

**On The Portents of Peak Oil
(And Other Indicators of Resource Scarcity)**

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Abstract

Economists have studied various indicators of resource scarcity but largely ignored the phenomenon of “peaking” due to its connection to non-economic (physical) theories of resource exhaustion. I consider peaking from the *economic* point of view, where economic forces determine the shape of the equilibrium extraction path. Within that framework, I ask whether the timing of peak production reveals anything useful about scarcity. I find peaking to be an ambiguous indicator. If someone announced the peak would arrive earlier than expected, and you believed them, you would not know whether the news was good or bad. However, I also show that the traditional economic indicators of resource scarcity (price, cost, and rent) fare no better, and argue that previous studies have misconstrued the connection between changes in underlying scarcity and movements in these traditional indicators.

Keywords: resource scarcity, peak oil, resource depletion

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“Portent: An indication of something important or calamitous about to occur.”

— thefreedictionary.com

1. Introduction

For better or worse, “peak oil” has gained considerable prominence as an indicator of growing resource scarcity. Since Hubbert (1956) introduced the hypothesis that oil production must reach a maximum and then fall into inexorable decline, economists have remained skeptical. That skepticism is largely due to the fact that Hubbert’s methods and predictions treat production of oil as an exogenous process divorced from market incentives. Nevertheless, the general public, and numerous scientists from disparate fields, remain clearly focused on the prospect of an impending and inevitable decline in oil production and embrace the notion that “peaking” manifests a scarcity that necessarily limits future economic growth. The peak, in other words, is undesirable because it ushers in a new age of painful, and potentially catastrophic, change.¹ Motivated by these sentiments, Campbell and Laherrère (1998) have declared that dating oil’s peak is more important even than dating its exhaustion. Consistent with this view, we have seen a virtual tournament of among analysts who have attempted to date the peak.²

¹ See, for example, Leigh (2008), Bardi (2005), and Campbell and Laherrère (1998).

² Recent attempts to date the peak include Wood, Long, and Morehouse (2003), Bartlett (2000), Duncan and Youngquist (1999), and Korpela (2006).

This paper considers the economic implications of peak oil. However, we take a different view of the peaking phenomenon than what is represented by the Hubbert Curve. Any well functioning market economy, endowed with a limited amount of an exhaustible resource, will arrange production through time according to prevailing economic incentives that reflect market fundamentals such as the size of the resource stock, the cost of production, discount rates, the strength of current versus future demand, and the availability of substitutes. In contrast to the Hubbert Curve, where the peaking phenomenon is a physical imperative caused by “running out” of the resource, the forces that regulate production in a market economy might cause production to fall due to insufficient demand, rather than insufficient supply.³

Just as the interaction of supply and demand determines the equilibrium price path in a market economy, so too do these forces determine the equilibrium production path. Taking market forces into account does not avoid the inevitable peak, of course, but since both sides of the market (demand as well as supply) are integral to the rate of production, the peaking phenomenon generated within a market economy presumably conveys more information than what is implied by the Hubbert Curve. With this in mind, it seems at least possible that “peak oil” might serve as some kind of useful economic indicator of scarcity. Therefore, despite economists’ justifiable rejection of the Hubbert Curve, they may nevertheless reasonably ask whether the phenomenon of peaking within a market economy reveals something important about the state of resource scarcity—something that would not be revealed by market prices or resource rents, for example.

³ The simple analytics of Hubbert's approach to peak oil are sketched in the appendix.

A major objective of this paper is therefore to explore whether peaking provides a useful economic indicator of scarcity. The criterion I apply to make that determination is very basic and follows Brown and Field (1978), who set forth two criteria by which any indicator of resource scarcity might be judged. The first states quite simply that:

A minimum condition (for a good index of scarcity) is that the index go up when underlying determinants shift to increase actual or expected demand for the resource relative to actual or expected supply.

The second criterion goes quite a bit further:

It would be much more useful, furthermore, if it were possible to distinguish the contribution to the changes in the index made by each important determinant of demand and supply shifts.

The second criterion is notable because it requires the indicator to signal not just that a change has occurred, but also the source of the change. Although this may be a desirable characteristic of an ideal indicator, in practice it seems beyond reach, as I argue later. Thus, I will focus on Brown and Field's first criterion, which refers to an exercise in comparative statics and expresses the idea that an indicator of scarcity should provide reliable directional signals of unexpected changes to the balance of supply and demand.

The rest of the paper proceeds as follows. In section 2, I present within Hotelling's framework the simplest possible model of equilibrium resource depletion and resulting peak production. More realistic (i.e., complicated) models could be explored but they are not of the essence. If peaking signals scarcity, it should be possible to demonstrate that in a simple model. Thus, in Section 3, I examine the comparative static properties of peaking within the simple Hotelling model. The traditional economic

indicators of scarcity are subjected to similar analysis in Section 4. That analysis not only demonstrates the limitations of the traditional indicators, but also corrects a common misunderstanding regarding what the previous literature has demonstrated. The findings of the study are summarized in the concluding Section 5.

2. Hotelling's Peak

Hotelling (1931) pioneered the *economic* study of peak oil, although his work is usually not described in those terms.⁴ Because the Hotelling model is well known to many economists, only a cursory review of the simplest possible application is provided here.⁵ More elaborate and realistic versions of the Hotelling model have been developed, and, as Gordon (2009) emphasizes, those extensions undoubtedly provide better empirical predictions of real-world production and price trends. However, our goal is not to predict the future, but to determine conceptually whether the peaking phenomenon provides a consistent indicator of scarcity. As we will show, peak oil fails this simple test even in models where the economy is deliberately oversimplified and the depletion phenomenon is entirely straightforward. Adding further complexity (realism) to the model would only increase the degree of ambiguity that surrounds the peaking phenomenon.

⁴ Holland (2008) is one of the very few authors who have explored the timing of peak oil within the Hotelling framework. Greene, Hopson, and Li (2006) also investigate peaking behavior in the context of an economic transition from conventional to unconventional resources. Although Farzin (1995) does not specifically focus on the production peak, he does explore the relationship between a declining (or increasing) production trend and other measures of resource scarcity. Without embracing Hotelling's full equilibrium framework, various authors have shown via *ad hoc* specifications that economic variables improve the fit of the Hubbert Curve to historical data; see for example Bopp (1980), Kaufmann (1991), Cleveland and Kaufmann (1991), and Kaufmann and Cleveland (2001).

⁵ Readers who are interested in the many extensions to the basic model are referred to Hotelling (1931), Herfindahl (1967), Solow (1974), Levhari and Liviatan (1977), Devarajan and Fisher (1981), Krautkraemer (1998), Farzin (1992), etc.

Let there be a fixed volume of the depletable resource (R) available at time t_0 . The unit cost of production (C) is constant through time, which implies no variations in resource grade and no technological change. The relevant discount rate (r) also remains constant through time. Demand for the resource is given by a constant elasticity demand function and the quantity demanded at any given price is assumed to grow exogenously at the rate g —which may represent the combined force of population growth, economic development, etc.⁶ Thus, the demand function can be written as:

$$Q_t^d(P_t) = K \times P_t^\varepsilon \times e^{gt}$$

Moreover, a perfect substitute for the depletable resource (i.e., a backstop technology) is available in unlimited quantities at constant unit cost (B). The cost of the backstop is assumed to be known but may be relatively high.

Under these conditions, and assuming that markets are competitive and that a full set of futures markets exists, a unique inter-temporal equilibrium exists and is characterized by the price path that satisfies the following three conditions:

- 1) $P_t - C = (P_0 - C)e^{rt} \quad \forall t \in (t_0, T)$ [no inter-temporal arbitrage]
- 2) $P_T = B$ [transition to backstop at time T]
- 3) $\int_{t_0}^T Q_t^d(P_t) dt = R$ [resource exhaustion at time T]

Because production of the resource is positive only during the finite interval $[t_0, T]$, it follows that a peak rate of production must exist. Although a closed-form solution does not exist for the date of the peak, it can easily be computed once specific

⁶ I have also investigated models with linear demand and they give similar results.

functional forms and parameter values are specified. The timing of the peak will generally depend upon the fundamental economic factors that describe the economy. The peak may come at mid-course (as predicted by Hubbert), or early, or late in the course of exploitation—all depending upon the elasticity of demand, the economic growth rate, the discount rate, the initial volume of resource available, and the cost of producing the depletable resource relative to that of the backstop technology.⁷ At issue is whether changes in these underlying economic parameters are consistently reflected in, and might therefore be inferred from, corresponding changes in the timing of the peak.

3. Peaking as an Indicator of Scarcity

I illustrate the relationship of the Hotelling peak to underlying economic fundamentals using a series of concrete examples. In each case, the long-term elasticity of demand is assumed to be -0.35. The discount rate is 10%, and the initial volume of the resource is arbitrarily assumed to be 4,000 units. The unit cost of production is \$20 for the resource versus \$100 for the backstop technology. In what I will refer to as the *Benchmark* scenario, the growth rate of demand is taken as 1.5% per annum, and the demand function is calibrated such that, if the resource were priced at the cost of production (i.e., \$20), demand would exhaust all available supply in roughly 23 years.⁸ The case is hypothetical, of course, and the unit of physical measurement is

⁷ Gordon (1967) and Levhari and Liviatan (1977) were among the first to characterize the influence of various economic factors on the shape of the equilibrium path. Indeed, in more elaborate models that incorporate exploration, technological change, etc., the rate of production may peak more than once along the equilibrium path.

⁸ I do not mean to imply that the market would price the resource at cost, or that it would be depleted in 23 years. The comment is only intended to convey a measure of the physical scarcity of supply relative to demand.

arbitrary, but the assumed costs, growth rates, and reserve-to-production ratios adopted here are within the realm of historical experience.

This particular set of assumptions leads to the equilibrium price and production paths shown in Figure 1a.⁹ The price starts at \$26.61 (30% above cost, which represents the scarcity rent or “user cost” of the resource at that time). Over the course of 26 years and 3 months, the price (dotted red line) rises to \$100, which is the cost of the backstop, and given the strength of demand at these prices, the total resource endowment is produced and exhausted just as the backstop technology becomes economic. Beyond that point, the price no longer increases due to the unlimited supply of the backstop technology. Production, on the other hand, first rises then falls. Peak production occurs after 36% of the original resource has been depleted—roughly one-third of the way into the period of exploitation. If we were to rely on the peak to signal impending exhaustion, it seems that substantial warning is supplied; it certainly provides more than a last-minute indication. In that respect, this particular economic scenario of depletion is not much different than the standard Hubbert result, where the peak comes around the half-way mark.

It should not be surprising to find that different results can be obtained by varying the underlying economic parameters.¹⁰ Indeed, it is perhaps heartening (at least on first examination) to find that very slight changes in the underlying economic factors tend to cause rather dramatic changes in peaking behavior—for if the peaking phenomenon did not register changes in the underlying economic factors, it could hardly serve as an

⁹ The trajectories of price and production shown in the figure were computed in Excel using a discrete-time approximation to equations (i) – (iii), where each time-step represents one month.

¹⁰ Gordon (1981) showed, for example, that the shape of the equilibrium path will depend on whether demand is stationary, rising, or falling over time.

Figure 1a: Benchmark Scenario (elasticity = -0.35, growth = 1.5%)

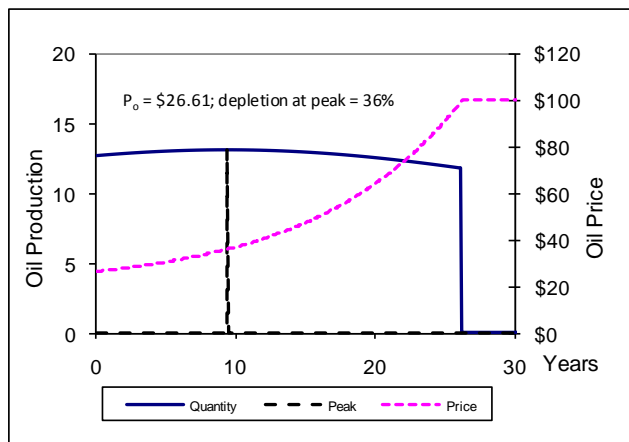


Figure 1b: High Growth Scenario (elasticity = -0.35, growth = 2.75%)

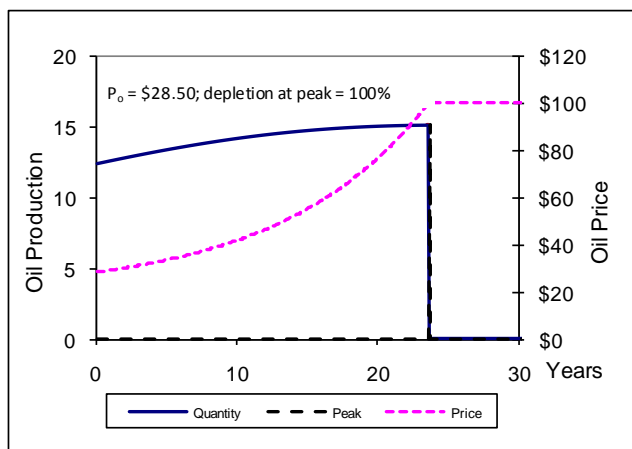
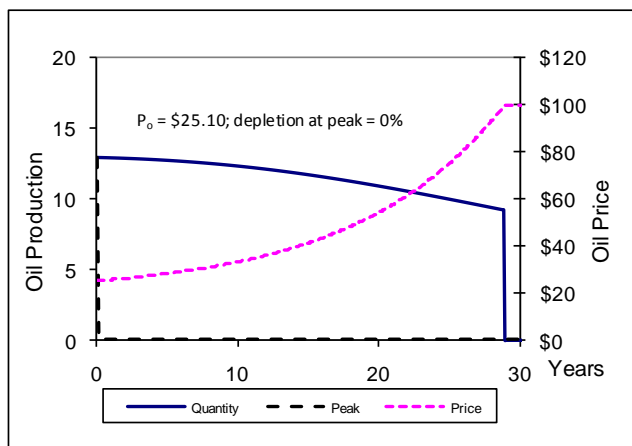


Figure 1c: Low Growth Scenario (elasticity = -0.35, growth = 0.5%)



indicator of changes in the degree of scarcity. This is illustrated by the next two scenarios (*High-Growth* and *Low-Growth*) which deviate from the *Benchmark* case only in terms of the assumed economic growth rate. In the *High-Growth* case (Figure 1b), the rate of growth is increased from 1.5% to 2.75%—a small change well within the range of historical experience. The resulting impact on price is also relatively small, it now starts at \$28.50 instead of \$26.61, but the impact on peaking behavior is dramatic: the peak is now delayed to the very end of the exploitation period when none of the resource remains. The *Low Growth* outcome (Figure 1c) provides additional contrast. When the growth rate is reduced to 0.5% (also within the realm of historical experience), the peak occurs at the very outset of exploitation, when 100% of the resource remains.¹¹ From that point on, production is all downhill. The results of these various scenarios are summarized in Table 1.

Table 1: Summary of Equilibrium Depletion Paths, by Economic Scenario

Economic Scenario	P_0	P_T	T	t_{peak}	t_{peak}/T	Q_{peak}/URR	$r_{monthly}$	r_{annual}
Benchmark	\$26.61	\$100.00	315	113	36%	36%	1.20%	15.39%
High Growth	\$28.50	\$100.00	284	284	100%	100%	1.24%	15.98%
Low Growth	\$25.10	\$100.00	348	0	0%	0%	1.15%	14.73%
Resource Disappointment	\$30.64	\$100.00	255	53	21%	21%	1.29%	16.60%
Cost Breakthrough	\$22.42	\$100.00	308	62	20%	21%	1.46%	18.98%
Continuous Innovation	\$27.72	\$100.00	311	123	40%	40%	1.17%	14.93%
Life Style Change	\$23.76	\$100.00	386	184	48%	48%	1.10%	13.98%

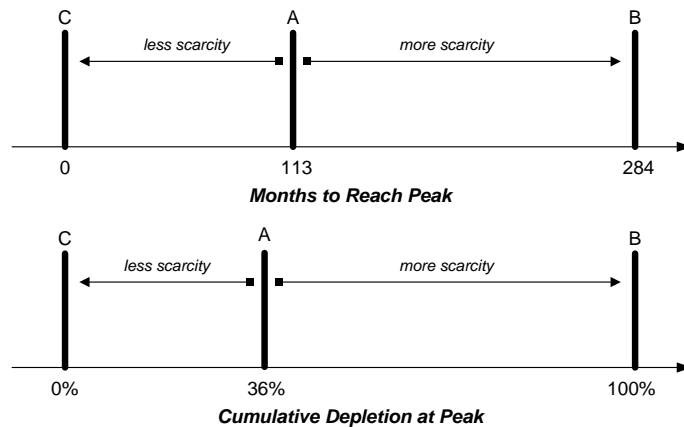
<p>Legend:</p> <p>P_0 = Price at initial time.</p> <p>P_T = Price at time when resource is fully depleted.</p> <p>T = Elapsed time before depletion occurs (in months).</p> <p>t_{peak} = Elapsed time before peak production occurs (in months).</p> <p>t_{peak}/T = Relative timing of peak production.</p> <p>Q_{peak}/URR = Cumulative depletion before peak production occurs.</p> <p>$r_{monthly}$ = Average monthly price change.</p> <p>r_{annual} = Average annual price change.</p>

¹¹ In Hotelling's original specification, with stationary demand and constant cost, the peak always occurs before any depletion has occurred. Levhari and Liviatan (1977) and Gordon (1981) demonstrate how relaxing those assumptions gives rise to varied production trends.

Does the earlier peak of the *Low-Growth* case signify greater scarcity? Certainly not in a physical sense because the same resource endowment is common to all three scenarios. Indeed, since demand is always smaller (holding prices constant) in the *Low-Growth* case, it would be reasonable to claim the resource is in fact less scarce. The apparent implication is that peaking provides an inverse indicator of resource scarcity: the more economically abundant is the resource, the earlier will the peak arrive. This is reflected in Figure 2, which summarizes the results obtained thus far. The peak arrives earlier (whether measured in terms of calendar time or cumulative depletion) if demand is reduced. Unfortunately, however, the behavior of the peak is not so simple or consistent as Figure 2 might suggest.

Figure 2: Impact of Demand Growth on Peak

- A: Benchmark scenario (1.5% growth)
- B: High-growth scenario (2.75% growth)
- C: Low-growth scenario (0.5% growth)

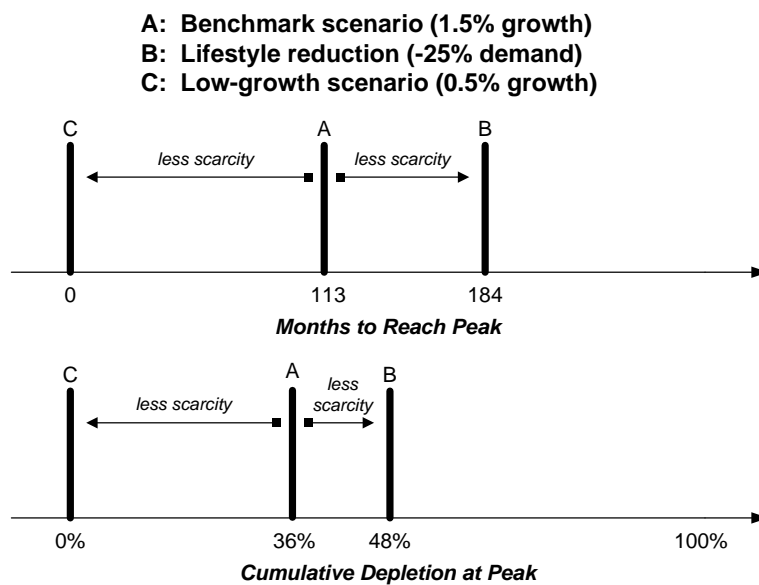


Consider, as an alternative to the *Low Growth* scenario, the impact of a uniform and permanent 25% reduction in demand, as might occur if consumers were suddenly to adopt a more conservation-oriented lifestyle.¹² Just as in the *Low-Growth* case, this

¹² This is effected, holding all else constant, by a 25% reduction in K , which scales the demand function.

Lifestyle scenario takes pressure off the finite resource base relative to the *Benchmark* case and reduces the degree of scarcity. The impact on peaking behavior, however, is in the opposite direction (Figure 3). Here the reduction in scarcity causes the peak to be delayed, arriving not until 48% of the resource has been depleted, as opposed to 36% in the *Benchmark* case (and 0% in the *Low Growth* case). Thus, a demand reduction may either advance or retard the peak—depending on the particular circumstances of the reduction. Apparently, the timing of the peak is an inconsistent indicator of changes in the underlying degree of resource scarcity.

Figure 3: Impact of Lifestyle Scenario (25% demand reduction)

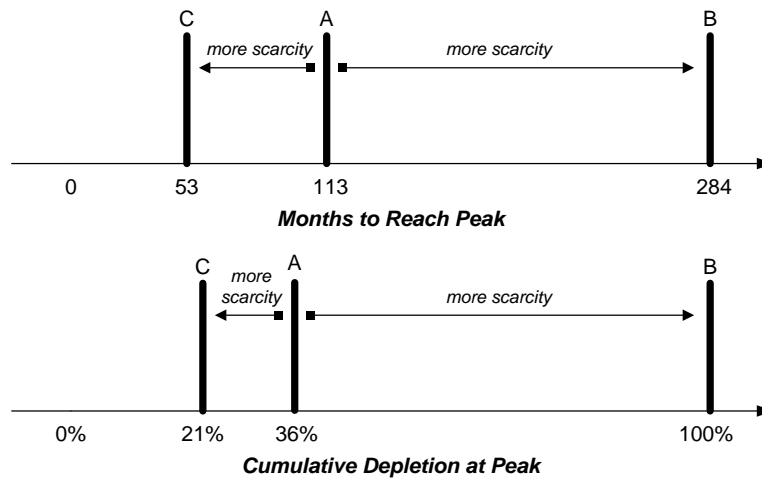


The next case to consider is the impact of diminished expectations regarding the remaining physical endowment of the resource. If, for example, the initial volume of resource were reduced by 25% (falling from 4,000 to 3,000) units, that certainly represents an increase in scarcity. Under this *Resource Disappointment* scenario (Figure 4), in which all other parameters are held constant at *Benchmark* values, the

peak arrives substantially earlier, after only 21% of the (diminished) volume of resource has been consumed. But, this comparative static reaction conflicts with the *High Growth* case considered previously: “faster growth = more scarcity = *later* peak” vs. “less resource = more scarcity = *earlier* peak.” The difference cannot be ascribed to market myopia or mistaken expectations since all of these scenarios reflect rational equilibrium behavior predicated upon perfect information and a well functioning set of futures markets.

Figure 4: Impact of Resource Disappointment

- A: Benchmark scenario (1.5% growth)**
- B: High-growth scenario (2.75% growth)**
- C: Disappointment scenario (3,000 units)**



Before leaving the *Resource Disappointment* case, it may be worth noting that the immediate price impact of what is a fairly spectacular downward revision to the resource endowment is muted: although the resource stock was reduced by 25%, the price of the resource rises initially by only 15% (relative to the *Benchmark* case) and production declines by only 5%. Although consumption must decline, on average, by 25%, the initial decline is much smaller. Part of the reason for the muted response, of

course, is that it is more economical (due to the impact of discounting) to postpone much of the adjustment in consumption to the future. This does not represent myopia, but the efficient functioning of a market economy that weighs future benefits against present costs.

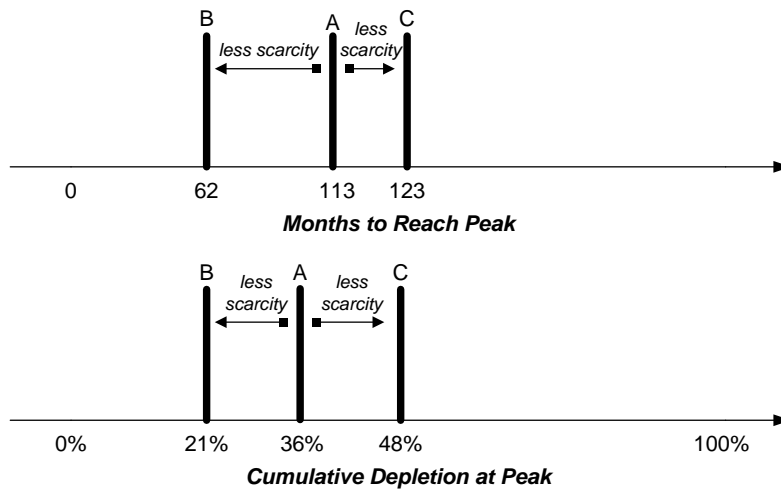
Further Ambiguity

Based on the results thus far, we have an impression that the timing of the peak does not consistently register the pressure of demand on physical supply of the resource. However, there is further ambiguity with respect to measuring the impact of technological progress and costs. Imagine, for example, that due to a one-time technological breakthrough the cost of producing the resource could be reduced to \$15 (from \$20 in the *Benchmark* case), which by most definitions would reduce the economic scarcity of the resource. The impact of this breakthrough on the market equilibrium (Table 1) would be to reduce the initial price to \$22.42 (from \$26.61). Notice that the entire cost reduction is not passed through since the market price incorporates the resource rent as well as the cost of production—and resource rent rises due to the increased cost advantage relative to the backstop technology. However, the peak production now arrives after only 21% of the resource has been consumed—much earlier than in the *Benchmark Case* where the peak arrived after 36% had been consumed (Figure 5). Thus, this result seems to conform to the “less scarcity=earlier peak” pattern that we encountered before. However, if technological progress is continuous, rather than one-shot, the pattern is again reversed. Instead of the one-shot cost reduction, assume an exogenous 3% annual reduction in the cost of producing the resource, with all else as in the *Benchmark case* (Figure 5). By most accounts this, like

the previous cost-saving example, would signify decreased economic scarcity. However, the impact of this type of technological progress is not to advance, but to delay the peak, which now occurs only after 40% of the resource has been produced (as opposed to 36% in the *Benchmark* scenario and 21% in the *Technological Breakthrough* scenario). Reduced scarcity due to technological innovation may either advance or delay the peak—depending on the particular circumstances.

Figure 5: Impact of Cost Reductions

- A: Benchmark scenario (cost = \$20/unit)**
- B: Cost breakthrough (cost = \$15/unit)**
- C: Continuous innovation (cost \$20/unit -3% pa)**



4. Traditional Indicators of Scarcity

I have demonstrated that peak oil fails Brown and Field's minimum condition for a useful indicator: it does not always "go up" or "go down" in a consistent manner. Do the traditional economic indicators of resource scarcity (i.e., unit cost, resource rent, and market price) fare better? Although many previous studies have investigated this question, the answer is not altogether clear. Whereas previous studies have been widely interpreted as having demonstrated that the traditional indicators fail this test, I

argue that the basis for that conclusion is open to question and requires clarification through a fundamental reinterpretation of the literature.

A Reinterpretation of the Literature

There have been many investigations of the dynamic behavior of the traditional indicators. But that literature follows a different tack: one where the *comparative static* impact of changes in scarcity have not been the subject of inquiry. What has been investigated is a very different issue: how the traditional indicators evolve and progress as the economy moves along a given equilibrium depletion path.¹³ A rising equilibrium price trajectory can easily be rationalized, but so can a U-shaped curve, as in Slade (1982). Moreover, given the range of plausible variation in the structural factors that enter into these models (e.g., technical change and exploration), almost any pattern or trend involving price, cost, and resource rent might be encountered as a given economy progresses along its equilibrium depletion path.¹⁴

These studies give a correct picture of how a given equilibrium unfolds through time, but they have been misinterpreted, in my opinion, as also addressing the impact of *comparative static* changes in the degree of scarcity. Thus, Fisher (1979) finds that:

“cost and rent are sometimes well behaved indicators of scarcity, sometimes not. ... Where cost moves in the right direction [*as the economy progresses along the equilibrium depletion path*], rent does not, and *vice versa*.”¹⁵

¹³ Analyses of this type include Fisher (1979), Slade (1982), Devarajan and Fisher (1982), Halvorsen and Smith (1984), Livernois and Uhler (1987), Norgaard (1990), Reynolds (1999), Cleveland and Stern (1999), and Farzin (1995), to name but a few.

¹⁴ For example, see Halvorsen and Smith (1984), Farzin (1992), and Krautkraemer (1998).

¹⁵ I have inserted the italicized phrase to clarify the context.

Likewise, Farzin (1995) notes that the search for an appropriate indicator of scarcity is complicated by the fact that, in numerous cases, the three traditional indicators will not move in concert along the equilibrium path. Halvorsen and Smith (1984) observe that

“increasing physical scarcity may be associated with either increases or decreases over time [*along the equilibrium path*] in any or all of the proposed measures.”

And Cleveland and Stern (1999) opine that along the initial portion of a U-shaped equilibrium price path, the market price might provide a false signal of reduced scarcity.

I argue that the reported failure of these indicators is somewhat peremptory because the question of what is to be signaled has not yet been properly framed. What is the policy relevance or prescriptive importance of evolutionary changes in scarcity indicators that are observed as the economy progresses along a given equilibrium path? These changes do not indicate *unexpected* shifts in the underlying fundamentals, nor do they mark a departure from the existing equilibrium. They are not the result of a comparative static shock to the economy. Rather, the evolving measures of scarcity are the predetermined result of society's choice of an optimal depletion path (assuming that markets function well and without externalities, which is typical of this literature). Within that framework, the degree of resource scarcity observed at each point along the equilibrium path is exactly the level that is required to maximize social welfare. Should movement in such an indicator be interpreted to mean that scarcity has increased from yesterday to today? Or, that the level of social welfare has fallen? I believe that such an interpretation is misleading. Society chose the given path of exploitation (and increasing scarcity) and any deviation would only impose unnecessary costs on the economy. In other words, it would not make sense to interpret the trend of increasing

resource scarcity that is experienced along a given equilibrium path as an indication that we have become poorer, or as an invitation for the government or some other intervener to take actions designed to slow the rate of depletion or otherwise alter the course of events.

In this respect, the discussion of scarcity indicators may benefit from a closer connection to the literature on economic sustainability. A sustainable path, as defined by Solow (1993), is one that allows every future generation the option of being as well off as its predecessors. If discount rates are not too large, and the rate of technological progress not too small, then such a path must exist.¹⁶ Moreover, the *maximal* sustainable level of income is attained by a market economy that reinvests each year all resource rents in reproducible capital, a result well known in the literature as "Hartwick's Rule."¹⁷ In other words, despite continuous depletion of the resource stock, an economy that simultaneously reinvests aggregate resource rents in reproducible capital will preserve its capacity to sustain a constant level of income. Thus, as the economy proceeds along its dynamic equilibrium path, the maximal level of sustainable income does not change from year to year, or generation to generation—the cumulative effects of resource depletion notwithstanding. The sustainable level of income *would* be affected, however, if there were an unexpected shock to resource stocks, technology, or demand; that is to say, if there were a comparative static change in the economic fundamentals.

¹⁶ Given the usual assumption about the marginal rate of substitution between the natural resource and produced capital, this statement remains true even if we assume production cannot take place without some use of the resource. See Solow (1993).

¹⁷ See Hartwick (1977). It is also well known that the maximal sustainable level of income is identical to net national product if depreciation of the resource stock is measured by the size of resource rents.

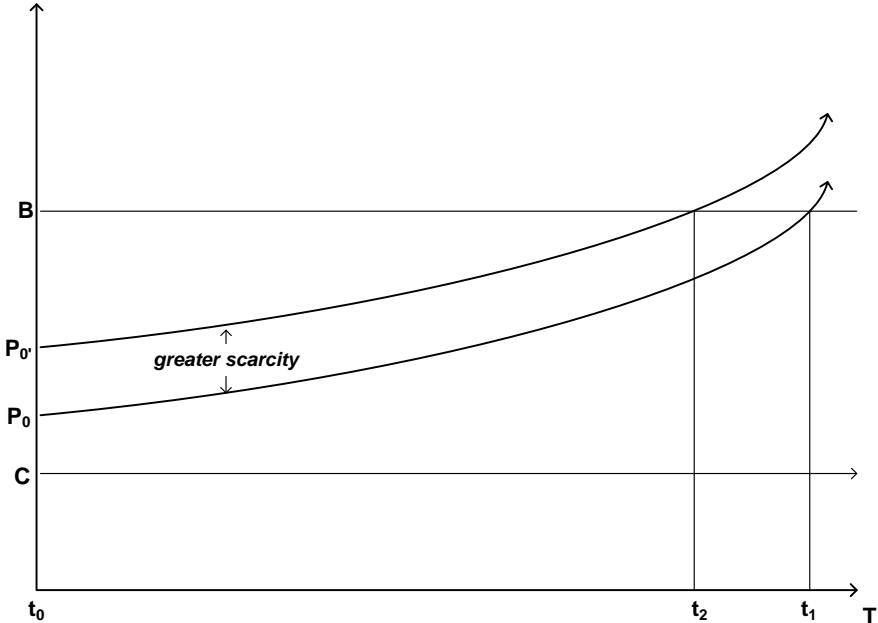
I understand this to mean that not all changes in scarcity indicators are created equal. Changes caused by unexpected shocks must be interpreted differently than changes that simply record the economy's continued progress along a given equilibrium path, as indicated by Figure 6. The upper panel demonstrates the comparative static shift to a new equilibrium path (with higher prices and lower welfare) due to the unexpected loss of resource endowment at time t_0 . The lower panel demonstrates the movement, starting from t_0 , to higher prices along one equilibrium path (with no effect on welfare). This poses the practical problem of how the two types of change can be separated or distinguished, and that is where the equilibrium models have an important role to play. If it is established, for example, that resource rent must grow in equilibrium at the rate of interest, then comparative static changes in the underlying fundamentals would be indicated by any deviation from that trend. It is not the change in the scarcity indicator that signals a favorable or unfavorable development, it is a *deviation from the expected change* that matters.

Apparently, such deviations are frequent based on the lack of success reported in fitting historical time-series data to the Hotelling model.¹⁸ These failures should not necessarily be interpreted as rejections of the Hotelling framework, although they are often characterized that way. As Swierzbinski and Mendelsohn (1989) and Krautkraemer (1998) point out, the flow of information constantly generates unanticipated changes in expectations regarding relative scarcity of the resource, which means that historical time series data should not be expected to conform to an equilibrium path, even though expected future prices may do so.

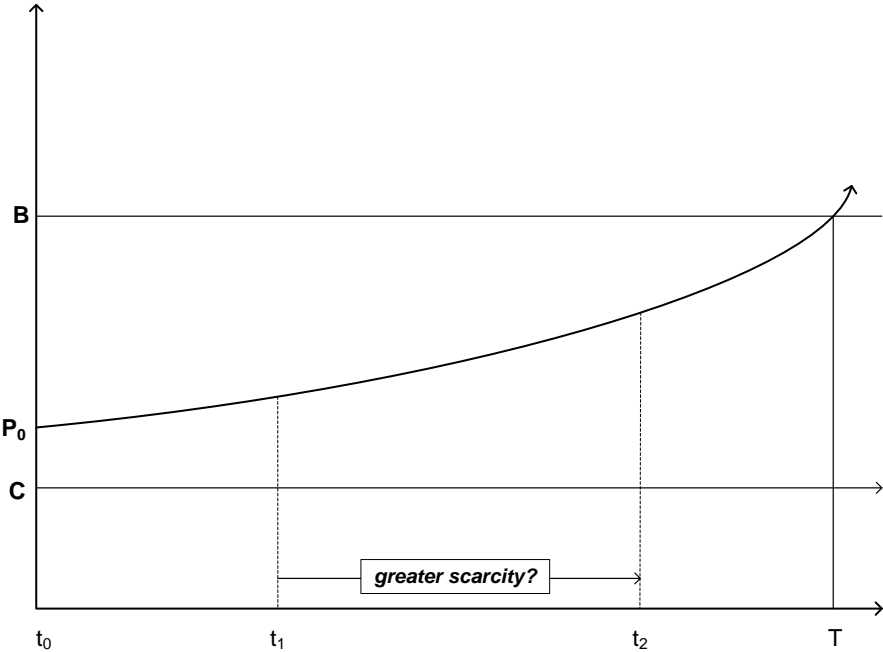
¹⁸ For example, see Barnett and Morse (1963), Smith (1979), Slade (1982), Heal and Barrow (1980), Smith (1981), Farrow (1985), and Halvorsen and Smith (1986).

Figure 6: Comparative Statics vs. Equilibrium Dynamics of Scarcity

Panel A: Impact of Unexpected Reserve Loss



Panel B: Impact of Equilibrium Depletion



What follows from this discussion is that the usefulness of a given indicator of resource scarcity is determined by its ability to accurately signal comparative static shifts, not by its evolution along an equilibrium path. In other words, I am not bothered that Farzin (1992) has found conditions under which resource rent may *fall* as the economy progresses along a given equilibrium depletion path, as long as that same indicator would rise if some portion of the remaining stock were unexpectedly removed. This distinction takes us back, of course, to Brown and Field's first criteria, which is focused on an indicator's ability to consistently signal comparative static changes in the underlying fundamentals.

Unfortunately, it is not so easy in practice to recognize shocks to long run equilibrium trajectories as they occur, or to separate the comparative static movements from the evolutionary trend. What the previous literature has established is that the traditional indicators of scarcity are partially driven by long-term trends that are unrelated to scarcity. Thus, movements that truly signal unexpected changes in scarcity (i.e., movements away from the trend) may be difficult to isolate and identify.

Comparative Static Behavior of the Traditional Indicators

Even if it were possible, with sufficient research, to isolate comparative static movements in the traditional indicators from their evolutionary trend, those movements would not provide consistent or reliable signals of underlying changes in scarcity. In light of my reinterpretation of previous studies, this point is new to the literature and requires further elaboration.

The comparative static properties of the traditional indicators are simpler in some respects than the previous literature might suggest. Unit cost, for example, is a direct

measure of the inputs required to produce the resource, and any increase in unit cost implies that, holding output in the rest of the economy constant, there is a reduced capacity to produce the resource in question. Or, if the level of resource production is to be maintained, then production of something else somewhere else must be sacrificed. Thus, unexpected changes in unit cost provide unambiguous signals of changes in the underlying degree of scarcity. However, as Krautkraemer (1998) and others have observed, unit cost is driven by technology, not forward looking, and therefore cannot be counted on to signal changes in relative scarcity that are triggered by shifts in demand.

Resource rent, the second traditional indicator of scarcity (and one that is favored by a number of resource economists), unfortunately provides comparative static signals that are not well behaved.¹⁹ On the one hand, resource rent represents the shadow price of the resource constraint and (holding all else constant) varies directly with the degree of physical scarcity.²⁰ Thus, unexpected variations in the resource stock will be reflected by contemporaneous changes in resource rent: greater scarcity creates higher rent. On the other hand, other factors (like technical change and the strength of demand) also impact the shadow price of the resource and in certain cases will exert a countervailing influence that garbles the signal and creates ambiguity.

For example, recall the *Continuous Innovation* scenario from Section 3, where the *Benchmark* equilibrium was perturbed by introducing an exogenous 3% annual reduction in unit cost (less scarcity). The immediate impact is to *increase* resource rent since cheaper extraction makes each unit of the resource more valuable relative to the

¹⁹ See for, example, the discussion in Devarajan and Fisher (1982).

²⁰ Fisher (1979) expresses a presumption that this result would hold even if there were not a complete set of futures markets for the resource in question.

backstop technology (see Table 1). We have an ambiguity because, in this case, it is a *decrease* in scarcity that triggers higher rents. (Recall in the previous paragraph we argued that an *increase* in physical scarcity would trigger higher rents). Thus, diagnosing underlying changes in scarcity on the basis of observed changes in resource rent obviously requires additional, more specific information about the underlying fundamentals.

The third indicator of scarcity, market price, is just the sum of the other two indicators. It therefore inherits whatever ambiguity they possess. For example, although the onset of a factor like *Continuous Innovation* marks a decrease in scarcity, it triggers an increase in resource rent (see above), which in turn causes the market price to rise. Thus is the price higher under *Continuous Innovation* than under the *Benchmark Scenario*, even though scarcity is lower (cf. Table 1). So, how should we interpret an unexpected increase in the price of the resource? Without more specific fundamental information, it seems impossible to say.

One answer to this critique of the traditional indicators is to say that reliance on comparative statics is inappropriate because changes in underlying fundamentals alter not just the current price (or rent), but the entire future course of prices (and rents). Thus, in the *Continuous Innovation* scenario, where cost falls each year, the initial increase in price must eventually give way to lower prices in the future (relative to the benchmark case).²¹ The sustainable level of income rises due to technological progress, and although the initial price increase does not signal this, that favorable end result would be apparent to anyone who contemplates the full equilibrium path. This

²¹ If the resource price were to increase *and remain forever higher* than in the former equilibrium, the backstop price would be reached before the resource is exhausted--which violates the definition of equilibrium.

argument is correct as far as it goes, but seems to beg the question of what is meant by the term "indicator." I use the term to refer to observable and contemporaneous market information that might be used to infer changes in underlying fundamentals. The future equilibrium path is not an "indicator" in this sense because it is not observable. It can only be computed, but not without direct knowledge of the underlying fundamentals—in which case there would be no need for an "indicator" in the first place. If we focus on the ability of contemporary market indices (like cost, price, or rent) to signal changes in the underlying fundamentals, we are left with the conclusion that none of the traditional indicators are free of ambiguity.

Brown and Field's Second Criterion

Brown and Field's desire for an indicator that would signal not just a change in scarcity, but also the source of that change, is demanding and on close inspection probably unattainable. The reason for this is not specific to exhaustible resources; it applies also in the realm of renewable resources. Consider, for example, the market for a regular good, like wheat. Instead of an intertemporal equilibrium price path, the market is presumed to clear independently in every period (for simplicity, I ignore inventories). Figure 7 shows a succession of two such equilibria where both the price and quantity of wheat have increased during the given time interval. Taken by itself, that information does not allow one to infer whether supply has *increased* or *decreased* from one period to the next.

As demonstrated in Smith (2009), knowledge of the elasticities of supply and demand is required to say more. In Figure 8, which gives a more complete picture of the market for wheat, we see that equilibrium shifted from (p_1, q_1) to (p_2, q_2) because both

Figure 7: What Do Market Indicators Reveal?

What is the Cause... Supply or Demand?

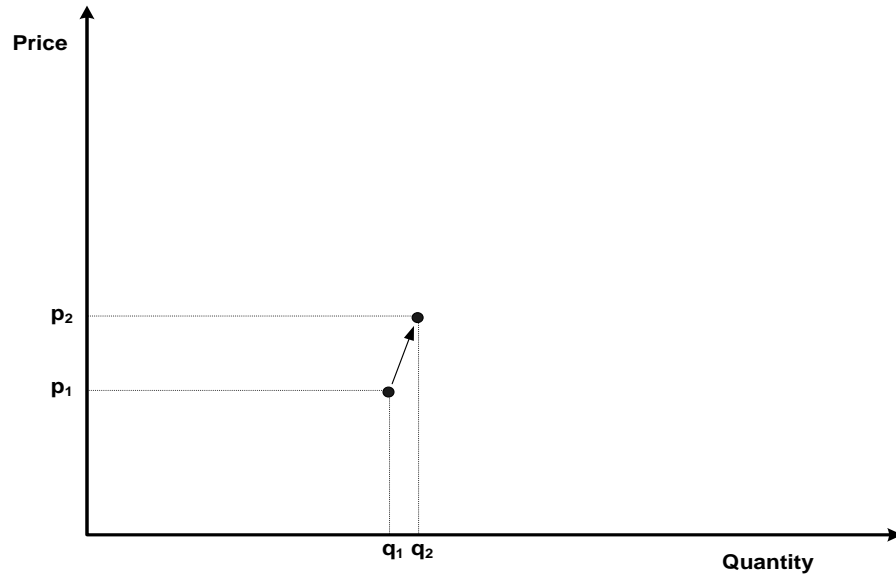
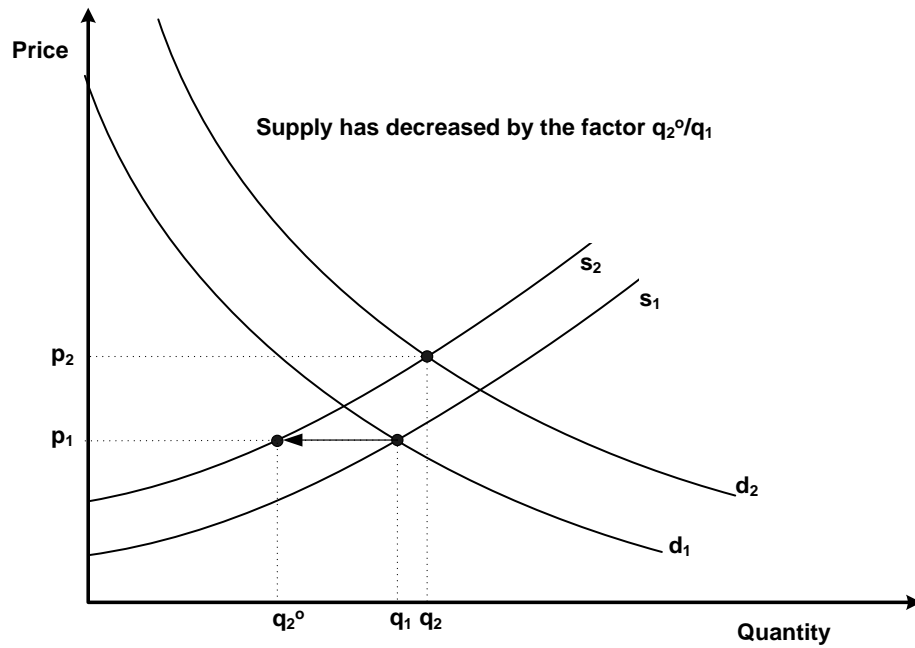


Figure 8: Disentangling Shifts in Supply and Demand

Quantifying a Shift in Supply



demand and supply have been perturbed. The shift in supply is measured by the decrease (holding price constant) from q_1 to q_2^o , or in percentage terms by $\Delta_S = q_2^o/q_1$. Although q_2^o is not observable, its value can be deduced based on an estimate of the elasticity of supply, as follows. The difference between q_2^o and q_2 represents a movement along the new supply curve from price p_1 to p_2 ; thus: $q_2^o/q_2 \approx (p_1/p_2)^{\epsilon_S}$. This approximation is good for small price changes, and exact for all price changes if the elasticity of supply is constant. Making this substitution in the previous equation allows us to identify the supply shift: $\Delta_S = (q_2/q_1) \times (p_1/p_2)^{\epsilon_S}$. By similar means, the underlying shift in demand can be inferred from the presumed elasticity of demand: $\Delta_D = (q_2/q_1) \times (p_1/p_2)^{\epsilon_D}$. Thus, the observed prices and quantities must be supplemented by knowledge of the respective elasticities if we are to disentangle the shifts in demand and supply.

Even with a comprehensive set of historical market data (price and quantity) for the good in question it would be impossible to statistically estimate the elasticities in question without knowledge of concomitant movements in other variables (incomes, costs, etc.) that serve to identify each curve. Analysts study market fundamentals for at least two reasons. First, of course, is the fact that they wish to anticipate changes in prices before those changes are registered in the market. Second is the fact that, even after such changes are recorded, it is impossible to disentangle the causes solely on the basis of the observed movements in price and quantity. The punch line is that no simple indicator of increasing scarcity is available and examination of all the available indicators of industry conditions is needed to identify the size of a shift as well as its cause.

5. Conclusion

Although the concept of peak oil originated outside the field of economics, the peaking phenomenon can be viewed as an integral part of a market process. Placed in that context, where timing of the peak is endogenously determined by economic forces rather than nature, peaking is an event that might reveal meaningful information regarding the underlying market fundamentals. As part of the ongoing search for useful economic indicators of resource scarcity, it seems reasonable therefore to investigate the properties of the peak and compare its usefulness to that of the more familiar alternatives.

Unfortunately, as this paper demonstrates, peaking is an ambiguous indicator that provides inconsistent signals regarding resource scarcity. Even if it were announced that the peak will arrive earlier than expected, and you believed it, you would not know whether the news was good or bad. However, we have also shown that the traditional indicators of resource scarcity (unit cost, resource rent, and price) fare no better. They provide inconsistent signals of real changes in the underlying degree of resource scarcity, and they also incorporate the confounding influence of long-term trends unrelated to changes in economic scarcity. The latter point is new to the literature and emerges only after reinterpreting the implications of previous studies of resource depletion paths in terms of the literature on sustainable growth.

Thus, we cannot rely on any limited set of market indicators to gauge the status of our exhaustible resources. This conclusion echoes the view of Cleveland and Stern (1999), who suggest that in order to develop more effective forecasts of future resource scarcity we need to look beyond the indicators to the production technologies, natural

resource bases, and market structures that influence the indicators. In other words, although the market fundamentals determine the indicators, the indicators do not reveal the fundamentals. That knowledge comes only from detailed study of the primary economic factors that lie further below the surface.

List of References

- Aleklett, Kjell and Colin J. Campbell. "The Peak and Decline of World Oil and Gas Production," *Minerals & Energy – Raw Materials Report*, October 22, 2003.
- Bardi, Ugo. "The Mineral Economy: A Model for the Shape of Oil Production Curves," *Energy Policy*, vol. 33, pp. 53-61, 2005.
- Barnett, H. and C. Morse. *Scarcity and Growth: The Economics of Natural Resource Availability*, Johns Hopkins University Press, Baltimore, 1963.
- Bartlett, Albert A. "An Analysis of the US and world oil production patterns using Hubbert-style curves," *Mathematical Geology*, vol. 32, no. 1, pp. 1-17, 2000.
- Bopp, Anthony E. "A Combined Decline-Curve and Price Analysis of US Crude Oil Production, 1968-76," *Energy Economics*, pp. 111-114, April 1980.
- Brandt, Adam R. "Testing Hubbert," *Energy Policy*, vol. 35, pp. 3074-3088, 2007
- Brown, Gardner M., Jr. and Barry C. Field. "Implications of Alternative Measures of Natural Resource Scarcity," *Journal of Political Economy*, vol. 86, no. 2, pt. 1, pp. 229-243, 1978.
- Campbell, Colin J. and Jean H. Laherrère. "The End of Cheap Oil," *Scientific American*, pp. 78-83, March 1998).
- Cavallo, Alfred J. "Hubbert's Petroleum Production Model: An Evaluation and Implications for World Oil Production Forecasts," *Natural Resources Research*, vol. 13, no. 4, pp. 211-221, 2004.
- Cleveland, Cutler J. and Robert K. Kaufmann. "Forecasting Ultimate Oil Recovery and its Rate of Production: Incorporating Economic Forces into the Models of M. King Hubbert." *The Energy Journal*, vol. 12, no. 2, pp. 17-46, 1991.
- Cleveland, Cutler J. and David I. Stern. "Indicators of natural resource scarcity: a review and synthesis." *Handbook of Environmental and Resource Economics*, ed. By Jeroen C. J. M. van den Bergh, 1999, Edward Elgar.
- Devarajan, Shantayanan and Anthony C. Fisher. "Hotelling's 'Economics of Exhaustible Resources': Fifty Years Later," *Journal of Economic Literature*, vol. 19, pp. 65-73, 1981.
- Devarajan, Shantayanan and Anthony C. Fisher. "Exploration and Scarcity," *Journal of Political Economy*, vol. 90, no. 6, pp. 1279-1290, 1982.
- Duncan, Richard C. and Walter Youngquist. "Encircling the Peak of World Oil Production," *Natural Resources Research*, vol. 8, no. 3, pp. 219-232, 1999)
- Farzin, Y. H. "The Time Path of Scarcity Rent in the Theory of Exhaustible Resources," *Economic Journal*, vol. 102, no. 413, pp. 813-830, 1992.
- Farzin, Y. H. "Technological Change and the Dynamics of Resource Scarcity Measures," *Journal of Environmental Economics and Management*, vol. 29, pp. 105-120, 1995.
- Fisher, Anthony C. "Measures of Natural Resource Scarcity," in *Scarcity and Growth Reconsidered*, ed. By V. Kerry Smith, Johns Hopkins University Press, 1979.
- Gordon, Richard L. "A Reinterpretation of the Pure Theory of Exhaustion," *Journal of Political Economy*, vol. 73, no. 3, pp. 274-286, 1967.

- Gordon, Richard L. *An Economic Analysis of World Energy Problems*, The MIT Press, 1981.
- Gordon, Richard L. "Hicks, Hayek, Hotelling, Hubbert and Hysteria or Energy, Exhaustion, Environmentalism, and Etatism in the 21st Century," *Energy Journal*, vol. 30, no. 2, pp. 1-16, 2009.
- Greene, David L., Janet L. Hopson, and Jia Li. "Have we run out of oil yet? Oil peaking analysis from an optimist's perspective," *Energy Policy*, vol. 34, pp. 515-531, 2006.
- Halvorsen, Robert and Tim R. Smith. "On Measuring Natural Resource Scarcity," *Journal of Political Economy*, vol. 92, no. 5, pp. 954-964, 1984.
- Halvorsen, Robert, and Tim R. Smith. "A Test of the Theory of Exhaustible Resources," Discussion Paper No. 86-6, Dept. of Economics, University of Washington, 1986.
- Harris, DeVerle P. "Conventional Crude Oil Resources of the United States: Recent Estimates, Methods for Estimation and Policy Considerations," *Materials and Society*, vol. 1, pp. 263-286, 1977.
- Hartwick, John M. "Intergenerational Equity and the Investing of Rents from Exhaustible Resources," *American Economic Review*, vol. 67, no. 5, pp. 972-974, 1977.
- Heal, Geoffrey, and M. Barrow. "The Relationship Between Interest Rates and Metal Price Movements," *Review of Economic Studies*, vol. 47, pp. 161-181, 1980.
- Herfindahl, Orris C. "Depletion and Economic Theory," in *Extractive Resources and Taxation*, ed. by Mason Gaffney, pp. 63-90, Univ. of Wisconsin Press, 1967.
- Holland, Stephen P. "Modeling Peak Oil," *Energy Journal*, vol. 29, no. 2, pp. 61-79, 2008.
- Hotelling, Harold. "The Economics of Exhaustible Resources," *Journal of Political Economy*, vol. 39, no. 2, pp. 137-175, 1931.
- Hubbert, M. King. "Nuclear Energy and the Fossil Fuels," Shell Development Company Exploration and Research Division, Publication 95, 1956.
- Hubbert, M. King. "Degree of Advancement of Petroleum Exploration in United States," *AAPG Bulletin*, vol. 51, pp. 2207-2227, American Assoc. of Petroleum Geologists, November 1967.
- Kaufmann, Robert K. "Oil Production in the Lower 48 States: Reconciling Curve Fitting and Econometric Models," *Resources and Energy*, vol. 13, pp. 111-127, 1991.
- Kaufmann, Robert K. and Cutler J. Cleveland. "Oil Production in the Lower 48 States: Economic, Geological, and Institutional Determinants," *Energy Journal*, vol. 22. No. 1, pp. 27-49, 2001)
- Korpela, Seppo A. "Oil Depletion in the World," *Current Science*, vol. 91, no. 9, pp. 1148-1152, November 10, 2006)
- Krautkraemer, Jeffrey A. "Nonrenewable Resource Scarcity," *Journal of Economic Literature*, vol. 36, pp. 2065-2107, December 1998.
- Leigh, James. "Beyond Peak Oil in Post Globalization Civilization Clash," *The Open Geography Journal*, vol. 1, pp; 15-24, 2008)
- Levhari, David and Nissan Liviatan. "Notes on Hotelling's Economics of Exhaustible Resources," *Canadian Journal of Economics*, vol. 10, no. 2, pp. 177-192, 1977.

- Livernois, John R. and Russell S. Uhler. "Extraction Costs and the Economics of Nonrenewable Resource," *Journal of Political Economy*, vol. 95, no. 1, pp. 195-203, 1987.
- Nehring, Richard. "Two Basins Show Hubbert's Method Underestimates Future Oil Production," *Oil and Gas Journal*, vol. 104, no. 13, pp. 37-44, 2006.
- Nehring, Richard. "How Hubbert Method Fails to Predict Oil Production in the Permian Basin," *Oil and Gas Journal*, vol. 104, no. 15, pp. 30-35, 2006.
- Nehring, Richard. "Post-Hubbert Challenge is to Find New Methods to Predict Production, EUR," *Oil and Gas Journal*, vol. 104, no. 16, pp. 43-51, 2006.
- Norgaard, Richard B. "Economic Indicators of Resource Scarcity: A Critical Essay." *Journal of Environmental Economics and Management*, vol. 19, pp. 19-25, 1990.
- Reynolds, Douglas B. "The Mineral Economy: How Prices and Costs can Falsely Signal Decreasing Scarcity", *Ecological Economics*, vol. 31, pp. 155-166, 1999.
- Reynolds, Douglas B. "Using Non-Time Series to Determine Supply Elasticity: How Far do Prices Change the Hubbert Curve? *OPEC Review*, pp. 147-167, June 2002.
- Slade, Margaret E. "Trends in Natural-Resource Commodity Prices: An Analysis of the Time-Domain," *Journal of Environmental Economics and Management*, vol. 9, pp. 122-137, 1982.
- Smith, James L. "World Oil: Market or Mayhem," *Journal of Economic Perspectives*, vol. 23, no. 3, pp. 145-164, 2009.
- Smith, V. Kerry. "Natural Resource Scarcity: A Statistical Analysis," *Review of Economic Studies*, vol. 61, pp. 423-427, 1979.
- Smith, V. Kerry. "The Empirical Relevance of Hotelling's Model for Natural Resources," *Resources and Energy*, vol. 3, pp. 105-117, 1981.
- Solow, Robert M. "The Economics of Resources or the Resources of Economics," *American Economic Review*, vol. 64, no. 2, pp. 1-14, 1974.
- Solow, Robert M. "An Almost Practical Step Toward Sustainability," *Resources Policy*, vol. 18, pp. 162-172, September 1993.
- Swierzbinski, Joseph E. and Robert Mendelsohn. "Information and Exhaustible Resources: A Bayesian Analysis," *Journal of Environmental Economics and Management*, vol. 16, pp. 193-208, 1989.
- Wood, John H., Gary R. Long, and David F. Morehouse. "World Conventional Oil Supply Expected to Peak in 21st Century," *Offshore Magazine*, April 2003, pp. 90-150.

Appendix: Hubbert's Peak

The Hubbert Curve is built upon the assumption that production is distributed continuously through time according to a bell-shaped curve, which we denote by the function $q_t = \text{URR} \times f(t)$, where q_t represents the production rate at time t , URR represents the volume of ultimate recoverable reserves (assumed to be fixed and known), and where $f(\cdot)$ represents a normal probability distribution with mean T and standard deviation σ —which are parameters to be estimated.²² In addition to the presumed value of URR, the data which support estimation consist (minimally) of the production rate at t_1 (denoted q_1) and cumulative production to t_1 (denoted Q_1). Hubbert's original sketch, which projects the eventual decline of global oil production, is shown in Figure A1. Figure A2 is a generalized sketch that ties our terminology to Hubbert's construct.

Because the maintained assumptions are quite strong, and although the given information (q_1 , Q_1 , and URR) is sparse, it is then possible to determine T and thus predict the onset of peak production. To demonstrate the procedure, we note first that the integral of q_t over the entire domain is identically equal to URR, and that peak production occurs at time T , the mode of $f(\cdot)$. We also note that Q_1/URR measures the proportion of the resource that has already been depleted, which according to the standardized normal distribution implies:

²² This is a stylized formulation of the Hubbert Curve for illustrative purposes only. Most practitioners refer to $f(\cdot)$ as a time-series function rather than a probability distribution, but analytically they are the same. Many variations are possible and many have been employed. Hubbert (1967) actually applied the logistic distribution and many researchers have followed that lead. The assumption of symmetry is sometimes relaxed. The domain of the distribution can be specified in terms of number wells drilled, rather than time, as in Reynolds (2002), but unlike the Hubbert Curve, that approach produces something roughly akin to a production function, not a production forecast.

$$\Pr\left(z \leq \frac{t_1 - T}{\sigma}\right) = \frac{Q_1}{URR},$$

Or equivalently:

$$\frac{t_1 - T}{\sigma} = z_\alpha, \tag{i}$$

where $\alpha = Q_1/URR$, and z_α marks the lower tail of the standard normal distribution.

We also know that current production relative to ultimate recovery (this ratio is denoted β) gives the height of $f(\cdot)$ at t_1 . Thus:

$$\frac{q_1}{URR} = \beta = f(t_1) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left(\frac{t_1 - T}{\sigma}\right)^2}. \tag{ii}$$

After substituting for σ in (ii) using $\sigma = (t_1 - T)/z_\alpha$ from (i), the implied value of T is obtained:

$$T = t_1 - \frac{z_\alpha}{\beta} \times \frac{1}{\sqrt{2\pi}} e^{-z_\alpha^2}. \tag{iii}$$

The predicted date of peak oil (T) will be highly sensitive to the presumed value of ultimately recoverable reserves (through the impact of URR on both z_α and β). This is problematic for economists since the volume (and timing) of ultimate recovery presumably depends upon price—which in turn depends upon demand, interest rates, and the cost of production—none of which are incorporated here.²³ There is no assurance in Hubbert’s model that the projected rates of future production will actually clear the market. Although the prediction is simple, it is not credible due to neglect of

²³ Proponents of the Hubbert Curve have an entirely different perspective on this point. Aleklett and Campbell (2003), for example, refer to depletion models that include things like investment, demand and supply, and other economic factors as the “flat-earth approach,” and claim that “the malign influence of doctrinaire economics” acts as an obstacle that stands in the way of efforts to date the peak.

these fundamental economic factors. Empirical tests of this procedure performed by Brandt (2007) and Nehring (2006), encompassing numerous global petroleum basins, failed badly in predicting the peak, which reinforces economists' theoretical objections to the underlying method.²⁴

It is possible to proceed along similar lines without presuming to know the volume of ultimately recoverable oil, at least if there are sequential observations available on production. For example, suppose that q_1 and q_2 represent the historical rates of production observed at two distinct dates, and let Q_1 and Q_2 represent the cumulative production volumes associated with those dates. The problem of calculating T is then reduced to identifying the unique normal distribution that conforms to these two points on the density function. As in the previous case, there are two equations and two unknowns, which gives a unique solution for T and σ . Once those values are obtained, one solves for the volume of ultimately recoverable reserves by integrating the distribution. It is important to realize, however, that although URR is not assumed to be directly observable here, none of the structural assumptions of the model have been relaxed: ultimate recovery is still determined independently of the relevant economic variables.

In most applications of the Hubbert Curve, a time-series of *many* production data points is available, which means the two-parameter model is over-identified. Thus,

²⁴ The Hubbert Curve might have been forgotten altogether but for the fact that Hubbert's 1956 prediction that U.S. oil production would peak around 1970 was famously borne out. It should also be noted (but usually is not) that the predicted volume of oil to be produced at the peak was 37% too low, and that Hubbert's predictions regarding coal and natural gas ran badly amiss. Hubbert predicted that U.S. oil production would peak at 3 billion barrels per year; actual production in 1970 was 4.1 billion barrels. Hubbert predicted that U.S. gas production would peak at 14 trillion cubic feet per year in 1973; actual production was 21 trillion cubic feet in 2009. Hubbert predicted that global coal production will peak in 2150 at about 6.4 billion metric tonnes; actual production reached that level in 2007 and is still growing rapidly. (Actual production data are from the *BP Statistical Review of World Energy*, 2010 edition).

some type of estimation criteria must be specified to identify the parameter values that minimize the fitted errors. Empirical attempts to apply the model in this fashion have revealed the poor quality of estimates (and predictions) that result. For example, Harris (1977) demonstrated that a simple OLS regression fit to Hubbert's data produces an estimate of URR that falls short even of the volume of already known discoveries—which implies that the volume of future discoveries must be negative. Cavallo (2004) reexamined Hubbert's data and found that the historical production curve does not reliably distinguish between alternative values of URR; the regression R-squared of Hubbert Curves with URR ranging between 150 and 600 billion barrels varies only in the third decimal point. Cleveland and Kaufmann (1991) also document the difficulty of estimating URR based on the goodness-of-fit of historical data to the Hubbert Curve.

Figure A1: Hubbert's Worksheet (1956)

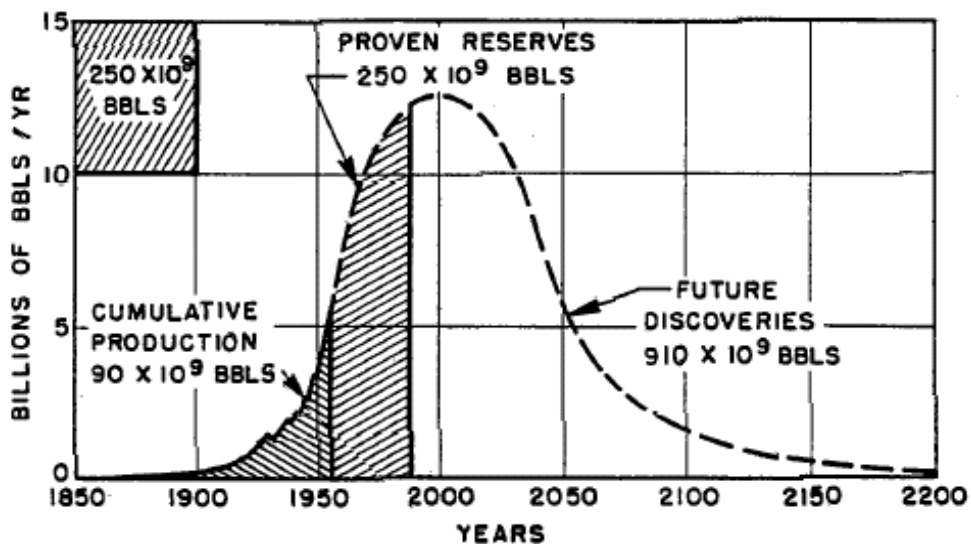


Figure A2: Hubbert's Curve—General Scheme

