Fundamental Economics of Depletable Energy Supply

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Abstract

In this paper, we first present and discuss the basic logic underlying all neoclassical economic theories of "optimal" energy supply: maximization of the present value of some stream of economic returns. We then discuss how the economic theory of optimal resource depletion has evolved since Hotelling's classic 1931 article. We also consider the power of the theory to support improved empirical understanding of actual behavior. Our discussion of empirical literature indicates that this work has so far provided only limited empirical understanding.

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Introduction

The economic principles governing the efficient production of depletable energy resources (oil, natural gas, and coal) have been a subject of interest and controversy for over 70 years. The pathbreaking article on the subject by Hotelling (1931) was motivated by then-current concerns about scarcity of energy and other natural resources that have a remarkably familiar ring to contemporary ears. More recently, the "energy crisis" of the 1970s motivated new concerns about the availability of sufficient energy resources and the capacity of economic markets to effectively allocate those resources over space and time.

In this article, we first present and discuss the basic logic underlying all neoclassical economic theories of "optimal" energy resource provision: maximization of the present value of some stream of economic returns. We then discuss how the economic theory of optimal resource depletion has evolved since Hotelling's article. We consider in turn theories of economically efficient energy resource extraction and new resource development. After presenting the basic theoretical framework, we discuss extensions incorporating investment in fixed production capacity, uncertainty, and various market distortions, as well as extensions incorporating nondepletable "backstop" energy resources.

The utility of an economic theory is to be found not merely in its conceptual elegance, but also in its power to support improved empirical understanding of actual behavior. Our discussion of empirical literature indicates that this work has so far provided only limited empirical understanding of observed energy supply behavior.

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Throughout the article, we cite some key examples in which the theory and application of depletable energy supply are developed in the literature. Some relatively recent surveys provide more detailed references (Cairns 1990, Walls 1992, Epple and Londregan 1993, Toman and Walls 1995, Krautkraemer 1998).

1. Basic Hypotheses in the Economics of Depletable Energy Supply

The fundamental assumption underlying all of mainstream economic theory is that economic actors are motivated to make choices by the goal of maximizing some measure of economic returns. The textbook model of commodity supply is a simple case in point. In that model, competitive producers (producers lacking any market power, taking prices of inputs and outputs as given) seek to maximize profit, the excess of gross revenue over their opportunity cost of production, including returns to capital and entrepreneurial effort. Profit is maximized when the market price of output, a measure of incremental gain from expanding production, equals the incremental cost of output expansion taking into consideration all possible technological possibilities for cost-effectively combining various inputs.

The same assumption underlies the economics of depletable energy supply. However, in that theory, the measure of returns assumed to motivate behavior is a present value of current and future net revenues that accrue over time from a sequence of production decisions. A present value metric is used in depletable energy economics because, for reasons explained further below, the act of producing or developing more or less resource today has unavoidable consequences for future potential returns because of the interplay of economics, geology, and technology. If these future consequences were ignored by totally myopic producers, their cumulative effects would come as an unanticipated and unwelcome surprise later. Since there is every reason to assume that producers are aware of these intertemporal connections and, being aware, are motivated to account for them, it makes more sense from the standpoint of theoretical logic to suppose that producers systematically account for them in evaluating the present value of a sequence of decisions over time.

The foregoing does not imply that energy producers are omniscient or free of forecast error. That is prima facie not the case. Later in the article we discuss how the theory of depletable energy supply has been extended to incorporate various kinds of uncertainties. Those extensions emphasize the key role that expectations play in influencing supply behavior. What is assumed in the economics of depletable energy supply, however, is that producers are capable of avoiding systematic and persistent errors over time. This assumption can and sometimes is questioned, but we know of no persuasive economic theory based on alternative assumptions that has been formulated.

It is worth noting in this regard that the calculation of a present value involves the choice of discount rate(s) to deflate future returns relative to current returns. In characterizing producer behavior in depletable energy supply theory, the appropriate discount rates would reflect the competitive rate of return capital invested in the energy industry could earn in other uses, including adjustments for various kinds of financial risks. Since in practice market-based rates of return put disproportionate weight on returns in the first few years of an activity, the assumption that producers are not systematically biased in their expectations of future returns is not as difficult to swallow as it might first seem.

The standard theory of depletable energy supply can be extended well beyond a simple description of a single competitive firm. In addition to uncertainty, already noted, the theory can be extended to incorporate a number of market distortions, including property rights problems, environmental spillovers, taxes, and market power. However, efforts to describe the exercise of market power by energy producers like the Organization of Petroleum Exporting Countries (OPEC) and its members have been especially unsuccessful. A number of political and other factors must be incorporated to properly treat market power.

2. The Simple ‘Cake-Eating’ Model of Resource Extraction

In the simplest case, it is assumed that a known, finite stock of the energy resource is being allocated over some number of time periods to maximize the present value of net returns. Producers calculate returns to extraction in different periods based on price expectations (in the simple model expectations are assumed always to be realized), and knowledge of costs based on technological and geological information. Returns across periods are linked in this model by the simple fact that any energy resource produced in some period is by definition not available for production in future periods (energy resources obviously cannot be recycled). Only a finite amount of energy resource is available in this framework, and all of it will eventually be extracted. But the finite availability of fossil fuels is not the only key feature of energy supply, even in the simplest framework.

In this framework, the present value of net returns is maximized when the "equi-marginal principle" is satisfied. This principle requires that the marginal net return from the extraction and sale of the energy resource be the same in every time period with positive extraction. This, in turn, requires the current value of marginal net profit to be increasing at the rate of discount applied to future returns.

This principle can be stated in simple mathematical terms. Let P_t denote the price of extracted energy resource at time t, q_t the quantity extracted at time t, $C(q_t)$ the cost of extracting P_t, and δ the discount rate. Then, under the equi-marginal principle, it must be that:

$$(1) \qquad P_0 - C'(q_0) = \frac{P_1 - C'(q_1)}{(1+\delta)^1} = \frac{P_2 - C'(q_2)}{(1+\delta)^2} = \cdots \frac{P_t - C'(q_t)}{(1+\delta)^t} = \cdots = \lambda \, ,$$

where λ denotes the common present value of marginal net profit. This number can be interpreted as the present value shadow price or *in situ* value of the resource stock, since it reflects the incremental increase in present value that would be enjoyed if a resource owner could experience an augmentation of resource stock. It also is referred to in the literature as the user cost" or "scarcity rent" associated with depletion of the resource stock.

At any point in time, then:

$$(2) \qquad P_t = C'(q_t) + (1+\delta)^t \lambda$$

In any successive time periods,

$$(3) \qquad \frac{P_{t-1} - C'(q_{t-1})}{(1+\delta)^{t-1}} = \frac{P_t - C'(q_t)}{(1+\delta)^t} \quad \text{or} \quad P_t - C'(q_t) = (1+\delta)[P_{t-1} - C'(q_{t-1})] .$$

These conditions are known as the “Hotelling Rule” [see below] in honor of Hotelling's contribution to the literature. The first efficiency condition requires that at any point in time, the marginal gain from additional extractions equals the full opportunity cost of extraction, including the present value of future losses from a diminished future resource stock as well as conventionally defined incremental production costs.

The second efficiency condition requires that the rate of return to holding the asset be equal to the rate of discount. This condition can be thought of in terms of asset market equilibrium, since presumably the discount rate is the rate of return that could be earned by investing in other assets. The markets for assets will not be in equilibrium if the rate of return to holding one asset is greater than the rate of return to holding some other asset. If that were the case, investment in the higher (lower) return asset would increase (decrease). Thus, asset market equilibrium requires that the rate of return to holding a nonrenewable resource asset be the same as the rate of return to other assets in the economy as represented by the discount rate.

The user cost, or shadow price of the remaining stock, depends upon future extraction costs and the future price path. These depend in turn on developments in resource production technology, the size of the remaining stock, and future availability of substitutes. The future price of the resource can depend upon the general level of economic activity, so expectations about population and economic growth are important determinants of the scarcity rent or user cost. Technological progress can affect extraction cost, the availability of substitutes, and the remaining resource stock. For example, the development of directional drilling techniques has lowered the cost of extraction and increased the amount of recoverable oil from some deposits. Increased computing capability has enhanced the ability to use information from exploration activities and lowered the cost of discovering and developing new oil reserves (Bohi 1999).

The model we have described above can be extended in several directions. If we switch from considering a single competitive producer to a price-setting monopolist, we can infer that the monopolist will reallocate output from earlier to later in the life of the resource base, since this generates higher prices early on and near-term returns are worth more than discounted future returns. But since the stock of resource is fixed and is necessarily exhausted under either market structure, resources that are not produced earlier will be produced later. If, to take another scenario, the stock of the resource is fixed but uncertain, then again extraction early on would be less than in a situation with certainty about the resource stock since producers would put weight on the possibility of more scarce and therefore more valuable carry-over stocks. If, on the other hand, there is a renewable "backstop" energy form that can be supplied if the price of depletable energy climbs high enough, the Hotelling Rule will still hold, but the net price path will rise at the rate of discount until it meets the unit cost of the backstop just at the point of full depletion.

Despite its seeming intuitive appeal, however, the basic Hotelling model is built upon very shaky assumptions. It assumes a known stock of a resource of homogeneous quality and that the extraction technology does not change over time. In fact, nonrenewable resource stocks are not a given: exploration for new deposits, as well as the further development of existing deposits, is an important feature of fossil fuel supply. For many nonrenewable resources, including fossil fuels, the discovery of additional deposits has exceeded consumption so that known, or proved reserves have actually increased over many time periods. For example, U.S. oil reserves increased from 13 billion barrels in 1930 to 33.8 billion barrels at the end of 1990, while production in that period was 124 billion barrels (Adelman 1993). More than 30 billion barrels were produced from 1991 to 2000, but reserves at the end of 2000 were 29.7 billion barrels. The increase in world oil reserves is even more dramatic—proved reserves increased from 660 billion barrels at the end of 1980 to 1,009 billion barrels at the end of 1990. This increased slightly to 1,046 billion barrels at the end of 2000 even though 250 billion barrels were produced from 1991–2000 (British Petroleum 2001).

Nonrenewable resources, including energy resources, also vary in quality and in their cost of extraction. Moreover, cost conditions for extraction in a specific petroleum reservoir change over the economic life of the reservoir: as natural drive is depleted, cost rises and yield per unit extraction effort falls, unless costly secondary and other recovery enhancement measures (e.g., injection of water or carbon dioxide) are undertaken to stimulate reservoir pressure. In short, resource stocks are neither fixed nor homogeneous, contrary to the assumptions underlying the simple Hotelling Rule. It is not surprising, therefore, that the simple rule has done poorly in describing actual supply behavior (see below). We must look to a richer theory if we want to better understand observed behavior.

Empirically, since the resource price should reflect both the marginal extraction cost and the scarcity rent, one generally would expect from (3) that the price of a nonrenewable resource would be increasing over time. However, there has not been a persistent increase in prices of fossil fuels (or other nonrenewable resources), but rather fluctuations over various time periods. Fossil fuel prices fell over much of the twentieth century, peaked dramatically in the 1970s and early 1980s, and have generally fallen since then—see Figures 1–3. This further illustrates the need for a richer theory to capture observed behavior.

3. A More General Theory of Economically Efficient Depletable Resource Supply

A more useful general theory must take into account the stylized facts noted above—that resources are heterogeneous, with extraction costs that vary systematically over time with depletion of resource deposits; and that resources can be augmented through exploration and development. Moreover, a complete theory must account for the high degree of capital intensity of the extractive sector and the implications of this in terms of potential constraints on productive capacity.

3.1 Resource Extraction

Let us first address generalization of the Hotelling extraction model to deal with resource heterogeneity. Among the many good papers to deal with this case, Pindyck (1978) and Heal (1976) are particularly noteworthy. To examine this part of the problem, we continue to treat reserves as fixed for the moment, and we ignore capacity constraints.

The cost of extraction is assumed to be given by some function, $C(q_t, R_t)$, where R_t is the stock of resource that has not yet been depleted. Incorporating this "stock effect" into extraction cost is a simple if somewhat imprecise way to introduce resource heterogeneity into the extraction cost relationship. The relationship is relatively straightforward if we focus on a single energy resource development: as the resource in this development declines, cost is assumed to rise (deeper pits to be dug, more waste material to be removed, weaker reservoir pressure). It is less straightforward if we are attempting to describe heterogeneity among resource deposits, as discussed below.

With cost rising as the resource is depleted, the assumption of complete physical exhaustion from extraction—which is not empirically realistic anyway—no longer makes sense in the theoretical model either. Instead, what drives extraction behavior is economic exhaustion of the resource—at some point, cost becomes so high relative to the price that buyers are willing to pay that a particular mine or field is abandoned.

With resource heterogeneity and incomplete physical exhaustion, the simple Hotelling model summarized by the efficiency conditions (1)–(3) no longer applies. Instead, we must modify the equi-marginal principle as in the following equation:

$$(4) \qquad P_t = C_{qt} + (1+\delta)^t \lambda_t = C_{qt} + \sum_{s=t+1}^{T} (-C_{Rs})(1+\delta)^{t-s}$$

In (4), subscripts *q* and *R* on cost *C* signify rates of change of cost with respect to the extraction rate and the depletion of reserves, respectively. The term λ_t is a generalized measure of user cost that reflects the rate at which future extraction cost is increased as a consequence of future depletion. This stock effect is part of the full opportunity cost of current extraction.

Manipulating (4) a bit algebraically yields:

$$(5) \qquad P_t - C_{qt} = (1+\delta)[P_{t-1} - C_{q,t-1}] + C_{Rt}.$$

Equation (5) shows how with increased stock providing a kind of “dividend” in terms of holding down extraction cost over time ($C_{Rt} < 0$), the net return from depletion no longer has to rise at the rate of discount rate to induce resource owners to retain their holdings.

Application of this framework to describe the depletion over time of different energy deposits is frequently done but somewhat more problematic (Livernois and Uhler 1987). In the simplest case where resource quality varies across deposits but is homogeneous within a deposit, the optimal extraction pattern generally requires exploiting those deposits in a sequence from low cost to high cost. The user cost for a lower-cost deposit is greater than the user cost for a higher-cost deposit. At the time of transition from one deposit to the next-most-costly deposit, the marginal extraction cost plus user cost is the same at each deposit. This implies that the resource price rises at a rate slower than the rate of interest during the transition. Simultaneous extraction from different deposits can be optimal when marginal extraction cost at a deposit increases with the extraction rate, or if extractive capacity is fixed.

The current pattern of petroleum extraction obviously violates the rule of exploiting lower-cost deposits before higher-cost deposits. The cost of extraction from petroleum reserves in the Middle East is much lower than the cost of extraction from reserves in the United States. This suggests that the simple modeling device of incorporating resource inventory in the extraction cost relationship probably aggregates over and therefore blurs some important distinctions. The case of petroleum is further complicated by the actions of large oil producers in OPEC using market power to restrict their output to levels below what would occur under perfect competition. The higher-than-competitive price that results provides the incentive for higher-cost producers to extract from their reserves. The higher noncompetitive price also distorts the capital investment decision, as the marginal cost of investment in capacity varies widely from \$343 in Saudi Arabia to over \$10,000 in the United States. Efficient allocation would result in the equalization of marginal investment cost across geographical regions.

3.2 Exploration and New Resource Development

Exploration is an economic activity and, like other economic activities, marginal benefit and marginal cost play a key role in determining how much exploration occurs. Again, a key paper in the development of this analysis is Pindyck (1978). Expenditures on exploration and development reduce current profit with an expected return of adding valuable reserves for future exploitation. The efficient level of exploration activity balances the expected marginal cost of exploration with the expected benefit of exploration.

The expected marginal benefit of exploration is not just the discovery and development of new reserves per se; in a model of incomplete resource exhaustion, the quantity of the resource stock is not determinative. The marginal benefit of exploration comes from the discovery of reserves whose cost of development and extraction is less than or equal to the cost of the reserves currently being depleted. In other words, the marginal value of new reserves equals the user cost of current resource depletion along an efficient time path of extraction and new reserve development.

One feature of the full opportunity cost of exploration activity is that it reduces the stock of exploration opportunities, so that future additions to reserves tend to become more costly. In other words, there is a user cost similar to that in (4) associated with depleting the stock of exploration opportunities, in addition to direct exploration costs. If we then combine the conditions for efficient exploration, development, and extraction, we get:

(6) price = (marginal extraction cost) + (extraction user cost)

= (marginal extraction cost) + (marginal direct cost of finding new reserves)

+(user cost of reduced long-term development prospects)

The heuristic equality in (6) can be related to intuition about opportunity cost in economics more generally. The extraction user cost is the cost of depleting an existing inventory, which can be replenished but only (in the model) at an ever-rising cost. The sum of marginal extraction cost and marginal direct cost of finding new reserves gives a measure of the cost of using and replacing the inventory, but it ignores the ultimate cost of natural capital depreciation reflected in the user cost of reduced long-term development prospects.

Once we allow for reserves to vary endogenously with economic (and technological) conditions, the inexorable upward movement of prices implied by (3) or even (5) no longer need hold. Depending on the degree to which current extraction costs are rising as a consequence of depletion and the cost of new reserve additions, including their user cost, it is possible in the model for new discoveries to outstrip depletion, at least for a while, causing a U-shaped energy price path. This is a reassuring finding since such behavior has been observed in energy and other resource markets (Slade 1982), and a model incapable of replicating such behavior would have little use. The ability to de facto enlarge reserves through technological breakthroughs that increase recoverability and lower the costs of extraction from existing deposits, or make new deposits easier to find and access (lowering reserve replacement costs), likewise could exert downward pressure on prices, possibly for a long period of time.

The simple model of endogenous exploration and reserves makes the simplifying assumptions that reserves are found on average in order of increasing cost and can be found in infinitely divisible amounts. Given the uncertainties surrounding the exploration process, the former assumption obviously is an oversimplification. When the discovery of deposits is more random, the aggregate extraction cost function cannot be described by a reserve stock indicator alone (Swierzbinski and Mendelsohn 1989).

If the discovery of deposits is "lumpy," exploration and discovery can occur in "episodes," with intervals of no exploration between those episodes. Exploration does not generally occur in strictly discrete episodes, but it does vary with the resource price, and large discoveries do put significant but temporary downward pressures on price. The theory would then predict that the *in situ* value of the resource increases between major discoveries and jumps up or down when exploration occurs, depending upon whether the exploration outcome is less or more favorable than expected. The resource price path can follow a "saw-tooth" pattern while still having a downward trend over some time periods, depending upon the actual exploration outcomes. The likelihood that the resource price will be increasing over time increases as unexplored prospects become more scarce.

Exploration also provides new information about future exploration prospects that can lead to revised expectations about the future value of the resource stock and generate new expected time paths for the resource price and quantity extracted. For example, a firm may revise its expectations about the probability of successful exploration either upward or downward in response to information obtained from its current exploration. In this case, a variety of patterns is possible for the realized price path, including a generally downward trend. The arrival of previously unanticipated information can alter the resource price, extraction, and exploration paths so that the observed price path deviates systematically from a deterministic calculation. The observed time paths for the resource price and *in situ* resource value may represent a combination of the initial portion of many different expected price paths rather than outcomes along one fully anticipated price path.

Moreover, because individual energy producers can learn something about the information possessed by others via observing their behavior (e.g., by another producer not drilling in a certain area), information has certain "public good" aspects. To ensure that enough information about energy resources is collected and disseminated to society at large, it may be necessary for the government to undertake or underwrite investments in resource delineation.

3.3 Capacity Investment and Capacity Constraints

The basic nonrenewable resource model does not capture the capital intensity of extractive industries. The development and extraction of fossil fuels is capital intensive, and the timing and size of investment in extractive capacity are functions of the cost of capital and the expected price path. Once the existence of capacity constraints is incorporated, the behavior of the energy resource price along an efficient path generally will depart from the kind of behavior implied by (5) (or its extension to incorporate new reserve additions). This problem too has been studied by a number of authors (Lasserre 1985, Powell and Oren 1989, Cairns and Lasserre 1991).

If extraction is expected to decrease over time, either because the present value price of the resource is declining or the extraction cost increases with depletion, the extractor would seek to reduce its capital input over time if it were able to do so. However, this is not possible if capital is nonmalleable (i.e., once invested in oil fields, it cannot easily be converted into rail car investments). The energy-producing firm takes this into account when the initial investment is made, and the initial capital investment is lower than it would have been if capital were malleable.

Once in place, this lower initial extractive capacity is likely to constrain the rate of extraction from the deposit, at least early in the extraction horizon. In addition, it may be relatively costly to increase extractive capacity, at least quickly. Firms may invest in advance of the need for some capacity in order to smooth out their investment costs over time, but they will also invest slowly in response to previously unanticipated price increases. Consequently, the short-run supply curve for an energy resource may be very inelastic and so variations in market demand (especially increases) may be mediated more by price changes than by quantity changes. The result is that short-term energy prices can be relatively volatile.

In the standard nonrenewable resource model, an increase (decrease) in the interest rate decreases (increases) the relative value of extraction in the future relative to current extraction and so tilts the depletion path toward the present and away from the future. However, if a large capital investment is necessary before extraction begins, an increase in the interest rate increases the cost of the capital investment. Thus, a higher interest rate reduces the incentive to use capital, and can lead to lower rather than greater initial extraction whether or not capital is malleable.

The effect of the higher interest rate on the capital investment outweighs the effect of the higher interest rate on user cost if the initial resource stock is relatively large (Farzin 1984). A lower interest rate increases conservation if the interest rate is low (when user cost is high and capital cost is low), but decreases conservation when the interest rate is high (user cost is low and capital cost is high). A higher (lower) interest rate also can increase the capital cost of a backstop technology, increasing the maximum or "choke" price for the depletable energy resource and resulting in less (more) rapid extraction.

4. Effects of Uncertainty

There is uncertainty regarding the future values of many important influences on the intertemporal supply of depletable energy resources: future price, future extraction cost, the costs and outcome of exploration and development activities, and the cost and timing of the availability of a backstop technology. The intertemporal extraction and resource development patterns and price path are affected by uncertainty in a variety of ways, depending on the source and nature of the uncertainty. From a financial perspective, the risk associated with holding reserves of a depletable energy resource can be mitigated by also owning other assets. The necessary return to holding the energy resource asset—including the rate of *in situ* appreciation plus the benefits of increased reserves in moderating costs can be less if the return is negatively correlated with the return to other assets in a portfolio, thereby reducing overall risk.

Even with modern developments in financial markets, like energy commodities futures that more tightly link energy and financial markets and provide added options for risk management, in practice it is not possible for energy producers to completely insure away fluctuations in net income. Moreover, firms will not be indifferent to risks even if their basic management posture is what economists call "risk neutral." Work by Pindyck (1980) and others shows that these impacts depend on the curvature of incremental cost relationships, among other factors. For example, uncertainty about the growth of demand would shift extraction from the future to the present; if the degree of uncertainty increases with time, a limiting case would be the risk of expropriation, meaning no return from future production. Uncertainty about reserves could increase or decrease the marginal value of new discoveries compared to a situation of the same average conditions with no uncertainty.

5. Market Failures and Distortions

Assessing the effects of various market failures and distortions on depletable energy supply is complicated by the inherently intertemporal nature of these resources. Whether a market imperfection results in depletion that is more or less rapid or extensive than the socially efficient depletion rate or volume depends upon how the distortions change over time and interact with dynamic changes in resource scarcity signaled by the extraction and exploration user costs.

For example, a monopolist would want to restrict output to raise price and increase returns. This would mean a lower cost of extraction in the future compared to a competitive industry facing the same demand conditions and extracting more quickly. (In actuality, demand conditions themselves would change in response to the higher monopoly prices, as energy users adapted to more energy-efficient and alternative-energy technologies.) This in turn would encourage more output. Nevertheless, the monopolist could restrict output over time in such a way that the cumulative depletion of the resource (and cumulative development of new resources over time) was less than under competition. This is a different prediction than the one obtained from a simple model with fixed homogeneous reserves.

Government interventions also can tilt the market's depletion path toward the present or the future. Energy resource industries are subject to a variety of taxes in addition to the taxes paid by firms generally. One motivation for depletable resource taxation is that depletable natural resources like fossil energy are part of the national heritage and resource rents should accrue to the general welfare. Depletable energy resources can be subject to severance taxes per unit extracted or royalty payments as a percentage of the resource price. In general, the effect of such a tax on the intertemporal extraction pattern depends on how the present value of the tax changes over time as well as on the magnitudes of depletion effects in the cost structure.

For example, the present value of a constant severance tax decreases over time and so shifts extraction from the present to the future. However, the tax still reduces net returns in any period compared to a no-tax alternative, thereby reducing the contemporaneous incentive to extract.

While less extraction would moderate the depletion effect on cost, it is still likely that total recovery of the energy resource will fall over time as a result of the tax. In particular, reserves that were formerly marginally economic to extract become sub-economic. Moreover, the tax would reduce the return to investment in new reserves (Deacon 1993).

The extraction and consumption of energy resources are associated with a wide variety of environmental externalities. The effect of externalities on the market's depletion path can depend upon the exact nature of the externality. There are two broad categories of externalities: flow externalities and stock externalities. Flow externalities represent a situation in which the environmental damage is a function of the current rate of energy production or consumption. An example relevant to energy supply would be the air pollution by-products of energy use in the process of mining. More persistent stock externalities arise when the environmental damage is a function of cumulative emissions. Examples of more persistent externalities would include atmospheric accumulation of carbon dioxide and its effect on the global climate, contamination of ground water from oil or coal extraction that is only slowly reversed by natural processes, and unremediated damage to natural landscapes through strip mining.

Flow externalities can result in a depletion rate that is too rapid or too slow relative to the socially efficient supply rate, depending upon how the present value of the marginal external damage changes over time. The effect of stock externalities is similar to the impact of resource depletion on the cost of extraction: these stock effects imply a slower rate of depletion and less total depletion than the market would choose on its own.

6. Empirical Analysis of Depletable Energy Supply

Efforts to empirically test the theoretical implications of resource depletion models as descriptions of observed energy supply behavior are hampered by a lack of data. Data for *in situ* reserve values are not readily available. Market data on the value of firms are generally available, but exclude depletable resource values, and data on extraction and development costs are usually proprietary information. Consequently, the empirical economic analysis of resource supply and scarcity has taken a variety of less direct paths. Analysts have attempted in a number of ways to use available data to construct dynamic empirical models based on the basic theoretical tenets sketched above.

6.1 The 'Hotelling Valuation Principle' for Assessing Resource Scarcity

An illustration of the methods for testing the resource scarcity implications of the depletable energy supply model involves the relationship between average reserve value and current net price using cross-section data. Miller and Upton (1985a) argue that this relationship can be written as:

$$(7) \qquad \frac{V_0}{S_0} = \alpha + (P_0 - C_0)\,.$$

Here V_0 denotes reserve value, S_0 is the resource endowment, and $P_0 - C_0$ is the price net of extraction cost; the term α, which can be positive or negative, reflects influences like changing cost and price trends.

The model was found to be consistent with pooled, cross-section data from December 1979 to August 1981 for 39 oil and gas producing firms in the United States (Miller and Upton 1985a). A subsequent test of the Hotelling Valuation Principle using data from August 1981 to December 1983 produced a quite different result: in that analysis, an increase in the net price translated into an increase in average reserve value less than half as large (Miller and Upton 1985b).

An explanation for why the Hotelling Valuation Principle might overvalue reserves, at least in the case of oil and natural gas production, is that it affords producers greater flexibility for choosing output than they actually have. The extraction of petroleum over time is restricted by declining well pressure as the reservoir is depleted. If the rate of extraction declines at the rate *a* because of declining well pressure, the average reserve value is:

$$(8) \qquad \frac{V_0}{S_0} = \frac{a}{a + r - g}(P_0 - C_0)$$

where *g* is the expected rate of change in net price (Adelman 1990, 1993).

This example and others in the literature provide strong empirical evidence that a simple model of finite resource depletion does not adequately explain the observed behavior of depletable energy resource prices and *in situ* reserve values. This is not terribly surprising given the many other features of depletable resource supply already discussed—such as exploration for and discovery of new deposits, technological change, and capital investment—that alter the implications of finite availability. It seems clear that these other factors have overshadowed finite availability of the resource as determinants of the observed dynamic behavior of nonrenewable resource prices and *in situ* values.

6.2 Data on Reserves

In the theoretical models of depletable energy supply we have discussed, measures of reserves or resources play a significant role as indicators of cost drivers, not just in terms of physical availability. Before looking at efforts to empirically model depletable energy supply, therefore, it is worth making some brief comments on the nature of available data for reserves.

The classification scheme of the United States Geological Survey defines total resources, including energy resources, as materials that have been discovered or might be discovered and used (Brobst 1979). Reserves are that portion of total resources that can be economically extracted. Undiscovered resources are classified as hypothetical, if in a known mining district, or speculative. Identified but currently noneconomic resources are categorized as para-marginal or sub-marginal. The physical measures of reserves often are compared to measures of the rate of use in order to determine the remaining life of the reserves.

Since reserves are defined in terms of economic recovery, whether or not a deposit is classified as a reserve changes with the resource price and extraction cost. In addition, since costly investment is required to “prove” reserves, there is a limited incentive to prove reserves beyond a certain point. The reserve to consumption ratio for petroleum increased from 35 in 1972 (Slade 1987) to 45 in 1990 (World Resources Institute 1994), even though commercial energy consumption increased by more than 50% between 1971 and 1991 (World Resources Institute 1994). Physical measures of reserves thus probably have more meaning as an indicator of inventory on hand than as a more fundamental indicator of resource cost (Adelman 1993).

6.3 Models of Depletable Energy Supply Behavior

Behavioral models of depletable energy or other resource supply seek to develop empirical counterparts to theoretical efficiency conditions like (4) through (6) in order to describe how supply decisions (reserve development and extraction) respond to economic incentives (prices and cost drivers). Much of this work has focused on oil and gas supply, though some applications to mineral resources (e.g., nickel) also can be found in the literature. Relatively little of this kind of modeling work has been done for coal, since the depletion effects central to the development of the dynamic efficiency conditions discussed above seem to be of very limited relevance to coal supply (with large reserves and continued technical progress in resource exploitation, see Darmstadter 1999).

The problem of developing empirical behavioral models based on the theory of efficient depletable energy supply is quite difficult for several reasons. One problem, noted above, is the poor data on reserves and costs. But even with better data, it is inherently complicated to develop reliable empirical models for complex dynamic process, and resource depletion is inherently dynamic. Moreover, because behavior depends so much on expectations of unknown future influences in this dynamic framework, the empirical analyst must formulate a hypothesis about the nature of the expectations driving behavior.

Finally, the theory we have discussed previously applies most directly to an individual decisionmaking unit and perhaps even to decisions within a specific resource-bearing location. Once the analysis is extended to cover multiple extraction and investment decisions from heterogeneous deposits, some difficult aggregation problems arise. Care is needed not to omit or mix together key influences. For example, the yield from exploratory drilling likely depends on both how much the best resource prospects have been depleted by past activity and what advances in drilling technique can do to raise discoveries per unit of effort.

Basically, two types of modeling approaches are found in the literature: process optimization simulation models and econometrically estimated models. Process optimization simulation models specify and numerically solve sets of equations based on first-order efficiency conditions like (4) through (6). For example, the model could incorporate a specification in which the reserves discovered per foot of new drilling depend on cumulative past drilling in that province. This specification could be used along with other information to determine the efficient level of reserve development as a function of the direct cost and user cost of drilling, plus the marginal (shadow) value of additional reserves. One prominent example of such a model in the United States is the oil and gas supply component of the National Energy Modeling System (NEMS) operated by the Energy Information Administration (EIA 2000); Deacon (1993) provides a smaller-scale example.

Numerical parameters in such models come from a variety of sources: statistical curve fitting, engineering experience, and informed judgment, among others. Because these models are not derived from statistically fitting equations to data, it is not possible to construct classical confidence intervals and statistics for assessing the reliability of the model outputs. They are useful principally for "what if" exercises—by supplying different sets of input variables (e.g., oil prices and technical recovery parameters for drilling), one can see the consequences of changes in these assumptions. Whether the model structure is properly specified empirically cannot be independently assessed. The simulation models also do not incorporate uncertainty and expectations formation. Implicitly in dynamic optimization models, individuals are assumed to accurately judge the future.

Econometrically estimated models also are rooted in the theoretical efficiency conditions. However, these models are parameterized using statistical methods that seek to define supply decisions as functions of causal variables. The most sophisticated of these frameworks explicitly model expectations formation using the rational expectations time series approaches pioneered in macroeconomics (Epple 1985, Hendricks and Novales 1987, Walls 1992).

In brief, these methods explicitly include representations of expectations formation based on past observations of price and cost influences; assuming that producers are not systematically biased in their expectations and fairly rapidly learn about a systemic change in market or technological conditions, statistical techniques can be used to estimate the parameters of the expectations process and the underlying parameters linking supply choices to the relevant economic influences. The point is to provide consistent estimates of the basic technological and geological parameters undergirding the supply process, so that the effects of policy intervention or shifts in market conditions can be separated out and understood.

However, success with this class of models has been limited, notwithstanding their conceptual appeal. The models are difficult and data-intensive to construct and estimate; they are not well-suited to geographical or other finer-grained breakdowns of activity into constituent parts; and the results have not always been very powerful. In particular, some approaches have not coped well with what appear to be basic nonlinearities in the relationship between unit supply cost and reserves. A prospect for future work is a better blending of the engineering expertise found in energy systems modelers with the dynamic economic models discussed here (Walls 1994).

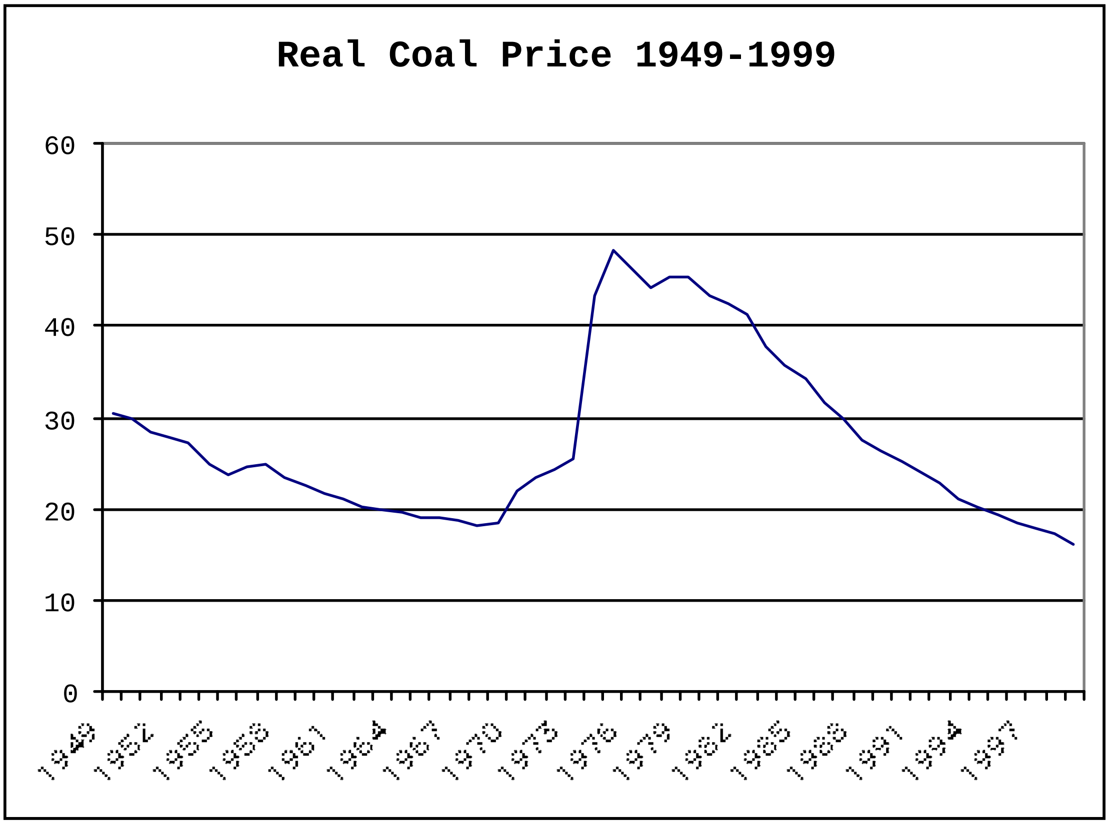
7. Concluding Remarks

Finite availability is one defining characteristic of a depletable energy resource and generates the “Hotelling Rule” that the marginal value of a nonrenewable resource stock increases at the rate of interest. However, many other factors, including exploration, capital investment, and heterogeneous reserve quality, also are important to the economics of energy depletion and development. The investigation of how these other factors affect the empirical implications of the Hotelling model has been spurred by the frequent failure of the basic Hotelling model to explain the observed dynamic behavior of nonrenewable resource prices and *in situ* values.

These other factors can affect price and depletion paths in a number of ways, particularly when considered in combination with each other. The variety of possible outcomes makes it difficult, if not impossible, to make any general predictions about the overall impact on price and extraction paths. These other factors, particularly the discovery of new deposits and technological progress that lowers the cost of extracting and processing nonrenewable resources, appear to play a relatively greater role than finite availability in determining observed empirical outcomes.

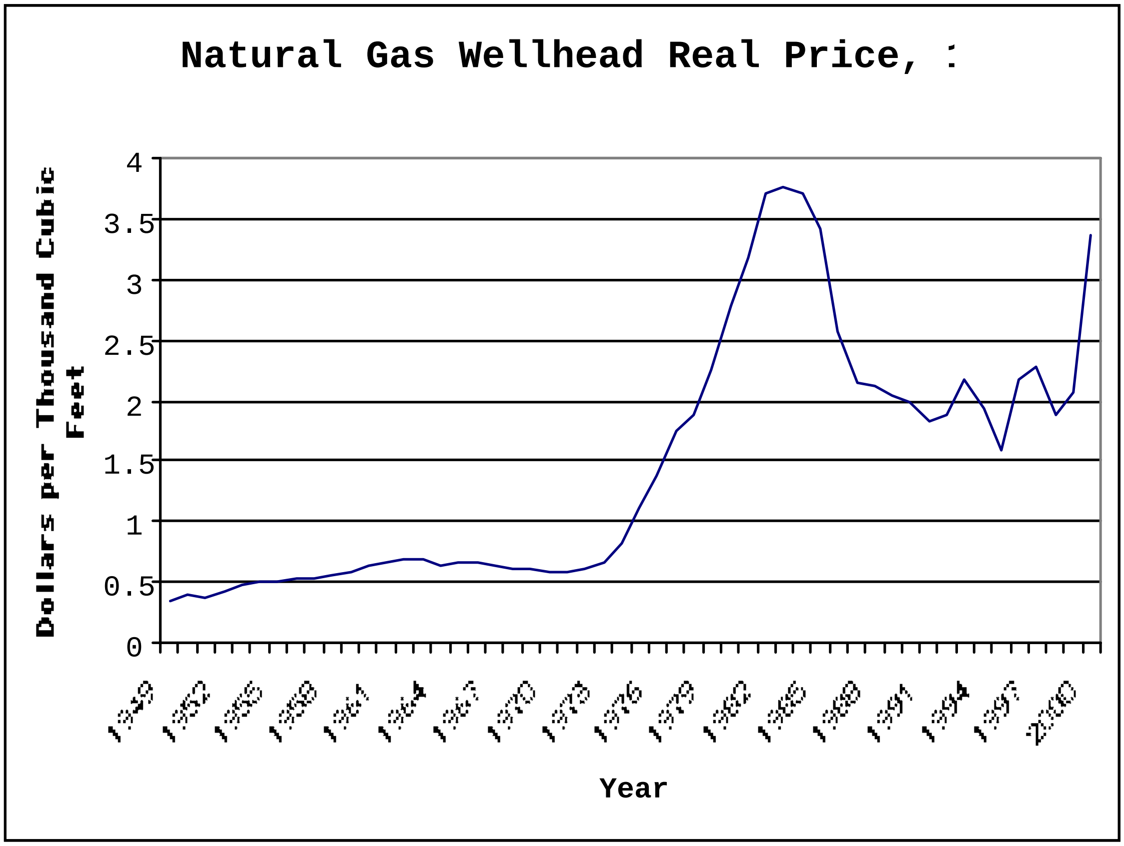
While models that include these other factors have enriched the Hotelling model, they have not completely reconciled the economic theory of nonrenewable resources with the observed data. The distinction between the responses of supply to anticipated versus unanticipated changes in extraction cost, interest rate, reserve discoveries, availability of backstop substitutes, and other factors figures prominently as a topic for future empirical research. The empirical evidence also indicates that the discovery of new deposits and technological progress in resource extraction and discovery have significantly mitigated the impacts of finite geological availability on the relative cost and supply of depletable energy resources. While the future holds promise with respect to the development of new substitutes for fossil energy and greater energy efficiency, improvements in extraction and exploration technologies that reduce costs and allow the economical use of lower-grade reserves also are likely to continue.

Figure 1: Real Price of Coal, 1949—1999, in chained 1996 dollars, calculated by using gross domestic product implicit price deflators.



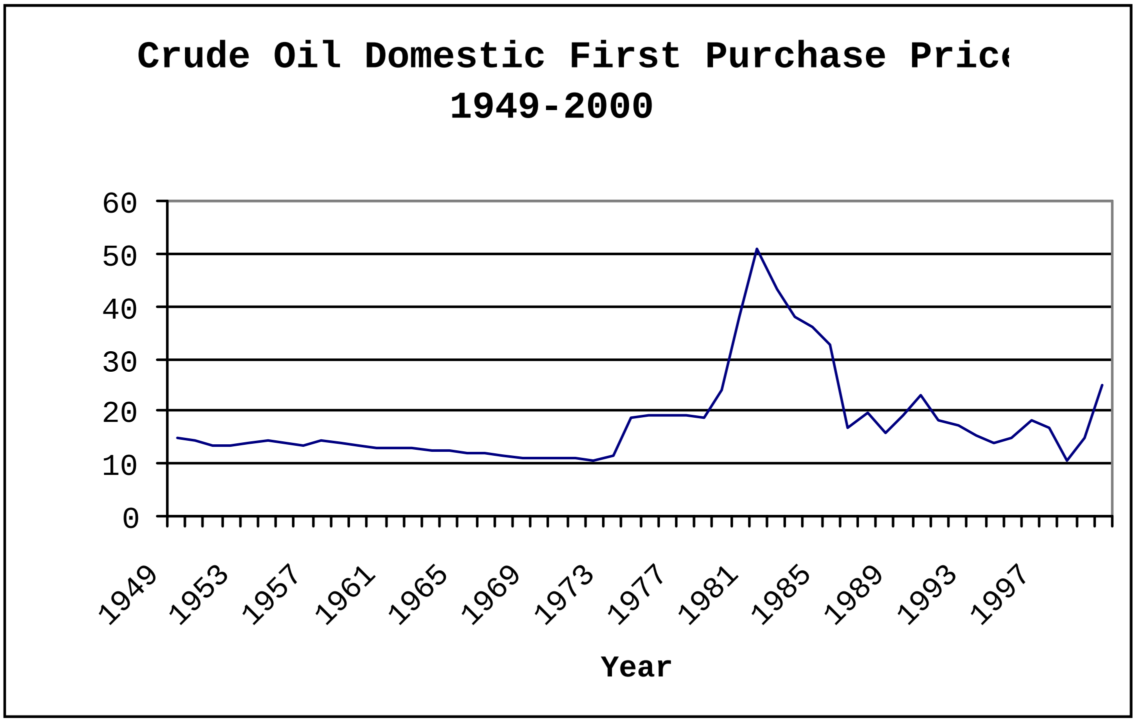
Source: Annual Energy Review, U.S. Energy Information Administration, United States Department of Energy, http://www.eia.doe.gov/emeu/aer/txt/tab0708.htm.

Figure 2: Real Price of Natural Gas, 1949–2000, in chained 1996 dollars, calculated by using gross domestic product implicit price deflators.



Source: *Annual Energy Review*, U.S. Energy Information Administration, United States Department of Energy, http://www.eia.doe.gov/emeu/aer/pdf/pages/sec6_19.pdf.

Figure 3: Crude Oil Domestic First Purchase Price, 1949–2000, in chained 1996 dollars, calculated by using gross domestic product implicit price deflators



Source: *Annual Energy Review*, U.S. Energy Information Administration, United States Department of Energy, http://www.eia.doe.gov/emeu/aer/pdf/pages/sec5_39.pdf.

References

Adelman, Morris A. (1990). Mineral depletion with special reference to petroleum. *Review of Economics and Statistics.* 72(1): 1–10.

_____ (1993). Modelling world oil supply. *Energy Journal* 14(1): 1–32.

Bohi D. (1999). Technological improvement in petroleum exploration and development. In *Productivity in Natural Resource Industries.* R. David Simpson, ed., Washington, DC: Resources for the Future.

Brobst, Donald A. (1979). Fundamental concepts for the analysis of resource availability. In *Scarcity and Growth Reconsidered.* V. Kerry Smith, ed., Baltimore: Johns Hopkins University Press for Resources for the Future, 106–159.

British Petroleum (2001). *BP Statistical Review of World Energy*, June. Available at http://www.bp.com/downloads/702/BPwebglobal.pdf (accessed November 12, 2002).

Cairns, Robert D. (1990). The economics of exploration for non-renewable resources. *Journal of Economic Surveys* 4(4): 361–395.

Cairns, Robert D., and Pierre Lasserre (1991). Investment in a multiple-deposit non-renewable resource industry: Some results and remaining puzzles. *Journal of Environmental Economics and Management* 21(1) (July): 52–66.

Darmstadter J. (1999). Innovation and productivity in U.S. coal mining. In *Productivity in Natural Resource Industries.* R. David Simpson, ed., Washington, DC: Resources for the Future.

Deacon, Robert T. (1993). Taxation, depletion, and welfare: A simulation study of the U.S. petroleum resource. *Journal of Environmental Economics and Management* 24(2) (March): 159–187.

EIA (Energy Information Administration) (2000). *The National Energy Modeling System: An Overview 2000*. Washington, DC: U.S. Dept. of Energy.

Epple, Dennis (1985). The econometrics of exhaustible resource supply: a theory and an application. In *Energy Foresight and Strategy*. Thomas J. Sargeant, ed., Washington, DC: Resources for the Future.

Epple, Dennis, and John Londregan (1993). Strategies for modeling exhaustible resources supply. In *Handbook of Natural Resource and Energy Economics*, Vol. 3. A.V. Kneese and J.L. Sweeney, eds., Amsterdam: Elsevier.

Farzin, Y. Hossein (1984). The effect of the discount rate on depletion of exhaustible resources. *Journal of Political Economy* 92(5): 841–851.

Heal, Geoffrey M. (1976). The relationship between price and extraction cost for a resource with a backstop technology. *Bell Journal of Economics*. 7(2): 371–378.

Hendricks, K., and A. Novales (1987) Estimation of dynamic investment functions in oil exploration. *Stanford Hoover Institute Working Papers in Economics: E87-52*. Standford, CA: Hoover Institution.

Hotelling, Harold (1931). The Economics of Exhaustible Reesources. *The Journal of Political Economy* 39(2), 137-175.

Krautkraemer, Jeffrey A. (1998). Nonrenewable resource scarcity. *Journal of Economic Literature*, 36(4) (December): 2065–2107.

Lasserre, Pierre (1985). Capacity choice by mines. *Canadian Journal of Economics* 18(4) (November): 831–842.

Livernois, John R., and Russell S. Uhler (1987). Extraction costs and the economics of nonrenewable resources. *Journal of Political Economy* 95(1) (February): 195–203.

Miller, Merton H., and Charles W. Upton (1985a). A test of the Hotelling valuation principle. *Journal of Political Economy* 93(1): 1–25.

_____ (1985b). The pricing of oil and gas: some further results. *Journal of Finance* 40(3): 1009-1018.

Pindyck, Robert S. (1978). The optimal exploration and production of nonrenewable resources. *Journal of Political Economy* 86(5) (October): 841–861.

Pindyck, Robert S. (1980). Uncertainty and exhaustible resource markets. *Journal of Political Economy* 88(6): 1203–1225.

Powell, Stephen G., and Shmuel S. Oren (1989). The transition to non-depletable energy social planning and market models of capacity expansion. *Operation Research* 37(3) (May-June): 373–383.

Slade, Margaret E. (1982). Trends in natural resource commodity prices: An analysis of the time domain. *Journal of Environmental Economics and Management* 9(2): 122–137.

____ (1987). Natural resources, population growth and economic well-being: Issues and evidence. In *Population Growth and Economic Development*. D. Gale Johnson and Ronald D. Lee, eds., Madison, WI: University of Wisconsin Press, pp. 331–372.

Swierzbinski, Joseph E., and Robert Mendelsohn (1989). Exploration and exhaustible resources: the microfoundations of aggregate models. *International Economic Review* 30(1) (February): 175–186.

Toman, Michael A., and Margaret Walls (1995). Nonrenewable resource supply: Theory and practice. In *Handbook of Environmental Economics.* D.W. Bromley, ed., Oxford and Cambridge: Blackwell.

Walls, Margaret (1994). Using a "hybrid" approach to model oil and gas supply: A case study of the Gulf of Mexico outer continental shelf. *Land Economics* 70(1) (February): 1–19.

Walls, Margaret (1992). Modeling and forecasting the supply of oil and gas: A survey of existing approaches. *Resources and Energy* 14(3) (September): 287–309.

World Resources Institute (1994). *World Resources 199495: People and the Environment*. Oxford: Oxford University Press.