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Prospective on world energy markets

by

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Organization of the Petroleum Exporting Countries

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THE CENTURIES-LONG TREND of prices for useful energy at the point of consumption has been ever downward. Technical progress has caused steady expansion in the known reserves of fossil hydrocarbons; it has steadily diminished the costs of energy extraction, conversion and delivery; and it has steadily enhanced the efficiency of energy use in final applications. The combined effect of these improvements has been more than sufficient to offset both growing demand and diminishing returns to a supposedly 'fixed' resource base. Despite an episode of unusually high prices in the late 1970s and early 1980s, energy markets continue to follow this long-established course. The real prices of energy from oil, gas and coal are not likely to show any sustained rise, either in this century or the next — when they will be supplemented and replaced by cleaner, easier-to-use and cheaper primary resources.

It is an uninteresting tautology to assert that the 'finiteness' of specific resources guarantees ever-rising marginal costs, because such an inference would be valid only if technology were static. In a world of dynamic technique, primary resources of useful energy are not finite. Instead, the anticipation of shortages and higher prices for one fuel or fuel-using technology creates economic niches for substitutes and enhances the incentives, pecuniary and otherwise, that make these substitutes available.

Sufficiency of oil and gas resources

The two leading fossil hydrocarbons — crude oil and natural gas — are only a fraction, and over time an 'ever-less-crucial' fraction, of humanity's potential energy resources. To see why the emergence of a sustained upward price trend is not imminent, however, it is sufficient to consider only these two hydrocarbon categories and, indeed, to consider only the present stock of proven and probable (or 'indicated') reserves in identified reservoirs. With respect to these fuels, moreover, we need consider only those means of extracting, transporting, converting and using them that are already proven and in service — embodied in durable goods that are already available 'off the shelf' and commercially viable at the range of end-user prices that prevailed during the late 1980s.

Globally for both oil and gas, the volumes of proven and probable reserves in identified reservoirs are capable of supporting several decades of consumption at

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current rates; world reserves-to-production (r/p) ratios are at or near their respective all-time highs. For both fuels, moreover, the bulk of the known inventory is contained in large deposits from which the long-term marginal production cost is at least of an order of magnitude less than recent market prices — leaving the former a long slope to climb before they begin to govern the latter. The historical record to date shows no sustained upward tendency in either costs or prices; those who assert that the onset of such a trend is now imminent bear the burden of explaining exactly why such a momentous and unprecedented change in direction must occur in this decade, rather than (say) five decades ago or five decades hence.

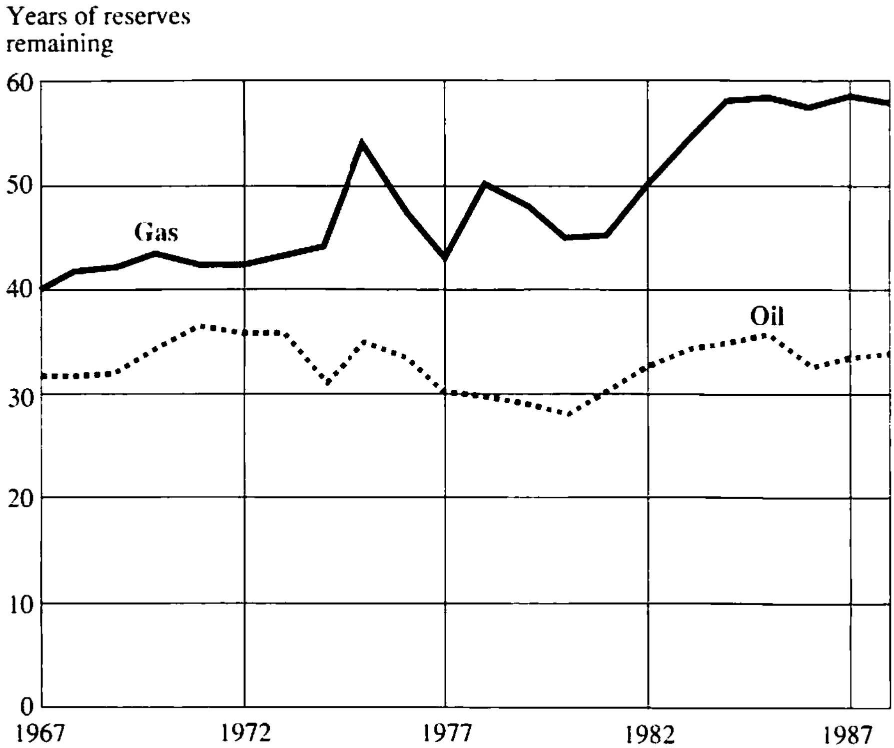
In the short term, crude oil and refined product prices are determined by the interplay between levels of working stocks and seasonal demand, refinery capacity and transportation logistics. In the long run, however, it is the relationship between the quality, location and quantity of primary resource inventories ('reserves') and current consumption that governs the prices of energy commodities. The ratio between reserves and annual production (or the 'reserve-life index') is the single best index of this relationship. So long as producers are free to choose both the timing and intensity of field development and the rate of production from existing wells, and also face an open market in which production can be sold freely at the prevailing price, determining the economically optimum (most profitable) r/p ratio is a straightforward exercize in inventory management.

R/p ratios for both crude oil and natural gas in the United States (where these conditions have persisted for more than a decade) offer a compelling empirical presumption that the optimum ratio overall has an average value of about ten. The primary resource in the US is made up of thousands of oil, gas and oil-and-gas reservoirs having a vast diversity of technical characteristics. A mature transportation infrastructure exists for both primary fuels, while producers now face relatively few governmental constraints regarding the intensity of field development or the rate of production.

Outside the US, the relationship between reserves and production is less consistent with the predictions of optimal inventory-management theory. Globally, the bulk of commercial hydrocarbon resources occurs in a few 'super giant' fields. Significant reserve additions are rare and random events which occur in 'lumps' that tend to be very large and which often — individually or in world aggregate — bear no direct or predictable relationship to current movements of supply or demand. Moreover, many such discoveries, especially of natural gas, are so remote from consuming areas or existing transport facilities that commercial development may not be in prospect for decades.

Trends in global reserve-life indexes are nevertheless unrivalled as long-view indicators of future prices. **Figure 1** depicts the r/p indexes for crude oil and natural gas since 1967. Indexes for both fuels are two-to-three times higher than would be technically necessary (or economically optimal from a producer standpoint) to

Figure 1
Oil and gas reserves-to-production ratios
1967–87



meet the current year's world demand or, for that matter, demand that was increasing steadily at (say) three per cent annually. It is worth noting, moreover, that the ratio for crude oil did begin to decline in about 1970, when constant-dollar crude oil prices were at their lowest level since the Great Depression. The index kept declining until about 1980, when consumption had begun to plummet in response to prices that were at their highest levels this century. By the mid-1980s, the world r/p ratio for natural gas was at an all-time high, and that for crude oil was not far below its historical maximum.

The flexibility of world energy supply arrangements

Ironically, nearly every prominent forecasting institution has nevertheless been predicting price increases for all forms of marketed energy, driven by relentless increases in the marginal cost of crude oil and other 'exhaustible' resources.

At the end of 1985, just before the collapse of world oil prices, analysts were nearly unanimous in their commitment to such views. More remarkably, many forecasters still base their outlook on the same primary assumption, and still infer from it the long-term necessity of rising energy costs — having modified their pre-1986 predictions only with respect to the timing and perhaps the pace of the inevitable upward march.

Given the present stock of primary oil-and-gas inventories and the absence of historical evidence that civilization has already entered the terminal depletion phase for fossil fuels, such a price outlook is tenable only for so long as product differentiation and interregional transport cost barriers are capable of segregating the world's primary energy sources into permanently non-competing segments. Those forecasting models that generate sustained rises in primary fuel prices, commencing immediately or within a decade or less, define their relevant product — almost without exception — as either oil or natural gas, and treat supply, demand and price data for the other principal hydrocarbon (and, indeed, for all other energy resources) as exogenous influences on the subject market.

Analyses of the global market for crude oil also typically assume that a critical structural boundary permanently separates Middle Eastern and/or OPEC oil production from all other production. Forecasting methodologies focusing on the long-term market outlook for natural gas are, in similar fashion, framed geographically to pair North American, European or East Asian gas demand, taken in isolation, with respective current and immediately prospective supply sources. North American gas market analyses, for example, ignore natural gas market conditions in other regions, and deal with the world oil price level as an exogenous variable.

Such conceptual divisions do indeed reflect the historical differences between oil and gas with respect to market organization and price structure. The mental division of crude oil sources into a Middle Eastern and/or OPEC sector and a sector containing all other supply, likewise, fits naturally with the political categories that preoccupied both the oil-exporting and -importing nations during the 1970s and early 1980s. The treatment of Eastern and Western Hemisphere natural gas markets in isolation from each other also seems reasonable, at least on first impression, inasmuch as a substantial trade in liquefied natural gas has failed to emerge in either direction. Such conventional demarcations may therefore be useful for describing or explaining past events, or even for predicting the near future, but they are capable of grave mischief in any conceptual scheme intended as a guide to longer-term economic trends. The relevance of these boundaries endures only within a time-frame short enough that analysts can safely disregard changes in the mix and location of capital assets in which energy production and consumption patterns are embodied.

At any particular time, the borders that separate 'relevant markets' for primary energy depend on the nature and location of the stock of durable goods previously put in place to serve those markets. To the extent that the analyst chooses a forecasting time-frame in which the stock of such assets is capable of changing, however, the boundaries between relevant product or geographic markets are also capable of shifting or disappearing. Most critically, the relevance of today's boundaries is sustainable only within a certain range of prices. Expectations of a world oil price level greater than $20 per barrel (inflation adjusted), or North American gas prices that approached or exceeded the equivalent of $20/b of oil at the plant or city gate, would steer both the new investment required for the replacement of old capacity and the investment in new capacity intended to serve demand growth in directions that directly threatened the existing boundaries between relevant markets.

How quickly can industrial and market structures change?

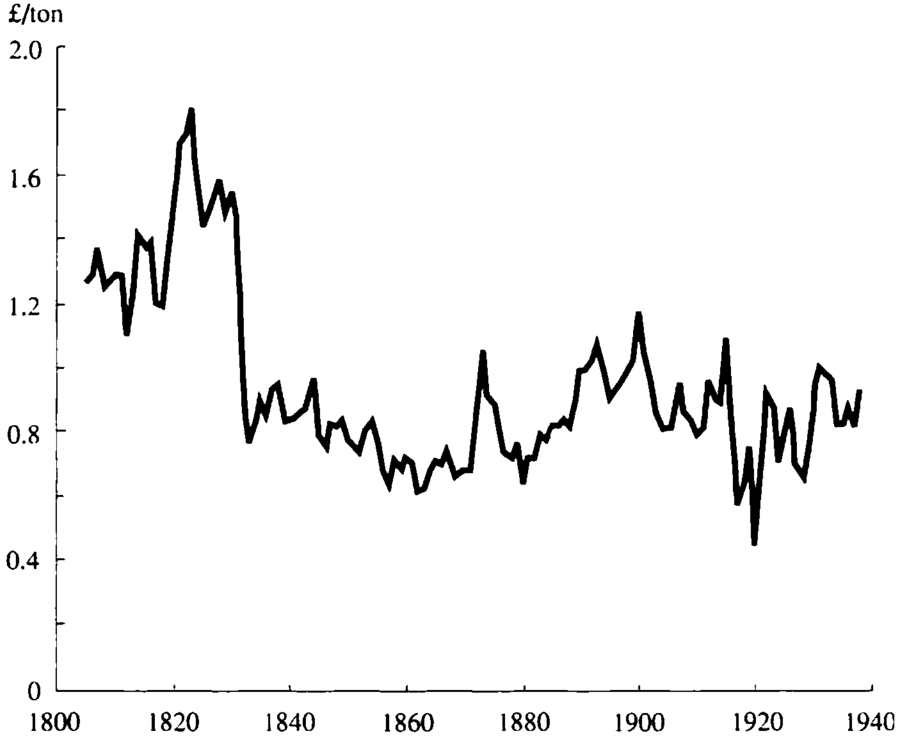
The time required for a market or industrial sector to change beyond recognition is surprisingly short, even in a 'painless' turnover of capital assets — i.e., one that does not require the scrapping of any capital goods before their otherwise expected retirement dates. A reasonable rule of thumb is that a typical class of producer durables has a 'half life' of ten years. With an average annual replacement rate corresponding to this figure and a three per cent annual rate of growth in demand for total capacity, a new primary resource, process or final product, whose superiority in cost and/or performance permitted it to capture all replacement demand and all growth in the market, would account for half the total capacity in 8.5 years, two-thirds the total in 11 years, and 85 per cent within 20 years.

The fuels and energy sectors have seen one such technical revolution after another. Deforestation in Britain and the North-Eastern US in the early 1800s was a powerful stimulus to the lasting substitution of coal and coke for wood as the chief steam transport fuel, and for charcoal in metallurgy.

Figure 2 depicts coal prices in England over about 130 years, that embraced repeated surges of consumption and frequent predictions that the depletion of higher-quality coal seams would make price increases inevitable. In the 17th and 18th centuries, prices of coal delivered to London fluctuated between £1 and £2 per ton (in constant 1900 £). Although the 1830s saw a huge increase in coal demand, prices fell dramatically, in part because of the emergence of rail transport — which, ironically, accounted for much of the added coal demand. Prices thereafter tended to fluctuate between £0.6 and £1.25 per ton.

In the 1840s and 1850s, the near-extinction of the sperm whale for the production of lamp oil created a market for kerosene — a superior lighting fuel — and with it the petroleum industry. The most dramatic upheaval in the history of energy use occurred during the Belle Èpoque — the years between about 1890 and the onset of the First World War — when electricity replaced manufactured gas as the dominant source of urban lighting throughout the prevailing 'modern' world.

Figure 2
Price per ton of coal delivered to London
1805 – 1938
1900 £



Source: Abstract of British Historical Statistics

During the same period, electric motors largely replaced steam and water as prime movers in manufacturing, while motor cars and trucks, together with electric street railways, were becoming the principal means of urban transport for goods and people.

Beginning in the 1920s, the development of welded steel pipe allowed the high pressures required for the long-distance movement of gas at acceptable costs. As quickly as pipelines could be laid, natural gas promptly replaced manufactured town gas in much of North America for cooking and space-heating. Through the 1960s (i.e., until the appearance of regulation-induced 'shortages'), gas was capturing virtually the entire replacement and growth demand for stationary heat in the US and Canada. In the 1950s and 1960s outside North America, however, it was the persistent cheapness of oil that allowed it to displace coal as the principal industrial, electrical-generation and spaceheating fuel. Between 1954 and 1970, oil consumption increased at compound annual rates of about seven per cent in Western Europe and 16 per cent in Japan.

The rise in crude oil prices in 1973–74 and again in 1979–80 had a big impact on both the growth of overall energy demand and the choice among primary fuels. In the decade 1965–75, global consumption of marketed energy increased by just about half, and more than half of this increase was served by oil. During the decade 1975–85, however, world energy use grew by less than one quarter, as a response to higher prices and conservation efforts, and, of that growth, oil played a much diminished part. The expansion of energy supply concentrated, instead, on natural gas, coal and nuclear fuel.

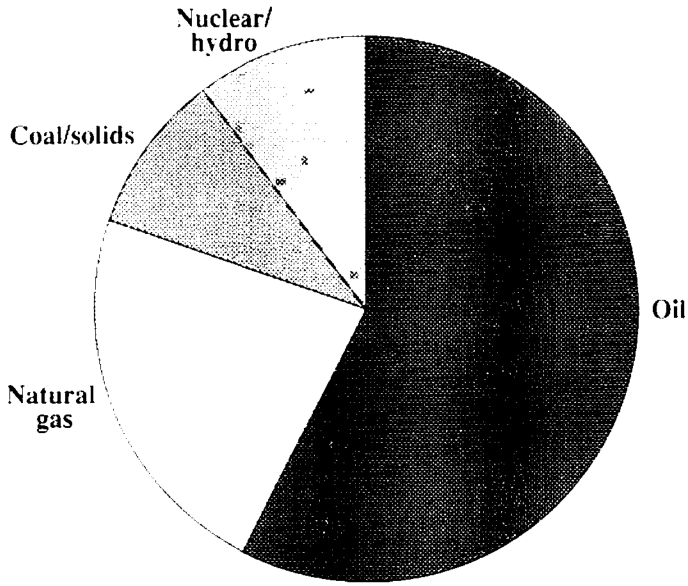
Figures 3 and **4** depict the change in direction between the two decades in primary energy growth. At one particular moment, the choice of fuels may seem

Figure 3

Percentage increase in energy consumption

1965–75

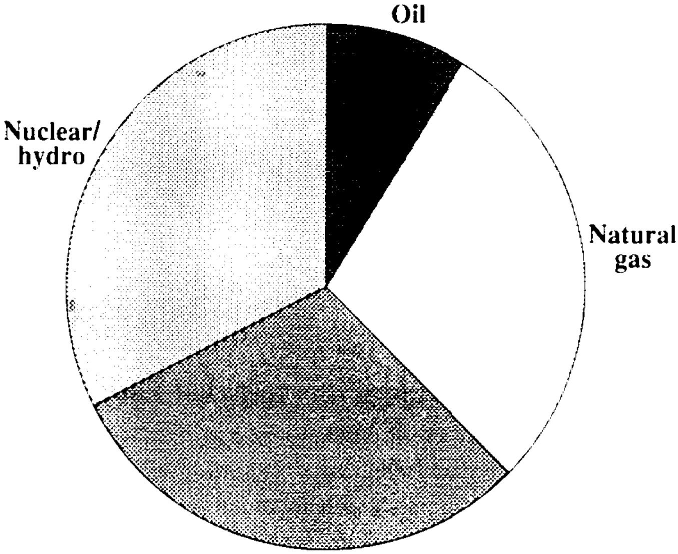
mtoe



inflexible but, given the opportunity to alter the stock of capital goods devoted to extraction, processing, transport and use, the changes can be dramatic.

As a group, these instances imply that oil, or any other primary fuel, is far more readily and easily dispensable than most people — energy analysts included — tend to infer from its present share of the commercial energy market.

Figure 4
Percentage increase in energy consumption
1975–85
mtoe



The unlimited potential for substitution

The factor that unites markets for oil and gas in the long run is their nearly unlimited ability to substitute one fuel for the other in almost any application. There is no large-scale use of petroleum liquids — or any other primary fuel — that is not now actually being served by methane or a methane derivative at a comparable cost. The reverse is also true: just about anything gas — or any other primary energy source — can do, a liquid petroleum product is now doing just about as well, also at comparable cost. Compressed natural gas or liquid fuels derived from methane (methanol and synthetic gasolines) already substitute for petroleum distillates even as transport fuels — in some cases, at lower prices and with lower fixed costs and non-fuel operating expenses.

Thus, there is no foreseeable combination of rising world oil demand with stagnant or declining oil production outside the Middle East and/or OPEC, which will give any oil producer or group of producers control over world energy prices — if 'control' means the ability to sustain those prices at levels exceeding the incremental cost of natural gas delivered into critical market areas, such as Western and Central Europe.

Half a century of natural gas infrastructure investments in North America, and a quarter century of such investment in Europe, have already made it possible to transport gas from remote locations to major consuming centres at remarkably low levels of incremental cost. Within the capacity limits of the existing infrastructure, natural gas suppliers are able to compete with petroleum products for all stationary-fuel uses at almost any price level. Much of the investment now embedded in the natural gas industry occurred in an era of high-cost oil. Crude oil at \$30–40/b, for example, made it economic to construct a major pipeline from Siberia to Europe. Once such a pipeline was built, however, the cost of moving gas over that route fell to a fraction of its alternatives, and gas from the Soviet Union is now Europe's lowest-cost source of incremental energy.

Throughout the 1980s, worldwide reserve additions for natural gas were being made at an average of more than three times annual production. According to the Oil and Gas Journal, natural gas reserves outside the US and Canada were equivalent to 80 years of production at year-end 1989 (reserves equivalent to 80 times current production could sustain 33 years of three per cent annual consumption growth, even without new discoveries, before the reserves-to-production ratio fell below ten). In addition, methane deposits are more widely dispersed than crude oil; there are natural gas finds or indications in almost every country. The existence of such resources undermines and negates any lasting power oil producers might have over world energy markets — the impact of gas reserves in this respect is no different from the impact of adding to crude oil reserves outside the Middle East or OPEC.

The relevant 'product' for long-term analysis thus includes both oil and gas. To the extent that a long-term forecasting model does specify supply, demand and prices separately for the two primary fuels, therefore, the sets of market variables for the two fuels must receive equal and parallel treatment, and the mutual feedback links between sub-markets for the two commodity groups will be among the model's most critical components.

Unity of the world market

The circumstance that has contributed most to the creation of a unified world market for primary energy is the cheapness of tanker transportation for crude oil. These costs are such a small fraction of the current commodity value of oil that systematic differentials between oil prices at the Middle East Gulf, the US Gulf, Rotterdam and Singapore are barely (if at all) discernible over the daily fluctuations of spot prices.

Intercontinental trade in natural gas or methane derivatives as such does not yet exert a directly unifying influence on global energy markets, as do the movements of crude oil and refined products. But, even in the present configuration of markets, Eastern Hemisphere gas supply already constrains the price of natural gas in the US and Canada — through the medium of the world oil price, which is itself constrained by actual and potential competition from gas in Europe and Asia.

The emergence of a direct intercontinental gas price link would not be an unthinkable development, however. Oil price expectations in the range of $20+/b (adjusted for inflation) would be adequate to support investment in supplying North American markets with methane or its derivatives from remote undeveloped sources — including pipeline supplies from the North American Arctic and gas from the Eastern Hemisphere transported by tanker as LNG, methanol or synthetic gasoline.

However finely one chooses to isolate individual fuels or geographic markets, therefore, in constructing a formal forecasting model, a simple mental paradigm that consists of a single fossil hydrocarbon combining oil and gas (and perhaps coal) and a unitary global market probably serves just as well for explaining the past course of energy prices and for understanding why a rising price trend is not a likely feature of the foreseeable future.

The inevitability of lower costs

While competition between oil and gas produced from the present inventory of proven and indicated reserves, using existing technology, may be sufficient to delay indefinitely any sustained upward tendency in energy prices, additional forces are at work expanding supplies and pressing costs downward. Investment in new oil and gas reserves and new producing capacity will occur, whatever the current level of expected prices. Technical advance will continue and, we believe, accelerate within the existing fossil-based energy-supply chains. Taking into account the effects of recent progress in oil and gas exploration, production and transport techniques, oil price expectations below $20/b may well prove sufficient to maintain steady growth in non-OPEC oil production. And it should not be surprising if gas price expectations lower than $2.50 per million btu (mbtu) sufficed to maintain current levels of conventional gas reserves in the established producing areas of the US and Canada.

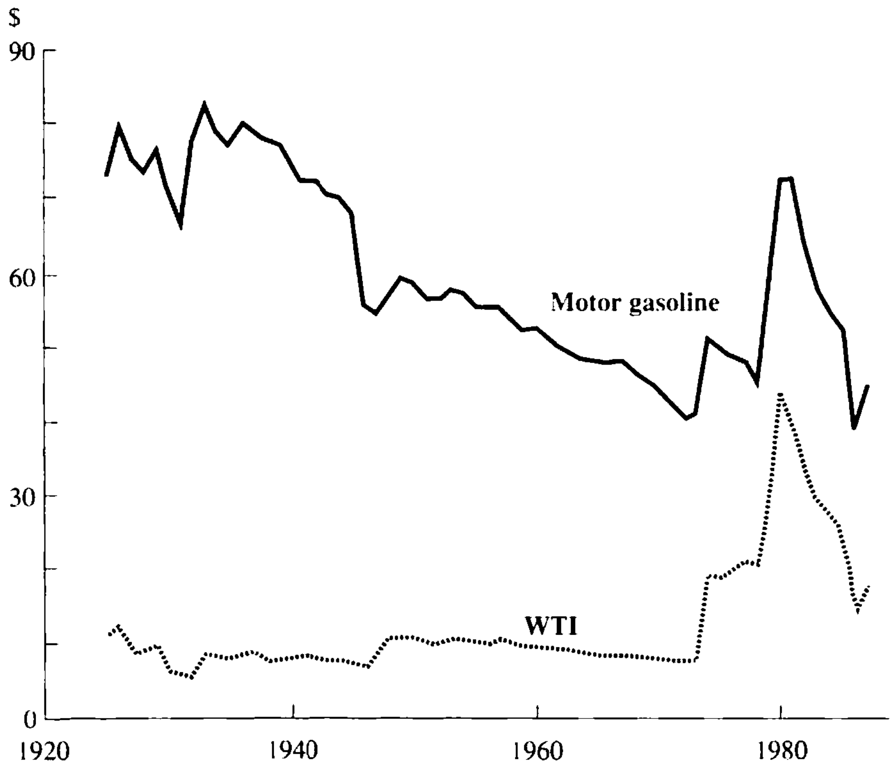
Today's menu of energy-supply options that are independent of the existing oil and gas delivery systems, and competitive in cost and acceptable with respect to environmental impact, is already more diverse than ever before and is almost certain to grow in diversity at an increasing pace.

Figure 5 depicts the relationship between the constant-dollar retail price of gasoline (before excise taxes) and the wellhead price of crude oil in the US from the mid-1920s to the present. The unbroken trend of prices was downward until 1973, when the surge in crude oil prices carried gasoline prices upward. By the latter half of the 1980s, however, retail prices were back on trend, despite crude oil costs that remained above pre-'crisis' levels, as costs other than crude oil feedstock continued to shrink. Changes missing from this graph would, if included, make the

Figure 5

Comparison of the retail price of motor gasoline and the wellhead price of West Texas Intermediate crude oil — 1925–87

$/lb (1982 $)



Source: Oil and Gas Journal

trend even more dramatic — the improved quality of motor fuel, the greater fuel economy and superior performance of automobiles, and the quantum reduction in pollutants released in the manufacture, distribution and use of each gallon of gasoline.

The motor gasoline illustration above is typical of the behaviour of energy costs generally, but it is quite at odds with popular and even 'expert' prejudices in this matter. During the 1970s, analysts and decision-makers came to assume, with little apparent reflection, that the cost of producer durables, particularly facilities for the energy industries, would inevitably increase with the passage of time. As with several other axioms that drove investment behaviour and public policy during that period, the truth is quite the opposite by a wide margin. The best rule, indicated by common sense and confirmed in the historical record, is to assume that the unit cost of producing any given thing or conducting any given activity will go down, unless there are specific and exceptional reasons to expect otherwise.

There is no reason to suppose that the costs of producer durables for the energy industries should be exempt, as a class, from this rule. There are obvious exceptions, but the downward slope of oil-and-gas industry input costs, as adjusted for performance, is strong and clear. Curiously, however, we have yet to encounter a long-term oil or gas supply projection or model that explicitly or implicitly incorporates the expectation of falling input costs.

Consider well-drilling costs. Over the last 25 years, myriad improvements in drilling bits, muds, lubricants, motors and the like have caused the constant-dollar cost of drilling and completing a well of standard depth and diameter in a given environment to decline by about five per cent per year. On the geographical and technical frontiers of the industry, where the bulk of new capacity is typically added, input costs tend to fall even faster. A development well at Prudhoe Bay on Alaska's North Slope, for example, now costs only about about one-third as much (in nominal dollars!) as did a comparable well in 1977.

Some activities have been changing so radically in character that it is difficult to define, much less measure, the cost per unit of input. Increases in computer power and programme sophistication have been driving a permanent revolution in oil and gas exploration strategy and technique that is making the exploration dry hole a threatened species in some exploration provinces. Three-dimensional reservoir mapping assures both a significant improvement in average production rates for new development wells and a quantum increase in the total recoverable hydrocarbons from a given structure.

The most dramatic single technical breakthrough of recent years, however, has been horizontal drilling, whose fruits will include higher production rates per well, greater ultimate recovery of the original 'in-place' oil and gas, lower unit costs of production and, as a combined result of all the foregoing, an expansion in the number and kinds of hydrocarbon-bearing structures that will be deemed 'commercial' In our judgment, horizontal drilling is an innovation whose significance will rank in petroleum industry history with the invention of the rotary drill, catalytic cracking and geophysical exploration.

Falling costs and improved performance are not confined to the primary-extraction sectors of industry. Estimated construction costs per unit of throughput capacity for the most recent proposals for pipelines and LNG systems to serve natural gas reserves in the US and Canadian Arctic are one-half to one-third those of their 1970s' predecessors. Similar trends are evident in the expected capital costs per unit of throughput for elements of the LNG, methane-to-methanol and methane-to-gasoline systems that will permit the marketing of natural gas from remote sources.

Another dramatic, efficiency-enhancing and cost-reducing revolution was barely noticed or noted until it was in full swing. Combustion turbines and their combined-cycle variants are superior to state-of-the-art coal- or nuclear-fuelled steam generators by a wide margin in virtually every technical or cost dimension. The conversion efficiencies of new combined-cycle turbines are higher than for any other thermal-generation mode, and their noxious emissions per produced kilowatt are lower than for any other any generation technique based on combustion of fossil fuels.

Capital costs per kilowatt of capacity are 80–90 per cent less, and the scale of generation is likewise of an order of magnitude lower for combustion turbines than for central-station steam plants, in terms of the optimum capacity in kilowatts per generating unit. The combined effect is to permit the addition of gas turbine capacity in units that cost tens of millions rather than billions of dollars.

The construction lead times for gas turbine technologies are commensurately shorter, thus reducing carrying costs and permitting substantially greater planning flexibility. Because of their smaller size, units can be installed in stages as and when needed. Modular construction allows for easy parts removal and replacement, and multiple units can be dispersed easily in order to facilitate cogeneration and economize on transmission requirements, or combined at a single plant site to increase a station's overall reliability.

In the face of such competition, nuclear construction programmes now cling to life only on the basis of political rationales — some of which are, at least, as outdated as the economic analyses that once seemed to support nuclear power.

Fewer moving parts: how the new 'alternative energy' differs from the failed ventures of the 1970s

The most exciting applications of new technology are bound to include new energy sources that will not be based on the combustion of fossil fuels, new means of converting one form of energy to another, and new, more efficient end-use devices. An unprecedented number of such revolutionary advances in the production, delivery and use of energy are on the threshold of breakthrough to scientific credibility or commercial feasibility. Only a small fraction of these will prove viable, but the number, variety and potential impact of candidate technologies are so great that one or more such innovations can hardly help but have an early effect on industrial and market structure as well as prices.

Generally, the innovations of the new era tend to embody quantum increases in efficiency. As a direct concomitant of greater efficiency, moreover, they will embody quantum reductions in the discharges of environmentally burdensome waste materials and heat. In these respects, the front-running candidates for such a role differ dramatically from the massive government-sponsored research, development and demonstration ventures in 'alternative energy' sources characteristic of the 1970s.

The technologies and hardware selected for commercialization at that time mostly involved increases in the scale and complexity of established technology — a bias that meant higher capital costs, larger financial risks, reduced operational efficiency and lower reliability. For this and related reasons, advanced coal-combustion systems, synthetic natural gas, the mining and retorting of shale oil or oil sands, and fast breeder nuclear reactors offered little or no relief from the environmental and safety problems connected with existing oil- or coal-fired energy systems. Similarly, the measures adopted or proposed during the 1970s for mitigating environmental damage from both old and new energy technologies tended to centre on add-on devices or processes, which would increase capital costs even more, degrade reliability and efficiency further, and add to solid-waste disposal problems. The characteristic response of government and big business to reliability and safety concerns had the same biases: they centred on overbuilding and redundancy, whose nearly inevitable result was to increase both short- and long-term incremental costs.

The innovations in the extraction, transmission and conversion of energy that herald the Third Millennium promise, as a class, to be very different. Based upon recent advances in the understanding of fundamental physical processes, they tend to involve or permit significant reductions in scale and complexity compared with homologous elements in the present system. On the whole and for the same reasons, they are likely to be cleaner, safer and more reliable.

Photovoltaic solar energy is one cluster of such technologies that has already passed the experimental stage, but whose breakthrough to commercial status occurred without any dramatic announcement. In the late 1970s, this power source was economically attractive only for the most minute and/or remote applications: spacecraft, isolated meteorological and radio-relay installations, timepieces and novelties. In 1990s, however, solar cells already make up a competitive energy source for lighting and appliance operation in rural homes; the biggest commercial market thus far is for such uses on recreational boats and vehicles.

The cost of solar cells per peak watt has fallen by about an order of magnitude over the last decade and promises to continue falling. Concurrent improvements in transistors and other electronic components are causing appliance manufacturers to shift to low-voltage direct current (DC) for a growing number of household and business applications. Such appliances are generally more energy-efficient than their 110-volt or 220-volt alternating-current (AC) counterparts, and are thus equipped with a converter when they depend for power on the AC utility line. The availability of such appliances has another consequence, however: taking into account the superior end-use efficiencies of low-voltage DC, solar power is becoming economically competitive for lighting and refrigeration — indeed for every household energy use except spaceheating and cooling. Thus, in some climates, entire homes can already be equipped to operate on solar electricity, whose total cost lies in the same range as that of power delivered by utilities.

Non-fossil alternatives

Solar electric power is just one of many new devices, processes or clusters of technology that might lead to early enhancements in energy supply, reduce supply costs and/or reduce real or perceived environmental damage. As this time, the odds appear not to favour 'cold fusion' (as described in 1989 by a group of Utah chemists) as being the basis for such a critical technical breakthrough. But if those finite odds, however small, are added to the greater or lesser probabilities that correspond to each of dozens of other 'maybes' — doubtless including some that you and I are not even aware of — the cumulative expectation is very great that at least one will be of truly revolutionary impact, and that many others will have a perceptible downward influence on costs.

Superconducting materials and their applications clearly deserve more than one entry in such an inventory of candidates. A long-overdue item is some electricity-storage device that will be smaller, lighter and/or cheaper per unit of capacity than the lead-acid battery (which was the first among such devices, and which has now dominated the field for a century and a half). This particular innovation could level peak-period generation and/or transmission costs toward base-load values, and powerfully enhance the economics of intermittent power sources, such as solar, wind and tidal energy. Its appearance could also be the critical event permitting electricity to replace gasoline as power for motor transport.

It is also a good bet that at least one commercially viable device will soon appear for producing electricity by some chemical process analogous to combustion, but which dispenses with mechanical intervention in the form of turbines, pistons and the like. Even if such a 'fuel cell' were based on the oxidation of a fossil fuel (most likely methane or a natural gas derivative), its conversion efficiency would certainly be much higher, and harmful discharges per unit of final product less (by an even greater proportion) than with current thermal-generation methods.

The reader's list will surely differ from ours, and should attach different probabilities to specific entries. It would, however, take a vastly shorter list, and/or considerably greater pessimism about the odds on specific items, to conclude that new, lower-cost and cleaner systems for delivering useful energy are not likely to dominate incremental and replacement capacity over the next 25 years. If such a shift does indeed fail to occur, moreover, we wager that the reason will not be the lack of suitable non-fossil technologies, but rather, improved performance and reduced costs associated with the supply of useful energy from conventional sources — principally oil and natural gas.

Innovation will accelerate

There are many forces working together to accelerate the pace of scientific and technical advance, and these forces will themselves gain immensely in power over the next decade or two. One potent influence is the quickening internationalization of science, technology, business and the culture of the world's elites. It is not a great exaggeration to say that everybody in the world is now potentially accessible to anyone else, and potentially exposed to everybody else's knowledge, views, tastes and perspectives. The two goods that increasingly dominate international trade are information and financial capital, moreover, which unlike traditional commodities are indifferent to national boundaries, and whose 'transport' costs are only a trivial fraction of their value.

The potential for universal, instantaneous communication combines with computerization to increase by several orders of magnitude the effective supply of services traditionally performed by all sorts of engineers, designers, appraisers, analysts, forecasters and scientists. The wide variety and availability of applications software utterly changes the distribution of intellectual power within society — the one kind of power that will henceforth matter most in human affairs. Millions of individuals, singly or in informal or organized groups, now command intellectual capabilities that are more sophisticated and more powerful, and have access to information resources that are wider and deeper, than any person or institution on earth (including Exxon or Chase Bank, MIT or Brookings, Bechtel or the Corps of Engineers, the IRS or SEC, or the CIA or KGB) could command only 20 years ago.

Another development favouring the acceleration of scientific and technical change is the increase since World War II in the number of national economies in the first rank with respect to per-capita income and product, and technical and organizational sophistication. Once a nation reaches that position, its further economic advance is no longer possible simply by 'industrialization' — increasing the crude ratio of capital to labour, while 'borrowing' productive and organizational methods from a handful of more advanced nations. Each front-runner acquires a set of needs, incentives and abilities, comparable with its erstwhile 'fore-runners', to make a proportional contribution to the overall productive prowess of humanity.

The sharing of this effort among different cultures and within institutions having different incentive structures imparts still further momentum to the innovative process, because it multiplies the number of perspectives from which mankind is likely to approach a given problem of technique or organization. Some kinds of inventions and innovations will surely be best nurtured where values and institutions encourage individual initiative and reward individual achievement; others will tend to emerge where the emphasis is on teamwork, consensus and group pride. The novelty whose invention springs from one social context, moreover, may find that another is more congenial to its practical implementation, while its greatest consumer or social benefits may be captured by members of still other cultural groups.

The ultimate guarantor that technical advance will quicken is the recent worldwide discovery (and re-discovery) of market mechanisms as the premier resource-allocator, and of political freedom as the most effective framework in which to motivate human imagination and effort. These discoveries appeared most dramatically in 1989 as a world revolution against Communism, which revitalized in that one year many of the unfulfilled liberal promises from 1776, 1789, 1848 and 1919. Concurrently, however, re-discovery of the market is manifesting itself in the capitalist West and Third World countries through movements for the privatization, unbundling, de-averaging or deregulation of various economic activities. A common theme in the many national variants of the World Revolution that closes the Second Millennium is the injection of optimizing behaviour and rewards for innovation into virtually every level and kind of human activity.

Summary

Energy is, after all, a resource of unlimited abundance, and is available for human use in an unlimited number of forms. There is no inherent social need for oil, gas, coal or any one primary energy source. Instead, we seek ways of supplying light, heat, motive power and the small hydrocarbon molecules that are the handiest building blocks for making organic chemicals. Our menu of options for serving these needs is already vast, and we will choose one primary fuel or delivery system from this menu only for those applications, and only where and when it is the cheapest (or most effective at a given price). For, so long as progressive market economies have coexisted with cultures that encouraged scientific inquiry and permitted economic rewards to innovation, mankind's menu of options has expanded and the choices it preferred on that menu have continually shifted.

The depletion of finite resource stocks and the full exploitation of renewable resource stocks on a local or regional level have played the triggering role for some historical shifts in primary energy supplies. Examples cited earlier included the deforestation of the North Atlantic rim and the extermination of the sperm whale. Equally significant innovations in energy production and use, such as electric lights and motors, were adopted because of their own superiority in cost or performance without any visible impetus from scarcity-driven price increases. The results in each instance improve performance and lower costs. In no memorable instance did they lead to higher real costs for primary energy inputs to production. So it is today, and so it will be into the New Millennium.

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