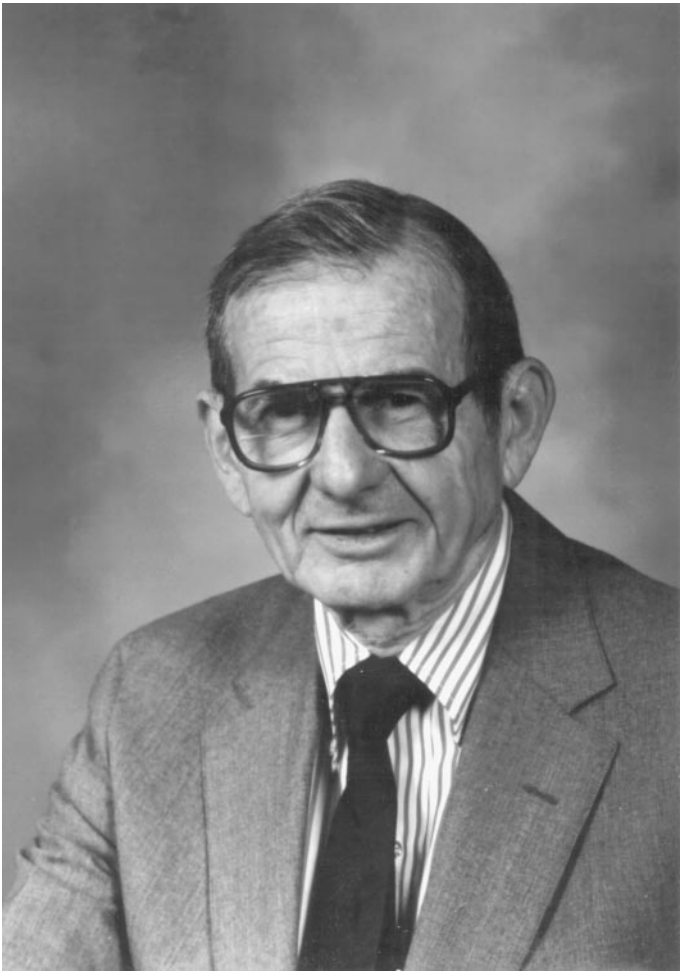

M. A. Adelman

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MY EDUCATION IN MINERAL (ESPECIALLY OIL) ECONOMICS

M. A. Adelman
Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA 02139

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ABSTRACT

The crude oil and natural gas markets have a long colorful history. To understand them, one needs some economic theory. The dominant view, of a fixed mineral stock, implies that a unit produced today means one less in the future. As mankind approaches the limit, it must exert ever more effort per unit recovered. This concept is false, whether stated as common sense or as elegant theory. Under competition, the price results from endless struggle between depletion and increasing knowledge. But sellers may try to control the market in order to offer less and charge more. The political results may feed back upon market behavior. These factors—depletion, knowledge, monopoly, and politics—must be analyzed separately before being put together to capture a slice of a changing history.

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THE STARTING POINT

The economics of mineral scarcity were summed up in the 1952 report of the Paley Commission (1). One member was my great teacher, Edward Mason of Harvard (2). As Boswell said of Johnson:

> His superiority over other learned men consisted chiefly in . . . a certain continual power of seizing the useful substance of all that he knew, and exhibiting it in a clear and forcible manner; so that knowledge, which we often see to be no better than lumber in men of dull understanding, was, in him, true, evident and actual wisdom.

As Mason might have said about mineral scarcity: Forget about running out of anything. What counts is the cost of new supply. To know this cost, follow the price, generated not in The Market, but in a particular market. The price in the market may reflect not only supply and demand, but also control by one or a few sellers, who can act together to offer less and charge more. So detecting and allowing for market control is high on the agenda for understanding price.

In 1948, I joined the economics department at MIT, which was a place few ever wished to leave. I tried to analyze iron ore supply, recalling some warnings a decade earlier (before I entered the Navy) about postwar exhaustion. But I soon learned an obvious lesson. If an alleged price is not a real market price, freely bargained over by buyers and sellers able to take it or leave it, it is not a data point. The "Lake Erie" ore price, at which ore was transferred within the vertically integrated iron and steel companies was a bookkeeping fiction. My hope of peeling away the value added by downstream processing to make steel, and of thereby discovering the value of the iron ore itself, soon faded. [Many years later a student got it right (3).]

The Interest in Oil

In teaching about markets, as I did at MIT, one example is worth a thousand words, and there were plenty of examples in the oil industry. My first thesis-writing graduate students were also interested in oil. Federico Baptista, a Venezuelan engineer, was one of a group of special students (the Sloan Fellows) sent to MIT by their companies to prepare them for later promotion. His master's thesis incidentally analyzed Venezuelan experience with oil revenues over the previous two decades. His work revealed that, despite that excellent slogan, popular in Venezuela, "to sow the petroleum," the revenues were more a hindrance than a help to development (4). My colleague, Charles Kindleberger, and I wanted some of his thesis to be published, but his company would not hear of it. The company was very cautious because the government had already revised the terms of the production concessions several times and was considering whether to stop any new ones (as they later did). Baptista's essay stayed in the MIT archives, and the problem was not studied for several decades (5).

The View From Texas

My first doctoral candidate, Leslie Cookenboo, wrote a thesis (6) on oil pipelines as a study in economies of scale and industry structure. The thesis had a Texas flavor—sound scholarship combined with a wry, unillusioned, and even amused appreciation of the process of building and trading political power.

In the United States, alone among producing nations, subsoil wealth (mineral wealth) belongs to the owner of the surface land. Pools of oil and gas do not respect property lines. Under the law of capture, fluid hydrocarbons, like wandering wild beasts, belong to anyone who can effectively possess them. Therefore, one can, and people often did, draw up oil or gas from underneath a neighbor's property and sell it as one's own. This gives everyone an incentive to produce the oil much faster than is economic. The easiest solution was to have the Texas Railroad Commission (TRC), a group of elected officials, set the whole oil output of the state at a fixed amount and prorate it among the producing wells. Each well's "allowable" was now a valuable right, and to drill more wells for more allowables profited the individual at everyone else's expense. The cost of overdrilling was high (see below).

The result of these events was a fascinating species of cartel. Tolstoy writes that happy families are all alike, but each unhappy family is unhappy in its own way. Competitive industries are all alike. Nobody can affect the total output or its division in order to set the price. But each cartel is unique in its price and output fixing. The TRC administered one of the world's longest-lasting such fixes.

The Commission members were not looking to maximize the industry's profits, or even its revenues. Their job was to stabilize the price and keep it from

plunging to the level that would exist under competition, especially given the law of capture. (Their concept of price in a normal unregulated market was the 10 cents a barrel of 1930, a result of the malign coincidence of the Great Depression and the development of the East Texas field, the largest ever found in the lower 48 states.)

Oil producers used their political clout to get favorable federal tax treatment, as well as federal shelter for the Texas and other state cartels. But there was unrestrained competition in bidding for oil leases. So, through competition, the producers lost most of these benefits in royalties to landowners, including state governments and the US government, which owned the offshore lands beyond the three-mile limit and therefore took in the most royalties. The ironic result was that the oil and gas producers collected a monopoly price mostly for others and paid the full cost politically, as natural gas price regulation would soon demonstrate.

The TRC used excellent timely inventory data to control output. When inventories rose enough to imperil prices, they cut production allowables. If inventories shrank beyond the lower peril point, they allowed increased output. [For both data and power, the Organization of the Petroleum Exporting Countries (OPEC) might well envy them!] To Europeans, and even to Americans from outside the oil-producing regions, this regime looked like a well-coordinated conspiracy, orchestrated by the huge and world-famous oil corporations, with independent producers serving as a kind of protective screen. In fact, the small producers and royalty owners were the major players in the political game. This rule was about to be proved again.

THE 1950s: IMPORTS; NATURAL GAS

After World War II, competitive market forces threatened to push the oil price down and push the natural gas price up. Political forces mobilized against both.

The Import Battle

After 1947, the last year of US net oil exports, the burning issue was the volume of oil imports. The documentary record was my first schooling in the interface of domestic policy and the world oil industry. The first tactic to minimize oil imports was established in Congressional hearings during 1947 and 1948: to identify and intimidate the importers—the six large international producers that were also large domestic producers. [They were, to use their most recent names, Exxon, Mobil, Shell, Gulf (since merged), Chevron, and Texaco.] Soon afterward, the TRC began to publish detailed import statistics. The moral was clear to everyone: Overly high import levels would create trouble for the producer/importers with the Commission, which ruled domestic production.

The Federal Trade Commission Report

In 1951, I was asked by one of those companies (then Jersey, now Exxon) to analyze a forthcoming report by the Federal Trade Commission (FTC), *The International Petroleum Cartel* (7). Several chapters provided a history of the activities of the interwar cartel of the seven sisters (the six companies mentioned above, plus British Petroleum). The 1928 meeting of the three largest sister companies at a Scottish hunting lodge (Acnacarry) has often been played as drama and replayed: the world oil cartel made flesh. But the conduct of that meeting was a cartel on the defensive, unable to agree on any orderly market division and forced to roll over its existing market shares. Between the wars, the increasing size of the market, and even the very few new entrants, made the task of cartel coordination increasingly difficult.

The history in the report set the stage for its last chapter, which aimed to show how post–World War II developments had changed the form, but not the substance, of the cartel. A careful reading, and the rearrangement of some text and numbers, showed that in 1947–1949, the world price structure had been turned upside down, as an incidental achievement of the Marshall Plan (see 18, pp. 131–140 for details). The Persian Gulf price had been the US Gulf price plus freight. It became the US Gulf price minus freight, and as a direct result, inflation-adjusted prices were cut roughly in half. Concealing these two facts was an achievement for the FTC.

The company read my report and asked me for another one aimed to do well what I thought the FTC had done badly. I did not do very well. There was no public knowledge of the world oil price, set at the Persian Gulf price after 1949. Arms-length transactions between independent buyers and sellers were very few and all private. As with iron ore, there was no way to proceed from real consumer prices at the pump (of which a few were known) back through distribution, refining, and tanker transport to determine the true FOB price (i.e. before freight) at the Persian Gulf. Costs there were obviously very low. I knew nothing of costs elsewhere; it was hard to discern the boundaries of the market, from which the United States was now partly excluded by the import barrier.

I learned some incidental lessons from my hosts in the company. They were anxious to avoid antitrust cases, which were considered impossible to fully win; one could only limit the damage. More important was that no one doubted that the Persian Gulf and other producing nations had been sovereign in the oil-producing areas since the unilateral tax increases of 1950. Opinions varied only on how long the oil companies could continue (very profitably) working the Persian Gulf and Venezuelan oil fields, because they were the producing countries' best vehicles for maximizing wealth.

Import Controls

The TRC managed to restrict the number of importers for a surprisingly long time. But the volume of imports of record increased greatly in 1948–1954, indicating numerous arms-length sales by the international oil companies outside their integrated systems. Since most new importers were not producers and were untouched by the TRC production regulation, inability to control them killed the system. In 1954, the federal government had to step in, creating a "voluntary" import limitation program. The controls established by this program became mandatory in 1959 and lasted through 1971.

Natural Gas—Back to Basics

While reading up on US oil production, I learned about natural gas. Production was competitive, since state controls could not be applied for various reasons. (Indeed, they never were.) Gas had for many years supplied local markets around producing areas. But after World War II, and great advances in welding technology, a national network of pipelines quickly developed. Effective demand for gas surged. As usual in a competitive market, the result was increased prices and expanded supply. Along with increased reserve creation came windfall gains on the old reserves, whose half-lives were about eight years. The public resented the higher prices. An ambiguous law of 1938 was interpreted by the courts as a requirement for federal regulation. From 1956 to 1958, I worked as a consultant and witness for a group of oil companies. The Federal Power Commission had the authority to fix "just and reasonable" field prices. I thought the best they could do was to approximate the results of competition; hence a functioning competitive market would do their work. Price-fixing policy was still unformed.

I addressed a small meeting, mostly of commissioners and their staff, with interested parties also attending. I spoke briefly, trying to make only two points. One was that gas production is competitive. (The purchasers, i.e. the gas pipelines, might have market power on the buying side.[1]) Second, competition was no badge of virtue, merely a basis for prediction. Fixing the price in a competitive market below the market level would lead to excessive demand and deficient supply, i.e. a shortage. Asked how soon the shortage would arrive, I gave the only possible answer: I do not know. Their interest ended there.

My later formal recorded testimony before a hearing examiner of the Commission had no effect. Natural gas field prices were regulated for decades;

[1]Shortly thereafter, Paul W MacAvoy, then a graduate student at Yale, began a thesis on this topic. Impressed with the difficulties of measuring prices, I urged him to desist. May such bad advice always be disregarded! He completed an outstanding piece of work (8) that proved that outside some areas of pipeline buying power, the geographic pattern of prices corresponds to what would be expected under competitive conditions.

the shortage arrived, followed by underinvestment and above-competitive prices. Great damage was done in the name of "just and reasonable" prices.

I wrote a short book on the supply and price of natural gas (9) but used none of the testimony. I maintained that there is nothing unique or perverse about petroleum production costs. The industry is inherently self-adjusting because expansion at any moment is subject to decreasing returns and rising costs. No economies of scale were such as would dictate or impose a natural monopoly. This fact contradicted the theory implicit in much discussion and clearly expressed in a United Nations document in 1955, which was actually written by an Oxford don (10).

Both the simple and the learned were obsessed—many still are—with the low marginal operating costs, allegedly so far below prices. These costs were characteristic of the industry, alike in the high-cost United States and the low-cost Middle East and Caribbean. They showed (allegedly) that the industry could not be left to the normal play of competitive forces.

In fact, a little analysis showed that marginal costs fall below prices only when there is excess capacity. But excess capacity can persist for years in an expanding industry only if prices are kept above the competitive level. So the obsession with low marginal costs helped reveal the truth—output restrained by monopoly, whether of the Texas type I knew or some other type I would try to know.

My thesis was treated as new and worthwhile by one of the few people interested in the subject in those days (11). The last chapter in (9) deals with the relation of natural gas to the international oil market, which by this time was the principal focus of my research life.

THE WORLD OIL MARKET IN THE 1960s: THE DISCOVERING OF PRICES

In 1960, the Organization of the Petroleum Exporting Countries (OPEC) was founded when the producing companies reduced the nominal, or posted, price. The companies alleged that prices realized in the market had gone down. This claim could not be proven or disproven with evidence in the public domain.

A lower posted price meant a lower nominal revenue per barrel and a lower nominal profit. The tax was 50% of the nominal profit and was lowered accordingly. The OPEC nations indicated that they would not tolerate lower taxes per barrel. The result, with neither side apparently ready to risk a conflict, was an understanding that the lower posted price would stand but would not be further reduced. As a result, the nominal profit per barrel and the tax per barrel were permanently fixed. Thus, almost inadvertently, the tax was transformed in 1960 from an income tax—a share of profits—into an excise tax, in cents per barrel.

Beginning in 1959, the posted price lost all relation to any market price. The posted price was henceforth an arbitrary number used to calculate the tax per barrel. Yet the posted price continued to be reprinted and discussed as if it were real, before its abolition around 1975. It is still cited as history.

In 1960, two genuine price series appeared for finished oil products—gasoline, heavy (residual) fuel oil, and light fuel oil—originating at Rotterdam. An association of mostly German independent oil importers (AFM) began to publish the prices at which their members were buying, either directly or from intermediaries. Shortly thereafter, Platts Oilgram Price Service (POPS) transformed its meaningless European prices into a series of genuine arms-length Western European prices reduced to a Rotterdam base. This event was part of a gradual trend of increasing competition in the industry. The level of independent refining and marketing, however small a percentage of the industry, was sufficient to generate a need for this information.

For me, the change was decisive. The availability of genuine arms-length product market prices ex-refinery meant that one could subtract from them a plausible estimate of short- or long-term refining costs. One could also subtract the publicly available tanker rates, which my student Zenon Zannetos had proved to be a coherent structure generated by a competitive industry (12). The residual was the price actually realized at the Persian Gulf. This price could be checked against the few reported arms-length sales of crude oil. Today, netback prices are routinely calculated, perhaps by the thousand every hour, but I believe this was the first such estimate published.

Comparison of 1960 prices with the original posted prices of 1949 showed that the price had indeed declined, even in nominal terms, and even more when properly adjusted for inflation. The reason was said to be a temporary surplus. In time, rising demand would dry out the "surplus." The argument does not sound much different today: It makes no sense in an expanding industry, let alone an industry doubling every decade, as it did then.

I spent 15 happy months in Paris *en famille* in 1962–1963 on a research grant, using the incomparable library of the Institut Français du Pétrole (IFP) and speaking informally with oil company executives, ship brokers, and others. The advent of price data had been the signal to me to begin serious research. In Europe, I was struck by the revulsion of oilmen and others for these and other spot markets. Prices reported there were considered marginal, peripheral, or "the tail that wags the dog." A few desperate fools, I was told, were dumping what they did not know how to sell.

I pointed in rebuttal to the tanker market, which was guided by arms-length prices. Spot contracts, six-month consecutive voyage contracts, three-year ship rentals, twenty-year rentals, and ship purchases were some of the many links in a chain of substitutes providing a menu of services at every moment. The

shock of big, sudden changes was diffused by the chain, making it less severe at every point. Nobody ever had to go without tanker service.

I failed to be convincing on price theory or practice. A French oilman, told that I had visited Rouen and seen where Joan of Arc was burned at the stake, warned: "That's the fate of heretics in France." His attitude might have concealed an interest. Certainly the integrated companies wanted to suppress competition at each level. But others felt the same way. The worst pseudo-price was the so-called AFRA, an average of various tanker rates, mingled long and short term, that conveyed absolutely no information about tanker service but was nevertheless used by governments for many years.

But my vivid memory of the early 1960s prepared me for what I would see about 30 years later, most clearly but not only in the ex-Soviet sphere: the resentment of state companies forced to deal with market prices, which were independent of their will and of ethical practices. A market price was an uninvited intruder. Prices came from a world they willed to not exist, and which they thought they could ignore. The distaste will be with us always: Prices are subversive. It doesn't seem to help to say that prices are just information, the more accurate the better.

Before leaving France, I wrote a paper for my IFP hosts (13). I said the price of oil would continue to fall, from the then-current level of about $1.50, possibly to $1.00 per barrel. In real terms, it did fall below $1.00 by 1970. The forecast was based on two propositions: (*a*) The cost of expanding supply by new investment was still far below price. (*b*) The force of competition would keep pulling price down in the direction of cost, though by no means all the way. The first proposition continues to be true. The second was correct before 1970 and after 1980, but certainly not during the intervening years.

PETROLEUM PRODUCTION COSTS

After completing the gas study, I worked on concepts and estimates of production costs. I worked through some of the new *Petroleum Production Handbook* (14, 15), and I think I understood tolerably well the methods of estimating primary reserves of oil and gas. The key fact in such estimations is the production decline rate in every reservoir and well, mostly because of decreasing pressure and increased water cut. But annual operating expenses per well were fairly constant. When output from a well falls so low that its sales can no longer cover operating costs, production is said to have reached the economic limit and has to cease, irrespective of how much oil is still in the ground. "Proved reserves" are defined by cumulative production over the life of the well or wells that have been, or are to be, drilled and connected. Output can only be maintained, or increased, by additional or improved wells.

Thus proved reserves are an engineer's concept, which can be translated into economic terms. This concept eliminates confusion and breathless hype about "finding reserves," which still afflicts us. Nobody finds reserves. Oilmen find deposits, with oil in place. Investment to develop capacity to produce part of the oil in place creates reserves. A decision to invest requires an estimate of cumulative output—proved reserves. They are inventories, the turnover measured in years, not weeks (see Table 1).

Unlike investment in most other minerals, nearly all hydrocarbon investment is made to create reserves. Once these reserves are in place, their extraction is cheap. The decline rate always operates, and continued fresh investment is needed even to maintain output. Hence, to understand the market we must learn, even roughly, the marginal cost of reserve-creation, either stated as an amount per barrel in the ground or converted to an amount per barrel produced.

The concept of proved reserves and production decline also demonstrated the improbability of a prolonged "surplus" of oil or gas. The decline rate was a built-in output reduction. Indeed, production would decrease even more rapidly, absent a minimum of workover and other maintenance. Yet the informed public believes there can be a prolonged surplus. In the United States in the 1980s and 1990s, there was supposedly a temporary surplus—the "gas bubble"—of temporary oversupply to explain the low prices.

The chance of any overcapacity is greatest when prices drop substantially for several years. After 1984, newly freed gas prices did fall, confounding the fears of those who expected a rapid increase. But the decline rate of US gas production was probably around 10% per year, nearly 39% in five years (see

Table 1 World production and reserve additions, 1944–1993[a]

	1944	1945–1960	1961–1970	1971–1980	1981–1993	(Total) 1944–1993
OPEC						
Cumulative production	—	26	55	103	100	284
Gross reserve additions	—	219	251	128	434	1032
Reserves at end	22	215	412	436	770	770
Non-OPEC						
Cumulative production	—	51	64	102	190	407
Gross reserve additions	—	98	187	114	207	607
Reserves at end	29	76	200	212	229	229
Total world						
Cumulative production	—	77	119	205	289	690
Gross reserve additions	—	318	439	242	640	1639
Reserves at end	51	291	611	648	999	999

[a]Data are given in billions of barrels.

footnote 2). Since output remained steady or even increased somewhat, substantial investments were made year after year to maintain capacity. Hence there was inducement to invest. This inducement was confirmed by independent data showing that investment was profitable at the "low" prices (16).

Oil Development/Operating Costs

In the late 1950s, information about capital expenditures began to appear, permitting me to make what I think were the first estimates of development costs in several countries. (Operating costs were low and best determined as an addition to development cost.) I wished to air these estimates before an engineering group (17, 18). In making these estimates, it was important to match development capital expenditures in a given time and place with the corresponding increments in reserves or in capacity.

One could approximate the production decline rate by the production:reserve ratio,[2] then calculate the constant price, which, collected over time, would have a present value just equal to the amount of spending needed for the additional output stream.[3] If the necessary Persian Gulf rate of return needed i was 20% per year, the decline rate a about 2% per year, and an annual allowance c 7% of the original capital expenditures for operating expenses and declining production, the annual cost of investing $100.00 was $29.00. If the investment procured an output of 1 barrel per day, or 365 barrels per year, then one could determine development-operating cost, setting to zero the value of vast amounts of oil remaining after the first twenty-odd years, at less than 10 cents per barrel. Even gross errors can have very little effect on the estimate. But the $100.00 is an overestimate, exceeding my calculation of the approximate investment per daily barrel of Persian Gulf oil at a time when the "abnormally low price," as best I could make it out in the mid-1960s, was in the neighborhood of $1.50. In other words, the return on new investment was 550% per year. This return was

[2]Assuming exponential decline, where R = reserves, Q = annual production, and $\underline{a}$ = annual decline, $R = Q\int_O^T e^{-at}dt = Q(1-e^{-aT})/a$. Taking final prediction time T to infinity, $a = Q/R$. In applied work, one may need to lower $\underline{a}$ to allow for limited T. Assume there is no other information. Then $a = (Q/R)(1 - e^{-aT}) = Q/R - (Q/R)(e^{-aT})$. Obviously, $(e^{-aT}) = Q(e^{-aT})/Q$. This fraction is the ratio of final output to original output, which I will call Q_f/Q. This ratio must be proportional to the ratio of original output to original reserves Q/R, because the higher Q/R, the higher the level of fixed annual outlays needed to maintain output, and therefore the higher the level of output at which sales can no longer cover expenditures. Hence, we use Q/R as a proxy for Q_f/Q, and estimate that $a = (Q/R) - (Q/R)^2$. In the United States, natural gas Q/R in the 1990s has averaged 0.109, so estimated $a = 0.109 - 0.109^2 = 0.097$.

[3]That is, where K = investment per reserve barrel, set $K = P\int_O^T e^{-(a+i)t}dt = P/(a+i)$, and calculate P, the break-even price, or cost. The value of c was an add-on to i. (See text for definitions of c, i, and a). Note that capacity was used, not reserves, which were too poorly defined and measured.

lower but still very impressive, even in Venezuela and other less lush profitable environments. If there was any competition in the system, there had to be downward pressure upon price.

The Value/Cost of Undeveloped Oil

These calculations brought me to the most difficult part of the cost reckoning. How much must be added to compensate the owner/investor for the original value of the oil before development, over and above the actual investment in development itself? This original value was used up by committing the oil to development today rather than later.

One could reason that the oil committed was worth what it cost to replace it with a newly discovered barrel. But to estimate discovery costs was impossible. A given year's "discoveries" remain an unknown. Initial estimates are always increased, often by very large factors. Given the irregular, episodic, and chance-dominated nature of exploration, the relationship between money spent and oil "found" in any year changes abruptly from year to year and from place to place. Over time, the newly found reservoir may or may not grow to become a field, then a play, then a basin. How much of the finding outlay goes for what portion of oil found is unknown.

Oil companies needed capacity and reserves estimates, and made them all the time, but ex-post discovery estimates gave no information about where it was advisable to invest or how much to invest. Instead, oilmen calculated the odds of finding a given quantity of oil of a given quality in a given place. Success was the few good guesses redeeming the many bad ones by enough to leave a profit (19). Incidentally, the corporate calculations were confidential.

These limitations posed a problem. One could not ignore discovery investment (although it was much less than development). But to calculate discovery cost ex-post was impossible and irrelevant; to calculate it ex-ante was relevant but also impossible. I devised a less-ambitious method of estimation that would yet suffice to answer our questions over the relevant economic horizon. All else being equal, the more one exploited a deposit, the higher the investment cost of developing one tranche after another. Discovery was needed to offset the otherwise inevitable increase in development/operating cost. Therefore, the undeveloped oil was worth what it saved in higher development cost.

I therefore calculated "maximum economic finding costs," by first making the limiting assumption that there would be no more discoveries of oil fields. There would still be (as the US history showed) much growth of reserves in existing fields, in deeper or shallower pools, and in outlying pools; in enlarging the boundaries of existing reservoirs; and in filling in the gaps between existing reservoirs. Such growth had been going on for a long time in many fields. Therefore, assuming that the enlargement of proved reserves outside the United

States would be similar to that within the country, one could calculate the amount by which reserves and capacity would be increased without any discovery. Then one could estimate constantly rising costs as output and the production:reserves ratio rose. One needed to assume some rate of output growth. I assumed not the rate that I judged most likely, but rather the upper limit of probable growth and the highest assumed rate in the Persian Gulf.

I could make no allowance for technological progress. As with reserves and with output, it was best to assume the worst (no progress) and be sure the measure would be biased upward. I did not try to discount the higher costs as removed in time.

Estimation of "maximum economic finding cost" eliminated the problem of price:cost relations for two or three decades. Prices were so far above development-operating costs that even an extravagant allowance for future cost increases, and hence for the present value of undeveloped oil used, could not greatly change the cost. To discount the future cost to a present value equivalent was superfluous. The possible higher prices due in 20 or more years to compensate for possible higher costs were not sufficient to make undeveloped oil worth locking up in the mid-1960s (or the mid-1990s).

The international industry itself, or at least those in it who were accustomed to thinking in these terms, found my numbers quite plausible. They were also willing to accept the idea of maximum economic finding cost, or at least to agree that it made good enough sense in context (20).

NEW DIRECTIONS IN RESOURCE ECONOMICS

A rethinking of mineral economics was underway in 1950–1970. The Paley Report had led to the establishment of Resources for the Future, led by Sam H Schurr, to whom mineral and energy economics are much indebted.

I had started with the lazy man's assumption: The particular industry that interested me happened to be an exception to the rule that mineral prices generally had to rise in the long run. I had read Hotelling's famous paper years before (21). The mathematics was practically impenetrable, but a simple heuristic made sense. Growing scarcity was registered by a gradual price rise. But future scarcity would raise present discounted values, thereby slowing demand and production and stretching out the decline. Humankind was in no danger of crashing into the scarcity wall, or going over the cliff, or whatever metaphor has scared people.

The gradual accumulation of knowledge showed the exception to be the rule (22, 23). To Barnett & Morse (24), the important conclusion was that mineral scarcity and mineral price increases posed no threat to economic growth. They wrestled, in my judgment with only partial success, with the reasons mineral

prices were stable or decreasing. One statistical problem they faced (as I had, see above) was of stripping out the value added after the material was brought above ground. In fabrication, normal progress was assumed. It was not so clear—the statistics were fuzzy—how far the in-ground prices also tended to decrease.

In 1967, papers appeared by two people to whom I owe much: my former student Richard Gordon (25) and the late Orris Herfindahl, who had set me a worthy model in his copper study (26, 27). They started with the fact that mineral prices did not persistently rise in the long run.

Given a large indefinite resource of minerals of widely varying quality, technology worked to flatten out the curve of rising disadvantage. Thus, the line between the known mineral and all substitutes for it became blurred. If the course of substitution was long enough and the trajectory flat enough, it was not worth holding minerals for future use. To this point, it had not been worth it. Or as Gordon put it, the minerals industries acted as if their finite stocks were infinite. Hindsight shows that they were right to act this way.

The new theory was not necessary at this time for my study of oil, but it was the correct theory. I thought future progress would lie in amplifying it and trying to fill in the blanks. In 1970, I was invited to address a geophysics meeting (28). This forced me to explain myself to a noneconomic but scientific audience and to say briefly what I was about. I said, "Perhaps the very concept of exhaustible reserves ought to be discarded as wrong or irrelevant. Not much of the resources we know today will ever be used because better ones will be found. Or the need itself may disappear before the resource . . ." (28; see 43, p. 83). I failed for years to develop the thoughts contained within that statement or bring them to economists' attention; I finally did so only because of the prodding of Gordon and another ex-student, Paul Bradley.

Public Policy; Security of Supply; Proved Reserve Estimates

Around this time, I made some efforts to influence public policy. In 1964, I published some estimates of the economic waste of the cartel system operated by the producing states in the United States (29). I was the only economist, to my knowledge, ever to be denounced by name by the then-governor of Texas, John B Connolly.

In 1963–1964, I assisted the Secretary of Defense, Robert S McNamara, in drafting a suggested revision of railroad coal freight rates designed to do away with discrimination against exports. The railroads expected European coal prices to rise soon and wanted to preempt the rents. Perhaps some of the suggested changes might have been made, but a meeting scheduled for August 1964 was delayed, then canceled, because of "an incident in the Gulf of Tonkin." I did publish some of the economics (30).

The resistance in Europe to importing more coal or oil was justified in the name of national security. In Europe, and during a 1965 lecture tour in Japan, I heard much about this resistance. In the United States, imports were considered dangerous. What worried people in Europe and Asia was access to oil. Would there be enough for their needs, or would they be left in a scramble for resources, the stronger shoving aside the weaker?

I heard in the 1960s what I hear today: "Of course there is plenty of oil now, but look to the future. Resources are limited. Consumption is rising at 7 percent per year [today, 2] because of swift growth in Europe and Japan [today, China]." Yet access was a nonproblem, even assuming oil would get more scarce; a market acted to distribute supply to all who paid the price.[4]

The giant Anglo-American companies, who stood between consumer nations and the source countries, might act as the tools of the American hegemony. The feeling of insecurity was perhaps greatest in Japan. Of course, this feeling was understandable, as the oil embargo of June 1941 had led to the decision to go to war. To the Japanese, security meant production at home, or by Japanese companies. (My recently deceased friend, Hidezo Inaba, was never subject to this delusion.) But the multinational oil companies' only power had been the support of their home governments, which they no longer had. Gunboat diplomacy had vanished. The local producing-country governments had the local physical force. Their 1950 assumption of power to tax, and the later tax increases (see above), showed who was in charge. A producing company, wherever its headquarters and no matter who owned it, either took orders from the local government or left.

Security of the fuel supply had very little to do with the percentage of fuel produced nationally and everything to do with building a safeguard against sudden, sharp, and brief interruptions or reductions in the fuel supply. I suggested in 1967 that European coal was no longer an industry, but only a means of social insurance, and therefore should be phased out. I suggested what later became known as a strategic petroleum reserve. The paper was published in French, Italian, and Japanese; only a summary appeared in English (31). Fifteen years and two oil shocks later, the shock mechanism was much more clear (see

[4]"You Americans have oil. Therefore you cannot understand the danger we run, of losing access as oil gets scarce, cut off or jostled aside by more powerful claimants." One heard this sentiment everywhere in Europe and Japan. My efforts to explain why these ideas were fantasy were the most ill-received in France, precisely because I was and am an incurable Francophile. Like the title character in Molière's *Bourgeois Gentilhomme*, people in France would ask themselves, "Do people of quality have that? Then I'll have some." The hard-boiled DeGaulle paid the Algerians repeatedly for worthless oil rights, tried for a foothold in Iraq, and delighted in Third World applause. To borrow from LaFontaine (*The Crow and the Fox*): It is costly to listen to flatterers. The self-satisfied diplomat (American or French) is forever preserved, like the fly in amber, in Proust's chapter on M. de Norpois at dinner.

below). I suggested a decision rule that "could hardly be more simple. The SPR [Strategic Petroleum Reserve] 'window' should be open for sale at all times, to sell any amount of crude oil [at] the highest price being charged anywhere. . . . For anyone fearing dearth, the price is a bargain. Nobody else would want to buy" (32). The SPR in this country has never been used, except unwisely and too late in 1991. But its mere existence has helped stabilize the market, by eliminating panic among the decision-makers.

In 1966, the American Petroleum Institute (API) and the American Gas Association undertook to expand and improve the reserve and capacity statistics. The API set up an oversight committee; I was one of the two public members. Over the next 13 years, the reserve statistics were more complete and accurate than ever before or since. In 1979, the prevailing mindless distrust of the oil industry eliminated much of the data they had carefully gathered and improved over the years, a change I found highly regrettable.

The Department of Energy did a commendable second-best by asking each reporting company to estimate its reserves of oil and gas. Under the old system, annual estimates had been made for small areas by groups of local engineers and geologists. Continuity and peer review guaranteed accuracy. But even more important, since results were made year after year for the same area, the estimates of increments to reserves could be made with great accuracy, area by area. These estimates and more were lost after 1979. For the United States and the world, increasingly sweeping statements and models are built on an increasingly slender data base.

WORLD PRICE REVERSAL IN 1970–1971

The excise tax was a floor to price and could be used to increase it (13). But as late as 1969, I did not expect the OPEC nations to act together to turn from raising their profit shares to the much bigger and more rewarding task of raising the whole level of taxes and therefore prices. To achieve this goal, they had to restrain output, which they had tried repeatedly to do and always failed, the last time as recently as early 1970.

But between the summer of 1970 and January 1971, first Libya and then the Persian Gulf nations (quickly followed by others) together raised their excise taxes, and prices followed. Press reports at the time showed the prior approval of the US government; documents made public in 1975 showed the support to be stronger and more blatant than it appeared to be at first (33). The OPEC nations needed US support most in getting started, and they may or may not have dared to act without such support; one cannot tell. The US State Department rightly claimed credit, looked upon its work, and found it good: They expected "the previously turbulent oil market to calm down following the new agreement" (33,

p. 79). I expected that the agreement would be quickly broken and said in March 1971: "The genie is out of the bottle" (33, p. 776). I expected the price to rise to the monopoly ceiling, wherever that was, and I expected a parabola in the 1970s. These predictions were borne out, but the peak was reached only in 1980 (33).

In 1972, output exceeded a sluggish demand, but the producing countries' ranks held, and they raised prices in each quarter. But Iraq demanded that its resident company raise production forthwith. When this demand was refused, Iraq expelled the company.

In 1972, I wrote a long paper in a foreign-policy journal (34) explaining the damage caused by the emerging oil monopoly. There would be no valid price as an index of scarcity and a guide to investment. Monopoly distortions would affect the world economy. The flood of petrodollars into a few undeveloped nations would have some unpleasant results. "The world oil shortage is a fiction, but belief in the fiction is a fact" (34, p. 331). The price rise and all that followed it was *unnecessary* (my original emphasis) (34, p. 355). It was not a misfortune wrought by nature, to which mankind had to adapt, but a scarcity made by collusion.

I received a grant to visit seven NATO capitals in 1973 to see what was being done about security of the oil supply, a problem which I expected would soon be more acute. There was much talk about it. In September 1973, after the tour, I finished a 40-page report, never published and best summarized by King Lear: "Nothing will come of nothing."

PRICE EXPLOSION AND THE "EMBARGO" OF 1973

In 1973, all expected the OPEC nations to continue raising prices. To buy for inventory was a profitable investment. The additional purchases raised prices still more and scared everyone more. Then the governments raised taxes, which again raised prices, beginning the cycle anew. The agreements the companies made with the producing governments—of which the US State Department had been so proud in early 1971—were quickly violated that same year, then formally scrapped in 1973, before the outbreak of war in October. Indeed, the scheduled increase, which the OPEC ministers warned would be very large, was actually postponed by the war.

In early October, the Arab oil producers—but not Iraq—cut output during a two-month period. What a disproportion between cause and effect! In the right conditions the beating of a butterfly's wings is said to be able to set off a hurricane. The oil production cutback was less than the net inventory additions in the previous nine months. There was no lack of oil. But fear of the unknown caused panic. A surge of precautionary and speculative demand for ever more inventories multiplied the price several times over.

By January 1974, there were overflowing oil stocks and excess productive capacity. After price volatility upward, one would expect volatility downward. But the OPEC nations curtailed supply while they raised taxes to drive the price higher still.

The production cutbacks and the price upheavals were all too real. The Arab oil producers' so-called embargo against the United States and the Netherlands had no effect. The world oil market, then as now, was one great pool. I was not alone in pointing out, months beforehand, that if the Arab countries embargoed the United States, non-Arab output and diverted Arab output would supply us. The net result would be confusion and wasted motion but no embargo (35). The decreased production and higher speculative demand simply meant a higher price for everyone.

The US Secretary of State bounded all over the Middle East to get the nonexistent embargo lifted, and others hinted darkly at using force. For five months, after the panic subsided and supply was visibly far in excess of demand, the US government was, as Secretary Kissinger later said, obsessed with ending the nonexistent embargo. After 23 years, "the embargo" is still referred to as if it had really happened. The United States was the special enemy, but it was, if anything, better off than the "friendly, preferred" British and French, but not as well off as Japan, which Arab producers had called "odiously neutral."

At home, gasoline prices were fixed. This provoked the mile-long gasoline lines. These lines were made in America, not by Arabs. Crude oil prices, we were told, were to be held and even brought down by the friendship and goodwill of the King of Saudi Arabia. Yet it was a matter of public record that Saudi Arabia acted as largest sellers usually do, as the leader in raising prices. US statesmen gave speeches—now conciliatory, now tough, but always ignored.

Energy "Crisis," "Shortage," Etc.

So began the time of illusions. There was no rush to judgment, but rather an instantaneous judgment. Many believed there was an energy crisis, whatever that meant. The idea of an energy shortage was perhaps rational but had no basis in fact. Many thought the possibility of a monopoly was simply unimportant because the price was bound to rise anyway; the timing and steepness were incidental. The rise would be greater at first under monopoly, slower under competition, but inevitable. Furthermore, a higher price sooner rather than later promoted conservation; hence, the monopolist was the consumer's friend. Much good work was done on energy demand, but supply economics seemed dominated by assumptions about limited reserves and their impending exhaustion.

Some excerpts (I have run sentences together but added nothing) from a brief paper published in 1975 (36, p. 91–93) state the view that had so little credence:

> The recent dramatic increase in price has nothing to do with real scarcity, and is simply the change from a slowly retreating monopoly into a rapidly advancing one.
>
> *We shall never know* our endowment in fluid hydrocarbons. Long before we get to the end of these resources, we shall have ceased to use them, either because the cost has become so impossibly high or because a better and cheaper form of heat has been found.
>
> A functioning market provides a distant early warning signal of scarcity ahead. The existing inventory is more rapidly depleted when owners are reluctant to commit underdeveloped mineral deposits, hoping for larger profits from later exploitation. As development is speeded up, investment requirements must also increase, registering a general expectation of approaching exhaustion. But oil investment requirements outside the United States fell by about half in the 1960s.
>
> Economic growth will not be constrained by lack of oil, but may be by air or water pollution. The heating up of the atmosphere may be as dangerous as some now suspect.

The concern stated in the last sentence of this quotation is now taken more seriously. Nature has provided no fix, and there will be downward pressure on oil and coal prices for a long time.

Aside from the circumstances of the sudden price jump, I thought the clearest evidence of OPEC monopoly was production/investment behavior of the OPEC nations. Previously, the lowest-cost producers had been increasing output most rapidly. But now water ran uphill: Low-cost producers began to produce only as much as they could sell at then-current prices, while the non-OPEC countries produced up to capacity.

Even at the old price level, the return on fresh development investment to the Persian Gulf had been several hundred percent per year. Following the price increase, it was many times higher. I thought only collusion could explain why OPEC investment was contracting instead of exploding. But one could assume that the low-cost producers had a far lower time-preference compared with private companies, and a far lower discount rate on future income. The low-cost producers preferred to leave the oil in the ground for future appreciation than to sell it at the then-current price. This low time-preference assumption still persists (37). One variant of this assumption is that these nations were not profit maximizers; they did not want all the revenues they could gather, but were content to sell enough "for their needs" or to "meet revenue requirements."

The low time preference was not self-evident. An oilman had reported the following to his company in the 1930s when negotiating with Middle East governments: "The future leaves them cold. They want money now" (33, p. 47). Venezuelan experience seemed to be consistent with this assessment. In the 1950s and 1960s, producing governments had always pressured resident companies for more output, never for less.

Moreover, in theory, the more oil costs to produce, the greater the gain in holding it until prices rise. Conversely, the less oil costs to produce, the greater

the benefit of developing and selling it immediately. Yet, worldwide and even within OPEC, we saw precisely the opposite occur.

The price explosion was greeted by distinguished economists as the long-delayed inevitable scarcity. Temporary forces had by chance kept oil and other mineral prices flat or declining for a remarkably long time. My estimates of the price-cost gap and the astounding rate of return on fresh investment fell into a void. Not unkindly, I was reminded that "Hotelling rent" explained it all; that is, the producing nations preferred to hold the oil for the distant future, when it would be worth more. The present value of undeveloped oil exceeded the present value of revenues to be earned by development. For reasons explained above, this argument rested on a false assumption and could not be reconciled with the facts. I did find one actual transaction in undeveloped oil: Saudi Arabia agreed to pay its resident companies a discounted value of 1 to 2 cents per barrel for newly found oil (33, p. 142). This arrangement did not explain a price-cost margin of $12.00 in 1974, let alone higher prices.

CARTEL-WATCHING, 1973–1981

While trying to reconcile my research with new economic literature, I watched the newly fledged OPEC cartel find its bearings. I mistakenly thought that they would not nationalize the resident producing companies. It was in their interest (as Sheik Yamani of Saudi Arabia had pointed out in 1969) to keep these firms as a buffer between themselves and the market. I wrote in 1975: "Haggling over market shares, surveillance, and compensation of losers would be a constant divisive irritant. Confrontation in council, month after month, would strain and I think severely damage the cartel" (43, p. 380). Nevertheless, the OPEC nations expropriated the companies. The compulsion to show the world who was master was too strong. The results I expected soon arrived; the nations have been paying for their moment of bliss. Over the last 15 years, much has been said but little done to get foreign operators back, though the pace will now probably quicken.

In 1976, I suggested a scheme of auctioning import licenses, to cause the exporters (OPEC nations) to bid against one another (39). Japan had auctioned foreign exchange for imports in the 1950s, according to the lowest FOB prices offered. In the mid-1970s, I thought such auctioning would work as well on a wider scale. The plan was recommended to President-elect Carter by his task force on economic policy but was never tried. The President, briefed by the CIA and the new Department of Energy, warned of "a major economic and political crisis in the 1980s as the world's oil wells start to run dry and a physical scramble for energy develops" (33, p. 164). To assure a growing supply, we were told we had to cultivate good relations with the Persian Gulf oil producers, especially

Saudi Arabia. Why these nations should produce more because they liked us was never explained, but the idea allowed statesmen to posture.

I wrongly expected the OPEC governments to raise the price slowly, in small increments, testing the waters each time. In fact, an OPEC committee recommended this approach in 1977 or 1978, yet there was a huge price increase in 1979–1980. Again there was no lack of oil. Even during the brief shutdown in Iran, there was a visible surplus of productive capacity. But Saudi Arabia and the other Persian Gulf producers refused to use this surplus. The second price explosion, like the first, was deliberate. Again the surge of precautionary speculative demand generated a huge price increase, even greater than in 1974, and again production cutbacks fixed the new higher price level. In 1980, as in 1974, a large excess of capacity soon appeared. But restriction of output proved more difficult. The burden of restriction was thrust more and more on Saudi Arabia.

From 1974 to 1982, there was a quick test of the thesis that the OPEC nations were reluctant spenders with long time horizons and low discount rates. The price rise in 1974 had resulted in huge budget and current-account surpluses. By 1978, after only four years, the OPEC nations as a whole (and Saudi Arabia in particular) ran budget and current-account deficits. Their 1980 surplus was the largest ever, and in two years it turned into a deficit. The anticipated higher revenues were overspent even before they were received.

Higher oil revenues made oil producer nations more oil dependent. Oil ruined agriculture and native industry. Towns filled up with dependents for whom the state had to provide food and other imported necessities at subsidized low prices. Subsidies spread the wealth; withdrawal of subsidies threatened disorder. Cutting budget and foreign exchange deficits was hard and dangerous. So decision making was more difficult and less predictable, and pressures to get more money were ever increasing. Moreover, some governments were unstable at home or unruly abroad, or both. Therefore, time horizons for the government producers were shorter than for private companies, and their implicit discount rates were higher. The gains from higher prices were immediate. The penalties—lower sales—were farther off in time. In theory, sellers with high discount rates will raise prices faster and more (40). In 1979–1981, they did.

The Cartel As Political History

Politics had nothing at all to do with the cartel members' basic aim: higher revenues. Whatever a nation wants to spend on, the more money it gets the better.

The OPEC monopoly was distinctive because it was composed of sovereign nations. No private companies in a modern industrial state could even dream of raising the price of oil tenfold. They would damage interests more numerous

and powerful than themselves. Every such state would have its own methods of stopping or punishing them. But in a small less-developed producing country, there is no conflict between producers and consumers. Higher revenues all come to the local economy. The burden is all borne by foreigners. Hence, these sovereign monopolists were completely unrestrained in raising the price of oil.

The Two Cartel Tasks

Political power only removes the obstacles to exercising power; it does not accomplish the two cartel objectives: finding the value-maximizing price and output for the group, and dividing the output and revenues. The route to the first goal is hidden in the "fog of war," so the goal must be approached by trial and error—especially error. The second task is a zero-sum game. Any market change, even a favorable change, means fresh contention over revenue sharing. Under competition, market division is automatic. Each producer carries output to the point where further expansion would raise incremental cost above the price. But in a cartel, each member would profit from higher output and has reason to cheat and to shade the price (by making some terms more favorable) to sell a little more. The two problems must be solved simultaneously. In practice, the group solved both problems by ad hoc expedients, but these did not last long.

The Non-Cartel Producers

Non-cartel producers might have been expected to act like simple price takers and expand output as fast and as much as possible. Some nationalized industries appeared to do this for a time: The Soviet Union, China, and Mexico "are expanding like rational if sometimes sluggish capitalists. However, in most private enterprise countries, political forces have not permitted that simple response of output to higher prices. . . . [because] the producing companies would get 'too big a share' of the increased national income. Governments would rather prevent windfall gains than get the production response" (38, p. 382). In the United States, oil prices came under government control, as gas prices had been for years. In Canada, higher prices led to higher provincial and national taxes, and large-scale disinvestment. The decrease in Canadian reserves in turn triggered a move to restrict exports lest Canada run out of oil and gas. In offshore Britain, "the price explosion of 1973 led to . . . a wild bidding up of factor prices and [a] steep increase in taxation. . . . [Expected North Sea] output . . . will be considerably less than attainable, and there is also a considerable reluctance by private investors to explore and develop further" (38, pp. 382–383).

These and related developments increased OPEC confidence. North Sea and Mexico discovery and development had started before 1973. In northern Alaska, discovery and development was delayed for years because of a dispute

over the pipeline to tidewater. Little could be known about big discoveries after 1973, and development was sluggish. The conclusion drawn was that supply responded very little to price, which reinforced the idea of a fixed amount and encouraged heavier taxation. I did not know how long this "strange and self abuse" would continue.

THE CONSENSUS

The consensus was clear by the mid-1970s. Figure 1 pictures the average forecast of many business and academic experts, compiled and published annually by the International Energy Workshop. Regarding its usefulness as a forecast, the less said the better. But it is important to find the implicit major premises held by many disinterested and well-qualified observers. I think they are two.

First, the current price was close enough to competitive to make monopoly secondary or unimportant. If the price changed, the new value was entered, as more recent data. Its level was still the best estimate of the equilibrium price. But, second, the price would keep rising because of fixed supply and increasing scarcity. The slope of the expected increase became lower in time but was always upward. (My view was that the price had been raised by collusion

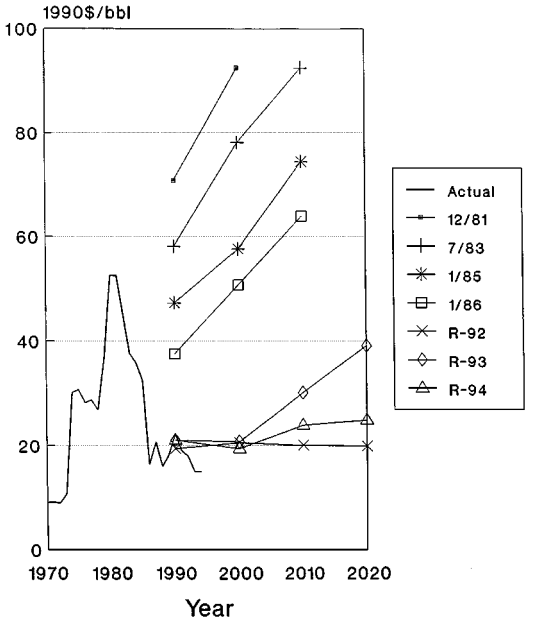

Figure 1 Crude oil prices. Actual and successive IEW polls.

above any possible supply-demand equilibrium and would in the future gravitate downward.)

THE TURNING POINT, AND A NEW RESEARCH PROJECT

The 1979–1980 price increases seemed to incur only the risk of another world recession. The most recent data available (1977) showed no supply or demand response to the higher prices. OPEC perceived a ceiling in the cost of synthetic crude oil, estimated (perhaps correctly) at $60.00, and as shown in Figure 1, at about $96.00. Prices were kept well below that.

But the later statistics showed that the demand response had been an investment response—slow to start, but growing annually as new equipment and practices were phased in. The new price rise reinforced the demand response, partly because governments did not try as hard to abuse consumers by "protecting" them. The $60.00 synthetic cost, even if true, was a non-binding constraint. Consumer demand set the true ceiling much lower.

While the consensus was that only higher prices lay ahead, the cartel struggled to stop or slow the decline. In price fixing, as in singing or mountain climbing, it is easier to go up than to come down. Before 1981, Saudi Arabia had taken the lead when decisive action was needed, in cutting output and raising the price level. Then, by underpricing at the new level, they gained market share and thereby profited greatly.

But after 1980 the cartel had great excess capacity and budget and current-account deficits. Every member shaded and then openly reduced the price to shove the burden on to everyone else. Saudi Arabia, who had the most to lose, cut back output the most, a classic example of "leader's curse" in a collusive group. By the summer of 1985, their exports were down by 80%, and revenues were only a minor fraction of expenditures. The other members would not cooperate.

In late 1985, the Saudis finally began to set crude oil prices at a given margin below uncontrolled product prices. Thereby they automatically matched everyone else's price cuts. Others in the cartel continued to overproduce, and all prices plunged in late 1985 and 1986. By the time the ranks reformed, the drop was over 50%.[5]

[5]An amazing story is now told (41) that Washington used its "special relation" with the Saudis to persuade them to reduce the world oil price, in order to damage the Soviet Union. There is no objective evidence for the story; it contradicts every detail of the public record. [Vice-president Bush's April 1, 1986, appeal for higher prices is perhaps merely comic relief (33, p. 228).] A request for lower prices, if made, would have been as easily disregarded as were earlier requests. But the myth is now widely treated as history.

While the price declined, non-OPEC production in several minor countries began to increase faster than when prices were rising exuberantly. The paradox seemed worth a look. However, this brings us ahead of the story.

The price decline after 1981, and the fall in consumption, indicated that the cartel might have overreached itself and gone higher than its own optimum. I thought it was time for another major research effort, with a dual focus: the historical evolution of the cartel up to (and beyond) the price maximum and a fuller analysis of mineral scarcity. The lack of interest in my proposal was a bit disconcerting.

I wrote in 1983–1984 to every funding source I could think of, but none hinted of a grant. In more than one referee's report, I fear I was called an obstinate crank. Perhaps my denial of the consensus looked like an argument for a flat earth. At the last moment, the National Science Foundation granted much of the amount requested, and I was able to start in the hope that the MIT Energy Laboratory might make up the difference, which they ultimately did. My debt to these two organizations is great. But I do not think I could have proceeded without the support of my long-time coworker Michael Lynch and of the friends, colleagues, and former students who on my 1987 retirement brought out a festschrift (42). I then tried to reexamine supply, restate depletion theory, and apply it to the market since 1970.

SUPPLY AFTER 1981: ECONOMICS AND POLITICS

Lower costs of new reserves added, or of capacity added, do not suffice to prove more plentiful supply. Lower cost may be due to downsizing—discarding the poorer and higher-cost prospects in favor of the better. The industry may thus be moving down the supply curve. But, unchanged or lower marginal cost accompanied by higher output means an outward shift of the supply curve. This was true in the onshore United States for at least 40 years after 1930, the year of the last great discovery (the East Texas oil field).[6]

For the rest of the world, Manoj Shahi and I (44) calculated the approximate investment requirements per daily barrel for many producing countries and arranged them from lowest to highest cost. The result was fairly clear. The crude approximation to a supply curve marched rightward from 1955 to 1975, then stagnated through 1985 because output stagnated. The thesis of rising scarcity had failed again.

[6]But there was evidence of a retrograde movement in crude oil (not natural gas) in later years. I estimated in 1986 (43, p. 155) that the US industry would shrink because finding cost (however guessed at) exceeded the surplus of value over development cost. This has actually happened (see 33, p. 22).

The Underachievers

After 1986, as in 1973–1985, the investment picture was full of ironies. In 1975–1987, Middle East–African OPEC members spent only 1.7% of revenues on oil production investment. Yet after 1986 they complained publicly of financing difficulties. It was not a charade. OPEC countries found it very hard to reduce spending on subsidies, consumption, and weapons (see above). Oil investment and maintenance had to compete with other spending and were postponed. Foreign assets were gone. Saudi Arabia had about $160 billion in assets in 1981, liquidated them all before the 1991 war, and is now in debt. OPEC nations (and others) also lack management-engineering know-how.

For years, OPEC tried and failed to attract foreign investment, which required foreign ownership of producing capacity and freedom of sale. Ownership of the in-ground resource is superfluous. Sovereignty was settled by the unilateral tax hikes of 1950. By 1970, taxes were nine tenths of profits.

The later expropriations made people feel good. If foreigners were brought back in, insiders would lose jobs, contracts, perks, and payoffs. The rest of the public would lose the prized symbol of independence. These barriers to private investment will not soon disappear, either in OPEC or in Mexico, which became the exemplar of public enterprise.

Non-OPEC production was always about to shrink because of so-called limited reserves.[7] In 1986, Petroconsultants Inc. of Geneva revealed to an anxious world that a decline in non-OPEC (excluding the Soviet Union) output was "imminent and unstoppable . . . well before the end of the decade" (i.e. well before 1990). This was based on an analysis of reserves, for which the data and analysis were proprietary, of course.

In the three years after 1986, non-OPEC growth supplied 16% of what the industry refers to as the call, i.e. world consumption growth plus declines in production in the United States and the Former Soviet Union (FSU). In 1989–1992, their growth supplied 44% of the call; in 1992–1995, 76%. The trend should not be extrapolated. But non-OPEC output keeps growing and invites a pause to think about the basics of supply.

In 1995, the real price was about one fourth that of 1981. Yet in 1995, the industry in non-OPEC areas installed nearly twice as much new capacity as it did in 1981. (I think properly estimated reserves would show the same change.) That big rightward shift in the supply curve was not a uniform

[7]So was natural gas. In 1985–1986, Michael Lynch and I did the supply work for a three-volume Energy Laboratory study of world trade in natural gas (45–47). The study never received the attention I thought it deserved. Lynch and I scavenged cost data wherever we could, concluding that supply was ample for a very large-scale expansion in Europe, much growth in Asia, and some in North America. This conclusion too was contrary to the consensus and has held up well.

trend. In some areas, including US crude oil, supply decreased or was barely maintained.

The rightward shift in the oil supply curve was partly due to the growth of knowledge. But in addition, the price decline was a signal to non-OPEC governments and the public to stop dreaming of riches and to start thinking of tax and regulatory reform and privatization. The clearest example is the price decline after 1981 that caused Canada to abandon the National Energy Program and promote investment and exports (48). Much has been done, but the non-OPEC countries are still underachievers, far below their potential. As production taxes are lowered and aimed more at net profits, less at gross revenues, the supply curves will keep moving rightward.

The FSU is the worst underachiever. The pieces of the old national monopoly were given to insiders skilled in maneuvering to seize wealth, not in investing to create wealth. Production fell. The FSU governments have been unable to discard an irrational system and to create the laws and taxes needed for private investment, especially by foreigners leading the way. Pathological suspicion of foreigners, which so impressed the visitor of 400 years ago (49), has cost them a flow of export earnings that would have immediately eased the transition from the Soviet economy to a market economy.

A basic fact in the world oil industry is the cost differential between the Persian Gulf and the rest of the world, which is due largely to the difference in oil flows per well. The differential has shrunk in 30 years (see above), but so has our knowledge, as data get more scarce. Costs have come down greatly in the North Sea and have declined elsewhere but not as much. Instead of knowledge of investment per unit of reserves or of capacity, we have the so-called finding costs per barrel of oil equivalent. This concept is incoherent in two ways. First, it is impossible to know how much oil or gas was found in any recent year. Second, there is no such thing as oil equivalent (see below).

But what about 2010 AD—can one prove that something awful won't happen by then? Of course not, just as I could not prove in 1966 that there would be plenty of oil in 1996. The Industrial Revolution, as Karl Marx saw it, started around 1750. By 1789, some were already writing about exhaustion of British coal. As production rose, so did worry. In 1865, a famous book was written (50) to warn of a coal shortage ahead.[8] People saw a future oil shortage 30 years ago; they now see it in the next 30 years.

[8]It was in fact a good book, based not on an assumed fixed stock but on rising marginal costs. Jevons went on to sketch out a supply curve, based on the cost-determining factors of depth, water, ash content, etc. But he never factored in what he was quite aware of: new technology, the expansion of existing deposits, and the discovery of new ones. Therefore, his conclusions were wildly wrong.

MINERAL DEPLETION THEORY RECONSIDERED

Mineral depletion seems self-evident. There is only so much of the resource. Every unit used up today means one less for the future. As the stock shrinks, its value rises. The logical consequences are many and fascinating. There is great seductive power in an elegant theory, based on a self-evident axiom, that predicts the prices of minerals—something not possible for any other prices.

Max Planck once described what he called phantom problems. One of them "used to keep many a great physicist busy for many years: the study of the mechanical properties of the luminiferous ether" (51, p. 56). In time, physicists decided they could not find the luminiferous ether, did not need it, and had best forget it.

After 1973, a great structure of theory and calculation arose as an upside-down pyramid, resting upon one assumption. As a Nobel laureate wrote, "[Hotelling] applied the calculus of variations to the problem of allocation of a *fixed stock* over time. All of the recent literature is essentially based on Hotelling's paper" (52, p. 67; original emphasis). Thus, "an exhaustible natural resource . . . a fixed stock of oil to divide between two or more periods" (53, p. 655; see also references in 43, p. 219) and the resulting "basic upward tilt" in the price of oil kept some fine economists busy for many years. But the fixed stock, like the luminiferous ether, does not exist. Its optimal allocation over time between us and our posterity, i.e. deciding how much of the remaining stock to use up, is a phantom problem. A milder assumption, which destroys much of the theoretical structure, is at best a half-truth: Humankind is condemned to go from good ore to bad and from bad ore to worse. But increasing knowledge has so far more than overborne decreasing returns.[9] The burden of proof, if it rests on anyone, rests on those who think the process will reverse in the foreseeable future or has already reversed.

Often used to bolster the assumption of greater future scarcity are estimates of probable and possible reserves, or of undiscovered reserves, which is surely an oxymoron. But these estimates are simply forecasts of future cumulative demand and supply, allowing for the growth of knowledge. Nobody knows any of these trends, and nobody should pretend to know them.

Lewis G Weeks, a leading geologist of his day, believed that ultimate reserves are ordinal. "A potential resourse estimate . . . is an indicator of the area or areas in which [the exploration] dollar may best be spent." This conclusion reveals the

[9]Mineral economics and human nature do not change. There were diminishing returns in the Athenian silver mines at Laureion, then a new strike in the old field in 484 BC, which let the Athenians build a navy to beat the Persian Empire back from Europe. The Athenians then used the navy to acquire an empire as well as a hubris, which got them into a ruinous 30-year war.

real significance and proper use of these estimates. They imply nothing about current and future scarcity (54).

The idea of finding reserves is very misleading. Reserves, like other assets, are not found but made. Every day, reserves are added in thousands of places. The industry is a great sensing/selection instrument that scans all deposits, old and new, to develop the cheapest increment or tranche into a reserve-addition. Oilmen invest in a wide range of projects: improving recovery; putting more wells into the same pool; putting wells in adjacent strata or pools; investigating prospects that are more or less known; and searching for new reservoirs or even new fields or plays, which are areas expected to contain fields. A discovery initiates a long sequence of reserve-additions through development, in copper and iron ore as in hydrocarbons (55).

All these methods of reserve addition are partial substitutes for each other. All are in competition for investment funds. Buying reserves is an alternative to all of them. Thus, the market value of developed reserves in-ground is comparable to, and ties together, all methods of reserve creation. Breathless hype about "an increasingly desperate scramble for giant, low-cost reserves" (56) supported by no evidence is refuted by flat values for already developed reserves. These values reflect expected wellhead prices and therefore differ only to a minor degree among countries in which oil production is competitive (see below).

This analysis brought me to the prevailing view, the theory well summarized in Das Gupta & Heal (57).[10] There might be a phase of exploration and a temporary price drop, followed by the final irreversible price rise. Das Gupta & Heal stated the basic Hotelling Valuation Principle: $V = P$, which means the value of oil in-ground equals the current net spot price, i.e. net of the cost of extraction. Since the price must rise at the rate of discount, the discounted future price is the current spot price. Thereby the holder of the underground asset does not lose by holding the oil rather than extracting and selling it.

Accordingly, some econometric research was done in comparing price changes and interest rate changes. Miller & Upton (59) first praised these efforts and then discarded them. Their approach was to take a sample of companies, and

[10]Heal & Chichilnisky (58) applied the theory. According to their analysis, oil prices had to rise because of the fixed stock. (They did not note that most mineral prices were flat to declining.) The in-ground value of oil depended on the rate of interest, as proved by econometric studies. But they cited Miller & Upton to prove that the in-ground value was equal to the net price. They ignored Miller & Upton's later work (60), which showed the value to be only one half of the net price. Heal & Chichilnisky said the international oil companies had held the price artificially low before the governments took control. They did not explain why companies should reduce their own profits. They said the companies had exploited the oil deposits too intensively. In fact, the rates of exploitation in the Persian Gulf were the lowest in the world, and the governments had ceaselessly pressured their resident companies for more, not less, output.

subtract out each company's other assets, to estimate the value of its oil and gas reserves. They concluded that $V = P$ is true: The value per barrel of oil equivalent (BOE) is indeed close to the net price of the BOE.[11] But their second study (60) showed that the value was only about half of the current spot price. Miller & Upton demonstrated their scientific integrity by promptly publishing these results as well. They analyzed the reasons for so radical a difference, but they did so wholly in econometric and statistical terms. It never occurred to them to state, even as a mere logical possibility, that the values in the second study might be more accurate than those in the first study.

Building on my previous work, I reached some results that included $V = P$ as a special case (43, 61). The crucial variables are as follows: P = current wellhead price per barrel (net operating expenses, royalties, and excise taxes); V = current in-ground value of a developed (proved) reserve barrel; K = current development investment per additional barrel; $(V - K)$ = current in-ground value of an undeveloped barrel; a = production decline rate, percent per year; i = relevant discount rate, percent per year; g = change in price, percent per year.

It can be proved that

$$V = Pa/(a + i - g).^{12} \qquad 1.$$

If we postulate $i = g$, then a cancels out and $V = P$. Conversely, if we find empirically that $V = P$, it follows that $g = i$.

The United States became the laboratory example (62). It was the only place with statistics and a long enough history to let basic forces work themselves out. Estimates of companies' in-ground reserve values had been privately compiled since 1947. They had passed a market quality test of sorts and could be taken as showing long-run trends. For later years, there are actual transaction data, which are obviously better (63–66).

If the received paradigm was correct, one should observe a long-term increase in the wellhead price P, the development cost K, and the in-ground values of a

[11]The BOE does not exist. Gas:oil price ratios and cost ratios have varied substantially. Moreover, changing gas:oil proportions in reserves and output introduce haphazard year-to-year changes in BOE. Thus, there are errors in the independent variables of the regression system. Their results, therefore, are unacceptable for reasons both of econometrics and of substance (65).

[12]For the derivation of reserves R from output Q, see above, footnote 2. Let PQ equal initial-year revenues. Price P is subject to an annual discount factor i, the interest rate, less the expected annual rate of price increase g. Initial quantity Q must be discounted by the decline rate a. These discount factors are all independent and multiplicative. $VR = PQ\int_O^T e^{-(a+i-g)t}dt$, converging at unlimited T to $VR = PQ/(a + i - g)$. But from footnote 2, we have $R = Q/a$; hence, $V = Pa/(a + i - g)$. Let K be the independently measured development investment per barrel. Then U is the value of an undeveloped barrel. $V - K = U$. U is the equivalent of maximum economic finding cost (see above) but applied to reserve barrels in-ground rather than to barrels as produced and with no assumption about future changes.

developed barrel V and of an undeveloped barrel $(V - K)$, which was a form of the maximum economic finding cost (see above). In fact, all four variables were stable to declining from 1947–1972.

As for the expected equality $P = V$, from 1947–1994, P was rarely less than two standard deviations above the mean of V. The results supported an industry rule of thumb, which must have reflected industry experience, that V is roughly one half of net P (one third of gross P). For the years before the turbulent 1970s, one could even verify the components of the customary $P = 2V$ ratio. Since the price was stable to declining, one might assume expected price increase $g = 0$. The decline rate and the prevailing hurdle rate were each about 9%. Therefore, V/P should have been, and in fact was, stable around 0.5.

There were other verifications. In theory, the value of an undeveloped barrel $(V - K)$ should lie between a maximum of equality with V, and a minimum of zero (61, p. 55). The value has fluctuated within that range, around 0.6. Equation 1 predicts that the higher the value of a, the higher the ratio V/P. (The quicker the recovery, the higher the present value of the income stream.) This prediction is supported by some scanty data for oil reserve sales in the 1950s, by the comparison of V/P ratios for coal and for oil reserves (67), and by natural gas reserve sales from 1990–1994. [Oil reserve sales had the right sign, but coefficients were not significant (66).]

Furthermore, one can rearrange Equation 1 as follows: $g = i + a[1 - (P/V)]$. With separate prices and in-ground values for gas and oil, one can calculate g_o and g_g, the expected price changes for oil and gas. In the late 1980s and early 1990s, the higher g_g was in accord with industry opinion (63, 65).

Equation 1 is well borne out. The Hotelling Valuation Principle is discredited; it is a valid theory built on a wrong premise, the fixed stock. It was bound to and did give wrong results.

Estimating the value of oil and gas reserves also helped in measuring sustainable national income. One can now measure the value of in-ground assets depleted and therefore of the net change. The 1994 net reserve changes, valued at 1994 asset prices, were minus $2.4 billion for oil and plus $1.8 billion for gas. The total private value of developed oil and gas reserves was $233 billion; an allowance for transfer payments added approximately another 20%.

As part of the allowance, we estimated that the federal government's royalty rights on proved reserves had a value of nearly $14 billion in 1994. But from 1954–1991, the value of lease bonuses received, for future discoveries, was 1.25 times the royalties received. Bonuses ranged from a maximum of 9.4 times royalties in 1974 to 3.7% of royalties in 1991. Assuming for the future the same probability of price eruptions and declines as in the past, the present value of future bonus payments is very roughly 1.25 times the value of current royalties (66). If so, the value of all federal lands is 2.25 times the value of royalty lands, or $31 billion.

My research was aimed to translate the general statements made in 1975 (see above) into a more precise statement and an actual measurement scheme for changes in oil scarcity. The in-ground values of the developed and the undeveloped reserves were market values and expressed industry expectations. They could have been wrong but had to be taken seriously. I like to think of my results (alone and with Campbell Watkins) as a first or Model T version. Improved, they might also measure changes in productivity. But the basic data available in the public domain are dwindling in amount and quality. The vacuum is filled by pseudo-measures.

Differences of Opinion

Miller & Upton (59, p. 24) said of the Hotelling Valuation Principle and the long-run rise in price: "No viable alternative paradigm exists." In Mexico in 1980, I heard economists argue that since Mexico reserves were about 50 billion barrels and the current market price was about $40.00 per barrel, the present value was approximately $2000 billion. Hence, foreign borrowing of about $60 billion was conservative.

The *American Economic Review* published an article (67) estimating along similar lines that the current value of oil and gas underlying land holdings of the US government was $819 billion, "higher than the privately owned debt" it owed. I criticized their theory and numbers in a four-page note submitted to the *American Economic Review*, pointing out that if, as a check on their estimate, one used (*a*) the 1985 not 1981 price, (*b*) the discount rate required by the Securities and Exchange Commission, and (*c*) a constant future price, then the value of US hydrocarbon holdings was about 5% (1/20) of their estimate. [Years later, as described above, a completely independent estimate (66) came to less than 4%.] My note was rejected by the *American Economic Review*. My selected papers (43) were not reviewed in the sister publication, the *Journal of Economic Literature*.

CONCLUDING THOUGHTS

Having enjoyed a lifetime of teaching and research I look back with some mild guilt at having been paid to do what I took pleasure in doing. Perhaps illicit enjoyment is doubly pleasant. I am also frustrated at having accomplished too little and at not being heard. A Venezuelan friend and former student, Mariano Gurfinkel, told me years ago, "Don Quixote saw giants. Sancho Panza saw only windmills. You are Sancho Panza."

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