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Withagen, C.A.A.M.

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# Untested Hypotheses in Non-Renewable Resource Economics

CEES WITHAGEN
*Department of Economics and Tinbergen Institute, Free University Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands; and Department of Economics and CentER, Tilburg University, 5000 LE Tilburg, The Netherlands (e-mail: cwithagen@econ.vu.nl)*

**Abstract.** The present paper reviews the literature on the empirical implications of the Hotelling rule and suggests directions for further research in this area.

**Key words:** Hotelling rule, resource economics

**JEL classification:** Q30, Q31

## 1. Introduction

This paper deals with the tests of theories about the exploitation of exhaustible natural resources. Hotelling's rule constitutes a central element in these theories. It is a condition that must be satisfied in order for resource extraction to be dynamically efficient. It is derived under assumptions with respect to technology, price expectations, interest rates expectations, and market structure. The Hotelling rule, if actually applicable, might give some insight in the scarcity of the exhaustible resource under study because it has implications for the in situ price of the resource. Also, the rule could be used to derive statements about the evolution of market prices for the raw material from the exhaustible resource. For these reasons it is important to test for the rule. In this essay no attention will be paid to scarcity measures derived from so-called biophysical models (see e.g., Cleveland and Stern 1998).

Actually, many tests have already been performed in the past, but, as I hope to make clear, there is still room for fruitful and important research. In particular it will be argued that recently there have emerged new theoretical insights regarding optimal exploitation under full competition as well as under alternative market conditions which might give rise to alternative approaches to the questions posed. In Section 2 we shall deal with competitive markets for the extracted commodity. Section 3 is goes into the so-called cartel-versus-fringe model. Section 4 concludes.

## 2. Competitive Depletion

### 2.1. A SIMPLE THEORETICAL MODEL

We consider a single firm that exploits a deposit of a non-renewable resource ($S$) and sells the raw material ($E$) on a competitive market. It is worth stressing that this involves already several assumptions: the firm has to deal only with one deposit and does not need to decide on the optimal order of exploitation of deposits, the firm is not processing the raw material itself and the output market is competitive.

The firm chooses an extraction path so as to maximize total discounted profits over time. The present interest rate ($r$) is given to the firm, which has fixed expectations with respect to the future time-path of the interest rate. This also holds for the market price ($p$) of the raw material. The extraction costs ($c$) depend on the rate of extraction, the stock of the exhaustible resource and time can be included as a parameter in order to capture the possibility of technical progress. For the time being we abstract from exploration.

Mathematically, the problem facing the firm can be written as follows.

$$\max \int_0^\infty \pi(t)[p(t)E(t) - c(E(t), S(t), t))]\mathrm{d}t$$

subject to

$$S'(t) = -E(t),\ E(t) \geqslant 0,\ S(t) \geqslant 0,\ S(0) = S_0, \text{ given}$$

where

$$\pi(t) := e^{-\int_0^t r(\tau)\mathrm{d}\tau}$$

is the discount factor and $S'$ denotes the time derivative of the resource stock. It is assumed that the cost function is differentiable with $\partial c/\partial E > 0$ and $\partial c/\partial S \leqslant 0$. So the extraction costs are increasing in the rate of extraction and non-increasing in the stock, which seems a plausible assumption. The optimal extraction model given here is quite general and captures many models found in the literature.

The Hamiltonian of the problem, in present value terms, reads

$$H(E, S, t, \lambda) = \pi(t)[p(t)E - c(E, S, t)] - \lambda E.$$

The necessary conditions for optimality require a.o. that there exists a function $\lambda$ the present shadow price of the resource stock, such that for all $t \geqslant 0$

$$\partial H(E(t), S(t), t, \lambda(t))/\partial E(t) = 0, \text{ if } E(t) > 0$$

$$-\lambda'(t) = \partial H(E(t), S(t), t, \lambda(t))/\partial S(t).$$

Hence:

$$\pi(t)[p(t) - \partial c/\partial E] = \lambda(t) \tag{1}$$

$$-\lambda'(t) = \pi(t)\partial c/\partial S \tag{2}$$

Equation (2) is most easily understood after writing it in integral form:

$$\lambda(0) = \pi(t)[p(t) - \partial c/\partial E] + \int_0^t \pi(s)\partial c/\partial S \mathrm{d}s.$$

Suppose the extractor buys an additional marginal unit of the resource at the outset of the planning period. The left-hand side denotes the cost of acquiring it. The additional amount is mined at $t$. The first term on the right-hand side gives the additional discounted profits of selling the unit. The second term is the total discounted additional profits up to $t$ caused by the fact that the resource contained more ore before $t$ and hence was more easily depleted.

The simplest case occurs if extraction costs are absent. Then it follows from Equation (2) that the present value shadow price of the resource stock is constant, implying from Equation (1) that the market price of the raw material rises at a rate equal to the interest rate. This is the Hotelling rule in its rudimentary form, which can also be stated by saying that the current price of the in situ reserves ($\psi(t) := \lambda(t)/\pi(t)$) increases at the rate of interest.

If the extraction costs do not depend on the resource stock and marginal extraction costs do not depend on the rate of extraction nor on time ($c(E, S, t) \equiv \alpha E$, with $\alpha$ a positive constant) then the present value shadow price of the exhaustible resource is constant and marginal revenues of selling the raw material increase over time at a rate equal to the rate of interest. The current price of in situ reserves increases at the same rate. Moreover, since $\lambda$ is constant and since total extraction over time equals the given initial stock, it readily follows that total discounted profits equal

$$\int_0^\infty \pi(t)[p(t) - \alpha]E(t)\mathrm{d}t = \lambda S_0 = [p(0) - \alpha]S_0. \tag{3}$$

The more general case is studied by Farzin (1992 and 1995) who assumes that basically the resource base is infinite but that the extraction costs become prohibitively high when the accumulated extraction goes to infinity. One way to model this is to assume that, for any $t$, $p(t) - c(E, S, t) < 0$ as $S$ becomes smaller than some given value (independent of $t$). Farzin shows that, under plausible assumptions, the current value shadow price converges to a constant as time goes to infinity, but might be monotonically increasing, monotonically decreasing or might not be monotone. Hence the time path of the price of the in situ reserves crucially depends on the specification of the cost function and there is no reason a priori to suppose that resource rents are increasing. These observations have far-reaching consequences for testing the Hotelling rule. Indeed the rudimentary Hotelling rule could easily be refuted despite the fact that the underlying richer theory is applicable.

Some authors use a slightly different model to test for the Hotelling rule. They assume that the extracted commodity ($E$) needs to be processed in order to get a final product ($Z$) that can be sold on a market at a price $p$. Let the production cost be denoted by the cost function $c(E, Z, S, t)$, which is the minimal cost to produce $Z$, given the amount extracted $E$, the remaining stock $S$ and time (allowing for exogenous technical progress). Assuming an interior solution we have among the necessary conditions

$$p(t) = \partial c/\partial Z$$

$$\lambda(t) = -\pi(t)\partial c/\partial E$$

$$\lambda'(t) = \pi(t)\partial c/\partial S.$$

The second condition is the static efficiency condition and the third one is a condition for dynamic efficiency, which is the Hotelling rule.

Before turning to the empirical issues a few remarks are in order.

First, it should be noted that the assumption that extraction costs increase as the stock decreases might be plausible for a single well, but that it is by no means the case that costs will be smaller the larger is the total stock available. If we allow for exploration it might be the case that a new well turns out to be more costly to exploit than existing ones. See on this issue Toman and Walls (1995), Livernois and Uhler (1987) and Swierzbisky and Mendelsohn (1989). These observations are very important in relation to the empirical work discussed below, because it often rests on aggregated data. As a first recommendation for further research I therefore cite Toman and Walls (o.c., p. 186): "... considerable further work is needed to understand the microfoundations of the industry cost function." Some authors, e.g., Slade and Thille (1997) and Chermak and Patrick (1997), begin to do so, using data that are as much disaggregated as possible.

Second, in the model exploration has not been taken into account. For an early study on this issue, including a discussion of the resulting time path of the shadow price, the reader is referred to a model by Long (1977), where labour can be employed to search for new deposits. In this particular model the growth rate of the shadow price still equals the interest rate. This will alter if there is a relationship between the existing resource stock and the effect of exploration activities.

Third, it is appropriate to address the issue of scarcity. Suppose the assumptions made in the theory, with regard to perfect foresight and competitive markets, hold in reality. Moreover assume that no new (unexpected) discoveries are made and that there is no technical progress. Then the shadow price of the resource is an appropriate measure of scarcity of the resource, if this is defined as the marginal contribution to welfare. However, it is highly unlikely that the assumptions are satisfied in reality. For example, Norgaard (1990) argues that there are problems with regard to the information available to the resource owners. Norgaard (o.c.) even puts forward that in the case of imperfect information scarcity tests are based on a logical fallacy, because the price paths on the basis of which statements are made about scarcity may only reflect the ignorance of the decision makers. Based on this critique and the fact that other assumptions of the theory may not hold, one should be very careful with regard to the interpretation of the empirical results.

### 2.2. EMPIRICAL TESTING

There are several ways to test for the Hotelling rule, depending among other things on the formulation that is deemed applicable.

(*A*). In the case of constant marginal extraction costs ($\alpha$) one can apply Equation (3), provided data are available on property values, resource stocks and marginal profitability. Miller and Upton (1985) employed data on U.S. gas and oil companies in a cross section study. The equation estimated is:

$$\frac{V_0^{it}}{S_0^{it}} = \beta_0 + \beta_1[p_0^{it} - \alpha_0^{it}]$$

where $V$ denotes the value of the property, the index $i$ refers to the firm and 0 refers to the at $t$ current values. The Hotelling rule holds if $\beta_0 = 0$ and $\beta_1 = 1$. Miller and Upton (o.c.) find support for this hypothesis. However, Adelman (1990) argues that this approach overvalues the resources, because of the neglect of develoment costs, which in Adelman's view are crucial.

(*B*). If the requirements with respect to data on the in situ price are not satisfied, one needs to use a proxy. An approach frequently followed is to postulate a functional form for the cost function (for example translog or generalized Cobb-Douglas) and to estimate the parameters. Subsequently a test is performed to see if the shadow price $\lambda$, derived from the static efficiency condition, satisfies the Hotelling rule. In order to do so assumptions need to be made concerning the price expectations and the interest rate.Then there are three crucial elements in such a test of the Hotelling principle: the functional form, the formation of output price expectations and the appropriate interest rate. We shall briefly review the literature in order to see where the main challenges for future research lie. The survey also gives an impression of the resource markets that have been subject to research. We start by discussing papers where price expectations are implicit in the information available on actual behaviour.

– Chermak and Patrick (1995 and 1997) study the market for natural gas in the U.S. using monthly data from 29 tight gas sand wells. They employ a generalized Cobb-Douglas cost function, giving monthly costs as a function of gas produced, remaining reserves and a time trend. They also allow for cost differences between firms. They find that the Hotelling rule cannot be rejected for high interest rates, which, as they argue, might be applicable to the firms under consideration. For further research they suggest to incorporate uncertainty into the firm's decision problem.

– Halvorsen and Smith (1984 and 1991) study the Canadian metal mining industry on an aggregate level and use a generalized Cobb-Douglas cost function as well. They strongly reject the theory. They suggest further research on disaggregated data and uncertainty in a world of imperfect arbitrage.
– Pesaran (1990) deals with oil exploration and exploitation on the U.K. continental shelf. With respect to the formation of price expectations Pesaran considers several alternatives such as rational expectations and adaptive expectations. He finds that adaptive price formation is getting more support from the data than rational expectations. See also Hanley et al. (1997) for a discussion of Pesaran's work.

(*C*). There are quite a few studies that do not derive the (implicit) in situ price of the resource from a cost function. They infer the in situ price from the evolution of the price of the extracted commodity. The idea is that increasing prices together with non-increasing marginal costs indicate that the current resource price itself should be increasing. The seminal work in this area is without any doubt done by Barnett and Morse (1963) who found that mineral prices (fuels, metal, nonmetals) show a horizontal trend over the period 1870–1957 and conclude that the scarcity hypothesis fails (Barnett and Morse (o.c.), p. 211). Smith (1979) considers basically the same data starting at 1900 and extending the sample period to 1973. He concludes that for minerals one could detect an increasing trend over the final part of the period under investigation, but also that "evaluations of resource scarcity . . . do not seem possible" (Smith (o.c.), p. 426). Slade (1982) finds that price series for a large number of nonrenewable resources display a U-shaped form over the period of investigation (1870–1978). However, in a later paper Slade (1991) shows that prices have been very volatile after the sample period, which finding does not provide evidence for a sustained trend. Berck (1995) remarks that this strand of the literature exhibits some weaknesses. First, referring to Slade (1982), the parameters of the model are not constant over time: they change as estimates are made for subperiods. Moreover, the price series might not be stationary around a deterministic trend, but around a stochastic trend. This issue is addressed in a recent paper by Ahrens and Sharma (1997).

*Intermezzo*

*A time series is called stationary if its mean, variance and covariances are constant over time. A non-stationary time series may exhibit a deterministic trend or a stochastic trend. The former can be made into a stationary time series (trend stationary) by appropriate detrending. Processes which, after a random shock, do not return to the trend or the mean, are called stochastic trend processes or unit root processes. The econometric literature provides several tests for unit roots. See e.g., Stewart (1991). The importance of this approach lies in the fact that the assumption of trend stationarity (made e.g.,* *by Slade (1982)) may lead to wrong conclusions using conventional regression techniques, when the real underlying process exhibits a stochastic trend.*

Slade (1988) performed the first test for unit roots in the Hotelling model. She finds that the prices of six out of the seven commodities (copper, iron, lead, bauxite, silver, petroleum, coal) under study exhibit a random walk. Her work was extended by Abgeyegbe (1993), who finds that three out of four resource prices can be characterized as unit root processes. Ahrens and Sharma (o.c.) employ ARMA and ARIMA (with lag lengths of 6 years) forms to describe trend stationarity and difference stationarity respectively. And they use several procedures to test for unit roots. In their sample of 11 resource commodities (aluminum, bituminous coal, copper, iron, lead, natural gas, nickel, petroleum, silver, tin and zinc) they conclude for six resource commodities that the price is generated by trend stationary processes. This is contrary to what Slade (o.c.) and Agbeyegbe (o.c.) found. As the next step the authors suggest that more general ARMA models are used to study the long run behavior of prices. We also refer to Berck and Roberts (1996) who depart from a very general model and find no evidence for rising prices. It should be worthwhile to investigate further the issue of unit roots in resource prices.

(*D*). The fourth approach rests on the idea that the resource is an asset and its price should satisfy the usual equilibrium conditions on the asset markets. The theory is as follows. Suppose that the extraction technology or the competitive market price of the extracted commodity is subject to uncertainty. Then the stock of the exhaustible resource is a risky asset. If there are other risky assets in the economy this implies that the rate of return on the exhaustible resource (after correction for inflation and taxes) is a convex combination of the risk free rate of return and the return on the market portfolio. No other variables are needed to explain the rate of return on the exhaustible resource. Berck (1995) clearly points out that it is very important to note that this presupposes knowledge about the actual rate of return on the market portfolio, which is not known at the moment the decision is taken. Moreover, other types of arbitrage equations are possible as well.

An application can be found in Slade and Thille (1997). They first derive the so-called Hotelling/Capital Asset Pricing Model, giving the following equation:

$$\lambda'/\lambda = r + \frac{\partial c/\partial S}{\lambda} + \beta(r^m - r)$$

where $\lambda$ is the current value in situ price, identified with marginal profits $(p - \partial c/\partial E)$, $r^m$ is the rate of return on the market portfolio and $r$ is the risk free rate of return. This model is applied to Canadian copper mines. For the rate of return on the market portfolio is taken the Toronto Stock Exchange 300 index, and for the risk free interest rate is taken a Canadian bond rate. The analysis of the data does not reject the model, although the authors are very cautious, since the estimated $\beta$ coefficient is deemed very high. In an earlier paper, Berck (1995) goes into other problems that can be encountered in this approach. He puts forward that in general the stock market does not obey the rules economic theory "imposes." Moreover, predictions of the rate of return on the exhaustible resource should use information available to the decision makers before the actual decision is made. It is therefore questionable to use the actual interest rate. It would be preferable to use lagged interest rates.

Studies that also use the CAPM are Heal and Barrow (1980) and Agbeyegde (1989). The former authors construct an arbitrage model for copper, lead, tin and zinc and show that changes in interest rates rather that the interest itself is likely to determine the resource price. Agbeyegde (o.c.) confirms this empirical result and underpins this theoretically by arguing that the expected rate of capital gains on the exhaustible resource should equal the rate of return on other assets, where expectations are formed on the basis of past rates of return on the exhaustible resource.

## 3. Imperfect Competition

One important area of research addresses the question of cartelization and its effects on prices and profitability. Here it is necessary to make a distinction between different resource cartels as is done in the comprehensive survey by Teece et al. (1993), who discuss the oil market and the markets for mercury, uranium and diamonds, also from an empirical point of view. Here we wish to restrict ourselves to the oil market. Teece et al. (o.c.) identify three views with respect to cartelization of this market. First, OPEC acts as a cartel with Saudi Arabia as leader. Second, as argued by e.g., MacAvoy (1982), the price increases on the oil market in the seventies were not due to OPEC but to market conditions such as minimal excess capacity. Third, there is the target revenue model where OPEC behavior is characterized by budgetary needs of the governments.

The seminal empirical work is done here by Griffin (1985), who finds support for the cartel point of view in a very simple model of an individual country's supply, as a fraction of total OPEC supply. However, these models may not sufficiently take into account the strategic interactions on the world oil market. These can be modelled in several ways but one appealing approach is the so-called cartel-versus-fringe model introduced by Salant (1976). By now there is an abundant theoretical literature on this issue, which is surveyed elsewhere (see Withagen and De Zeeuw 1998). I therefore restrict myself here to the basic issues and propose to develop tests of one particular model.

Consider the case where there is one coherent cartel and a large number of small oil producers (called the fringe). Demand for oil is linear in the price $p$ and the demand function is constant over time. Denoting supply of the cartel by $E^c$ and aggregate supply of the fringe by $E^f$, we have $p(t) = \overline{p} - E^c(t) - E^f(t)$, where $\overline{p}$ is the choke price. For simplicity it is assumed that the extraction costs only depend on the rate of extraction and that marginal extraction costs are constant but differ among the cartel and the fringe. They are $k^c$ and $k^f$ respectively. In the case treated here we assume that the cartel does have a cost advantage over the fringe but that the cost advantage is not extremely large. Specifically: $k^c < k^f < \frac{1}{2}(\overline{p} + k^c)$. The aggregate fringe acts as a price-taker and maximizes its discounted profits given by

$$\int_0^\infty e^{-rt}[p(t) - k^f]E^f(t)\mathrm{d}t$$

subject to

$$S'^f(t) = -E^f(t),\ E^f(t) \geq 0,\ S^f(t) \geqslant 0.$$

The interesting part of the modelling concerns the cartel's behavior.

The first alternative is to assume that the cartel is a price-taker as well. Secondly, one could attribute some market power to the cartel.

One way to do this is to assume that the cartel sets the market price (as a time-path), the fringe reacts to that and the cartel takes the fringe's supply as given. We will refer to this as the Nash equilibrium. There is a problem here, namely that the fringe's reaction is a correspondence rather than a function because the Hotelling rule makes the fringe reaction indeterminate as long as this rule holds. Nevertheless the equilibrium can be calculated (see e.g., Ulph and Folie 1980). Some empirical work on this type of this model has been done by Polasky (1992). He studies the equilibrium where all agents act as Nash players, in an open loop setting. Also Pindyck (1978 and 1982) has made an important contribution to this field in the Nash approach.

One other way to proceed is to assume that the cartel is a von Stackelberg leader and takes the fringe's reaction into account in setting the price path. It makes a major difference how the equilibrium is precisely defined. If the open-loop equilibrium concept is employed then the phenomenon of dynamic inconsistency may occur (see Newbery 1981; Groot et al. 1992), which makes the equilibrium concept obsolete, at least in the absence of binding contracts. The better equilibrium concept is the feedback von Stackelberg equilibrium, where time-inconsistency is ruled out by definition because the strategies of the players depend on the existing resource stocks. For the particular model at hand the equilibrium has only recently been calculated by Groot et al. (1997). A similar model with extraction costs depending on the remaining resource stocks (in such a way that the physical resources are never depleted) was studied by Karp and Tahvonen (1996). It would be very challenging to test these theories, because they are more sophisticated than the very simple model underlying the work by Griffin (o.c.). For the functional forms used above the theory derives explicit expressions for the time paths of supply by the cartel, the fringe and of the price. So, the theory allows for a straightforward test.

## 4. Conclusions

The conclusions of this paper can be summarized as follows. The testing of Hotelling's rule, in any formulation, encounters difficulties. Data on in situ price are usually not available, and we do not know much about the formation of expectations on the part of the resource suppliers. With respect to the data much work is to be done in this area. Also information on disaggregated extraction cost functions would be very welcome. Furthermore I would recommend further research based on the CAPM model (or extensions like Arbitrage Pricing Theory and the Extended CAPM) for other markets than studied so far, possibly using techniques such as ARCH or GARCH. However, this does not mean that in the application of these theories less problems will be encounterted. Finally, there is much room for testing Hotelling type rules for resource commodities that are traded on non-competitive markets.

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