirs are present in almost every petroleum province, the regional allocation shown in Table 7 was obtained by weighting the estimates global volume of the almost 190 Gtoe with the regional distribution of conventional gas.

2.3.5 Geopressured Gas

The solubility of a gas in a liquid increases with increasing pressure while increasing temperatures reduce solubility. Methane dissolved in water is quite common when oil and natural gas reservoirs are in contact with water bearing pore space. Because the solubility of methane in underground water is much more influenced by pressure than by temperature, the concentration of methane in underground water increases greatly with depth (Marsden 1993). Because most hydrocarbon reservoirs tend to be in contact with water, it is plausible to expect methane in geopressured aquifers in almost all sedimentary basins. In analogy to other unconventional types of natural gas, the in-place resource volume of geopressured gas has not been assessed at any degree of detail but the global resource volume is expected to be gigantic—8,900 Gtoe (Eickhoff and Rempel 1995). Although some aquifer gas is already produced from shallow aquifers, it is impossible at this point

Table 7: Estimates of unconventional natural gas in place by type, in Gtoe.

Region	Coalbed methane	Gas from fractured shales	Tight formation	Clathrates	Remaining *in-situ* [a]	Total non-conventional occurrences
NAM	77	98	35	6,089	20	6,319
LAM	1	54	33	4,567	8	4,662
WEU	4	13	9	761	7	794
EEU	3	1	2	0	1	7
FSU	101	16	23	4,186	42	4,367
MEA	0	65	21	190	25	302
AFR	1	7	20	381	4	413
CPA	31	90	9	381	3	514
PAO	12	59	18	1,522	1	1,612
PAS	0	8	14	190	4	217
SAS	1	0	5	381	2	389
World	232	411	189	18,647	117	19,595

[a] Gas remaining *in-situ* after commercial production of conventional natural gas has ceased

Sources: BGR (1989), Rice *et al.* (1993), Eickhoff and Rempel (1995), Law and Spencer (1993), Kuuskraa and Meyers (1983), Marsden (1993), Kvenvolden (1993), Dillon, Lee, Fehlhaber, and Coleman (1993), MacDonald (1990a, MacDonald (1990b), Collet (1993), Dyman *et al.* (1993)

in time to delineate the recoverable portion of this potentially enormous volume. The economics of the only case of methane production from a deep aquifer appear to be driven by the extraction of the by-product iodine. In fact, methane bearing aquifers contain many valuable trace elements and the eventual extracting of geopressured gas my well become the byproduct from the quest for these trace elements. The regional resource data in Table 7 were derived by multiplying the global in-place estimate of 8,900 Gtoe by the regions' relatives shares in the world's sedimentary area.

2.3.6 Natural Gas Hydrates

Natural gas hydrates are crystalized ice-like mixtures of natural gas, chiefly methane, and water. In hydrates, the gas is contained within cavities formed by lattices of water molecules. Such hydrates are stable at temperatures and pressure conditions that exist (1) onshore and offshore in permafrost regions and (2) near or just beneath the sea floor where water depths exceed 300 to 500 meters (Kvenvolden 1993; Dillon *et al.* 1993). The latter can be found almost everywhere in the world's oceans (Dillon *et al.* 1993) probably with higher than average concentrations at the foots of continental slopes (Eickhoff and Rempel 1995). Because hydrates can penetrate and seal sediment pore space, they not only trap natural gas in their lattice structure but may also function as hydrate-cemented traps for free natural gas beneath.

The recovery of gas hydrates requires one or any combination of three measures to release the gas from the lattice trap, i.e., thermal stimulation, depressurization or inhibitor injection. Appropriate techniques for the gas extraction from hydrates have not been developed yet and is will be technically challenging to engineer methods where the natural gas gains exceed the energy expenditures. In the foreseeable future, there will be little need for the development of gas hydrates. However, it is important not only to acknowledge their mere existence but their astronomic in-place occurrence estimated at more than 19,000 Gtoe (MacDonald 1990a; MacDonald 1990b). Even if only 1 percent of this volume will become techno-economically recoverable, this would represent a volume larger than current identified global natural gas reserves.

Although a geographical allocation of the gas hydrates is speculative at best, an attempt to that effect was made (see Table 7). The world map of locations of known and inferred gas hydrates in marine sediments of outer continental margins and in continental permafrost by (Collet 1993) was used at face value, i.e., each location was assumed to host equal amounts of gas hydrates, and applied to the global occurrence estimate of MacDonald.

2.3.7 Natural Gas from Fractured Shales

Devonian Shales have been a source of natural gas for more than 100 years (Milici 1993). Devonian Shales are organic-rich shales with 5 to 65 percent indigenous organic matter (Ray 1977). Such geological formations are principal source beds for petroleum and natural gas. Natural gas production from shale depends on several preconditions. The source rock must contain a suitable type, amount and thermal maturation of organic matter. Furthermore, the source rock must have a trapping mechanism as well as sufficient porosity and permeability. Resource estimates for organic-rich shales have been limited to the USA primarily and essentially nonexisting for the rest of the world. Moreover, natural gas extraction from shales requires that all the above preconditions are met simultaneously. Although quite speculative, the ratio of the USA estimates for natural gas from shale formations to the in-place shale volume was used as a guide to calculate the regional natural gas resource from fractured shales resource potentials. The resource data shown in Table 7 are based on the assumption that the shale oil occurrences outside the USA also contain the USA gas value of 17.7 TCF/Gt of shale in-place.

2.3.8 Ultradeep Gas

Deep gas reservoirs, i.e., at a depth between 4,600 meters (15,000 ft) and 7,600 meters (25,000 ft) are assessed to host some 25 percent of the total undiscovered natural gas resources of the USA (Dyman *et al.* 1993). These resource volumes give reason to assume that there are even larger gas occurrences in the ultradeep region (below 7,600 meters or 25,000 ft). Although the role of organic matter in producing large amounts of gas at such depths has yet to be determined, there is no doubt that in a dry reservoir environment methane is stable at and can withstand the temperature and pressure conditions prevailing at a depth of 10,000 to 13,000 meters. However, in the presence of fluids and minerals, the stability of methane is quite uncertain (Wyman 1993). In addition, theories of abiogenic methane sources have further sparked interest in deep gas resource estimates. While the deep gas category is accounted for within the gas occurrence estimates for the tight formation gas, geopressured aquifers, etc, no attempt has been made to assess ultradeep gas. The prerequisites with respect to reservoir and geologic characteristics of ultradeep gas-bearing rock are simply not understood.

2.3.9 Summary Natural Gas Resources

Table 8 summarizes assessment of the regional distribution of conventional and unconventional natural gas occurrences. As in the case of oil, Categories I to III correspond to the estimates of Masters *et al.* for conventional reserves and resources (see Table 6). The rationale and procedure for the calculations of Category IV to VIII quantities were adopted as described in the previous section. Again, the recoverable portion of these natural gas occurrences will be a function of the degree of future technological progress, the overall evolution of the energy system and prevailing and anticipated energy market conditions.

Table 8: Estimates of natural gas occurrences, in Gtoe.

	Conventional natural gas			Unconventional natural gas reserves and resources					
					Coalbed methane, tight formation gas, etc.[a]				
	Proved recoverable reserves	Estimated additional reserves	Additional speculative resources	Enhanced recovery	Recoverable reserves	Resources	Additional occurrences		
Region	I	II	III	IV	V	VI	VII	VIII	Total
NAM	11.8	14.3	15.6	8.4	35	70	105	6,100	6,361
LAM	7.6	8.0	13.8	3.9	13	30	44	4,571	4,691
WEU	7.3	4.9	7.2	3.0	4	9	13	765	813
EEU	0.7	0.7	1.2	0.5	1	2	3	1	10
FSU	39.1	45.0	65.0	20.2	26	45	68	4,208	4,517
MEA	48.2	23.0	26.9	12.5	13	29	44	203	400
AFR	3.9	5.3	8.4	2.2	4	9	14	383	431
CPA	1.1	4.6	7.1	1.6	21	24	36	432	527
PAO	2.1	0.5	0.8	0.5	14	30	45	1,523	1,616
PAS	5.4	3.8	5.0	1.9	3	8	11	192	231
SAS	1.6	1.8	2.6	0.8	1	2	3	381	395
World[b]	129	112	153	56	138	258	387	18,759	19,990

[a] Coalbed methane, gas from tight formations, geopressured gas, clathrates, and gas remaining *in-situ* after commercial production has ceased

[b] Totals may not add up due to rounding

Sources: BP (1995), Masters *et al.* (1994), WEC (1992)

2.4 Coal

Estimates of proved recoverable reserves of coal have hovered just above the 1,000 Gt mark ever since the first worldwide inventory of world coal resources was presented at the International Geological Congress held in Toronto in 1913. Fluctuations in reserves periodically reported by national bureaus appear to have compensated each other without affecting the world total notably. National reserve revisions have colluded with energy market price trends, i.e., during periods of lower prices reserve estimates decline and rise with higher price expectations. Coal resources have generally been estimated to exceed reserves by one order of magnitude, i.e., their occurrences surpass 10,000 Gt (Arbatov and Astakhov 1988; Fettweis 1973; WEC 1980).

Although there is no internationally accepted convention for the demarcation between different ranks of coal, many institutions group coal occurrences into two major classes, i.e., "Hard Coal" and "Brown Coal". Hard coal usually consists of anthracite and bituminous coal; brown coal of lignite and sub-bituminous coal. The dividing line between these two macro-categories is the coal's carbon, moisture, volatile material, and ash contents. Typically, the heating value of coal tends to increase with greater amounts of carbon and lesser amounts of moisture and volatile matter per unit of coal mass. A heating value of 25 Megajoule per kg of coal (MJ/kg) appears to be an often applied value for a differentiation between hard and brown coal deposits: hard coal has a heating value greater than 25 MJ/kg up to 36 MJ/kg while the heating value of brown coal is less than 25 MJ/kg and can be as low as 4 to 5 MJ/kg for lignite.

In order to put the energy relevance of coal reserve and resource quantities into perspective with those of oil and natural gas, the heating values of different carbonaceous deposits must be known. Because the chemical composition of coal varies widely even within a deposit, coal resource surveys often report only the physical quantities in place or provide information on the coal characteristics which is specific to one location and cannot be easily generalized. BGR is one of the few institutions that makes an attempt to publish their coal reserve and resource estimates in physical and energy units (BGR 1989)[7]. The joint IIASA-WEC Study adopted the BGR coal reserve data and the country specific average heating values were applied to the physical coal resource estimates of WEC (1992). BGR reports two reserve categories "proved recoverable reserves" and "proved additional reserves" as well as one "total coal resource category". WEC's coal reserve and resource estimates are grouped into "proved amount in place", "proved recoverable reserves", "estimated additional amount in place", and "estimated additional reserves recoverable". Depending on whose reserve classification is applied, aggregate world coal reserves, i.e., "proven recoverable" and "proved additional" reserves, vary between 606 and 1,003 Gtoe. Ultimately recoverable coal occurrences amount to some 6,200 Gtoe.

Viewed through the lens of conventional energy reserves, coal firmly holds the position of the world's most widely available fossil energy source. Given this large reserve base it is not surprising that the coal industry generally focusses on short-term coal market prospects and very little on resource exploration. Moreover, coal deposits tend to extend continuously and laterally over extended distances which reduces actual coal exploration requirements and increases the geological assurance of most coal deposits.

[7]The WEC Survey of Energy Resources discontinued to report coal resources in units of tons of coal equivalent (WEC 1980).

Table 9: Estimates of coal reserves and resources, in Gtoe.

	Category I: Hard Coal					Category II: Brown Coal					Total
	Grade A	Grade B	Grade C	Grade D	Grade E	Grade A	Grade B	Grade C	Grade D	Grade E	
NAM	140	0	104	97	387	12	0	3	28	111	883
LAM	6	1	3	7	28	0	0	0	0	1	47
WEU	18	3	14	46	185	9	1	8	1	4	289
EEU	22	22	26	9	35	8	4	2	0	2	129
FSU	88	0	22	506	2,025	22	0	2	44	176	2,885
MEA	0	0	0	3	12	0	0	0	0	0	15
AFR	37	0	37	16	64	0	0	0	0	0	153
CPA	34	40	274	165	660	14	28	22	12	47	1,295
PAO	20	147	18	47	188	9	23	1	0	0	452
PAS	2	0	1	0	1	0	0	0	1	3	9
SAS	7	28	19	7	28	1	0	0	0	0	89
World:	372	241	518	903	3,612	75	56	38	86	344	6,246

Grade A: Proved recoverable reserves
Grade B: Additional recoverable resources
Grade C: Additional identified reserves
Grade D: Additional resources (20% or remaining occurrences)
Grade E: Additional resources (80% or remaining occurrences)

[a] Totals may not add up due to rounding

Sources: BGR (1989), WEC (1992)

2.4.1 Summary Coal Resources

Table 9 depicts the allocation of coal occurrences adopted by the joint IIASA-WEC Study. Hard and brown coal resources are each distributed over five resource grades. Grade A corresponds to "proven recoverable reserves", Grade B to "additional recoverable reserves", and Grade C to "additional identified reserves". The remaining occurrences or "additional resources" were divided 20:80 and allocated to Grades D and E.

2.5 Uranium

Natural uranium and thorium resources are no different than their fossil counterparts, i,e., their occurrences in the Earth's crust are finite and the recoverable shares will be the result of future technological change and market conditions. However, the ultimate potential of nuclear energy that can be generated from uranium and thorium sources is even more a function of technology than is the case of fossil energy sources. In the long run, the quantities of fossil sourced energy services available will be predominantly determined by the technological progress in the hydrocarbon upstream sectors (exploration and development) and less by that of conversion technologies. In contrast, the converse is expected to occur for uranium and thorium. With present "once-through" nuclear fuel cycles and "burner" reactors, the nuclear energy potential will largely be governed by the availability of, and access to, natural uranium and thorium resources. The deployment of "breeder" reactors and closed fuel cycles including plutonium reprocessing, however, would essentially decouple nuclear power from any natural resource limitations.

Global conventional natural uranium resource recoverable at costs of less than US$ 80/kg are estimated at 4 million tonnes of uranium (OECD-NEA 1993; WEC 1995) of which 1.5 million tonnes would correspond to "proved reserves". The total resource base of natural uranium in the world is estimated at some 18.5 million tonnes. This does not include low concentration occurrences such as natural uranium in sea water or granite. Zero-order estimates quantify the recoverable part of these low grade uranium resources at a minimum of 10 million tonnes. In summary, ultimately recoverable global natural uranium resources amount to roughly 29 million tonnes (see Table 10).

Thorium reserves and resources are reported only for a few countries, and on that basis are estimated at 4 million tonnes, but circumstantial evidence by way of geological analogy suggests that the resource base should be much larger.

2.6 Summary of Reserves, Resources and Occurrences

Table 11 summarizes this assessment of global hydrocarbon and uranium reserves, resources, and occurrences. Table 11 also contrasts the estimated quantities with their past cumulative consumption and present rates of utilization, respectively. Conventional hydrocarbon reserves are assessed in excess of 1,600 Gtoe. This quantity is five times larger than the cumulative fossil resource consumption since the beginning of the coal era in the mid – 19^{th} century. Theoretically, present fossil reserves could fuel the world for another 160 years at the present level of global energy use of 10 Gtoe per year. Coal accounts for the lion's share of fossil reserves (60%) while crude oil and natural gas reserve quantities are practically identical (i.e., 20% each of total reserves).

Table 10: Estmates of natural uranium reserves and resources, in 1000 tonnes of uranium.

Region	Reasonably assured conventional Grade A < 80 $/kg U	Undiscovered conventional resources Grade B 80 - 130 $/kg U	Speculative conventional resources Grade C < 130 $/kg U	Speculative unconventional resources Grade D 130 - 600 $/kg U	Total	Additional low concentration occurrences
NAM	1,318	980	1,585	461	4,344	
LAM	267	20	243	173	703	
WEU	80	109	51	90	330	
EEU	30	60	0	41	131	
FSU	747	1,033	0	465	2,245	
MEA	26	0	0	15	41	
AFR	797	263	25	1,114	2,199	
CPA	24	61	100	3,342	3,527	
PAO	734	184	0	3,900	4,818	
PAS	0	22	0	0	22	
SAS	0	13	0	66	79	
World	4,023	2,745	2,004	9,667	18,440	> 10,000

Grade A: Reasonably assured resources, estimated additional recoverable resources for less than $80/kg U
Grade B: Reasonably assured resources, estimated additional recoverable resources for less than $130/kg U
Grade C: Speculative resources I
Grade D: Speculative resources II

a) Totals may not add up due to rounding

Sources: BP (1995), Masters *et al.* (1994), WEC (1992)

Table 11: Aggregation of Global Fossil and Nuclear Sources — All Occurrences, in Gtoe

Units: Gtoe	Consumption		Reserves	Resources[a]	Resource base[b]	Additional occurrences
	1860 - 1994	1994				
Oil						
Conventional	103	3.21	150	145	295	
Unconventional	6	0.16	183	336	519	1,824
Natural Gas						
Conventional[c]	48	1.87	141	279	420	
Unconventional	–	–	192	258	450	387
Clathrates	–	–	–	–	–	18,759
Coal	134	2.16	1,003	2,397	3,400	2,846
Total Fossil Occurrences:	291	7.40	1,669	3,415	5,084	23,815
Uranium in kt U	1,329	32.53	4,023	14,416	18,440	10,500
Uranium in Gtoe	19	0.46	57	203	260	150
in FBRs[d]	–	–	3,391	12,152	15,550	9,800

- negligible volumes
[a] Reserves to be discovered or resources developed to resources
[b] Resource base is the sum of reserves and resources
[c] Includes natural gas liquids
[d] FBR = Fast Breeder Reactor

Sources: Historial consumption (Nakicenovic *et al.* 1993). Reserves, resources and occurrences see Tables 3 to 10.

Fossil resources are estimated at twice the amount of reserves. Reserves and resources combine to a total resource base of 5,000 Gtoe. Although the extent of future recovery is unclear, the inherent uncertainty is dominated by techno-economic considerations, primarily and less a question of geological availability. For example, a resource base of some 5,000 Gtoe is also corroborated by the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic *et al.* 1995).

Additional occurrences beyond the resource base are so vast that fossil energy almost appears "unlimited". Irrespective of the speculative degree of their geological existence, from today's techno-economic perspectives only a miniscule share of these occurrence is likely to become available in the course of the 21st century. The assessed quantities of clathrates dwarf all other fossil occurrence estimates suggesting that methane may be the most abundant form of hydrocarbons in the Earth's crust (Nakicenovic *et al.* 1993). Even without accounting for these occurrences, the sheer size of the fossil resource base alone makes fossil sources an energy supply option for many centuries to come. Numerous factors will be at work determining the long-term rate of fossil resource utilization. The same factors which potentially advance their techno-economic availability may well become barriers to fossil resource utilization. For one thing, technical progress may improve non-fossil energy sources to a point where, contrary to their present dominant role, fossil energy supplies may play a subordinate role by the end of the 21st century. For another, there is the imminent question to be resolved of fossil energy's compatibility with the environment at large.

3 Modeling Energy Sources

The quantitative assessment of regional energy resource availability is an essential prerequisite for the development of future regional energy demand and supply scenarios. However, in an analysis spanning more than half a century it does not suffice to simply apply reserve and resource volumes based on the static concept of present technology and cost regimes. Given current oil and gas reserve-to-production ratios of 43 and 65 years respectively, the prospects of a growing world population and the aspiration of the developing world to substantially improve their standard of living, it is obvious that these reserves will be depleted long before the study horizon will have drawn to an end.

The nature of this study calls for a dynamic resource concept, i.e., a concept that accounts for factors that affect existing and future conditions responsible for the transition or reclassification to reserves of quantities previously considered as resources. In essence, this concerns the rate of the mobilization of resources (Bourrelier *et al.* 1992a) based on both anticipated technology advances and undetermined technical breakthroughs. The latter definitely play a major role in the commercialization of unconventional resources (Adelman 1995).

Given the relative long-run constancy of the reserve-to-production ratio, reserves can be viewed as stocks continuously replenished from resources. The question, then, is what fraction of the reserve replenishment is price induced (i.e., is the result of higher market prices) and what fraction is technology induced (i.e., the result of technological progress). The latter is of particular interest because of its long-term energy price capping effect similar to that of a backstop technology.

At this point explicit assumptions on the rates of technology change and advances of knowledge enter the analysis. This means the construction of curves of resource-to-reserve mobilization as a function of time, the proxy applied here for technology change. The final result, then, is a two-dimensional representation of resource availability versus production costs. In this analysis a productivity gain in the upstream sector of one percent per year is assumed. This increase is close to the average of historically observed rates[8]. Assuming that history is a guide for the future, a resource which presently commands production costs of, say, $40 per barrel of oil equivalent (boe), would over a period of 50 years drop gradually to $24.

The point of departure for the construction of quantity versus cost curves is an appraisal of the existing quantity-cost relations, especially for unconventional resources. Numerous studies (Lübben and Leiner 1988; Rogner 1990; Bourrelier *et al.* 1992a) estimate current production costs for the bulk of unconventional oil and gas resources at $30 to $45 per boe. Based on the information in the literature, the various unconventional resources are regionalized and classified into several distinct production cost categories starting with $15 per boe for heavy oil in Venezuela or $23 per boe for the tar sands of Alberta, Canada and up to $50 or more for various shale oil projects. Likewise conventional reserves and resources are allocated by region to up to five different cost categories.

The quantity-cost allocation for this study is based on the historical marginal resource development and production cost profiles shown in Figures 3 and 4. In Figure 3 the resource development curve depicts the cost spread of the accumulated petroleum reserve additions for the USA during the 1980s. The USA are considered the best explored region of the world and one would have expected that most of the low-cost oil, i.e., less than $10 per boe, had long been developed. Instead more than 90% of the hydrocarbon reserves newly developed during that period occurred at costs of less than $10 per boe[9].

Similarly, the North Sea hydrocarbon operations are considered among the most complex and costly worldwide. Still, in 1987 production costs of less than $10 per boe were the norm rather than the exception (see Figure 4).

The shapes of these curves appear commonplace and quite stable over time. What may vary slightly between regions and, particularly, over time is the exact location of the actual curve in the cost-quantity plane. One should recall that in an ideal world market prices are determined by the marginal production costs. Consequently, price induced exploration activities are driven by a very small fraction of total production. In contrast, non-price induced technology change such as learning curve effects, are determined by production volume. The development of regional quantity-costs relations, therefore, is based on the assumptions of a perfect world and perfect foresight with respect to future rates of technology change[10].

[8] In the short run, historically observed productivity gains have been much higher than one percent per year (Shell 1995; Adelman 1995; Jansen *et al.* 1995; Rogner 1988). Periods of two-digit growth rates are often followed by periods of zero or negative increases. Because data availability is sparse and data consistency is poor, estimating productivity gains over extended periods of time is a risky undertaking. A one percent per year growth rate may well prove to be conservative.

[9] It has been argued correctly that for the United States (1) most of the oil and gas developed during the last decade was discovered before 1970, (2) no giant oil fields (500 million to five billion barrels) have been found after 1970, and (3) the additions to reserves States have been, to a large extent, the result of reappraisals of existing plays (MacKenzie 1996; Jansen *et al.* 1995; USGS 1995). What is often left unmentioned is the explicit role of technology change leading to the reappraisal of previous discoveries or already developed fields.

[10] Perfect foresight is prediction which is not the objective of this analysis. Instead of developing a series of quantity-cost relations for a larger range of future rates of technology change, a single rate derived from historical observations

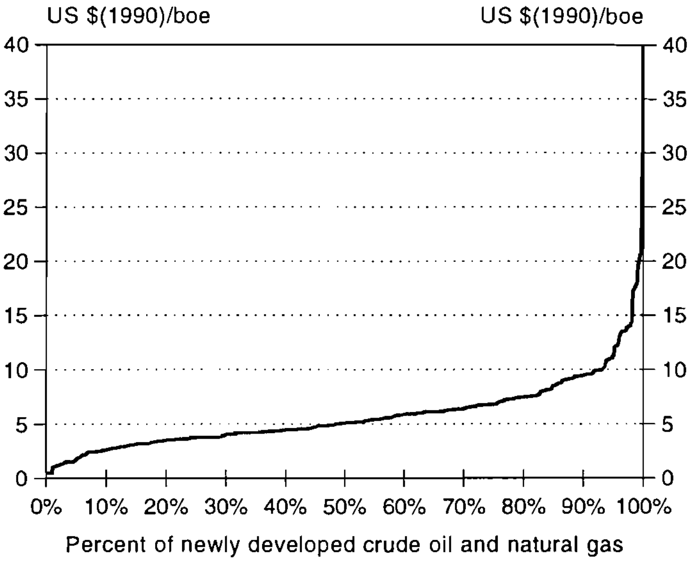


Figure 3: Marginal petroleum development costs in the United States, 1980 - 1993. Cost curve based on 343 observations and 34.3 billion boe of oil and gas developed. Source: Adapted from API (1989-1995).

The following points summarize the underlying rationale and the principals applied for the estimations of resource occurrences and the development of regional quantity-cost relations:

1. The *resource base* quantities as reported in Table 11 represent the maximum occurrences of oil, natural gas and coal derived from the literature. Whenever ranges of estimates were found, the highest plausible value was adopted. This is contrary to the usual practice of assuming the most conservative estimate. Here, the objective was to assess the ultimately available resource base beyond short-term techno-economic recovery limitations.

2. Hydrocarbon resource exploration, development and production is subject to a compounded productivity gain of one percent per year. This one percent productivity growth rate approximates the average long-term historically observed rates in the hydrocarbon upstream sectors.

3. All conventional and unconventional reserve and resource categories are valued as if all future productivity gains (i.e., their future production cost profiles) were realized immediately.

4. From the so calculated quantity-cost relations a single aggregate resource cost curve per source and region is developed. This means that the dimension of time is taken out of the resource

was selected (conservative "dynamics-as-usual" assumption). The uncertainty associated with the actual realization of the rates assumed then was reflected within the energy supply modeling part of the IIASA-WEC Study. First, the resources allocated to each scenario differed in terms of volumes (i.e., in terms of accessible resource categories and grades) with quantity-cost curves based on the "dynamics-as-usual" expectation. Alternatively, scenarios with accelerated technological learning and improvements in resource extraction or scenarios testing a policy preference with regard to a particular hydrocarbon source incorporated different quantity-cost relations.

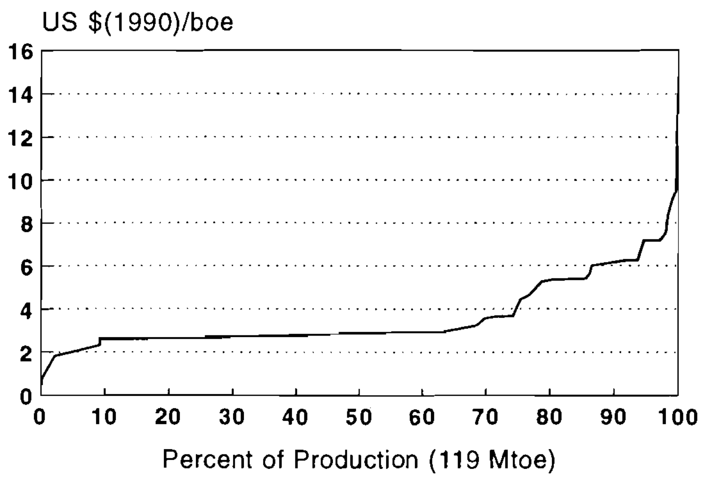


Figure 4: UK North Sea oil production costs in 1987. Source: BGR (1989)

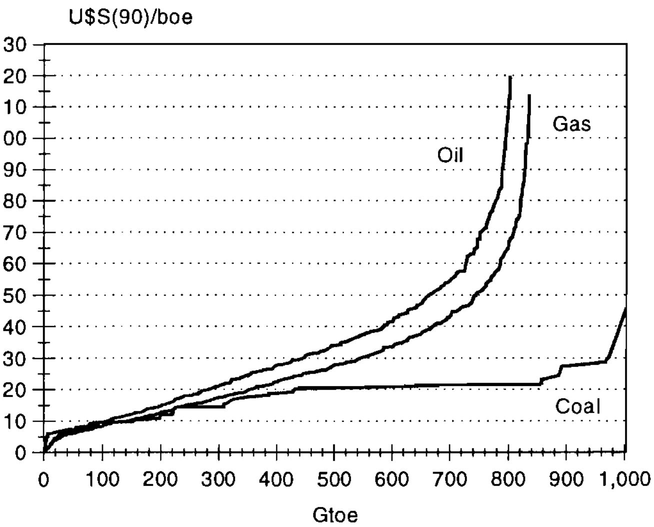
quantity-cost representations. Table 12 and Figure 5 summarize the various quantity-cost relationships for oil, natural gas and coal as deployed in the scenario analysis of the IIASA-WEC Study.

5. This approach valuates all of presently identified conventional oil reserves at production costs of less than $12 per boe. Obviously, not all the identified reserves are presently available at that cost. This quantity-cost relation is an artifact and the result of dropping the time dimension from the analysis. The data in Table 12 and Figure 5 must be interpreted as integrals of the impact of technical change on resource economics. Put differently, for each resource category a quantity-cost relation is assumed whose shape resembles the curve introduced in Figure 3. Hence, there will be low-cost production from unconventional occurrences of the higher resource categories as well as high-cost production of lower resource categories. The cost ranges per resource category shown in Table 12 are calibrated so that the aggregates over all categories of all similar cost volumes correspond to the resource volumes of specific categories.

6. The dimension of time is re-introduced in the actual modeling of resource extraction. Here a quantity-cost profile similar to the one shown in Figure 3 is imposed on annual production volumes. This guarantees that not all production occurs in the lowest categories and that truly marginal cost signals are provided to the downstream sections of the energy system.

7. The resource quantities for coal as applied in this study are summarized in Table 9. Coal reserves are modeled in less detail than oil and natural gas. First of all global coal reserves are plentiful and relatively inexpensive compared to oil and gas. On a regional basis coal production costs, however, vary significantly. For example, Germany and the United Kingdom are prominent cases for high cost coal production. Traditional coal producing regions (with

little or no subsidy) are all producing within cost Category I, Grade A with production costs of less than $44 per tonne of coal equivalent ($8.6/boe or $1.5/Gigajoule). This cost level approximates the long-run production costs within these coal producing countries (Jansen *et al.* 1995). In order to simulate marginal production costs, a quantity-cost curve similar to the curves for oil and natural gas was constructed across all coal resource grades (see Figure 5). In the short run, steep increases in coal demand will have to be met by partial production from higher cost grades.



The quantity-cost curve for natural gas excludes clathrates

Figure 5: Aggregate quantity-cost curves for global fossil resources.

The quantity-cost relations for the recovery of global fossil energy sources displayed in Figure 5 are aggregates of the regional resource occurrences shown in Tables 5, 8, and 9 for crude oil, natural gas and coal, respectively, and the production costs of Table 12. Compared to the fossil reserve assessments and production cost estimates routinely performed by hydrocarbon industries and government agencies, the resource quantities identified in this study are gigantic while the recovery costs remain relatively low for a fair portion of these quantities. The extension of the conventional reserve concept to also include resources and unconventional occurrences explains the considerably larger fossil resource base of some 5,000 Gtoe identified in this study. In fact, the probability of their geological existence is remarkably high. Uncertainty enters any long-term resource outlook as soon as the essential question of future recovery is addressed. Here assumptions regarding future rates of technical change become critical scenario parameters and the contrariety of recovery costs especially of unconventional oil and natural gas, among different studies can be reduced to differences in the assumptions concerning future technological progress.

Regardless of the eventually realized rate of technology change, long-term resource recovery will most likely be governed by a supply cost curve shaped similar to the quantity-cost relation shown in Figure 3. In terms of the two-dimensional McKelvey box, innovation and technology change

Table 12: Estimates of fossil resource extraction economics for the IIASA-WEC Study[a]. Production cost ranges in US$(90) per barrel of oil equivalent (boe).

Resource Category	I	II	III	IV	V	VI	VII	VIII
Oil	< 12	12 - 19	19 - 25	25 - 35	35 - 38	38 - 52	52 - 62	62 - 160
Gas	< 10	10 - 16	16 - 25	25 - 29	29 - 34	34 - 42	42 - 50	50 - 145
Grade	A	B	C	D	E			
Coal[b]	1 - 9	9 - 11	11 -16	16 -24	24 -36			

[a] The resource categories I through VIII for crude oil and natural gas correspond to the categories shown in Tables 5 and 8. Likewise, the coal grades A through E correspond to those of Table 9.

[b] Hard and brown coal

Sources: Adelman (1993), Arbatov and Astakhov (1988), BGR (1989), Bourrelier *et al.* (1992a), Jansen *et al.* (1995), MacKenzie (1996), Odell (1995), and Rogner (1990).

push the boundary between the reserve and resource areas continuously along such an implicit quantity-cost curve (see Figure 6).

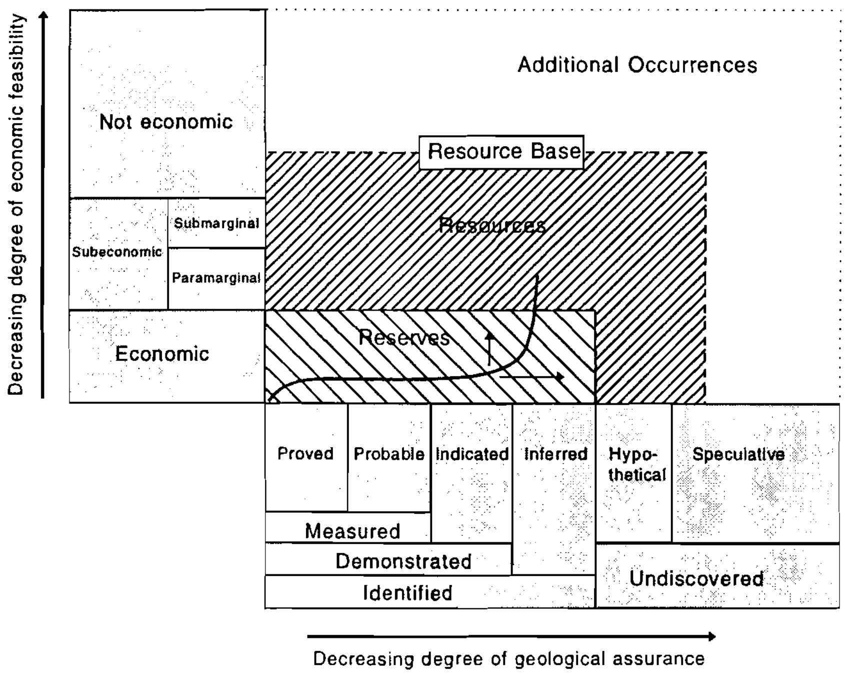


Figure 6: McKelvey box and the quantity-cost relationship of hydrocarbon resource recovery. Source: Modified from McKelvey (1972).

The regional quantity-cost relations for crude oil, natural gas, hard and brown coal, and uranium developed in the previous sections are both descriptive and normative. They are descriptive in the sense that the underlying average productivity growth rates are historically observed estimates. On the other hand, they are normative in that the recovery technologies involved will require drastic specific technology improvements with implicit improvement rates several times the historically observed average. Because normative elements shape the quantity-cost relations, a range of technology improvement rates rather than quasi-deterministic point estimates should have been applied. As a result, one would obtain a series of cost curves per fossil source and region reflecting alternative images of how the future might unfold. In the joint IIASA-WEC Study a different approach was chosen, i.e., alternative scenarios encompass different resource categories. For example, the allocation of additional oil resource categories thus mirrors accelerated rates of innovation in the oil upstream sector and in the chemistry of converting unconventional oil to synliquids. In contrast, limiting oil to Categories I through III (see Table 5) assumes low rates of technical change in the oil sector which then shifts the focus of technology change to other energy sources, e.g., coal, nuclear or renewables.

4 Concluding Remarks

The global fossil resource base is abundant and estimated at approximately 5,000 Gtoe. Compared to current global primary energy use of some 10 Gtoe per year, that is certainly sufficient to fuel the world economy well through the 21^{st} century, even in the case of drastic growth in global energy demand. However, as such the geological existence of hydrocarbon occurrences does not guarantee energy supply stability or supply security. First of all, supply uncertainties concern the costs of resource recovery and conversion to usable fuels. Immature technologies need research and development support, its magnitude and timing may affect the timing of resource availability. The scale of upfront investment requirements is expected to increase while the economic risk associated with upstream hydrocarbon projects will likely be higher than for alternative non-energy investment opportunities. The quest for short term profits may well be a road block to long-term resource development. Secondly, short-term hydrocarbon development and production decisions often lie with public sector agencies and, therefore, are not necessarily driven by market considerations alone. As well, the objectives of energy producers may differ from those of the energy users, especially when large-scale energy trade subject to international political intrusion is involved. Temporary energy supply shortages and volatile market price fluctuations will continue to mark long-term energy system development. In short, it is unlikely that future energy system development will be any less volatile than in the past.

Possibly the largest source of energy supply uncertainty is the environment. Emissions from the combustion and conversion of fossil fuels are substantially increasing the atmospheric concentrations of greenhouse gases (GHG). Higher GHG concentrations will enhance the natural greenhouse effect, raise the Earth's average surface temperature and cause global climate change. Hence, environmental considerations may constrain fossil fuel use to below present-day rates long before global resource scarcity becomes the limiting factor. On the other hand, the perception that resource scarcity will eventually resolve environmental problems may be seriously flawed.

If technological progress continues to better upstream productivity as observed in the past, resource constraints are unlikely to drive down hydrocarbon production during the 21^{st} century. While oil production from present recoverable oil reserves is expected to peak during the early decades of the next century, this will spur the development of alternatives. In the absence of environmental constraints, the closest alternative to conventional oil is unconventional oil. One critical advantage over other fossil or non-fossil alternatives is the latter's downstream compatability with existing oil-based fuel distribution and end-use infrastructures. The oil era, therefore, may well last beyond the time frame suggested by ultimately recoverable conventional crude oil reserves.

Current oil market prices are too low to stimulate investment in energy technologies with large upfront capital requirements and long-term payback prospects. With global demand for oil rising and production approaching full capacity upward pressure on oil prices can be expected in the longer run. World oil prices may well encounter at times volatile fluctuations around an otherwise long term trend of alternating periods of gradually rising production costs and stability.

In addition to unconventional oil, there are vast amounts of natural gas and coal waiting to be recovered from the Earth's crust. Using the quantity-cost relations for oil, gas and coal shown in Figure 5 it is possible to construct an aggregate carbon quantity-cost curve for the entire global fossil resource base (Rogner *et al.* 1993). Figure 7 displays a supply curve based on the carbon content of each fossil source and their respective production cost estimates. Recalling that the production

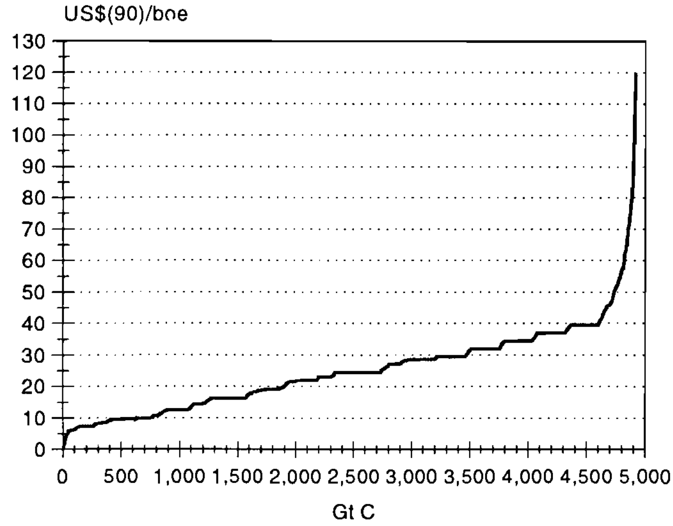


Figure 7: Aggregate quantity-cost curve for carbon contained in the global fossil resource base.

cost estimates incorporate anticipated technical progress over a hundred year period, the carbon supply curve may be better understood if viewed from the vantage of the year 2100. Until then the oxidation of carbon atoms remained the dominant source of world energy supply throughout the 21st century while energy policy continued to be preoccupied with issues of supply security and economics (meaning "cheap" energy with prices reflecting only part of the full social cost of energy production and use). Over that period, mankind may have oxidized and released to the atmosphere some 1,700 Gigatonnes of carbon (GtC) pushing atmospheric CO_2 concentrations well above the 700 ppmv (parts per million by volume) level, i.e., a doubling from present concentrations (IIASA-WEC 1995). The observer in 2100 will almost certainly experience a different global climate situation than today and may wish that the fossil resource scarcity perception of the late 20th century had been real.

Resource availability limitations are unlikely to drive the energy system away from a continued reliance on fossil sources. In the absence of environmental constraints and full cost pricing, mankind is well positioned to substantially increase climate destabilizing and local air quality assaulting emissions. Most importantly, if the supply cost curve of Figure 7 is of any indication, this can be done quite cheaply.

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