

**Sustainable Growth and Valuation
of Mineral Reserves**

by

M. A. Adelman

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M. A. Adelman
Center for Energy & Environmental Policy Research
M.I.T.

ABSTRACT

The annual change in the value of an in-ground mineral is equal to the increase or decrease of inventories ("reserves"), multiplied by the market value of a reserve unit. The limited shrinking resource base does not exist. Its inter-generational optimizing is a phantom problem. If there is any "Hotelling rent" it is captured by the reserve market value, which is created by investment in knowledge (exploration) and in productive facilities (development). There are problems of concepts and data. But examples for recent years suggest that mineral value changes are small.

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SUSTAINABLE GROWTH AND VALUATION OF MINERAL RESERVES¹

M. A. Adelman
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To reckon the sustainable national product in any year, we must subtract the value of assets used up in that year. This paper covers mineral assets, particularly oil and natural gas. For this task, we need a theory of mineral values and depletion.

A paper published ten years ago (Boskin et al 1985) calculated the value of the U.S. Government's mineral assets, mostly oil, by taking 1981 prices and assuming they would increase by 3 percent real, i. e. by 43 percent by 1993. In fact, the real oil price fell about 70 percent. The overstatement is by a factor of 4.8. Then the authors discounted future income at a riskless 2 percent. If one uses a conventional 10 percent, that shows overstatement by a factor of 5, or a total overstatement of 24 times. This was no aberration. It followed what is still the received theory of mineral depletion.¹

The received theory In its current professional form the doctrine now comprises a large body of theory and econometrics,

¹ This paper is a shortened and re-written chapter from a forthcoming book, The Genie Out Of The Bottle: World Oil Since 1970 (Cambridge: MIT Press, 1995). It draws on The Economics of Petroleum Supply (Cambridge: MIT Press 1993), particularly chapters 11-13, and on a paper, "Finding and Developing Costs in the United States 1945-1986", in John R. Moroney, ed., Energy, Growth and the Environment: Advancement in the Economics of Energy and Resources, vol. 7. (Greenwich, Conn.: JAI Press, 1992) For other works referred to, see Note on Sources.

and a systematic treatise by DasGupta and Heal (1979). There are many variations on a simple and apparently self-evident proposition.

There is only so much of the mineral resource. Every unit used today means one less for the future. As the finite stock shrinks, its value rises. The owner must find the optimal way to ration it out, the correct rate of exchange between present and future use. If conduct is rational, the present value of any barrel in the ground must equal that of every other barrel, regardless of when the barrel is to be produced. Otherwise it would pay to shift the barrel from a lower-value year to a higher-value year. As compensation for keeping the asset in the ground for later use, the price must rise at the "appropriate" discount rate. It follows, and is basic to the theory, that the value of a unit in the ground is equal to the current price, net of operating cost.

What is the correct discount rate for discounting a flow of output from a deposit in ground? Market discount rates will not do, because they relate to the supply and demand for investible funds. But the distinguishing mark of a mineral resource is that it precedes investment. The value is born not made.

Some economists think the time to exhaustion is so long that market prices of mineral assets do not express real scarcities. The market cannot work. Even those who do not go that far still seek a rate unrelated to investment and investment risk, as did (Boskin et al). The appropriate interest rate is considered as

the riskless rate or perhaps a "social discount rate" to be evolved by some kind of political process. Higher discount rates means faster depletion, threatening social catastrophe.

Applying the theory runs into problems. First, mineral prices should rise over time; in fact, the trend is if anything down. Second, if the value of the in-ground barrel equalled its current net price, that would be a very convenient rule of thumb for the oil industry. In fact, there has been a rule of thumb for many years: a barrel in ground is worth one-third the gross wellhead price, or half the net price.

Moreover, since it should not matter whether the barrel is sold early or late, a barrel which is to be produced quickly should be worth no more than one which is to be produced slowly. Yet papers written forty years ago--I regret that there is nothing more recent--show clearly that a reserve with a high production: reserve ratio sells for more than a reserve with a low ratio. This can be shown to make good sense. (See Appendix Par 3, and Adelman 1993, page 228)

Mineral depletion theory restated The physicist Max Planck once described "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." (Planck 1949, p. 56) In time, physicists decided they could not find the luminiferous ether, they did not need it, and had best forget it. (As chemists had forgotten phlogiston.)

Particularly after 1970, the study of "an exhaustible

natural resource...a fixed stock of oil to divide between two or more periods" (Stiglitz 1976) and the "basic upward tilt" to the price, kept some fine economists "busy for many years". But the fixed stock is like the luminiferous ether--it isn't there. Its optimal allocation over time to do justice as between us and our posterity is a phantom problem.

No mineral, including oil, will ever be exhausted. Only a portion of what is underground will ever be extracted. If and when the cost goes above the price which consumers are willing to pay, the industry will begin to disappear. How much was in the ground before extraction began, and how much is left when it stops, are both unknown and unimportant. The amount extracted depends from first to last on cost and price, nothing more.

Curves like Figures 1,2 please the eye and sum up the history of many industries. On the horizontal is time, on the vertical is production. The upper curve shows it for each period, and the lower cumulates it up to the end of each period. The cumulative curve first grows at an increasing rate, then flattens to approach the limit.

For 1948-1990, the graphs

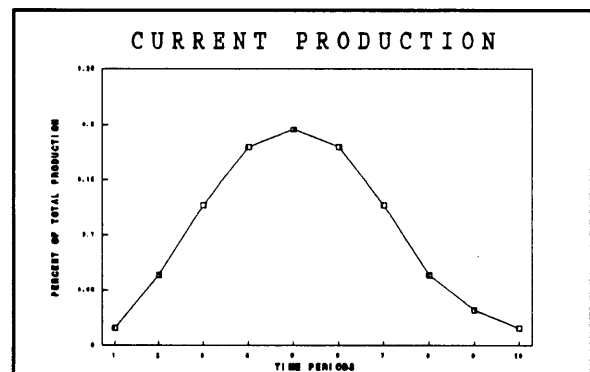


Figure 1

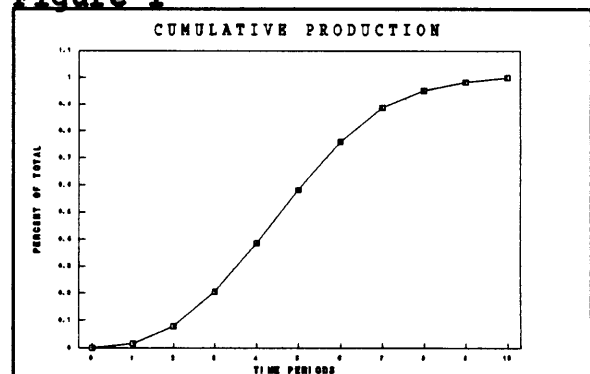


Figure 2

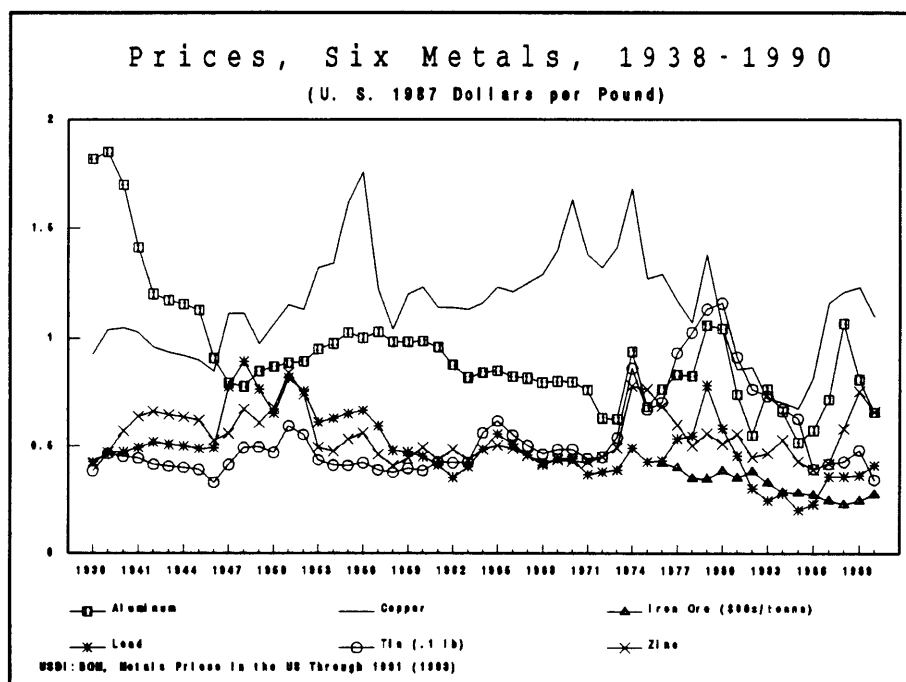
are a fairly good picture of the production of $33\frac{1}{3}$ RPM phonograph records; for 1953-2000, of production of mainframe computers, which IBM expects will cease by the end of the decade. [Wall Street Journal 9-12-94:B4] As was pointed out 60 years ago, most manufacturing industries have followed similar curves, whereby the rate of growth at first increases, then declines. (Burns 1934) Nobody suggests that the total cumulative output of a manufactured product over time is somehow fixed in advance, and must stop when there is "nothing left to produce."

The cumulative amount cannot be estimated in advance, unless future costs and prices are known. A forecaster might extrapolate the growth of phonograph records or mainframes (or vacuum tubes, typewriters, horseshoes, whale oil, etc.) into a logistic curve, based on his gut feeling for prices, costs, and how long it would take until the product was displaced by something better. He could be right, for people may know much more than they can prove. But there would be no way to tell. A logistic curve for a mineral industry is no different.

Reserves=inventories Mineral production is a flow from an unknown physical resource, first via exploration into identified "fields" and "reservoirs," then via development into current inventories or "proved reserves," to be extracted and sold. Reserves are renewable and constantly renewed, if--and only if--there is enough inducement to invest in creating them. The illusion of a fixed resource, forever running down, hides the real problem.

The real cost-price problem There is a good reason why the costs of renewing mineral reserves should keep rising, and prices with them. All else being equal, the larger more accessible fields would be found first, even by chance. Once found, the better deposits (lower cost or higher quality) would be developed first. As mankind went forever from good to bad and from bad to worse, minerals should become ever more scarce, and prices rise.

What really happens is shown in Figure 3: six important metals over 50 years. A simple time trend shows three statistically significant decreases (aluminum, lead, iron ore);



one significant increase (tin); one borderline decrease (zinc) and increase (copper). There is an endless tug-of-war, diminishing returns versus increasing knowledge, which includes formal science and technology in a two-way interaction with a vast amorphous body of know-how.² Mankind has won big--so far. I

think our successors will wonder why it took economists so long to see that the ghost of mineral scarcity should be laid to rest along with the ghost of land scarcity.

One should not think of Figure 3 as "three downs, one up, two undecided, the downs have it". What it really shows is that over time each mineral price has fluctuated as one or another force has dominated. Therefore a unit in the ground is a risky asset. The discount rates which govern holding it, or creating more of the same, are risky rates .

CREATING OIL RESERVES

A new well can produce an initial daily amount, which will decline over time because of pressure loss, water encroachment, etc. (Additional investment in "enhanced recovery" may bounce the output back up.) Operating expenses per well are fairly constant, hence cost per barrel must rise as output declines. When it just equals the market value of the output, production stops at the "economic limit." The estimated aggregate output of the new wells over time is the "proved reserves added" or "reserves booked".³ This is the marginal cost of providing inventory. The unit value and the marginal cost of renewal constantly gravitate toward each other throughout the market network.

In the United States, annual reserve estimates are accurate enough to permit estimating the annual net and gross additions to reserves. There are also reliable data on the expense of drilling and connecting new wells. Until 1992, we also had a record of non-drilling investment outlays. Investment data do not always

closely match the reserve data, but one can estimate cost per additional barrel added, year by year, over a long period, within tolerable error limits.

Reserve growth in a field Once a field is found, reserves are created over time. In California, the Kern River field was discovered in 1899. In 1942, after 43 years of depletion, its "remaining reserves" were 54 million barrels. In the next 44 years it produced not 54 but 736 million barrels, and had another 970 million barrels "remaining" in 1986. The field had not changed, but knowledge had--science, technology, and not least, the detailed local geology learned by development.

In England, as the onshore Wytch field was developed, it was perceived to extend under the sea. A 1991 development plan for drilling the undersea section from an artificial island was rejected because it was in a scenic area. Two years later the undersea reservoir was reached by drilling horizontally from the onshore, to a record length. The investment was actually 56 percent less than with the island. (Oil & Gas Journal, January 3, 1994, p. 30.) Wytch reserves will be increased accordingly. These examples are unusual but help us understand how most reserve creation is in old fields, and how reserves eventually booked are many times the initial estimate.

Persian Gulf A special expert mission estimated Persian Gulf reserves in 1944 at 16 billion barrels proved, 5 billion probable. By 1975, those same fields, excluding later discoveries, had already produced 42 billion barrels and had 74

billion "remaining". Both numbers are much larger today, but not published. Indeed, since 1981, we no longer have even current Gulf production by fields. We cannot tell when fields grow together into one, as several grew into the Saudi giant Ghawar. But Gulf discovery effort has been small. Probably most output is still from those pre-1944 fields. Cumulative 1945-93 Gulf output was 188 billion barrels, nine times the 1944 estimate. At end-1993, Gulf "remaining reserves" were 663 billion--estimated more generously than they would be in the USA.

"Ultimate reserves" Along the way, predictions of "undiscovered" or "ultimate" reserves have repeatedly been made, and surpassed, sometimes with embarrassing speed. At end-1984, it was estimated that there was a 5% probability of another 199 billion barrels remaining to be added at the Gulf, ever. Within five years, it had already happened.

These "ultimate reserves" are implicit forecasts: how much it will be profitable to find, develop, and produce, given current costs and current knowledge. The estimator of "ultimates" is doing economics without knowing it. We pointed out earlier that a forecast may be right,⁴ but we cannot tell. As knowledge grows, so do the "ultimates".

United States In the United States, crude oil discovery peaked in 1930, when proved reserves were 13 billion barrels. In the next 60 years, the US ex-Alaska produced 130 billion. The inventory turned over ten times and is today about 17 billion (with another 6 in Alaska). Many small fields were found. More

important was the continuing expansion of old fields. In 1966-1977, the only years when comparison is possible, 19 billion reserve barrels were added, of which 17 billion were in fields discovered before 1966.

These huge new reserves in old fields were no gift of nature. They were a growth of knowledge, paid for by investment. This history explains why today in various parts of the world there is interest in letting foreign companies develop so-called "marginal" fields. Much oil can be added in these fields, an additional return on the knowledge gained by operators elsewhere, especially in the USA.

The sensing-selection instrument At any given moment, reserves are being added everywhere. The industry is a great sensing-selection instrument, scanning all deposits, old and new, to develop the cheapest increment or tranche into a reserve. The reserve-increments of any given period are overwhelmingly in existing fields. Nobody "finds" a reserve, just as nobody finds a factory. Oilmen find new fields, then new reservoirs in old fields, and new strata or pools in old reservoirs. Development usually leads to discovery just as discovery usually leads to development. The constant search for least-cost prospects takes the industry to the fringes of known reservoirs, and beyond it. The search process is driven by cost comparison.

PETROLEUM DEVELOPMENT COST

In a brief treatment, we can safely neglect operating costs, and treat them largely as a subtraction from price. Development

investment expenditures are made to drill and complete wells, install equipment, and connect to a pipeline or tanker terminal. Marginal development investment is the amount spent per barrel newly booked into reserve inventory, or per barrel of newly installed capacity. (Endnote 3 shows the conversion between reserve-additions and capacity-additions).

The harder we squeeze a sponge, the less the additional liquid from squeezing still harder. The more intensive the development of a reservoir, measured by the ratio of production to reserves, the higher the marginal cost per unit. Development expands reserves and capacity so long as the cost is below the value.

But the value, allowing for location and quality, is the same for all pools because it is derived from the market price. Therefore, over any area where capital can flow freely, marginal cost in every single project is in competition with marginal cost in every other project. Under competition, operators keep expanding the better projects most, driving marginal costs up toward equality everywhere.⁵ But the average cost, the total of all expenditures made from the start, divided by the total of all reserve barrels added from the start, varies enormously among pools. The rent per barrel produced, which is the difference between marginal and average cost, will vary even more, and there is no reason to expect equality, ever.

If the process continued indefinitely, lower-cost wells would expand most. Their marginal cost would rise until it became

equal everywhere. This result is postponed as new choices appear.

The discount rate (return on investment) Return on investment drives the whole process of reserve-addition. Since there is no pre-existing stock, there is no pre-existing value. The discount rate in any given kind of oil development is governed by risk, as in any other investment.

More intensive development means a higher ratio Q/R , production to reserves. This raises the required investment per barrel. But--it speeds up the inflow of revenues, and raises present value. A higher discount rate penalizes slower depletion. It also raises the operator's cost of investing more to deplete faster. Thus it makes quicker depletion more desirable, but less accessible.

Macbeth's porter said of strong drink: "Lechery, sir, it provokes and it unprovokes. It provokes the desire, but it takes away the performance." So too, a change in the interest rate affects development both ways, to speed it up and to slow it down. The net effect is probably small.

DEVELOPMENT COST, IN-GROUND VALUE, FINDING COST, "SCARCITY RENT"

Substitution among development, purchase, discovery
Operators invest in a wide gamut of projects: improved recovery; more wells into the same pool; wells into adjacent strata or adjacent pools; prospects which are completely known; less completely known ... and so on to the deliberate search for new reservoirs and new fields or even new "plays" in new areas expected to contain an array of fields. "Development" shades

into "exploration", or in French recherche, i.e. research.

All these methods of reserve-addition are imperfect substitutes for each other, and all are in competition. If development is becoming more expensive, it pays more to explore for new pools and fields to freshen the mix and moderate the increase in development cost. Conversely, if the newly-found fields are getting smaller, deeper, more heterogeneous and faulted, etc. then development cost per unit of reserves booked into those new fields will be higher. This pushes operators into drilling more wells into and around the older pools, and to drain the older pools faster. Thus higher finding cost is registered in higher development cost.

But there is no way to calculate past finding cost per unit. (A popular expedient, "finding cost (or replacement cost) per barrel of oil equivalent" is well worth avoiding. See Appendix Note 2.) Annual exploration expenditures in the USA were tabulated in 1955-1991, but we have hardly an idea how much was discovered in a given year. A discovery engenders a stream of reserve-additions over decades, perhaps over more than a century. At any moment, operators calculate the odds on finding a new pool of a given size and development cost in a given place. There is no way to aggregate those estimates, even if we knew them.

So finding cost is a blank, but there is often a proxy. An alternative to adding reserves by any combination of developing-finding is simply to buy them. Reserves of oil and gas are frequently bought and sold, as are companies which own them.

Hence the market value of developed reserves is comparable to the cost of all other methods of reserve-addition. Because all are substitutes, changes in the cost of any are an indicator of changes in the cost of all the others.

Increasing oil scarcity means increasing values and costs across the board. A higher cost of finding and developing raises the value of a barrel already developed. Conversely, a higher value of a barrel in the ground is a greater incentive to invest more to create more. This drives up the cost. Thus in-ground value and finding-plus-developing cost always gravitate toward each other.⁶

The structure of prices, costs, and values Table I shows the layers in the USA in two recent years. Let the reader beware: first, comparison of any two years is chancy. Second, some of the statistics are subject to wide error. The "value" estimates are a fragment from a current research project by G.C. Watkins and myself. But by looking at actual numbers we can put some flesh on the bones of economic theory. Then we can look at long-term changes to gain perspective. I conclude with a suggested procedure for calculating the value of oil assets used up in a given year.

Table I. Price, Cost, In-ground Value
Two Recent Years USA
(Dollars per barrel)

	1984	1992
1 Gross wellhead price	25.88	15.99
2 Net price (ex operating costs, royalties, taxes)	16.67	10.68
3 Reserve in ground, market value	6.94	4.71
4 Development cost	3.84	2.87
5 Discovery value (line 3 less line 4) ("user cost")	3.10	1.84

Sources:

Line 1, Department Of Energy, Monthly Energy Review

Lines 2,4, factors from [Adelman 1993,p.248-250]

Line 3, average of "pure oil" market transactions, with no gas reserves. (From a current research project with G.C. Watkins)

Note. The operating margin (line 1 less line 2) includes 15 percent of the price as royalty. This is no cost, but rather a share of the profit. Another 5 percent corresponds to excise taxes, which are in part a charge for services (police and fire protection, etc.), in part a taking of profit. The true social current cost is not a third, but less than 20 percent of the price. However, the in-ground value of the reserve depends on the net to the owner, not the net to society. The development cost has been reduced by 11 percent to allow for the tax allowance. Thus lines 2 and 4 are private values, comparable with line 3, and permit the subtraction of line 4 from line 3 to arrive at line 5.

Factors affecting the cost of holding the asset oil in-the-ground, to get from line 3 to line 2:

	1984	1992
Production/reserves	0.108	0.101
Decline rate	0.096	0.091
Holding time (half life) of asset, years	6.131	6.574
Annual appreciation in value	0.154	0.133
Riskless rate	0.122	0.062

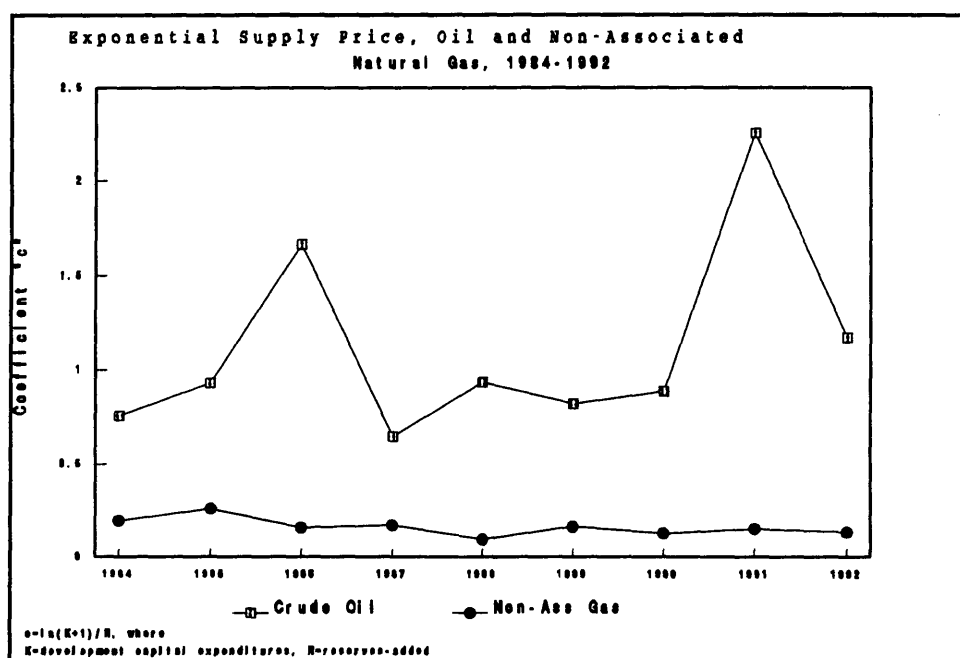
Production and reserves data from DOE/EIA, decline rate computed by formula in Appendix 1. Holding time computed from formula $T' = \ln(1 - (.5Ra/Q)) / -a$. Riskless rate, from Economic Report of the President, interpolating between 3- and 10- year Treasury notes.

The traditional industry rule of thumb, that the market value of an in-ground reserve fluctuates around one-third of the gross price, or one-half the net, has held fairly well in the past (see below), but seems to understate today. In the USA, a reserve barrel is held in the ground for production on average in 6 to 7 years. The increase in value from line 3 to line 2 is compensation for the investment in holding the barrel. The measure is inexact, but it is within the range of industry discount rates. It decreased with interest rates generally as inflation eased.

The difference between in-ground value of a developed barrel and its development cost is the discovery value of an undeveloped barrel, "user cost." It is sacrificed, over and above development cost, by the decision to develop. Under stable conditions, it is a proxy for finding cost. When this discovery value equals or exceeds expected finding cost, it is the signal for an investment inflow into exploration. Where cost exceeds value, there is no investment.⁷

Aside from errors, especially for a residual like Line 5, domestic oil is getting more scarce. True, development cost per reserve unit declined from 1984 to 1992. But reserves-added in 1984 were 3.8 billion barrels; in 1992, only 1.5 billion. The lower marginal costs resulted from discarding the poorer prospects.⁸ The supply curve swung to the left. The industry moved down the curve. Discovery value fell more than development cost, and, I think, was below finding cost.

Figure 4 shows diverging development cost trends for oil and gas since factor supply prices approximately stabilized in 1984. Of course the supply coefficients are very crude, but I doubt that better ones would make much difference. I have no explanation for the divergence. But oil and gas values are set in very different markets. Gas is a self-contained market, where prices and costs are mutually determining. But the wellhead price of oil is set exogenously. It is equal to the world price, hence the cost is no longer a floor.



Price, cost, and reserve values in the USA-- a test of depletion theory Table I presented four measures of oil scarcity, short and long run. Figures 5 and 6 show them over a long period, but much of it based on inferior data. The year 1948 marked the end of the repressed wartime inflation and industry distortion.

Figure 5.
CRUDE OIL: PRICE, IN-GROUND VALUE, DEVELOPMENT COST
USA 1946-1973

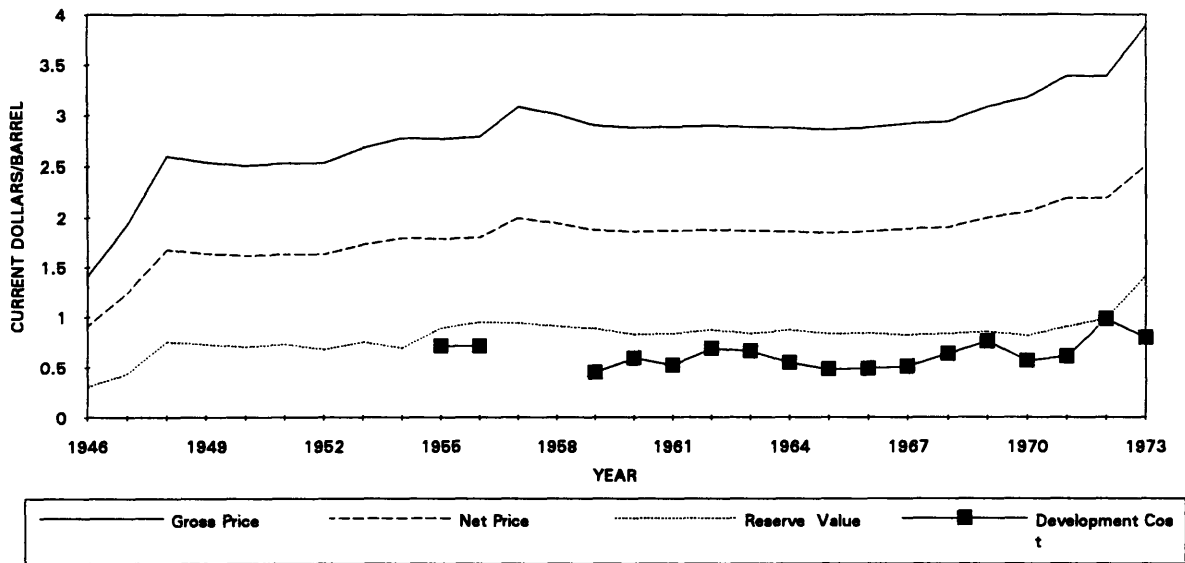
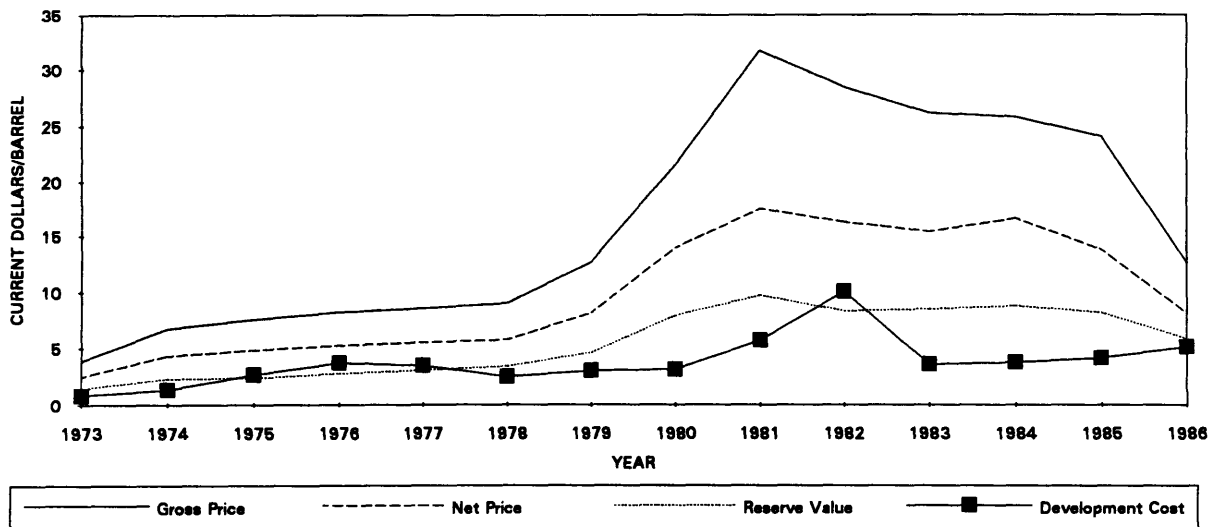


Figure 6.
CRUDE OIL: PRICE, IN-GROUND VALUE, DEVELOPMENT COST
USA 1973-1986



A long-run increase in prices and reserve values because of the fixed stock of "non-renewable resources", etc., would cumulate over 24 years, even at 2 percent per year, to a 61 percent rise. Since the price level doubled from 1948 to 1972, the nominal increase--in oil prices, reserve values, and development costs--should have been by a factor of 3.2. There was no such thing. Real prices and values actually declined.

Additions to reserves were fairly stable before 1972, between 2.5 and 4 billion barrels per year. Incremental development cost fell after 1960, but this was a one-time gain from gradual easing of wasteful regulation. The stable price, over and above remaining regulatory waste, was enough to pay for an inflow of reserves which was slightly greater than the current outflow. USA oil reserves were in a steady state; production even grew slowly.

Conclusion on oil scarcity and "scarcity rents" Development cost is a measure of long-run scarcity. So is reserve value, which is driven by future revenues. They move in the same direction, up or down. In the USA, they were steady to declining for many years, then fluctuated sharply with the price shocks after 1970.

SCARCITY IN THE WORLD MARKET 1944-1993

Except for the USA and a very few other countries, published reserves are not well defined, and estimation methods are not revealed. Year-to-year changes usually do not mean much. But over several years, changes have meaning, although not precision.

World reserves (Table II) were first calculated for 1944, at 51 billion barrels. By the end of 1993, the world had produced and consumed 690 billion barrels, and had 999 billion barrels left. The worldwide production/reserves ratio is half of what it was in 1944. Strong conclusion should not be drawn from weak numbers, but they do not suggest increased scarcity or shortage at any time.

Most of the net growth has of course been in OPEC. We are often told that non-OPEC producers will "empty out their reserves". Very true. Each decade, they use up most of what they have, and replace it with more. This need not continue forever, but cost trends show it is a good bet to continue for years. Thus the value of reserves in the USA is now governed by the difference between the worldwide price and the level of domestic operating costs.

TABLE II

WORLD PRODUCTION & RESERVE-ADDITIONS 1960-1990
(IN BILLIONS OF BARRELS)

	1944	1945-60	1961-70	1971-80	1981-93	. 1944-93
				O P E C		
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-O P E C		
Cumulative Production	--	51	64	102	190	. 407
Gross Reserve-Additions	--	98	187	114	207	. 607
Reserves at End	29	76	200	212	229	. 226
				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

SOURCE: Reserves:1944, from History of the Petroleum Administration for War (Washington, 1947), Appendix 12, Table 1. Later years from Oil & Gas Journal, annual "World Wide Oil" survey. Production from DeGolyer & MacNaughton, Twentieth Century Petroleum Statistics.

In principle, changes in development cost are an indication of change in value, in finding cost, and in oil scarcity in general. If we array, from lowest to highest, development (and much exploration) investment per unit of new capacity, for each country outside North America and Western Europe in 1955, 1965, 1975, and 1985, for 1955-1985, there was clearly no strain on resources. The supply curve moved far to the right. (Adelman 1993, p. 225) The "long lead times" of which we hear so much are only for exploration in new areas, much like research and development in manufacturing. There were no wild investment swings between 1933 and 1973. There was continuous addition to capacity, which expanded sevenfold while the price fell.

As for the value of oil in the ground, we have only one Persian Gulf observation: the value of a new-found barrel in Saudi Arabia (corresponding to line 5 of Table II) in 1976: 1 - 2 cents per barrel. This is of course a value under monopoly, related not to price but to marginal revenue, which approaches zero. (Adelman 1995, ch. 4)

CONCLUSION: CALCULATION OF OIL ASSET CONSUMPTION

Table III sums up two methods, following two theories. The upper panel treats the resource oil as initially fixed. Hence all production is a subtraction from it. The estimator follows (but does not explicitly cite) the "Hotelling rule" (Das Gupta & Heal), whereby the value of the asset in ground must equal the current net price. Thus value losses are respectively \$66 billion and \$35 billion. A milder version of the method of Panel A is to subtract total production, but credit output only with a charge for "resource rent" per barrel, the present value of the inevitable increase of the limited stock. But, first, there is no inevitable increase. But if there were any increase expected, its value is included in the current market value.

The method used in Panel B treats the resource as unknown and irrelevant. The net inventory (reserve) increased in 1984 by \$3 billion and decreased in 1992 by \$4.5 billion, about 13 percent of the estimate in Panel A.

Obviously I regard the method of Panel A as massive error, because what came out of the stock was nearly all replaced. The milder variant, assigning an allowance for resource rent, is a

smaller error. What pervades all variants is the lack of any reference to investment in oil, of all industries. It is Hamlet without the Prince or the rest of the cast.⁹

TABLE III

ALTERNATIVE CALCULATIONS OF OIL ASSET CONSUMPTION IN RECENT YEARS

	1984	1992
A. Assumption: an initial fixed stock		
1 Liquids produced, million barrels	-3813	-3219
2 Net value at well head, dollars per barrel	16.67	10.68
3 Asset consumed, billions of dollars	-65.6	-34.4
B. Assumption: reserve as inventory		
4 Liquids reserves, net change, million barrels	+453	-950
5 In-ground value, dollars per barrel	6.94	4.71
6 Net change in inventory, billions of dollars	+3.1	-4.5

Sources: lines 1,4 from DOE, Reserves Annual Report
lines 2,5 from Table I above.

Method: panel A, from Repetto (1989)
panel B, this paper

DEPLETION OF DATA

The asset valuations used are from a current research project by G. C. Watkins and myself. We hope to have some better numbers soon, despite serious data and econometric problems.

But we should be clear on the theory. The way to measure the value of oil assets used up is to multiply the net reserve decrease by the current market value of a barrel in the ground. A partial measure is the development cost of such a barrel. The value of a barrel in ground sums up the expected trajectory of prices, up or down. Because expectations are uncertain, reserves are risky assets, their returns discounted at normal risky rates. Reserve values are forecasts made by qualified observers with an interest in guessing right. The sale of a

producing lease or of a security concentrates the minds of scientists, engineers, bankers, and oilmen. They may be and often are beautifully wrong. But the only basis for disregarding them is to assume that private markets cannot--somehow--value mineral assets properly.

But much basic data is disappearing. The annual reserves reports are still of high quality, but not as useful as they were before 1980, on the basis of API-AGA groups estimating for small areas, year in year out. Mindless hostility to the oil industry dictated that they be compiled by government, and the sampling frame is now companies not areas. Investment and operating costs for oil and natural gas were last tabulated in 1991; I have extrapolated one year; it becomes less defensible as we move away from the benchmark. The oil development issues of the AAPG Bulletin ceased after 1991, both for North America and outside, and the worldwide investment expenditures tabulated by the Chase Manhattan Bank ceased after 1987. We are now afflicted with useless estimates of corporate "finding cost", and of worldwide capital "needs", invincible against any analysis because sources and methods are not known, and replication impossible. These pseudo-statistics will infect and burden all discussion, whether of sustainable growth or anything else.

NOTE ON SOURCES

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APPENDIX

1 Investment, capacity R is the new reserve to be developed, in barrels, by investing K dollars. Q is the initial output in barrels per year, and the investment per annual barrel is K/Q. (It is the

investment per daily barrel, divided by 365.) With a decline rate of a percent per year, $R = Q \int_0^T e^{-at} dt = Q(1 - e^{-aT})/a$

Decline rate In general, $a = (Q/R) - (Qe^{-aT}/R)$. With slow decline over a long lifetime, we can safely neglect the second right-hand-side term, and $a = Q/R$. Otherwise, we approximate: $e^{-aT} = Q_f/Q = Q/R$, where Q_f = final output. The theory is that the more intensive the development, the higher the fixed annual outlays, hence the sooner the cutoff. Then the formula becomes $a = Q/R - (Q/R)^2$. A check: Prudhoe Bay field 1993 output was 10.29 percent of reserves. (Oil & Gas Journal, 1-31-94:82) By formula $a = 9.23$ percent. The Reserves report (1992, p. 29] gives Prudhoe Bay "underlying decline rate" as 9 percent.

2 Expected growth rate and ratio of wellhead price and in-ground value As shown elsewhere (Adelman 1993, ch. 13), the expected rate of price increase is: $g = i + a(1 - P/V)$, where i is the interest rate, a the annual exponential decline rate of production, P the net price, and V the in-ground value. In the special case of $P = V$, a is irrelevant and $g = i$. But if in fact $P = 2V$, then $g = i - a$. Recalling Figures 5, 6: if i is the market discount rate on oil investment, it stayed for many years near the decline rate a . The predicted rate of price increase was zero, and this was borne out.

3 "Finding cost per barrel of oil equivalent" Often cited in the financial press, this consists of (a) exploration plus development expenditures, divided by (b) oil reserves-added plus the "oil equivalent" of gas reserves-added. The number is useless.

The addition in the numerator (a) is illogical. Exploration adds knowledge and development adds reserves. These are different

activities, for returns over very different time periods. Moreover, exploration outlays on oil are mingled with those on gas.

The addition of oil to gas in both the numerator (a) and the denominator (b) is wrong because there is no oil or gas equivalence. Oil and natural gas are not in a stable relation to each other with respect to costs, prices, or reserve values. They can and do move in opposite directions.

Moreover, even if "finding cost per barrel of oil equivalent" meant something for any one year, it would not be comparable with that for any other year. Changes in the exploration-development mix, or in the oil-gas mix, or both together, make comparison invalid. We are told not to add apples to oranges; this is fruit salad.

4 The Solow contribution Solow (1992, pages 8-12) states:

"Even apart from the possibility of exploration and discovery, the stock of nonrenewable resources is not a pre-existing lump of given size, but a vast quantity of raw materials of varying grade, location, and ease of extraction."

This sounds like but is not a modification of the received theory. There is said to be substitution between "greater inputs of labor, reproducible capital, and renewable resources for smaller direct inputs of the fixed resource." Each year we decide "how much to save and invest and how much of the remaining stock of nonrenewable resources to use up. . . . [We] have used up some of the stock of irreplaceable natural resources." (Emphasis added)

The discount rate is "a technical assumption of convenience" and in any case is "very small." This is consistent with the lack of any attention to investment in the creation of mineral stocks. Investment is again ignored in suggesting that:

"The correct charge for depletion should value each unit of resource extracted at its net price . . . minus the marginal cost of extraction. . . . [T]he correct measure of depletion for social accounting prices is just the aggregate of Hotelling rents in the mining industry."

This sounds like the method of Repetto (Table II), whom Solow cites as a source. Solow does not include development investment in extraction cost. But I think that for national income accounting the consumption of the asset created by development investment cannot be ignored, any more than any other type of capital consumption.

Line 5 in Table I, "user cost," is the value of the unit (line 3) less its current development investment. Line 5 also allows for, and is an indirect measure of, discovery investment per unit. Both these investment requirements may change in the future, and make the price change. But line 3, the present value of an asset to be sold off in the future, embodies future prices. Thus it catches the elements of price unrelated to current cost, i.e. rents to the mineral owner.

Solow does not explain "Hotelling rents," whose usual meaning is the increase in net present value of the shrinking stock. We have argued that the shrinking stock and its increasing value are phantoms. In the usual case of decreasing prices, market values, and user costs, the "Hotelling rent" would be negative. But this does not matter. Whatever its sign or size, any rent is captured in lines 3 and 5 of Table I.

1. Despite the protests of some economists and engineers. (See Lohrenz 1992 on the "X-x fallacy").

2. Zvi Griliches wrote ("Productivity, R&D, and the Data Constraint", (Presidential address to the American Economic Association, American Economic Review, Vol. 84, No. 1, at 16): "Knowledge is not like a stock of ore, sitting there waiting to be

mined. It is an extremely heterogeneous assortment of information in continuous flux. Only a small part of it is of any use to someone at a particular point of time, and it takes effort and resources to access, retrieve, and adapt it to one's own use." A mineral body in the real world is no exception. It is not "sitting there waiting", but is rather a heterogeneous mass of information needing investment for access, retrieval, and use.

3. Example: Suppose the estimate for a well is an initial 1000 barrels daily, 365 thousand barrels per year. If the decline rate is 10 percent per year, production after 25 years is only 82 barrels daily, 30 thousand barrels per year. If at current prices lower output will not pay operating expenses, this is the cutoff. The reserve will be booked as 335 thousand barrels, its cumulative expected output. A higher price, or lower cost, will extend the "economic life".

In algebra, $R = Q \int_0^T e^{-at} dt = Q (1 - e^{-aT}) / a$, where R=proved reserves, Q=initial output, a=decline rate in percent per year, and T=time. If T is indefinitely large, this simplifies to $R = Q/a$, or $a = Q/R$, which is usually but not always a good enough approximation. For our example, $R = 365 (1 - e^{-(25 \times 0.1)}) / .1 = 3350$.

4. "In the calculable future we shall live in an embarrass de richesse of both foodstuffs and raw materials. . . This applies to mineral resources as well." Joseph Schumpeter, Capitalism, Socialism, and Democracy (New York: Oxford University Press, 1943, p. 116).

5. Assume the price of oil is \$10 per barrel. One oil well produces 10 barrels daily, the other 10,000. The average cost in the big well is only a small fraction of cost in the small well. But under competitive conditions, the marginal cost in both wells is \$10. In each well, production is pushed to the limit, where producing one more barrel daily would raise costs on the whole operation by more than \$10. Profit is maximized (or loss minimized) in both wells.

6. In theory, the contribution of discovery to in-ground value in any given place ought to stay between an extreme of zero where available reserves are unlimited, and a maximum of equality with development cost. [Adelman 1993, pp.243-244] In the USA, discovery value has long fluctuated around 60 percent of development cost. Moreover, exploration outlays (omitting bids for leases, which are not a cost but a sharing of profits) have been around that proportion of development outlays.

7. I estimated in 1986 [Adelman 1993b, pp. 155-156] that the U.S. industry would keep shrinking because expected finding cost exceeded value. This has in fact happened, but there has been such

turbulence that one cannot be sure that the conclusion was borne out.

8. At any given time, capital expenditures have a non-linear relation to reserve additions. One plausible relation is exponential. Then $K=e^{bR}-1$, where K =expenditures in billions of dollars, R =reserve additions in billions of barrels, and "b" a coefficient of greater or lesser cost. Disregarding tax benefits, $K(1984)=16.2$, $R(1984)=3.8$, and $b(1984) =.72$. But $K(1992)=4.9$ billion, $R(1992)= 1.5$ billion, and $b(1992)=.91$, an increase of 26 percent. The precision of these numbers is deceptive. Other mathematical forms would give other results. But they would all show a strong increase for oil. Over this period, the coefficient decreased for non-associated gas reserve-additions.

9. One might ask: why not apply user cost rather than in-ground market value to place a value on net reserves added or subtracted? This would under-estimate the loss of assets, which are created by investment in both finding and development. But the neglect of development investment in the literature is striking.