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A View on Economic Theory of Exhaustible Resources

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By education Mr. Ole Gunnar Austvik is trained in economics (Cand. Oecon, University of Oslo 1980). He is also Master of Public Administration from John F. Kennedy School of Government (MPA Harvard University 1989). He was employed by the Central Bureau of Statistics 1981 - 85 and at the Norwegian Institute of International Affairs (NUPI) 1985 - 91. At present he is Associate Professor at Oppland College, Lillehammer and the Norwegian School of Management, Sandvika, Norway. His main area of work is in international economics and petroleum politics.

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Table of Contents

A View on Economic Theory of Exhaustible Resources

In research centers, consulting firms, companies, government agencies and international organizations, much effort is put into the analyses of markets for exhaustible (or non renewable) resources, such as oil, natural gas, coal and uranium. As most approaches has shown a rather weak record when confronted with the ability to foresee future price developments[1], nobody can claim to have found *the* right understanding of the behavior of these markets. Economic theory is the probably most widely applied approach. This paper will give a view of on it's possible interpretations and relevance in this field.

The underlying assumption in the theory for exhaustibles is that producers are wealth-maximizers. However, it differ from economic theory of other goods as it explicitly emphasizes the perspective of *time*. For 'normal' goods, marginal costs consists only of the physical costs of labor, capital and input materials. For an exhaustible resource, however, consumption today precludes consumption of the same unit tomorrow. The cost the producer of today imposes on the future, results, in addition, in an opportunity cost (the value of a foregone action).

[1] Shown in Manne & Schrattenholzer (1987) and Lynch (1992).

1 THE USER COST

When resources are scarce, greater current use diminishes future opportunities. The marginal user cost is the present value (PV) of the foregone opportunities at the margin. This is opposed to marginal extraction costs; a pure technical economic criteria. Thus, total marginal cost for an exhaustible resource (B) is the sum of the marginal extraction cost (b) and the marginal user cost (u). At time t this can be expressed as:

(1) $$B_t = b_t + u_t \qquad (t = 1,2,\ldots,n)$$

The user cost, also called the scarcity rent, is the payment to a resource owner. Since u_t is the opportunity value of selling the last unit in period t rather than today, the producer should choose to produce at the time the user cost is the highest. If user costs are the same, the condition to be indifferent between producing now and in the future is:

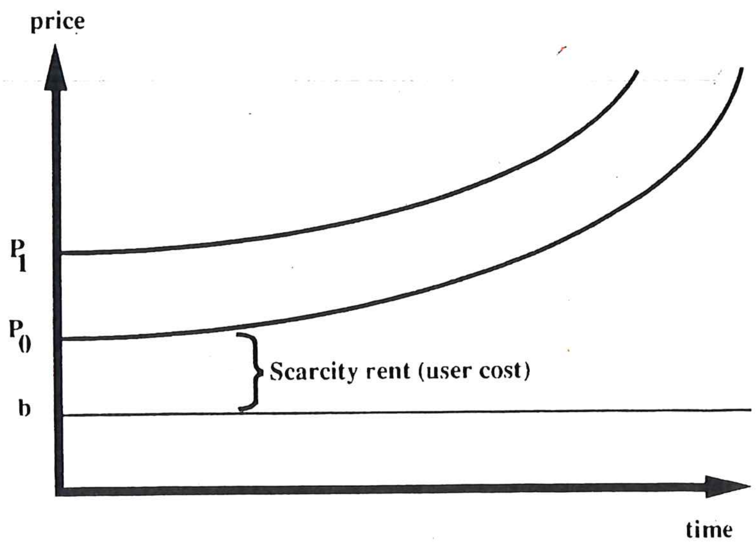
(2) $$u_0 = u_1 = \ldots\ldots = u_n$$

The producer must, however, take into consideration today's value of tomorrow's money. In fact, he could alternatively produced today, invested the money in something else, and earned the interest this money would yield. Therefore, he has to discount future user costs at a chosen discount rate (r). Taken the discount rate into consideration, his indifference-equation can be written as.

(3)[2] $$u_o = u_t * e^{-rt}$$

If $u_o < u_t$, the producer could improve wealth by postponing production until sometimes later. The discounted value of his production at time t would be larger than the value of today's production. Vice versa, if $u_o > u_t$, he should rather produce today. The extra price the resource owner gets in the future, shall at least be as large as what a chosen interest rate would yield on today's production.

1.0.1 Graph. Price path of an exhaustiable resource



In the graph above two price paths are drawn. Both are illustrating the necessary development of the price in order to make the producer indifferent when to produce. If the initial price is p_1, the price has to follow a path higher than if the initial price is lower, for example p_0. But the rate of increase in prices has to follow the same exponential path (growth rate) to cover the

[2] e is the irrational number 2.718....

alternative increase in the value of the money as a result of producing today and put the money into something else that with yield an interest.[3]

For simplicity reasons we have assumed constant marginal extraction costs (MC) in the graph ($b_t = b$). If marginal cost is increasing over time (MC-curve bends upwards) the scarcity rent diminishes and the sacrifice made by future generations diminishes. The net benefits that would be received by a future generation if a unit of the resource were saved for them becomes smaller and smaller as the marginal costs of that resource becomes ever larger. With increasing marginal extraction costs it will be the difference between the price [p_t] and the per unit extraction cost [b_t] that must raise with the rate of interest:

$$p_o - b_o = [p_t - b_t] * e^{-rt} \tag{4}$$

This is a more generalized way of describing the price path that makes the producer indifferent when to produce. Obviously, higher extraction costs can be compensated by higher prices. The main point is that by moving production between periods the resource owner can maximize wealth. The discounted value of the marginal user cost for the last unit produced in any time period should equal the marginal user cost in any other period for the producer to be indifferent when to produce.

2 THE HOTELLING RULE

The type of optimization problem faced, can formally be illustrated as follows example. The

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[3] Assuming no inflation, or p_i ($i = 1,2,\ldots,n$) as a concept of real prices adjusted for inflation.

owner of the resource wish to maximize the net present value (or net profit) of the stock from today until infinity. At time t, his profit π_t from production q_t can be expressed as:

*(5) $$\pi_t = p_t(q_t)^4 * q_t - b_t * q_t$$

The producer's objective will be to allocate production (q) between periods in a way that the net present value of the profit is maximized. He will reach that optimum when the integral of the discounted profit-function is maximized (T being the living age of the resource):

(6) $$\int_O^T \pi_t * e^{-rt} \, dt$$

Doing this, however, he is subjected to the fact that each extraction reduces remaining reserves (Q_t) equivalently;

(7)[12] $$q_t = - \dot{Q}_t$$

Thus, if initial reserves is Q_0, then the accumulated output cannot exceed this limit (SUM(t=1...n) q_t =< Q_0). Obviously, the reserves at time T, when resource are fully exploited, cannot be negative. He is also subjected not to put any previously produced resource back to the reservoir: q_t >= 0.

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4 The producer's price function is described as a function of q for it to cover both competitive and monopoly firms.

12 . denotes the time derivative of the variable.

Optimal control theory can be used to solve this type of dynamic problem. Optimal control methods are techniques that enables us to maximize a function that is subjected to a set of dynamic conditions expressed as differential equations. Equivalent to the Lagrange-multiplier in the non-dynamic case, we have multipliers in our dynamic case called Hamiltonians (h). Hamiltonians can be thought of as shadow prices. Shadow prices represent the opportunity cost of producing a commodity not traded. In fact, they express the external cost that extraction of the resource bring upon future generations, or the user cost in our terminology.[13] When (4) is maximized subjected to (5), the Hamiltonian function can be expressed as:

(8) $$H(p(q),t,q) = \pi_t * e^{-rt} + h\,(-q_t)$$

1. order condition will be:

(9) $$\frac{dH}{dq} = \frac{d\pi_t}{dq_t} * e^{-rt} - h = (MR^{14} - b) * e^{-rt} - h = 0$$

(10) $$\Rightarrow \quad MR = b + h * e^{rt}$$

This result is quite similar to the one in our discussion as expressed through equations (1) and (3), where the user cost is the equivalent to the Hamiltonian multiplier. Equation (10) simply expresses that, for a wealth-maximizing producer, marginal revenue shall equal total marginal cost

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13 For an introduction to the use of control theory see Aslaksen & Roland (1983) or Brock (1988).

14 Setting the derivative of π with respect to q equal to zero tells us that profit maximum is reached when marginal revenue (MR) equals costs. If the producer is a price taker (competitive), MR equals price (p), e.g. price shall equal unit cost.

(MR=B). But with the constraint that he is producing a non-renewable resource, he should not only consider the technical marginal cost of production but also the user cost he brings upon future generations. Thus, in optimum, he shall choose a production profile that satisfy:

$$(11) \qquad \mathbf{MR_t = b + u_o * e^{rt}}$$

This is the general condition both for a monopoly and for a price taker. Under competition marginal revenue equals price ($p_t = MR_t$):

$$(12) \qquad \mathbf{p_t = b + u_o * e^{rt}}$$

This condition is the Hotelling rule[15], expressing that the (net) price of an exhaustible resource should rise at the rate r in order to make the producer indifferent when to produce. The rate of capital gains enjoyed by exploiting resource must equal the rate of return earned in holding any other asset (e.g. the interest rate). Thus, in the most simplistic competitive case, where price equals marginal costs and extraction costs are assumed constant, the Hotelling rule can be expressed as that the rate of price increase shall equal the interest rate:

$$(13) \qquad \mathbf{\dot{p} / p = r}$$

Equivalently, for the monopolist that exploits the inelasticity of demand, the rate of increase in marginal revenue shall equal the interest rate.

[15] Named after the article of Harold Hotelling (1931).

(14) $$\dot{MR} / MR = r$$

If net prices (or marginal revenues) increases with the rate of interest, the producer will have the same present value of profits in all periods and the same present value of the user cost. The producer will be indifferent between keeping the reserves in the ground and to explore and sell it. Also, in order to be indifferent to buy the right to explore the resource or not, net prices have to rise with the rate of interest to make the investment as profitable as other investments. If prices shall follow an exponential path, either the price itself has to rise and/or the cost of production must fall. With simplified assumptions of zero extraction costs (as i.e. in Gray, 1914), the price has to increase with the rate of interest.

The rise in the marginal user cost (scarcity rent) reflects increasing scarcity and the accompanying rise in the opportunity cost of current consumption. In the following example, we consider the case of crude oil. If we assume marginal extraction costs > 0 but constant, b = 5 (5 dollars per barrel), r =0.1 (i.e. 10 per cent p.a.) and u_o = 10 (10 dollars per barrel), then the price in the first year is:

(15) $$p_o = b + u_o = 5 + 10 = 15$$

In order to make the oil producer indifferent when to produce, the price must in the following years be:

$$
\begin{aligned}
p_o &= b + u_o = b + u_o * (1 + r)^0 = 5 + 10 &&= 15 \\
p_1 &= b + u_1 = b + u_o * (1 + r)^1 = 5 + 10 * (1.10)^1 &&= 16 \\
p_2 &= b + u_2 = b + u_o * (1 + r)^2 = 5 + 10 * (1.10)^2 &&= 17.1 \\
p_3 &= b + u_3 = b + u_o * (1 + r)^3 = 5 + 10 * (1.10)^3 &&= 18.3
\end{aligned}
$$

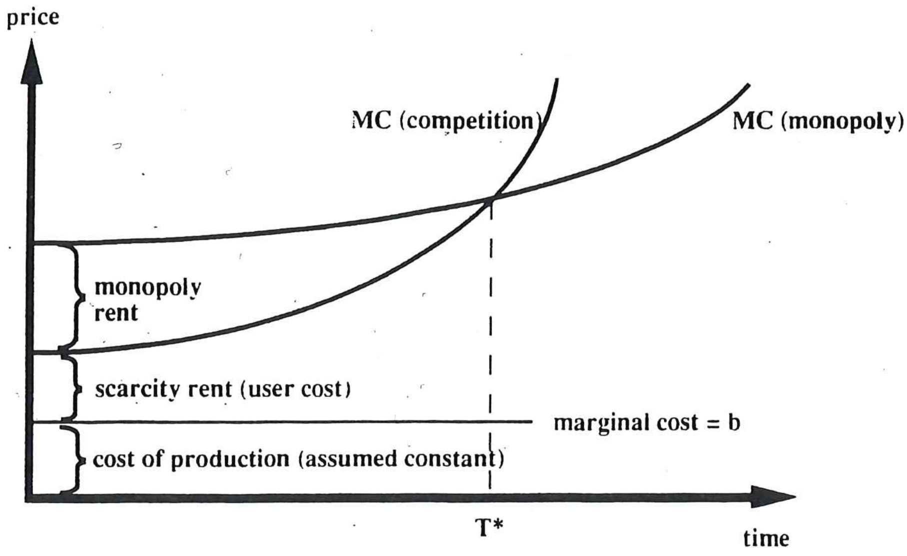
If the producer expects $p_3 = 17$, he should rather extract his oil faster. However, if he expects the $p_3 = 20$, the producer can increase economic wealth by extracting more in period 3 and reducing production in other periods. In marginal terms, his production profile should be scheduled in such a way that the marginal user cost for oil produced in any period are equal (equation 2).

2.1 Monopoly vs. Competition

With a linear demand curve, the monopolist price will initially be higher than under competition. On the other hand, the higher price encourages conservation measures. As is well known, demand for, for example, oil is substantially more elastic over the long than the short term. Therefore, over time, monopoly leads to lower consumption than do competition. The higher prices also initiate production in high cost areas, which in its turn also suppresses prices.[16] Taken together, the monopolist provides less oil to the market and conserves more oil in the ground than a competitive firm. But clearly, he may charge a very high fee (monopoly rent) in order to perform this rationing function. And, due to the higher elasticity of supply in the long run (compared to the short run), he may face loss of market shares as a result of the high prices, as well.

[16] It is usually not easy to determine what are the reserves in an oil field or for a country. It may, however, be helpful to distinguish between 3 different concepts (Tietenberg 1988, page 114-115). Current reserves are those that are known to be possible to extract with profit at current prices. Potential reserves are defined as a function of the price people are willing to pay. Thus, the size of the potential reserves are changing with the price of oil. The endowment is the natural occurrence of resources in the earth's crust. The third concept is geological rather than economic, and represents the upper limit on the availability of terrestrial reserves. Theoretically, the price of oil can become so high that a resource can be physically depleted. However, in practice, when the price becomes too high, backstop prices will set upper limits for how high the price of oil can be and thus how much of the endowment can be extracted. The current and potential reserves set the frames for the economic scarcity of a reserve. The higher the price of oil, the larger the current reserves. The size of the potential reserves depends on the expectations made for the development of the oil price. Adelman (1989;442) claims that because of the difficulties in estimating reserves, reserves of oil cannot be viewed as "a fixed stock to be used up, but an inventory, constantly consumed and replenished by investment." One reason for the uncertainty in determining both current and potential reserves, are technological development. If tomorrow's technology can squeeze out 10 per cent more oil of today's reservoirs (at the same cost as of today), depletion of these additional current reserves will take some 9 years at current production levels.

2.1.1 Graph. Price path under competition versus monopoly



Therefore, as the graph above shows, in the short run, the monopoly (with the lowest discount rate) will initially yield a monopoly rent in addition to the scarcity rent. However, after time T^* the competitive price (with a higher discount rate) will be *higher* than the monopolist's price. Demand is encouraged be the lower prices, the resource exhausted quicker and the scarcity emanating pushes prices up. How long time T^* is, is, however, an intriguing question.

2.2 The Structure on the Supply Side

In the market for crude oil, which both in economic and political terms is the most important commodity market in the world, this theory has been widely applied with some modifications on the supply side. A Stackelberg-solution interprets the Organization of Oil Exporting Countries's (OPEC) behavior as if the organization, a group within it or even one single country (Saudi Arabia) let other countries sell what they wish and that they balance demand by regulating their own production to maintain the monopoly price (they are "swing-producers"). The swing-producers take into account present and future demand, the production of all other suppliers in the market and chooses the optimal price path maximizing their wealth over time. All countries, except the swing-producer(s), adjust quantity produced to the prices fixed in the market. The swing-producers behave like monopolists taking into consideration both the degree of inelasticity of demand and the reaction to changes in prices among other producers. Such a partially manipulated market will lead to a price path somewhere between the one resulting from pure competition and monopoly.

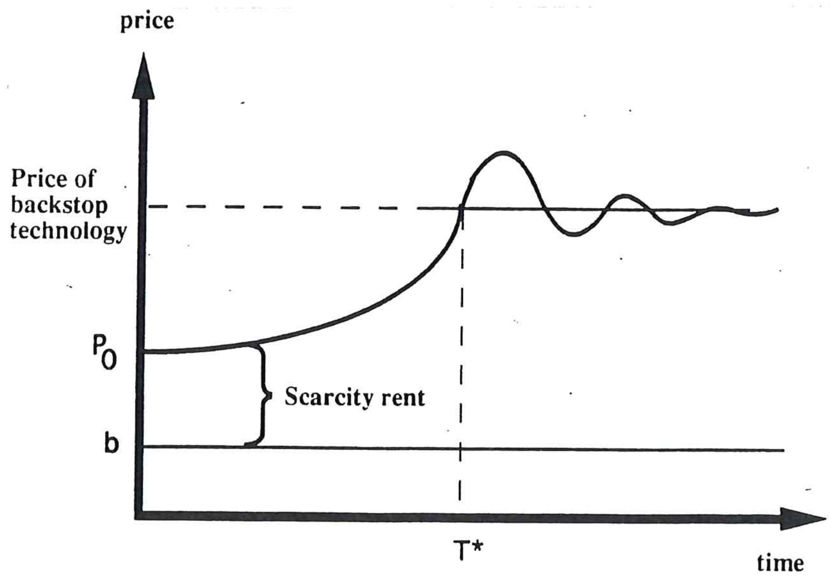
A Nash-Cournot solution is a modification of the Stackelberg-market. In this market all actors are active and a non-cooperative game is established. Thus, also the smaller sellers have expectations about the future price and other elements of the market that is important in order to optimize positions. This type of market generally leads to a higher price path than in the Stackelberg market. But distribution of production and income between producers may be different, to the disadvantage of the swing-producers and to the benefit of the smaller producers.

Whether one modification of the theory is better than the other, the question remains whether enough demand remains for swing-producer(s). With high prices, new entrants are attracted to the market and existing producers will be encouraged to increase production, as well. Demand will decrease as consumers will shift to alternative energies and introduce various conservation measures. Thus, the swing-producers must either set higher prices and accept declining market shares in the future or lower prices in order to limit entrance of other producers, increase (maintain) demand and expand profits in the future or something in-between.

2.3 The Backstop Price

If prices rises so much that they reaches consumers' maximum willingness to pay (WTP)[17], consumers will using the resource. Thus, if it exists a substitute at a price lower than consumers WTP, extraction will be pushed forward in time and stop earlier than if no substitute product existed. Prices may increase up to the point it reaches the price of the backstop technology. A backstop product is a known technology that can serve as a substitute for a product or a resource. The substitute can set the upper limit the price of the resource. The price profile in a competitive market with a backstop technology will be:

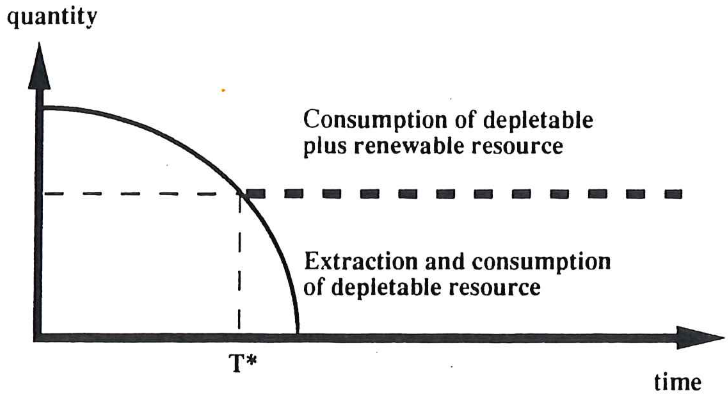
2.3.1 Graph. Price path with a backstop technology



20 Willingness to pay is the valuation placed by an individual on a good or service in terms of money. It can be expressed by the inverse demand function: Q = f(p) => p = g(Q). Total willingness to pay is the entire area under the demand curve. WTP is otherwise the same as consumers surplus. Maximum WTP is represented by the price so high that all demand is abolished.

The Hotelling model tells us, with the modifications mentioned, that prices will rise with the rate of interest until they reaches the price of the backstop fuel. At this price unlimited supplies of the backstop product is made available and the price of the resource will be the same as the price of the substitute. If it takes time to introduce the backstop-fuels (e.g. of technical reasons) the price may pass the backstop price for a while, until sufficient amounts of the alternative fuel(s) have reached the market, as illustrated in the graph above. The production profile for an exhaustible resource with a backstop technology is presented in the next graph.

2.3.2 Graph. Quantity profile with a backstop technology



This illustrates that the extraction of a nonrenewable resource will decrease over time (if the demand curve is stable). This is due to the fact that marginal user costs (or scarcity rents) increases over time. The bowed curve in the graph above is somewhat steeper than if it was no substitute. When the price of the resource reaches the choke price (price of the substitute or the backstop price), consumption of the substitute will start and the extraction of the resource will fall rather rapidly.

3 PRICE PROFILES

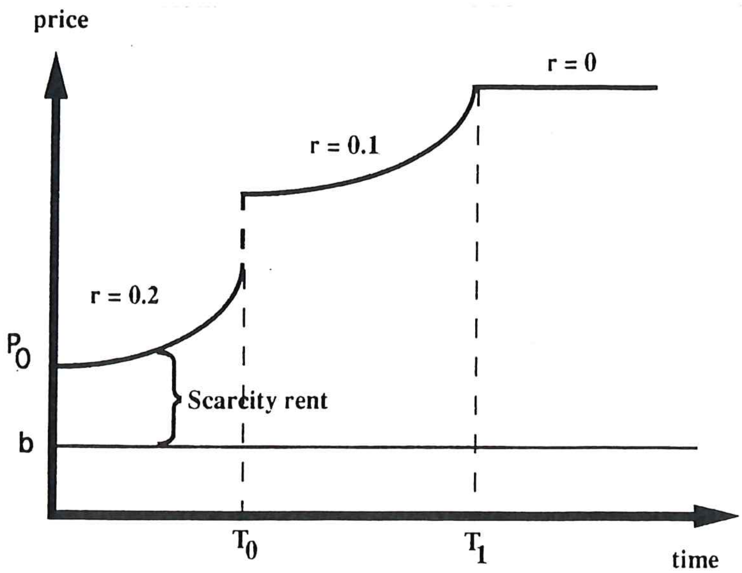
The user cost is not observable in any account. But the wealth-maximizing producer must take into account that such a cost exists because of the non-renewability nature of the resource. How he evaluate the future as opposed to today depends on numerous factors. The producer should chose the production profile according to his expectations about future supply and demand conditions. In this consideration elements as the size of the reserves, prices of alternative energies (backstop fuels), discount rate, price elasticity of demand, economic growth in the purchasing countries' economies, technological development and uncertainty are entailed.

Very simply he could, for example, pose that today's population is more important than tomorrow's and choose a high discount rate and produce a lot today. However, if he considers all generations of equal importance, he resides with the problem to determine all other factors influencing the price path. Thus, being a rational wealth-maximizing producer, there are many possible production and pricing paths depending on expectations made. Below, we will briefly discuss these issues.

3.1 Discount Rate

The discount rate influences the slope of the price path. A high discount rate make the slope steeper than a low one. An increase in the discount rate imply a larger return on investment and therefore increased production today, a shorter depletion horizon, lower prices and higher extraction If property rights are public, the discount rate will usually be lower than when they are private. This is due to society's usual more overall view of the economy including multiplier effects of investments and consumption than a private company. The society, is usually therefore assumed to give more to future generations than a private enterprise. The private company will use the market interest rate for discounting while the society will use a social discount rate.[18]

3.1.1 Graph. Price path with high and low discount rates



[18] Usually representing the rate at which society is willing to trade consumption between different time periods or the society's rate of time preference. In Norway, the market interest rate has been 10-15 per cent, while the social discount rate has been calculated to 7 per cent (annually) in the eighties.

In the graph above, the producer initially uses a discount rate of 20 per cent. His exploitation horizon is short. This may be a situation, with property rights belonging to the society that for example fear the invasion by an unfriendly neighbor. The country needs huge amount of money for defense paid for by increased extraction. During a war, short term revenue requirement and the overwhelming concern about surviving, may shorten the time horizon further. Thus, "infinity" for, for example, an oil producing country may, when a war threatens, change from being perhaps 50 years to 5 years or less. In a war, the "wealth-maximizing" process may be considered as how to maximize net present value of the resource over these 5 years. In the graph above, at time t_o the threat of this war is considered to be lower, and the need for government take is reduced. Thus, the country can take on a discount rate of let's say 10 per cent. Military budgets are reduced and economic considerations again more dominant. Finally, at time t_1, peace "for eternity" is established and the country can take on a long term economic view on the exploitation of resources and set the discount rate much lower. The effect of a theoretical 0 (zero) discount rate is illustrated in the graph after t_1.[19]

3.2 Size of Reserves

A resource owner that can upgrade reserves can produce at today's level at a lower cost for future generations than if reserves are more scarce. Therefore, an increase in <u>reserves</u> will decrease the scarcity premium. Obviously, when reserves are upgraded, more can be produced in total. Pindyck (1978) have extended Hotelling's model by the effects of additions to the reserves through exploration.

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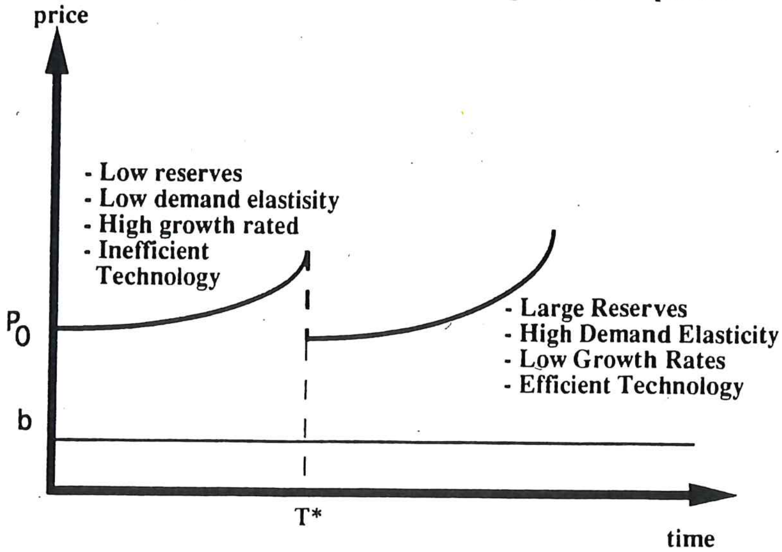
[19] Quite unrealistic, though, with a zero discount rate the country have no present need for revenues at all.

3.2.1 Graph. Shift in the price path.
Change in the reserve base, elasticity of demand, growth rates and technological development



In the graph above, we have initially a situation with low reserves and the price path stays at a high level up to T*. At T*, reserves are upgraded and prices can follow a lower path in order to exhaust the resource before "infinity" occurs; prices are revised down. But prices should grow with the same rate after this reconsideration takes place.

3.3 Elasticity of Demand

A similar effect can be observed as a result of a change in expected future (long run) elasticity of demand. When demand is rather inelastic, high prices can be sustained and a high price profile be chosen. If long run demand elasticities are revised down, a lower price profile is necessary for the resource to be fully exploited. In the graph above, long run demand is expected to be inelastic up to T* and then revised down.

3.4 Economic Growth

A decrease in the rate of economic growth will also change the price path similarly. Up to T* high economic growth is expected. At T*, expectations changes to a more modest growth level, and, accordingly, the resource is expected to be less scarce in the future. User costs becomes lower and the price must be revised down.

3.5 Technological Development

The introduction of a more efficient producers' or consumers' technology will also lead to a downward revision of the price path as more efficient technology can extract more (upgrade current reserves) and/or consumers use less for a given level of utility. In the graph above, new technologies are introduced at T*, user costs are lowered and the resource is made less scarce. In order to exhaust the resource, prices must be lowered.

3.6 Uncertainty

Obviously, the size of the user cost will vary with future supply and demand. Therefore, today's perceptions of the future will be of significant importance for determining the size of the user costs. If supply is sufficiently abundant in the foreseeable future (relative to demand), production today may not preclude production tomorrow. If the producer expects higher prices in the long run, he may restrict supply today in order to sell it at a later point in time. Equivalently, with low discount rates, the growth in the price has to be less than when discount rates are high in order to make it profitable to delay production. Obviously, how to deal with uncertainty in the believe of the future development of a number of factors is a major problem in determining user costs.

Production, however, imposes a lot of externalities on producers with it's geological, political, technical and economic risks. When uncertainty increases, discount rates becomes higher and production are pushed ahead in time. Uncertainty, in and by itself, shortens the depletion horizon, and gives a steeper price path and lower prices. Each of the factors we ave discussed above, involves uncertainties. In addition there are uncertainty concerning the interaction between them. For example, how will a more elastic demand reduce prices on how will these low prices influence growth rates and, subsequently, increase prices?

Many analysts have extended Hotelling's model to discuss how uncertainty affect production decisions and price paths. Dasgupta & Heal (1974) considers the role of uncertainty about production techniques of backstop fuels. Hoel (1978, 1980) studies substitute resources, assuming that there is knowledge about the time the substitute is available but not about its costs. Stultz-Karim & Economides (1989) examines the effect of uncertainty in ultimately recoverable oil reserves and its effect on price paths.

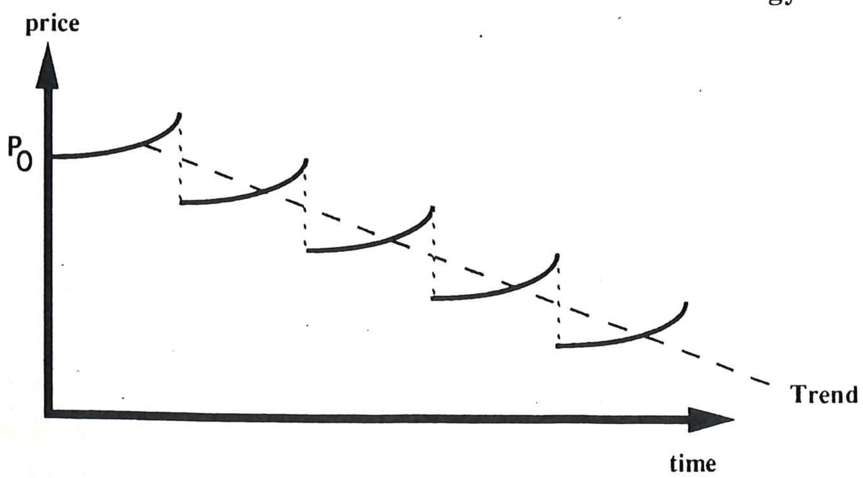
Particularly there is a problem that the market interest rate (for example from a deposit in a bank) is relatively more easily observable than the price development the commodity. A bank deposit is also more easily shifted from one type of investment to another. The owner of an exhaustible resource have often large fixed costs and may have long-term contracts making it impossible for him to shift to some other type of investment. Transaction rigidities therefore indicate that the Hotelling rule should only be considered to have a possible explanatory power for the market of exhaustibles in the long run when rigidities in production and short and medium term demand inelasticities have time to adjust.

4 PRICES MAY RISE OR FALL OVER TIME

Most analysts using this theory as a basis for understanding markets for non-renewables has concluded that prices must rise over time. However, as we have seen, this is only true in the *ceteris paribus* case. *If* reserves are upgraded, demand becomes more price-elastic, economic growth declines and/or technology becomes more efficient, prices should be revised *down*. This is illustrated in the graph below.

4.0.1 Graph. Prices <u>may</u> fall in the long run.

The case of a continuous upgrading of reserves, more elastic demand, decline in economic growth and/or introduction of more efficient technology



How, then, can this theory be used for understanding price developments for exhaustibles? Probably, in the *aftermath* it can explain why prices rose or fell. But for *predicting* prices, too much is unknown for the analyst to know whether higher or lower prices should be expected. Few, if anyone, can possibly know enough about all the factors influencing price paths and their revisions in order to predict the future outcome. The claim that prices necessarily must rise in the future seem to be a too extreme and partial use of the model. Nevertheless, the identification of a backstop price and the technical cost of production will give techno-economic upper and lower limits for how high or low prices can be at a given point of status of the variables influencing cost and backstop levels.[20] Furthermore, producer's inter-temporal considerations, being aware that they impose an opportunity cost on future generations when extracting the resource, due to it's non-renewable nature, may give some sound philosophical background for how her or she rationally should behave *if* he or she can optimize in the long run and possess all information needed, disregarding politics and other considerations.[21]

[20] See Austvik (1992) for a further modification of this issue.

[21] For a comprehensive discussion of the theory of exhaustbile resources, see Dasgupta & Heal (1979).

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