ECONOMICS OF NATURAL RESOURCES CONFERENCE

Jointly sponsored by:

The National Science Foundation

The National Bureau of Economic Research

The Center for Research in the Economics of Energy Resources, Stanford University

July 23 - 24, 1976

Contents:

I. INTRODUCTION

This report summarizes the second conference to be held at the National Bureau of Economic Research - West and Stanford University on the economics of the discovery, extraction, market structure, and use of natural resources. The conference brought together a group of economists to exchange information and criticism in an attempt to facilitate their studies of applying and extending microeconomic principles to the economics of natural resources. Twelve papers (summarized in section III) were presented at the conference held on July 23 - 24, 1976, under the auspices of the NSF, the NBER, and the Center for Research in the Economics of Energy Resources, Stanford University. (Formal papers for most of the presentations are available from the authors.) Although there is much overlap, for the purposes of summary the presentations fall into five categories:

Uncertainty and Exploration

Technical Change

Welfare Economics

Market Structure and Intertemporal Allocation

Quantitative Methods

With a growing body of theory related to the microeconomics of natural resources, recent work as presented in these papers is becoming more diversified. There continues to be a concern with the differences in allocation between the socially optimal policy and decentralised economies with varying degrees of competition. The investigators thus continue to be concerned with the specification of the production process, the characteristics of the resource stocks, the degree of imperfect knowledge about the extent of the stocks, and the degree of substitutability between the resource and present or future factor inputs.

As one participant points out, resource economics covers three areas of relatively intractible economics: imperfect competition, dynamic capital theory, and the uncertainty of exploration and research and development (R&D).

It is now generally well recognised that the absence of complete futures markets for natural resources is a significant reason for a divergence in intertemporal allocation patterns between the socially optimal economy and a perfectly competitive, decentralised market economy under the normal assumptions (convexity, absence of externalities, etc.). One paper examines the stock market as a substitute for the absent futures markets. Two papers examine the consequences of uncertainty about the extent of reserves for intertemporal extraction paths and alternative auctioning procedures given both this uncertainty and the incomplete knowledge held by individual bidders.

Two areas of widespread interest among the participants are market structures and R&D leading to technical change or new substitutes for the resource. Three papers are concerned with this latter subject, one from a historical perspective, possibly the first application of the new resource microeconomics to the analysis of economic history. The other two examine the allocation patterns and incentives of R&D under various market structures, with the possibility of government R&D; in particular the possibility of competitively or monopolistically owned resources, of competitive or monopolistic R&D, and a competitively or monopolistically owned substitute.

The emergence of cartels in several resource markets has probably been the impetus for three papers dealing with market structure and intertemporal allocation. These include a long run analysis of a particular market (oil); a theoretical analysis of a cartelized market with a higher-priced substitute, positive extraction costs, and uncertainty; numerical analyses of the gains from cartelisation in three resource markets (oil, copper, and bauxite); the determination of the internal shares within the cartel in the optimal case; and the inclusion of continuing exploration in the models.

Another paper considers the socially optimal allocation in the Keynesian case of aggregate consumption related to aggregate output, hence reducing by one the degrees of freedom of the model. This is the first attempt to extend resource economics beyond optimal growth models to medium-run macroeconomic models. Another is an empirical paper which examines a particular national economy (Canada's) and attempts to estimate the degree of substitutability between various alternative energy sources and between aggregate energy and other factor inputs.

The conference showed that the micro economic analysis of natural resources provides a robust foundation for theoretical economists and applied economists to build on, and that policy makers can gain understanding of practical problems using these tools. Future work will no doubt be concerned with such issues as uncertainty, information, and empirical estimation, which will result in the development of a body of economic knowledge to handle still more complicated problems of natural resource use.

II. Conference Schedule and List of Participants

Friday, July 23 -- UNCERTAINTY AND EXPLORATION

"The Inefficiency of the Competitive Stock Market and Its Implications for the Depletion of Natural Resources" ..... Joseph Stiglitz

"The Phillips Plan for Auctioning Oil Leases" ..... Robert Wilson

"The Optimal Utilization of an Unknown Reserve" ..... Glenn Loury

TECHNICAL CHANGE

"Incentives for Technical Change under Alternative Institutional Arrangements" ..... Partha Dasgupta, Richard Gilbert and Joseph Stiglitz.

"Some Disaggregated Models of Optimal Economic Growth Involving an Exhaustible Resource and Technical Advance" ..... Morton Kamien and Nancy Schwartz

"The Timber Famine in 18th Century England -- Cause or Effect?" ..... Edward Steinmueller

WELFARE ECONOMICS

"External Diseconomies and Averting Behavior" ..... Anthony Fisher and Richard Zeckhauser

Saturday, July 24 -- "A Second-Best Pricing Policy for an Exhaustible Resource: The Fixed Savings Ratio Case" ..... Donald Hanson

MARKET STRUCTURE AND INTERTEMPORAL ALLOCATION

"Imperfect Competition and the Allocation of Oil" ..... Richard Gilbert

"OPEC and the Monopoly Price of World Oil" ..... Martin Weitzman

"Optimal Pricing Models for Exhaustible Resource Cartels" ..... Robert Pindyck

QUANTITATIVE METHODS

"Modelling the Industrial Demand for Energy" .....E. Berndt, Mel Fuss and Leonard Waverman

PARTICIPANTS:

Charles Blitzer	World Bank
Paul Cootner	Stanford University
Partha Dasgupta	London School of Economics
Anthony Fisher	Univesity of Maryland
John Fleming	Oxford University
Mel Fuss	University of Toronto
Richard Gilbert	Stanford University
Albert Halter	Electric Power Research Institute
Donald Hanson	Federal Energy Administration
William Hogan	Federal Energy Administration
Donald Lessard	Massachusetts Institute of Technology
Glenn Loury	Northwestern University
Morton Kamien	Northwestern University
David Kendrick	University of Texas
Pentti Kouri	Stanford University
Alan Manne	Stanford University
Steven Matthews	California Institute of Technology
Daniel McFadden	University of California, Berkeley
David Newbery	Cambridge University
Daniel Newlon	National Science Foundation
Robert Pindyck	Massachusetts Institute of Technology
Steven Salant	Federal Reserve Board
Steve Salop	Federal Reserve Board
Jose Scheinkman	University of Chicago
Nancy Schwartz	Northwestern University
Vernon Smith	University of Arizona
David Starrett	Stanford University
Joseph Stiglitz	Stanford University
Ardy Stoutjesdyck	Stanford University

PARTICIPANTS cont.

James Sweeney	Federal Energy Administration
Edison Tse	Stanford University
Leonard Waverman	University of Toronto
Martin Weitzman	Massachusetts Institute of Technology
Robert Wilson	Stanford University

Also participating:

Jose Cordoba	Stanford University
Robert Marks	Stanford University

JOSEPH STIGLITZ: THE INEFFICIENCY OF THE COMPETITIVE STOCK MARKET AND ITS IMPLICATIONS FOR THE DEPLETION OF NATURAL RESOURCES

Stiglitz extends work done by Diamond on the optimality of the stock market, in which Diamond, by characterizing the distribution of returns across states of the world as commodities and by assuming "stochastic returns to scale", or "multiplicative uncertainty", which occurs when doubling the scale of the firm doubles its value, is able to show that the stock market results in a constrained Pareto-optimal solution. Stiglitz talks about the conditions necessary for multiplicative uncertainty, in which distribution of return is independent of scale.

In some work in progress[1], Stiglitz builds a two-period model with two goods and three securities: a consumption good, oil, oil futures, shares of land or (what amounts to the same thing) shares of exploration companies, and a safe asset, in an attempt to examine the efficiency of stock market allocation of a natural resource, such as oil. Although the model has many producers, many storers, many consumers and is thus reasonably competitive, Stiglitz shows that this market is not constrained Pareto-optimal, since, although each individual assumes private multiplicative uncertainty in assuming the price next period as given, the aggregate effect of their actions determines the price next period and social multiplicative uncertainty does not exit, and so the condition necessary for constrained Pareto-optimality no longer exists.

Stiglitz examines the nature of the bias, and finds that the equilibrium allocation depends in a complex way on the relative magnitudes of risk aversion of individuals, on the importance of the natural resource in consumption, and on the price and income demand elasticities.

If the "first best" solution is direct allocation, and the "second best" solution is the market with government lump sum redistributions to equate

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1. Paper not included here.

marginal utilities of income, then Stiglitz characterises the "third best" solution as one with producers worried about income risk but not consumption risk, and consumers worried about consumption risk but not income risk since consumers own little oil and producers consume little oil. Again the optimum, although very different from the general solution, depends on the degrees of relative risk aversion and the income elasticities. These two factors are also found to influence the bias occurring when consumers don't take into account the collective effect of their decisions about consumption modes on price variability.

ROBERT WILSON: THE PHILLIPS PLAN FOR AUCTIONING OIL LEASES

Wilson's discussion continues his work[1] on price formation via competitive bidding presented at the first Conference on Natural Resources, May 1975. He notes that economists have been influential in the wording of recent Bills which have allowed for experimental auctions of oil drilling leases; in particular, to reduce collusion bidding syndicates have been banned; in an attempt to reduce the total social cost of gathering information about tracts up for bid the government experimented with being the sole gatherer itself; and in an attempt to minimize the excess profit of the successful bidder the government experimented with royalty-bidding (the highest royalty rate is the winning bid) and profit-sharing. The aim of these experiments was to set up an institutional form of a market with a relatively small number of buyers which would maximize the social return to the seller (the government). However there have been political problems with government data collection, and high royalties mean little incentive to extract, and the tax laws mean that profit-sharing is similar to royalty-bidding.

In a discussion of work in progress[2], Wilson analyzes the equilibrium of the Phillips plan for auctioning oil leases (so called after Phillips Petroleum, which introduced the plan), which is a form of risk-sharing designed to get around the externalities of exploration and extraction.

In the plan, contiguous tracts are treated as a single, large tract, the mineral rights to which are vested in a corporation responsible for exploration and extraction. After initial sampling by the qualified bidders, shares in the corporation are sold at public auction: the bidders submit demand schedules and buy shares at an average price which is set somewhat above the market clearing price. The share-holders can then decide on the

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1. Subsequently published as "A Bidding Model of Perfect Competition", Technical Report No. 184, Institute of Mathematical Studies in the Social Sciences, Stanford University, 1975.

2. Paper not included here.

management of the corporation.

Wilson analyzes the consequent Nash equilibrium, with the small number of gaming bidders manipulating their demand schedules. He assumes a given unknown true value of the tract, independent samples, a symmetric strategy for reporting demand schedules, exponential utility functions, a normal probability distribution on the true value, and a normal probability distribution on the samples. He concludes that such equilibria are highly non-linear, that they involve much inference about other people's samples, and that collusive behaviour would readily occur.

GLENN LOURY: THE OPTIMAL EXPLOITATION OF AN UNKNOWN RESERVE

Loury investigates the problem of optimal planning when premature exhaustion is a real possibility due to lack of precise knowledge about the total supply of the resource. The treatment of unknown reserves confronts two issues. Firstly, there is the possibility of complete exhaustion at any moment. The choice of the rate at which to consume the resource must necessarily be influenced by the effect which this rate has on the probability of exhaustion by any particular time in the future. Secondly, there is the information gained about the distribution of reserves as the activities of exploration and extraction continue. In addition, the rate of extraction of the resource may affect the amount of remaining resource able to be recovered, despite the total amount. Loury abstracts from the information from exploration. He assumes that the planner begins with an objective distribution of possible endowments of the natural resource, and that he updates this over time by conditioning on the knowledge of his cumulative consumption at each instant.

Loury begins with a review of the problem of optimal depletion without production in a certain environment. The socially optimal allocation of resource use requires that the discounted marginal utility of consumption is constant, with strictly positive consumption everywhere and exhaustion occurring only asymptotically. With perfect futures markets and the social discount rate equal to the rate of return to privately held capital (i.e., the interest rate), the socially optimal allocation of resource use will be attained by a competitive resource market. Loury additionally notes that when the terminal date is a decision variable overall optimality requires both that discounted marginal utility is constant along the program, and that marginal utility equal average utility at the terminal date.

Loury extends the socially optimal problem to the situation where the total reserve is a random variable with cumulative distribution function known at the initial date. This is the "cake-eating" problem with a cake of unknown size. An important assumption is that there is no storage: extraction and consumption are identical. He proves the proposition that at any point along an optimal consumption path (if one exists) the discounted marginal utility of consumption must equal the expected value of discounted average utility at the end of the program, where the expectation is taken over the distribution of terminal dates, conditional on the terminal date being not less than the point in question. He shows that consumption will be increasing (decreasing) when the probability of exhaustion in the next instant is very high (low), a result at first counter-intuitive. But the optimal accumulation of a productive asset requires that the sum of the rental rate and instantaneous rate of capital gains on the asset be equal to the discount rate everywhere along an optimal path. If the probability of exhaustion in the next instant is very high, then the "rental rate", or return on deferred consumption, will be greater than the discount rate, requiring negative "capital gains", or a declining shadow price (marginal utility) of consumption, leading to rising consumption, and vice versa.

In the case of separable utility and independence of the rate of extraction of recoverable reserves, a more complete solution can be arrived at. In particular, Loury shows that a mean utility preserving increase in the riskiness of the distribution of the remaining reserves does not affect current optimal consumption. He shows, under rather general circumstances, that more noise, appropriately defined, in the distribution causes a more conservative exploitation of an unknown resource base.

Finally, Loury examines whether competitive markets exploit an unknown resource optimally. His model excludes exploration activity and, in the absence of complete markets, he assumes perfect foresight of future prices by agents acting in the market today. After some discussion, he concludes that the market equilibrium under uncertainty with frequent sequential trading approximates the certainty equivalent path with the most optimistic forecast of the economy's resource endowment. Thus such a path consumes more of the resource in the early years than would be optimal. Since both the competitive and optimal paths will have the same cumulative consumption asymptotically, the competitive path will consume less than the optimal path in the later years of the program. He concludes that the market allocation subjects the economy to too great a risk of exhaustion along the way.

PARTHA DASGUPTA, RICHARD GILBERT, AND JOSEPH STIGLITZ: INCENTIVES FOR TECHNICAL CHANGE UNDER ALTERNATIVE INSTITUTIONAL ARRANGEMENTS

Dasgupta, Gilbert, and Stiglitz are interested in the general question of research and development (R&D): in particular the intensity of R&D under different market structures (or institutional environments), the timing of the R&D search, and the date of introduction of the innovation. Following earlier work of Dasgupta and Stiglitz[1], the authors examine a partial equilibrium model of an economy with a finite stock of non-renewable natural resource (such as oil) available at zero extraction cost, and a backstop technology providing unlimited amounts of a perfect substitute for the natural resource at a constant unit cost. Possible sources of uncertainty are the size of the stock of natural resource, the date of invention of the backstop technology, and its unit cost, but in the work-in-progress presented[2], perfect certainty is assumed.

Three institutional arrangements are examined: the socially-managed economy, the monopoly/monopoly case where a single firm owns the stock of natural resource and the backstop technology, and the competitive/monopoly case where the natural resource stock is competitively owned but the backstop technology is patented (monopoly owned). Given a production function for R&D in which the length of development of the backstop technology is a decreasing function of the investment per period, the authors are interested in the relative intensities of R&D search (as measured by the investment per period) and the relative times of beginning the R&D search for the backstop technology. In the socially optimal economy they derive the efficiency condition that the discount rate times the length of development equals the length elasticity of investment per period. For smaller initial

1. "Uncertainty and the Rate of Extraction under Alternative Institutional Arrangments" Technical Report No. 179, Institute for Mathematical Studies in the Social Sciences, Stanford University, 1975.

2. Paper not included here.

stock of natural resource the time of starting the search is sooner and the investment per period is larger, so that the backstop technology is ready at the point when the stock of natural resource has dwindled to an socially optimal size. In the monopoly/monopoly case the long-run optimal stock of natural resource will be smaller than the socially optimal size, and the backstop technology will arrive "on tap" later. In the competitive/ monopoly case with "small" initial stock of natural resources and free entry in the race for the patent on the backstop technology, the investment per period in the R&D search will be greater than socially optimal, which in turn is not less than the investment per period in the monopoly/monopoly case. The third case is one of zero profit for the eventual patent holder, with the introduction of uncertainty bringing visible competition for the patent and hence duplication of effort.

MORTON KAMIEN AND NANCY SCHWARTZ: SOME DISAGGREGATED MODELS OF OPTIMAL ECONOMIC GROWTH INVOLVING AN EXHAUSTIBLE RESOURCE AND TECHNICAL ADVANCE

Kamien and Schwartz are concerned with modelling endogenous technical change, with the level of resources invested in the development influencing the probability of successful achievement by any particular date. They examine the role of different market structures and financing arrangements on the use of productive factors and on the development of a new technology that eliminates the need for the exhaustible resource. In particular they ask whether the dynamic resource allocation policies of a decentralized economy are the same as those of a central planner. They suspected that the possibility of externalities not taken into account by individual economic agents, and the existence of uncertainty and absence of complete insurance markets, and the impossibility of an individual's appropriating all rewards from any invention of his, and the more complex distortions in the use of an exhaustible resource due to its control by a monopoly would mean not.

This model is an economy with a single good to be consumed, or used to augment the capital stock, or used to develop the new technology. The good is produced by means of capital and the exhaustible resource, as described by a linearly homogeneous production function. Both factors are essential. The economy is disaggregated into a production sector in which factors' services are rented and the single good is produced; a capital goods sector with capital owners; a natural resource sector with owners of the exhaustible resource; and a government sector. Resource owners and capital owners have identical utility functions. The level of resources required for successful development of the new technology is uncertain as is its completion date. A larger research effort increases the probability of early completion, but there are decreasing returns. The new technology is drastic in that it completely eliminates the need for both the exhaustible resource and the stocks of capital.

In an earlier paper[1], the authors examined a centralized economy. They found that the consumption profile and the profile in investment in R&D were both single-peaked or downwards sloping through time (the peaks could lead or lag each other). In addition they found that there could be a period during which there was no investment in new technology. This leads to the possibility that if a certain minimum amount of production is necessary for development of the new technology then in a decentralized economy R&D might start too late to avoid exhaustion of the resource.

The first of three decentralized models is perfectly competitive. Owners of capital must determine their consumption profile, owners of resource must determine their consumption profile and the profile of exhaustion of resource, and the government (knowing the consumption patters of the two other sectors) determines the debt accumulated and the level of investment in R&D. The authors show that in this case resources are allocated qualitatively the same way as in a centralized economy. Identical allocations can be achieved by reallocation of initial endowments, if need be.

The second model is identical with the first except that resources are sold monopolistically. The authors show that in this model the optimal resource-capital ratio declines through time. The time profiles of consumption and investment in R&D are qualitatively the same as the two earlier models although not usually identical. The authors show that the rate of decline of the resource-capital ratio is the same in the competitive and monopolistic cases if and only if the production function is Cobb-Douglas. Solutions can coincide in this case. If the production function is CES and the resource is an essential factor with $\sigma < 1$, then the resource-capital ratio declines less rapidly under

1. Kamien, M.I., and Schwartz, N.L., "Optimal resource depletion with endogenous technical change", Center for Math. Stud. in Econ. and Magmt. Sci., Northwestern U., D.P. 213, March 1976.

monopolistic supply than under competitive supply of the resource.

The third model is one of competitive supply of resource as in the first, but with R&D carried out and financed by the resource sector, which can lend to the capital sector but not borrow from it. There is no opportunity for speculative gain based on differences of information between the two sectors. There is no government sector. The qualitative properties of the centralized model are retained, but the barrier to the flow of assets can lead to more rapid exhaustion of the resource even if the economy is otherwise perfectly competitive. A subsidy of the resource sector, perhaps in the form of a depletion allowance, might be necessary to offset its tendency to exhaust the resource more rapidly than is socially desirable. An alternative remedy would be collective R&D.

EDWARD STEINMUELLER: THE SEVENTEENTH CENTURY ENERGY CRISIS - A CRITIQUE OF THE "TIMBER FAMINE" THEORY

Modern concern for the imminent exhaustion of coal and oil is preceded in history by the concern during the transition from charcoal to coal as energy sources in Britain that timber reserves were nearing exhaustion and that this would undermine the national security and welfare. Historians of technology have argued that in the face of a growing energy crisis a series of inventions rescued the early industrial societies as well as providing a foundation for the industrial revolution. The transition from charcoal to coal was complete when the first successful smelting of iron ore with coke occurred in 1709.

This theory of technological change yields an optimistic view of the contemporary energy situation: it is only with a "crisis", a perceived need, that the forces of innovation necessary to advance technology can be set in motion; there is every reason to suppose that our history will reveal the many solutions which will successfully obviate the temporary discomforts of the adjustment period.

Steinmueller attempts to show, using models of the production of timber, of the production of charcoal iron, and an interpretation of the 1657 and 1668 Timber Acts, that the depletion of timber reserves from 1600 to 1800 was the result rather than the cause of the use of coal as a fuel. By implication, if history can teach us anything, it makes the origin of innovation less certain and contemporary optimism less comfortable.

In the short run timber is an exhaustible resource. Steinmueller argues that if in fact the "timber famine" existed, it was a market disequilibrium, and that rapid unanticipated growth in demand would have pushed up timber prices dramatically. He presents evidence that not only did prices remain low but that there was an enormous increase in the supply of timber during the two centuries after 1550, and concludes that any long- or short-run equilibria in the timber and fuel markets were insignificant overall.

After analysing the production of timber and of charcoal iron, Steinmueller concludes that instead of being protective laws for preserving Britain's diminishing timber reserves, the Timber Acts may be seen as an attempt to guarantee the Royal Navy an adequate supply of oak by fiat. Unfortunately the Crown was in no position to enforce such an edict: whether by rational plan or fortuitous custom, the author concludes, the oaks disappeared and the timber owner and charcoal burner prospered.

ANTHONY FISHER AND RICHARD ZECKHAUSER: AVERTING BEHAVIOUR AND EXTERNAL ECONOMIES

Fisher and Zeckhauser examine the consequences of the potential for averting behaviour by individuals or groups affected by external diseconomies on the optimal control of such external diseconomies as air pollution or noise. They distinguish between actions which reduce the level of externality, such as bribing the polluter to reduce the level of pollution, and those which reduce the level of disturbance to the individual at any given level of externality, such as moving away from a source of noise or air pollution. This latter behaviour is what is meant by averting behaviour.

In particular they attempt to develop procedures for calculating willingness-to-pay which explicitly consider the possibility of averting behaviour. One conclusion is that failure to consider changes in averting behaviour leads in general to an underestimate of the gains to be achieved by reducing the level of an unpleasant externality, and conversely that losses from increasing its level are over-estimated. Thus, if a benefit-cost calculation is used to formulate policy, ignoring averting possibilities, the valuations attached to any changed positions will be too low and the chosen policy will include externality levels which are too close to the status quo.

A second conclusion follows from an elaboration of the willingness-to-pay model to consider the averting behaviour of moving to a less affected location. Net changes in rents are shown in general not to be an accurate indicator of the gains or losses from changes in environmental quality, although in a number of circumstances the direction of the bias can be predicted. The change-in-location model demonstrates that if individuals are free to move, then political decision procedures that rely on the preferences of present residents to determine levels of output for localized public goods will in general not lead to optimal solutions: equating the sum of willingness-to-pay of present residents to marginal cost of provision (the traditional Samuelsonian efficiency condition) will not guarantee efficiency, since it ignores the preferences of potential residents.

DONALD HANSON: SECOND BEST PRICING POLICIES FOR AN EXHAUSTIBLE RESOURCE: THE FIXED SAVINGS RATIO CASE

Hanson considers some of the theoretical issues involved with choosing a price path for an exhaustible resource. In a first best world the problem of society's agreeing on a way to rank alternative inter-generational consumption paths has two parts: efficiency and distribution. That is, for any fixed consumption path maximize the value of the accumulated assets with respect to the resource allocation path; and choose the consumption path which maximizes the accepted criterion. In a first best world these two parts can be separated. A necessary condition for efficiency is the conventional Hotelling condition that the value of the resource (market price less extraction cost) must increase at the rate of interest.

But it may be that intergenerational consumption cannot be manipulated directly because it is determined from behavioral relationships and linked to other economic variable, such as current income. In this case the resource allocation path is the only policy variable and hence must be determined not for efficiency but rather to influence the intergenerational consumption path. As a consequence the value of the resource can increase at a much lower rate than the rate of interest.

Hanson emphasizes that once consumption is specified behaviorally no pure efficiency problem can be defined with respect to allocating the resource. If more resource is allocated in any period then output will increase according to the marginal product of the resource, and if consumption is linked to output by a Keynesian consumption function, then consumption increases in the period too. That is, it is impossible to hold consumption fixed and have the resource allocation path affect the investment only. Any policy regarding intertemporal resource allocation has distributional implications.

In this paper Hanson presents an example where the savings ratio is fixed. The value of the resource must then increase at a weighted average of the consumption rate of interest and the rate of return on investment. This growth rate may be much less than the rate of return on investment. Further, there must exist a transition period just before the resource is depleted in which both the resource and its more costly substitute are used. The optimal policy may be implemented in a competitive market using a severence tax to create a wedge between the social value of the resource and the market price equilibrium. During the transition period there may be multiple market price equilibria, requiring a licensing policy to ensure that the substitute source is developed at the optimal rate.

RICHARD GILBERT: IMPERFECT COMPETITION AND THE ALLOCATION OF OIL

Gilbert presents a simple model of profit-maximizing pricing strategy in a market for an exhaustible resource dominated by a cartel or a large firm. The cartel is assumed to be a Stackelberg price-maker, taking account of the reactions of the other firms in its price policy, while the other firms, the "competitive fringe", are price-takers. This model could describe the world petroleum market, or perhaps those for tin and bauxite. In a model which includes a "back-stop" technology available at a fixed price, Gilbert shows that the supply response of the competitive fringe can significantly limit the monopoly power of the cartel, depending on such factors as the proportion of total stock owned by the fringe, constraints on the rate of extraction, and the cost of extraction.

When the demand elasticity is greater than one, the cartel will be content to postpone extraction and earn capital gains at the equilibrium rate of price appreciation. When demand elasticity is less than one, a monopolist can increase revenue by restricting output. Existence of a substitute will lead to higher elasticity of demand, and hence a well-defined optimum.

Gilbert presents first a simple model with no uncertainty, zero extraction costs, and no capacity limits on the rate of production. Given certainty, markets will clear at all future points in time and the price will rise at a proportional rate to the market rate of interest, until the stocks of the competitive fringe are exhausted, after which time the cartel can choose the revenue-maximizing price of the substitute to earn monopoly profits: in the meantime the cartel's strategy will be to exhaust the competitive fringe quickly, by choosing a low initial price, and hence reducing its own profits in the short run. But there are limits to the freedom of the cartel in choosing the initial price. Gilbert shows that a cartel policed by a competitive fringe with unlimited production capacity will choose a price path such that the proportional rate of change of price is equal to the competitive rate of return on the resource stock, but the magnitude of the price at any time is bounded below by the efficient price for the total resource endowment, and bounded above by the efficient price for the stock owned by the fringe. The analysis demonstrates that the cartel's monopoly power is inversely proportional to the magnitude of the elasticity of demand, when this is less than one minus the ratio of fringe stock to total endowment. For more elastic (constant) demand the cartel maximizes profits by setting the price at the efficient level for the entire endowment: its monopoly profits are zero.

In the case of positive extraction costs, Gilbert assumes that extraction exhibits constant returns to scale when capacity constraints are non-binding. Rather than $\dot{P}/P = r$, the zero-extraction-cost case, where P is the price and r is the market rate of interest, the price path is characterized by $\dot{P}/(P - C_f) = r$, where C_f is the unit production costs of the fringe, which is assumed to have unlimited production capacity.

In the case of uncertainty of supplies, whether or not the price exhibits a rising trend depends on the nature of the expectations of remaining stocks and on the capacity constraints of the competitive fringe. But in all cases there is a tendency for prices to rise eventually toward the price of the substitute. A myopic response to pricing policy may lead to an allocation not only inefficient, but which in the long run increases the monopoly power of the cartel.

In a final speculation on the world oil market, Gilbert suggests, firstly, that his model predicts that OPEC perceives the demand elasticity to be no greater than 0.6 in magnitude; secondly, that increased fringe capacity, resulting from exploration, will raise the optimal OPEC output and reduce prices; thirdly, an increase in demand elasticity would unambiguously reduce prices; finally, as the fringe stock decreases, the equilibrium price for the unconstrained case increases and eventually exceeds the price corresponding to maximum fringe output, at which point producers in the fringe would curtail output (or at least reduce exploration effort), and the price should rise at an exponential rate towards the cost of a substitute source of energy.

MARTIN WEITZMAN: OPEC AND THE MONOPOLY OF OIL[1]

Weitzman presents a model aimed at quantifying in a rough manner what long-term world oil prices would be if the members of OPEC colluded in rational, concerted action to maximize their present discounted profits. He makes the point that long-run resource economics covers three areas of intractible economics: imperfect competition, dynamic capital theory, and the uncertainty of exploration. Any one of these creates difficulties for the economist, all three lead to drastic simplifications in order to obtain any results. In their model the authors abstract from uncertainty, including price uncertainty; their cost estimates are rough both conceptually and quantitatively, they assume a cumulative increasing cost function to include all costs associated with oil extraction including exploration, development, drilling, operating, and transportation. They abstract from costs dependent on the rate of extraction, assuming an upper bound on the production of the "competitive fringe", or non-OPEC oil producers: production is met by the OPEC cartel and the competitive fringe.

The model can be described as the OPEC monopoly deciding on a sequence of prices for all future periods. The competitive fringe takes these prices as given and sets its production schedule so as to maximize its present discounted profits; OPEC supplies the difference between the total demand and the competitors' production, having chosen its price sequence (or, equivalently, its production) so as to maximize its present discounted profits. Although this mechanism is unrealistic, the authors consider it better than lagged-prices models. The result of these behavioural assumptions is a dynamic equilibrium, with no incentive for anyone to do anything but attempt to maximize profits given the pattern of current and future prices.

In the preferred solution the demand schedule grows at 3% per annum, and in 1975 was D = 21 - .6P which gives a long-run elasticity of 0.4 at

1. Based on a paper jointly written with Jacques Cremer.

\$10/bl, with total demand of 15bbl/year, and zero demand at a price of \$35/bl. The cost of supplying oil is composed of two parts: the capital costs (exploration and development of new fields) assumed to be inversely proportional to the quantity of unexploited reserves; and transportation and current costs. The annual discount rates are: for OPEC 5%, for the competitive fringe 8%.

The simple, theoretically complete model developed leads to robust, plausible basic results. The most important result is that real oil prices will not increase much in the next 20 years, by only 50 cents (1975 dollars). The authors conclude that the recent increase in the price of oil was a once and for all phenomenon due to the formation of the OPEC cartel, and that real oil prices should remain approximately constant during the next twenty years.

ROBERT PINDYCK: OPTIMAL PRICING MODELS FOR EXHAUSTIBLE RESOURCE CARTELS[1]

Pindyck presents three models related to the pricing of exhaustible resources. The first is an attempt to put into figures the gains to producers from the cartelization of exhaustible resources, in particular oil (OPEC), copper (CIPEC), and bauxite (IBA). In this model the cartel is treated as a unit and differences in production costs for different members, differences in objectives etc. are ignored. Often, potential monopoly profits in a given market are calculated using a simple static model, given the elasticities of demand and of supply of the producers outside the cartel, a model appropriate for such goods as bananas, coffee, and sugar for which demand and supply can quickly adjust to price changes. But Pindyck is concerned with resources which are exhaustible and for which demands and supplies adjust slowly to price changes, leading to the possibility of large short-term monopoly profits flowing from adjustment lags.

Treating the cartel as a perfect monopolist knowing the structure of demand and cost, and ignoring the issues of distribution within the cartel, Pindyck is concerned with the difference between the sum of discounted profits along the optimum price trajectories under competition and under cartelization, which depends in part on the particular ways in which demand elasticities change and production costs increase as the resource reserve base is depleted, and in which the monopolist can take advantage of demand adjustment lags. He derives a classical unconstrained discrete-time optimal control problem for the cartel case, and solves it numerically with a general nonlinear optimal control algorithm. The optimal price and output trajectories in the competitive case must satisfy market equilibrium at every time and the transversality conditions, as well as a modified Hotelling condition for competitive price with increasing costs.

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1. Based in part on a paper jointly written with Esteban Hnyilicza.

For oil and bauxite, the producers are found to be in a position to accrue significant monopoly profits through cartelization, while the copper producers have little to gain, although the reasons for this, Pindyck concludes, have little to do with the fact that the resources are exhaustible, and more to do with the fact that OPEC and IBA each account for about two-thirds of non-communist world production in their respective markets, while CIPEC accounts for only a third in its. Demand and competitive supply of oil and bauxite adjust slowly to price changes, allowing large short-term gains to a cartel, while copper supply (specifically "secondary" supply from scrap and from wastage during milling) responds quickly.

But Pindyck finds that resource exhaustion does have a significant effect on the pattern of pricing and output in both the monopoly and competitive cases, tending to reduce the gains from cartelization when the discount rate is low. The fact that pre-cartel oil, bauxite, and copper prices were close to marginal cost could mean that producers had high discount rates or that they had made output decisions either ignoring future exhaustion or assuming that large additional reserves remained to be discovered.

In a second model, the authors relax the assumption of a monolithic cartel and look at the internal structure of output shares. In particular they consider an OPEC comprised of a bloc of "spender" countries (Iran, Venezuela, Indonesia, Algeria, Nigeria, and Ecuador) and a bloc of "saver" countries (Saudi Arabia, Libya, Iraq, Abu Dhabi, Bahrain, Kuwait, and Qatar). The spenders have large cash needs and therefore a higher discount rate, and the savers lower cash needs and a lower discount rate. Co-incidentally the spenders have lower reserve-production ratios than do the savers.

The authors' approach is to seek a bargaining solution for the two-part cartel based on Nash's theory of cooperative games: assuming the cartel maximizes a weighted sum of the objectives (sums of discounted profits) of each bloc, the authors determine the optimal trajectories for both price and the ratio of output shares. After deriving the Pareto-optimal frontier in the realized objectives plane, the authors determine the set of weights corresponding to a Nash cooperative solution, which corresponds to the bargaining solution, and which provides the optimal trajectories for price and market shares.

Numerical solutions show that when output shares are open for policy discussion, any resulting optimal policy will depend considerably on the relative bargaining power of the two blocs. Pricing strategy follows almost directly from output strategy. The optimal output strategy is drastic: savers produce nothing for the first ten or twelve years until the spenders are almost depleted, and then savers produce all. If output shares are held fixed, then the model predicts significant losses, especially for spender countries. In fact, at the moment we see Saudi Arabia, Iraq, and the other savers absorbing most of the cuts in production, while Iran, Indonesia, and other spenders have maintained production closer to capacity. The authors conclude that in predicting OPEC's responses to future drops in demand it is essential to recognize that the cartel consists of producers with somewhat different interests.

In a third model[2], Pindyck extends the campetitive model to include simultaneous production and exploration. As well as rising production cost, he considers drilling cost, a quadratic function of the level of drilling effort. One conclusion is that the optimal price trajectory rises more slowly than the non-exploration case since production cost is reduced as the level of known reserves rises. The author notes that there is the possibility of a "bang-bang" solution for drilling effort: maximum at first, and then zero. More usually, with large reserves

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2. Paper not included here.

initially, the level of drilling effort, the level of known reserves, and the production rate will all be monotonically decreasing, with increasing price through time. In the case of almost no reserves initally, the optimum will be an initially high level of exploration, falling to zero, peaks for the level of known reserves and the level of production, and a price trajectory initially falling and then later rising. This last case might describe the uranium situation. The case of a cartel with exploration remains to be modelled.

ERNST BERNDT, MELVYN FUSS, AND LEONARD WAVEMAN: MODELLING THE INDUSTRIAL DEMAND FOR ENERGY

This presentation is made in two parts: a paper by Mel Fuss on the demand for energy in Canadian manufacturing, and a paper[1] by Ernst Berndt and Leonard Waveman describing a dynamic model of the industrial demand for energy. The main contribution of the first paper is an econometric extension: a model is presented for the estimation of production structures with many inputs when aggregation into a small number of aggregate inputs is undesirable. The procedure used is one of two-stage optimization, which is valid under the assumption of homothetic separability. According to Fuss, a unique feature is the use of duality theory to integrate the two stages through the generation in the first state of an instrumental variable for the aggregate price index of the separable, disaggregated factors.

This conceptual model is applied to an analysis of the demand for energy in Canadian manufacturing, in which six energy components (coal, liquid petroleum gas or LPG, fuel oil, natural gas, electricity, and motor gasoline) are explicitly included in the set of factors of production (labour, capital, materials, and aggregate energy). The data were combined time series cross-section over 1961-71. Weak separability allows the modelling to proceed in two stages: the demand for energy input components, and the demand for aggregate inputs.

The energy sub-model provides empirical estimates of the price responsiveness of individual fuels. The own and cross-price elasticities of demand are derived under the assumption that aggregate energy input is held constant. All of the own price elasticities are negative and, but for motor gasoline, significantly so: the results do not violate the postulates of cost-minimizing factor demand theory. Except with respect to electricity

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1. Paper not included here.

and perhaps motor gasoline, there appears to be substantial scope for inter-fuel substitution. Excluding motor gasoline, the fuels can be ranked in the following of declining (absolute value) price elasticities of demand: LPG, coal, fuel oil, natural gas, and electricity. The last is inelastic.

The aggregate model provides empirical estimates of the parameters of the underlying production technology involving capital, labour, materials, and energy. As summary measures of substitution possibilities the price elasticities of demand are derived, holding gross manufacturing output constant. All of the own price elasticities are significantly negative, and there is some slight complementarity between energy and materials and between energy and capital. All aggregate factors have inelastic own price elasticities of demand. The own price elasticity of demand for aggregate energy is approximately -0.5. In most cases the cross-price elasticities are less than 0.3 in absolute value.

The energy-component price elasticities are estimated with aggregate energy variable and gross manufacturing output constant: a change in the price of an energy component also changes the energy price index, with both "substitution" and "income" effects. It is seen that total manufacturing in Canada is characterized by substantial inter-fuel substitution combined with relatively low substitution of aggregate energy for other aggregate inputs, although an own price elasticity of -0.5 is sufficient to question the use of fixed coefficient input-output tables.

In an investigation of the effect of increases in energy prices on production costs, Fuss finds that a doubling of the price of energy leads to a 2% to 4% increase in average production costs, while a tripling of energy prices leads to a 5% to 9% increase. If producers maintain their cost margins, the output price will also increase by the same percentages. Fuss notes the relatively small effect on average production costs of substantial increases in energy prices, although some individual industries might be affected more. In conclusion, Fuss states that substantial inter-fuel substitution is possible; that only moderate substitution of energy for other aggregate inputs occurs; and that, due to the combination of substantial inter-fuel substitution and the low proportion of energy costs relative to the cost of other factors of production over a wide range of relative prices, large increases in energy component prices can be accommodated with only small output price rises.

Berndt and Waverman present an attempt to extend the Fuss model to longer-term adjustments, by grafting a constant cost of adjustment model onto the static demand model. They suggest a simple adjustment mechanism for a change of shares of factor inputs as a function of the differences between last period's shares and the desired shares, given by a simple cost-minimization model, in a translog form. They discuss constraints on the parameters, which complicate the estimation procedure. The cross-cost terms in a matrix of coefficients relate the degree of influence of disequilibrium from one factor onto another. It is possible to write the model in terms of quantities rather than costs. Technological change can be included by prices having a constant rate of decay.