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Understanding Nonrenewable Resource Supply Behavior

Douglas R. Bohi and Michael A. Toman

The response of nonrenewable resource supplies to changes in prices and other economic incentives is widely debated and extensively analyzed, yet poorly understood. The issue has been raised repeatedly in recent years in connection with crude oil and natural gas, where the presumed response plays a major role in shaping national energy policies and assessing the future performance of the world's economies.

At the broadest level, the perception that nonrenewable energy resources are scarce in an absolute physical sense, and that market prices cannot be relied on to limit their use and to avoid "running out," has led to widespread support for government intervention to regulate production and consumption of energy (*1*). It is sometimes argued that society should not leave decisions about the use of energy resources to private firms that are motivated by the desire to earn profits. More specifically, debates in the United States about decontrolling prices of crude oil and natural gas, about the wisdom of taxes on oil companies, and about the need for government subsidies to stimulate synthetic fuel alternatives often turn on perceptions of how production of crude oil and natural gas will respond to increases in their prices. If oil supply is not responsive, it is argued, an increase in the price will serve to benefit the oil industry at the expense of the rest of the economy.

The supply process for nonrenewable resources in general, and for oil and natural gas in particular, is very complex and difficult to describe in a simple theory. Oil and gas production involves decisions at many stages in the process of finding, developing, and extracting the resource, with complicated dynamic interrelations operating both within and among stages in the process. Economists have developed a theory about how the supply process works, building on the initial work of Hotelling (*2–4*), which gives an internally consistent and intuitively plausible description of how decisions are made by profit-motivated firms. The theory provides numerous insights concerning how resource prices may be expected to behave over time, how prices affect supply decisions in a competitive market, and how government intervention may be expected to alter those decisions.

Yet there is a serious gap between the conceptual models of supply in economics and the empirical application of those models. It is difficult to test hypotheses derived from the theory, and empirical models give notoriously unreliable predictions of how supply will behave when prices and other economic incentives change (*5*). To illustrate the complexities, Fig. 1 shows the pattern of crude oil prices (adjusted for inflation), output, and discoveries in the United States from 1960 to 1980. In many years, output and price moved in opposite directions: production rose (fell) when the price declined (increased). Discoveries also showed no clear relation to price: generally they rose when the price increased, but with a lag of varying length. Economic theory can shed some light on how these patterns result from complex

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interactions among producer decisions, expectations, and regulatory constraints, but incorporating these influences in an empirical model is extremely difficult. Consequently, the economics literature provides only limited guidance on the possible impacts of energy policy alternatives.

The gap between theory and application is the combined result of three deficiencies: (i) the theory inadequately matches the kind of data that are (or can be) available; (ii) the data base is plagued by errors, inconsistencies, and confusion; and (iii) estimation methods cannot separate dynamic interrelations and identify separate influences.

Summary. Decisions concerned with finding, developing, and extracting nonrenewable resources are dynamically interrelated in complex ways. Economic theory provides a description of this process that yields useful insights, but there are gaps between theory and empirical applications that hinder our understanding of how supply responds to changes in economic incentives. Consequently, many questions concerning market efficiency as opposed to government intervention remain open.

In this article we begin by briefly reviewing the complexities in the supply process for nonrenewable resources (with an emphasis on oil and natural gas) and the fundamentals of the economic theory of supply. We then proceed to describe the deficiencies in theory, data, and estimation that confront empirical analysis of observed supply behavior. In the concluding section we offer some recommendations for further research.

The Supply Process

The process of transforming resources in the ground to extracted commodities ready for distribution and sale can be divided into three stages: exploration, development, and extraction (*6*). Exploration is the identification of resource deposits and an initial estimation of their size and geophysical characteristics; development involves additional delineation of deposits and preparation of sites for extraction; and extraction is the final step of removing resources from the ground in preparation for distribution and sale. Firms may specialize in one stage or engage in several, but there is a natural sequence to activities: exploration logically precedes development and development precedes extraction.

Each stage consists of numerous distinct activities. For example, development includes gaining access to the resource (sinking mine shafts, removing overburden, drilling wells) and installing surface equipment for extraction and access to a distribution system (for instance, pipelines); petroleum exploration includes seismic surveying along with the drilling of exploratory wells. A further distinction can be made between exploration and development activities on an "intensive margin" and "extensive margin." In the development stage the intensive margin consists of sites that are already prepared for extraction; further development is intended to achieve more rapid or more complete extraction. Development on the extensive margin consists of preparing new discoveries for extraction. The distinction between the two margins also occurs at the exploration stage: the intensive margin refers to regions where resources have already been discovered while the extensive margin refers to "frontier" regions (*7*).

A key aspect of decisions made at each stage of the supply process is the effect of current decisions on future costs. For example, current extraction reduces pressure in petroleum reservoirs and increases the cost of future extraction (*8*). Similarly, for a given "inventory" of discovered sites, a decision to develop relatively low-cost sites today leaves only higher cost sites for the future. Diminishing returns at the intensive margin also lead to increases over time in the cost of additions to capacity. Finally, reductions in the stock of resource-bearing sites and the tendency for earlier discovery of larger and more accessible sites lead to rising exploration costs over time (*9*).

Costs tend to increase over time because the resource is nonrenewable: there is only a finite stock of the resource in the earth's crust and hence there is a limited number of resource-bearing sites. As we discuss in more detail subsequently, however, it is not finiteness per se but the rising costs implied by this limitation which are significant in any analysis of resource supply. The assumption that producers take these intertemporal cost relations into account in planning their decisions at each stage of the process has important implications for producer behavior.

This description of the "depletion effects" of current decisions on future costs introduces another important aspect of the supply process: interrelations among stages of supply. These interrelations stem from the fact that activity at prior stages of the supply sequence ameliorates the effects of depletion at subsequent stages. For example, rising costs of extraction as existing reserves are depleted can be tempered by developing new reserves with lower production costs. Rising development costs for existing sites can be tempered by the discovery of new sites with lower development costs. In effect, activity at each stage satisfies a "derived demand" for inputs to subsequent stages: new discoveries are an input to development and new reserves are an input to extraction.

The ability to ameliorate depletion effects is, of course, limited by the finiteness of the total resource stock and the availability of exploitable sites and deposits (*10*). Within these ultimate limits, however, changes in prices and costs will influence decisions at all three stages of the supply process. For example, changes in the price of final output will influence exploration and development decisions as well as extraction decisions by changing the derived demand for inputs to the extraction stage. Similarly, changes in development cost will affect activity at that stage, derived demands for new discoveries, and extraction decisions through changes in the cost of replacing reserves. Thus, for a theory of supply to provide a full description of behavior, it must take into account dynamic interactions among stages as well as intertemporal relations among decisions within each stage.

Another crucial element in the decision process is uncertainty. Particularly at the exploration stage, firms face substantial uncertainty in the relation between costs and output. Expenditures for seismic surveying and wildcat drilling may produce dry holes or small discoveries. In addition, producers necessarily lack full knowledge of future prices and costs. Assuming that depletion effects are taken into account in planning supply decisions over time, it follows that producers must predict both future prices and the uncertain consequences of current decisions on future costs. A complete theory must describe influences on expectations of prices and costs as well as the determinants of decisions for a given set of expectations. In practical applications, the theory must also make it possible to take into account the effect of numerous government regulations and varying institutional and market structures (such as the Organization of Petroleum Exporting Countries) on expectations and decisions.

A Theory of Supply Behavior

Having described nonrenewable resource supply as a dynamic process composed of multiple interrelated stages, with uncertainty regarding future prices and costs an integral part of the decision process, we now briefly sketch the fundamentals of an economic theory of individual supply decisions (*11*). The core of the theory is a model of the depletion effects which individual producers are assumed to take into account in planning decisions over time. Depletion effects are modeled by assuming that costs of activities depend on certain "cumulative" or "stock" variables as well as on the rates at which activities are undertaken. The cost of extraction from a single deposit is assumed to be negatively related to the remaining stock of reserves, or (equivalently) positively related to cumulative past production from the deposit. Thus, the cost of any particular rate of extraction increases over time as the reserve stock diminishes or as cumulative production grows. Depletion effects at the development and exploration stages are modeled similarly by assuming that costs are positively related to cumulative developed reserves and cumulative discoveries, respectively, or that costs are positively related to cumulative exploration and development effort (for instance, drilling). It is also assumed that each deposit is operated by a single producer or a group of producers operating in concert. This rules out so-called common property externalities, which arise when a deposit is exploited by many uncoordinated producers and each operator's decision imposes costs on others (*12*).

The assumption that producers take depletion effects into account in planning their decisions is embodied in the hypothesis that producers seek to maximize the sum of discounted net revenues over time, rather than current profits, given expectations of future prices and costs. In choosing sequences of decisions over time which maximize this sum, producers take into account the effect of current decisions on current profit, the depletion effects of current decisions on expected future cost, and the relative profitability of current versus future activities based on their expectations of future prices. Changes in expectations about prices or costs induce producers to revise their plans. Shifts in aggregate product demand, changes in materials prices and interest rates, and changes in institutional and regulatory constraints can all affect a producer's plans.

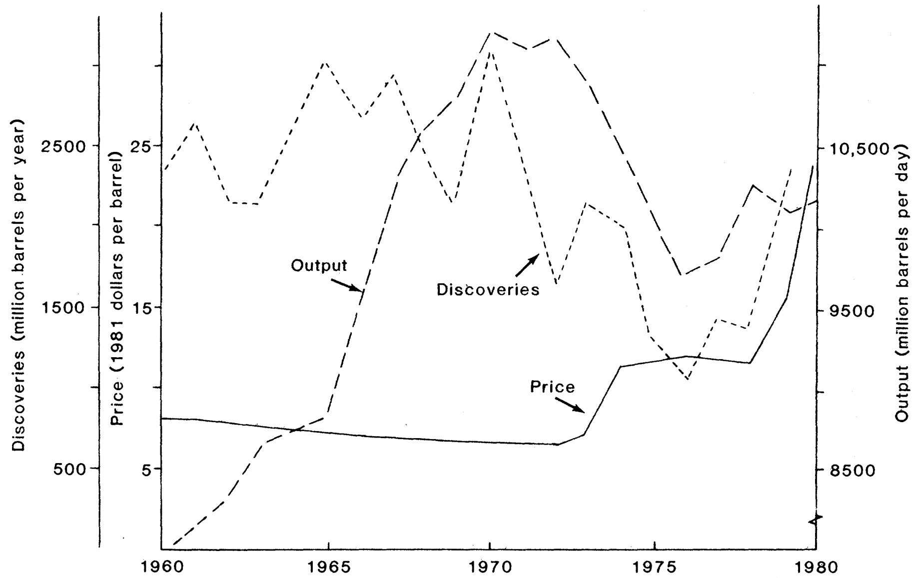

Fig. 1. Price, output, and discoveries of crude oil in the United States, 1960 to 1980.

The theory has substantial implications for the intertemporal characteristics of producer decisions and the dynamic interactions among stages of supply. In planning extraction from a single deposit, the producer's optimal (that is, maximum expected net present value) decision balances the stream of gains and costs. The gain from increased extraction is measured by the price, while the cost is given by the increase in operating cost and the reduction in expected net present value from increased operating costs in future periods. The sum of discounted future cost increases is known as the user cost of extraction, and the sum of marginal user cost and marginal operating cost is compared with the expected price to determine the optimal levels of production over time.

Intertemporal dependence of price and costs occurs in several dimensions. User cost in the current period depends on planned rate of extraction in future periods, and these plans in turn depend on anticipated future prices (*13*). Current operating cost depends on cumulative past production, so that current extraction decisions depend on past extraction decisions. The theory is therefore inherently dynamic, with current decisions depending on both past decisions and expectations of future prices and costs. One implication of this dynamic interdependence is that a simple elasticity measure of the responsiveness of output to a change in price is not meaningful. Declining reserves lead to systematic changes over time in the relation of output to price, and changes in current output reflect responses to changes in expected future prices as well as to the current price. For example, while an increase in the current price tends to shift extraction toward the present, an increase in expected future prices shifts planned extraction toward future periods.

Applications of the model to development and exploration point up the interdependence of decisions among stages in the supply process as well as within stages (*14*). Consider, for example, the planning of activities by a firm engaged in both extraction and development of new resources. Just as extraction decisions are based on the balance between the price of output and the intertemporal cost of extraction, including user cost, development decisions are based on the balance between the value of new reserve acquisition and the cost of increased development. Development cost includes a user cost which measures the depletion effect at this stage of the supply process: increased additions to reserves today lead to larger costs of reserve additions in future periods. The value of new reserves reflects the decrease in future extraction costs that is expected. Since the decrease in future extraction costs resulting from a unit increase in reserve additions is the same as the decrease in costs from a unit decrease in current extraction, the value of new reserve additions is the same as the user cost of extraction. Thus, optimal development decisions reflect a balance between the value of reserve additions, equal to the user cost of extraction, and the sum of the user cost of development and current outlays.

Because the user cost of extraction depends on planned future outputs, and these depend on current and expected prices of output, it follows that the decision to invest in new reserves depends on current and future prices of final output. This dependence also arises from the influence of the user cost of new reserves on development decisions. User cost depends on future investment decisions, and these decisions depend on planned future output and, in turn, on expected future output prices. Current development decisions also depend on past development effort through their effect on the current cost of additions to reserves.

The dependence of current development decisions on future output prices and cumulative past decisions indicates one source of dynamic interaction between the stages of supply: changes in current or future output prices will lead to revisions of both extraction and development plans. The stages also are dynamically related on the cost side by virtue of the equality between the value of new reserves and the user cost of extraction. A decline over time in developed reserves as a result of depletion increases the user cost of extraction and stimulates an acceleration of development as well as a deceleration in extraction. Similarly, a decrease over time in the stock of known prospects capable of development increases the user cost of development. This retards further development of reserves, raises the user cost of extraction, and slows current production. Decisions made in both stages also depend on other determinants of cost in each stage, as well as on anticipated changes in these determinants.

Another important implication of the theory concerns the distinction between economic and physical scarcity. Ultimate geological limits on the size of reserves and the volume of discoveries do not enter directly into firms' decision calculus but enter indirectly through the effect of depletion on costs over time. In this sense, the model emphasizes economic scarcity over physical scarcity. An implicit assumption is that rising costs will limit resource exploitation (and, on the demand side, will limit consumption and stimulate development of alternative energy sources) prior to the point at which ultimate physical limits are reached. These adjustments to costs would result from rising market prices for the resource.

Whether market-determined prices can be relied on to effectuate these changes in behavior more efficiently than other allocation schemes, and whether other sectors of the economy would remain viable in the face of the required price increases, are questions which cannot be resolved on the basis of theoretical analysis. While history is an ambiguous guide to the future, experience offers no definitive grounds for believing ominous projections of absolute energy scarcity and economic decline (*15*). Extrapolating historical experience into the future is also dangerous because such projections cannot take full account of producer and consumer adaptations to increased economic scarcity.

A highly simplistic version of this model is often used to make projections of the relation between resource scarcity and rising prices, but these projections should be viewed with skepticism. In the simplistic model, the resource base is treated as a fixed stock of known size and discovery and development of new reserves is ignored. It is also assumed that extraction cost is independent of cumulative production, though the cost may vary with the extraction rate at any point in time. In other words, depletion effects are assumed to be absent, and the only constraint on ultimate resource recovery is the physical limitation of the natural endowment. Thus, the model emphasizes physical scarcity over economic scarcity.

One prediction of this model is that physical exhaustion of a nonrenewable resource is inevitable unless the resource is made completely obsolete by development of an inexhaustible "backstop" or substitute which can be produced at lower cost (*16*). Because extraction cost is assumed to be uninfluenced by cumulative output in the model, the only force other than physical scarcity that limits extraction is a decline in price—resulting from development of a cheaper substitute good—to the point where continued extraction of the resource is unprofitable. The model also predicts that, in the absence of a substitute, the "net price"—the difference between price and incremental extraction cost—must grow at the rate of interest. The reason is that firms would increase the present value of profits by shifting output from future dates toward the present if the net price grew more slowly than the rate of interest. The shift in the production profile would drive down near-term prices and raise future prices until the discounted net price was constant over time, at which point firms would be indifferent between current extraction of the resource and holding it until a future date. Similarly, output would be reallocated toward the future if net price grew more rapidly than the rate of interest until an intertemporal equilibrium was established (*17*).

The principle that net price must grow at the rate of interest has been called the r percent rule (where r is the interest rate for discounting future profits) and has been the source of numerous projections concerning the likely course of future prices and supplies: prices are projected to grow at an (almost) exponential rate, while production and consumption are projected to decline. From the discussion in the two sections above, however, it should be clear that these projections rest on very shaky ground and that the r percent rule is not a reliable guide to forecasting. To begin with, the derivation of the rule ignores exploration and development of new reserves, the introduction of alternative energy sources, and shifts in demand due to conservation efforts induced by rising prices, all of which can cause prices and quantities to deviate from predicted paths. Even in the absence of these influences, the rule is valid only if depletion effects are ignored and ultimate total exhaustion is assumed. As noted previously, both depletion effects and incomplete exhaustion appear to be inherent in production of a nonrenewable resource. In contrast, the more general Hotelling model with depletion effects, described earlier, predicts that the net price of the resource will grow more slowly than the rate of interest, and may even decline, even if the resource ultimately is exhausted (*18*). There is also no empirical support for the prediction of exponential price growth: neither energy prices nor prices of other nonrenewable minerals exhibit this trend (*4*, *19*).

Finally, it should be pointed out that analyses based on the simplistic r percent rule are often couched in terms of a hypothetical centrally planned economy (*20*). These analyses abstract from several issues: real world interactions of demand and supply decisions in a market economy, heterogeneity of resources, and the influence of market imperfections and nonmarket constraints. As indicated in the next section, these issues are the source of substantial practical complications in empirical analysis of supply.

Practical Problems of Applying the Theory

The theory of supply is useful in determining how a statistical model should be specified by indicating which variables are to be explained, which are crucial explanatory variables, and how causal relation among the variables should be formulated. Unfortunately, the theory is far from unambiguous in suggesting the form and content of equations in a model, which forces researchers to supplement the theory with assumptions that are often ad hoc in nature. Additional assumptions are required because of gaps in data, deficiencies of estimation methods, and inconsistencies between the theory and available data. While the same generic problems arise to some degree in virtually all applications of economic models, as indicated below they are particularly serious in connection with nonrenewable resources. The following discussion describes some of the more important problems of application and is not intended to be exhaustive.

Several important issues are not addressed, or are not addressed adequately, by existing economic theory, creating a number of open questions about how to conduct empirical analysis of supply behavior. One of the more serious gaps arises because the theory describes behavior for individual participants in the market, while the data reflect aggregations across individual units. The problem disappears only if all observed units in the supply process are identical; otherwise, aggregate behavior will differ substantially from individual behavior in ways that defy description as simple summations or averages. The total will not be equal to the sum of its parts: aggregate behavior will not be the same as the summation of individuals' behavior, and conversely, behavior of the "representative" individual will differ from the average of aggregate behavior.

There are several factors that differentiate individual and aggregate behavior. First, individual resource prospects differ geologically at any moment and differ across time because of depletion and the addition of new discoveries. Consequently, aggregations across heterogeneous units will depend on the distribution of individual characteristics, while these factors have no relevance to decisions made at the individual level. Statistical procedures have not been developed to include these distributional characteristics because of the absence of the requisite data. A second reason is that a focus on individual decision-making by producers ignores the demand side of the market, leaving open the question of how prices are determined. Market prices, as recorded in available data, are the result of interactions between buyers and sellers at each stage of the supply process, from the value of final output back to the value of new discoveries. How these prices are determined is not directly important to an individual decision-maker who has no influence on the outcome, nor should these considerations enter into the theory of individual supply decisions. At the aggregate level, in contrast, supply behavior interacts with demand to determine market prices, which in turn determine production and consumption decisions. The influence of demand can be ignored only if demand is unchanged over time. In short, actual supply behavior cannot be determined on the basis of a theory of supply alone; a theory of demand is also required.

The focus on individual rather than market behavior also creates gaps for analyzing issues that arise at the market level. One such issue is the analysis of market structures that deviate from perfect competition. In general, the theory assumes competitive markets that adjust rapidly and completely to incentives and ignores conceptual problems of noncompetitive or disequilibrium market situations. Consequently, the theory provides little guidance for testing hypotheses about the degree of competition in the petroleum industry or about the effect of government programs that work at the market level (*21*). The theory also does not describe how common property externalities, referred to above, influence aggregate behavior, or even how these externalities affect the decisions of individual firms (*22*).

Another major weakness of existing theory concerns the treatment of uncertainty. With few exceptions, the theory presumes full knowledge by all participants of future prices and costs (*23*). As noted earlier, uncertainty is a generic aspect of energy supply behavior since future conditions cannot be known in advance. Consequently, the deterministic nature of the theory is a serious deficiency for analyzing what is essentially a stochastic process. It is not an easy matter to substitute probabilistic terms for their deterministic counterparts and still achieve definitive results. Additional conceptual difficulties arise in attempting to describe changing perceptions of probabilities on the basis of past experience. For example, when producers learn from experience or they are averse to risk, decisions depend on the variability of prices and costs as well as on expected values (*24*).

Turning from problems of theory to problems of estimation, the primary difficulty stems from interactions among decisions in the supply process and between supply and demand. The dynamic interactions among stages of supply mean that a reliable empirical analysis must attempt to describe the entire process rather than its individual parts. Focusing on one stage of the process, such as extraction, is incomplete and prone to yield misleading results. At one level, the interactions among supply decisions mean that simple methods of multiple correlation analysis are inadequate. Variables will be highly correlated among themselves as well as with statistical error terms, making it difficult, even in the absence of other problems, to obtain reliable statistics for prediction and hypothesis testing.

Even more troublesome is the problem of separating and identifying distinct influences on behavior from reported data that are a mixture of many influences working simultaneously. As indicated by the earlier description of aggregation problems, observed prices of crude oil and the quantity of oil produced are the result of actions by consumers as well as producers. Producers' extraction decisions are also influenced by other decisions at the exploration and development stages of supply. These exploration and development decisions are influenced in turn by extraction behavior, and behavior at all stages of supply is influenced by final demands and by impediments to the market process such as government regulations. To understand supply behavior, these interactions must be separated; if they are not, then supply behavior is statistically indistinguishable from other influences on the data (*25*). This identification of influences cannot be accomplished if one stage of supply is analyzed in isolation from other stages, or if demand and nonmarket constraints are neglected.

The problem of separating these influences is exacerbated by the fact that supply decisions depend on expectations about costs and prices. Expectations are not directly observable, but must be estimated on the basis of a separate hypothesis about how they are formed (*26*). Aside from the specific problem of specifying the expectation mechanism, there is the more general problem of identifying causal relations. In particular, variables that may be thought to statistically distinguish supply and demand decisions may not serve this purpose because of their interdependent link through expectations. For example, consumer income is usually thought to influence demand alone, but will also influence supply if producers form expectations about future prices based on changes in consumer income. The same problem arises in sorting out the effect of changes in government regulations, where, in addition, the effectiveness of the regulations depends on the extent to which producers anticipate and adapt to them.

Efforts to extend the theory by modeling expectations have been based on the concept of rational expectations, which assumes that individuals use all available information to efficiently forecast uncertain future prices and costs. This approach has been criticized as being an unreasonable description of real-world economic decision-making (*27*), but it does provide a tractable device for recognizing the multiplicity of possible influences on expectations and for sorting out interactions of dynamic influences on observed behavior. The approach also provides a solid analytical base for evaluating the effect of changes in regulatory and other institutional constraints on supply behavior, assuming that producers "rationally" respond to these changes (*28*).

The final category of problems confronted in empirical applications of the theory concerns the availability of data and whether the information is consistent with the requirements of the theory. Two examples will illustrate the nature of these problems. A model of development (or exploration) can be constructed in which reserve additions (or discoveries) depend on the rate of effort and cumulative effort. As noted previously, both of these stages of the supply process involve several distinct activities. Data are available only on drilling footage and the number of wells drilled. Each data series conveys information regarding input to the two stages, yet it is not clear how the two series can be combined to form a measure of effort. The drilling data also blur the distinction between intensive and extensive margins of activity, and in the absence of complementary data on the area of search activity and size of prospects, the two margins cannot be distinguished.

Problems also are encountered in combining the theory, which requires physical measures of reserves in the ground, with available data on "proved" reserves. The data represent extrapolations of current production trends rather than measures of reserves in place, which substantially understate the true size of new discoveries. Moreover, the error varies with changes in economic and operating conditions (*29*). Note in addition that the use of data on reserves calculated from extrapolations of production trends raises a logical problem of circularity in the analysis of supply behavior, regardless of the theory that underlies the analysis.

Conclusions

Numerous conceptual and methodological problems combine to make it difficult to specify and empirically test a model of supply behavior for nonrenewable resources in general and oil and natural gas in particular. The presence of these complications sheds some light on the poor performance of statistical models in explaining and predicting changes in the supply of oil and natural gas in the United States.

These problems also indicate that more basic research is required on the supply of nonrenewable resources at both conceptual and empirical levels. Empirical understanding of supply behavior could be considerably enhanced by using models that incorporate all stages of the supply process so that dynamic interactions among the stages could be assessed. The models should also include unambiguous measures of depletion, such as cumulative production and drilling, in order to assess the dynamics of depletion at each stage. Additional improvements could be obtained by incorporating explicit models of expectations, such as the rational expectations approach, to identify the effects on behavior of uncertainty, shifting market conditions, and changing nonmarket constraints.

Other issues require additional theoretical as well as empirical investigation. Particularly important is the distinction between aggregate and individual behavior, including how heterogeneous geological characteristics vary over time, separation of intensive and extensive margins, and the impact of uncertainty, learning, and risk aversion on producer decisions. Finally, greater attention should be paid to problems of inconsistency between the theory and available data. Available data should not be combined with a model to which they are not suited. On the other hand, since nothing ventured means nothing gained in terms of practical understanding of nonrenewable resource supply, and available data are all that exist, efforts should be made to tailor the theory to these data.

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5. P. Clark, P. Coene, and D. Logan [*Resour. Energy* **3**, 297 (1981)] compare several empirical models.
6. The market for mineral rights is a fourth stage that is important in countries, such as the United States, where these rights are privately owned. For some mineral resources—but not energy—recycling also is a stage in the supply process.
7. S. McDonald [*Petroleum Conservation in the United States: An Economic Analysis* (Resources for the Future Series, Johns Hopkins Univ. Press, Baltimore, 1971)] gives a concise overview of the supply process.
8. R. Uhler [in (*3*), pp. 93–118] describes the geophysical underpinnings of this effect for petroleum exploration.
9. See R. Solow and F. Wan, *Bell J. Econ. Manage. Sci.* **7**, 359 (1976).
10. This is true even for recyclable resources, since complete recovery of the resource is impossible.
11. The bulk of nonrenewable resource supply theory has focused on the behavior of an individual mining firm. As indicated below, there are extensions of the theory that address other issues; however, these developments are incomplete and thus are not readily translated into an empirical study of supply behavior.
12. See McDonald (*7*) for a discussion of these externalities. Their presence means that to forecast future costs, a producer must forecast the depletion effects of both his own and other producer's decisions—a substantial complication in the theory.
13. Planned output in future periods also reflects a balancing of anticipated prices and costs (including user costs).
14. R. Uhler, in (*3*), pp. 93–118; R. Pindyck, *J. Polit. Econ.* **86**, 841 (1978).
15. Alternative hypotheses about the relation among resource scarcity, economic growth, and economic welfare (including intergenerational welfare) are explored in V. K. Smith, Ed., *Scarcity and Growth Reconsidered* (Johns Hopkins Univ. Press, Baltimore, 1979).
16. Models with a backstop are reviewed in Dasgupta and Heal (*4*).
17. See R. Solow [*Am. Econ. Rev. Pap. Proc.* **64**, 1 (1974)] for a different derivation of this equilibrium condition that treats resource holdings as capital assets.
18. See D. Levhari and N. Liviatan, *Can. J. Econ.* **10**, 177 (1977).
19. M. Slade, *J. Environ. Econ. Manage.* **9**, 122 (1982).
20. These models are discussed in Dasgupta and Heal (*4*).
21. Dasgupta and Heal (*4*) and S. Devarajan and A. Fisher [*J. Econ. Lit.* **19**, 65 (1981)] review theoretical models of noncompetitive resource markets. There are two common gaps in this literature. (i) The models are based on the *r* percent rule, raising questions about the reliability of predictions based on these theories. (ii) The models are also typically based on an inadequate description of resource demand: they presume a fixed relation between demand and price and thus ignore shifts in demand due to conservation and substitution with other goods.
22. V. Aivazian and J. Callan [*Can. J. Econ.* **12**, 83 (1979)] give a theoretical description of common property externalities in the context of a noncooperative game. Whether this analysis has any practical content is open to question: it assumes that all producers are identical and, contrary to the historical evidence in McDonald (*7*), predicts that output per firm will decline because of these externalities.
23. An exception is the model in R. Pindyck, *J. Polit. Econ.* **88**, 1203 (1980).
24. K. Arrow and S. Chang, *J. Environ. Econ. Manage.* **9**, 1 (1982). A serious gap in the literature is that models of risk aversion are generally static and thus not readily applicable in dynamic contexts such as resource supply.
25. H. Theil, *Principles of Econometrics* (Wiley, New York, 1971), chapters 10 and 11.
26. For some resources, futures markets exist and futures prices can be used to determine a proxy for price expectations. But there are limitations to this approach, as indicated in D. Newbery and J. Stiglitz, *The Theory of Commodity Price Stabilization: A Study in the Economics of Risk* (Clarendon, Oxford, 1981).
27. The debate over rational expectations is summarized in R. Maddock and M. Carter, *J. Econ. Lit.* **20**, 39 (1982).
28. For a further discussion of this application of rational expectations, see R. Lucas, Jr., in *The Phillips Curve and Labor Markets*, K. Brunner and A. Meltzer, Eds. (North-Holland, Amsterdam, 1976), pp. 19–46; T. Sargent, *J. Polit. Econ.* **89**, 213 (1981).
29. For a review of these data and their suitability for empirical analysis, see W. Lovejoy and P. Homan, *Methods of Estimating Reserves of Crude Oil, Natural Gas, and Natural Gas Liquids* (Resources for the Future Series, Johns Hopkins Univ. Press, Baltimore, 1965).

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