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A petroleum life cycle model for the United States with endogenous technology, exploration, recovery, and demand

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This article describes a model of the life cycle of the petroleum resource in the United States. Expanding on prior system dynamic models of petroleum resources, the model endogenously generates the complete life cycle of the resource. It treats endogenously petroleum demand; the development of technology for, and investment in, exploration and recovery; discovery and production of petroleum; and the development of petroleum substitutes. With only two exogenous variables, GNP and the international petroleum price, the model portrays the evolution of the U.S. petroleum resource, and the associated industry, starting in 1870. The correspondence between simulated and actual data is examined through a variety of statistical measures. The model is used to show how the interaction between technological progress, depletion, imports, and the development of substitutes creates the life cycle by altering the dominance of the feedback processes in the system.

This article describes a model of the life cycle of the petroleum resource in the Uni States. Expanding on prior system dynamics models of fossil fuel resources (Na 1973; 1977; Backus et al. 1979; Choucri 1981; Sterman 1981; Sterman and Richards 1985), this model endogenously generates the complete life cycle of petroleum. synthesizes the perspectives of several disciplines, including geology, technolo and economics. It integrates exploration, production, pricing, demand, imports, a the development of substitutes. Finally, the model emphasizes the impact of del in both the physical processes and the information and decision-making processes the system.

With only two major exogenous variables, Gross National Product (GNP) and t international petroleum price, the model is able to portray the evolution of the U petroleum resource, and the associated industry, starting in 1870. The corresponden between simulated and actual data is examined through a variety of statistical m sures. The model is used to show how the interactions among technological progre depletion, imports, and the development of substitutes create the life cycle altering the dominance of the feedback processes in the system. The life cycle characterized by exponential expansion of the petroleum industry, driven by ec nomic growth, developing geological knowledge, and technological progress, f lowed by a transition to decline, driven by depletion, rising real costs of explorati and production, and ultimately by the development of substitutes.

The model is intended to provide a realistic microworld in which the geologi and technical parameters are known and can be varied to portray alternative scenari The model may thus be applied in a variety of petroleum-related analyses:

- The model has already been used to generate synthetic data for the modeling a evaluation of resource estimation methods (Sterman and Richardson 1985; Sterm Richardson, and Davidsen 1988).
- Integrated and mutually consistent forecasts of the total resource base, the econo ically recoverable resource, production, exploration activity, and costs can be ma
- Policy options such as price controls, taxes, and import fees can be evaluated i dynamic environment that represents the feedbacks important in the real systen
- The model is reasonably transparent and offers opportunities to teach resou management, dynamic modeling, and principles of feedback.

The modeling context

Most documented surveys of models comparable with the one presented here d back more than six years and focus on the ability to forecast or to address speci issues such as the macroeconomic impacts of energy shocks. Comparisons betwe models primarily concern systems behavior. To the extent that structural compariso have been made, these focus mainly on the interrelations between general macroec

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nomic variables, such as industrial inputs, capacity utilization and production, consumption, investment, trade, and financial variables (Salinas and Weyant 1987). The most relevant surveys of models are the ones carried out by the Energy Modeling Forum (EMF) in the period 1970–1983 and the poll carried out by the International Energy Workshop (IEW), International Institute for Applied Systems Analysis (IIASA) in June 1983.

A life cycle model tends to focus on the supply side, in particular the effect of depletion on productivity. A comparison of 13 models portraying the supply of gas and oil in the United States was carried out by the Energy Modeling Forum in 1979–1980 (EMF 1982). Nine of the models surveyed were classified as engineering-process models. They "focus on the process of exploring, developing, and producing oil and gas," and on "stimulating the process itself." Of these, one model (FOSSIL2) is a system dynamics model.

The remaining four were classified as econometric models that "focus on the important economic relationships which govern a process."

Even though we know of no documented structural comparison between these models, it seems clear that depletion is represented with a great variety of underlying structures, some of them fairly explicit (the class of engineering-process models), others less so (the class of econometric models), and most of them fairly simple. The impact of the ultimate resource base, however, has not been of major concern until recently, when the effect of depletion became obvious.

Polls with respect to specific items such as energy price, consumption, production, and imports have been carried out by Alan S. Manne and Leo Schrattenholzer among 328 energy modelers. The most recent poll was presented at the International Energy Workshop, IIASA, in June 1983 (Manne and Schrattenholzer 1984). In their introduction, the authors remark that "most of these analyses are concerned with short- and intermediate-run decisions (e.g., specific investment projects) rather than with long-term questions (e.g., resource depletion, global carbon dioxide emissions, and technological development)." They also point out that supply-scenario assumptions, in particular with respect to technology, are of critical importance, and that "over the next two decades, it is not the ultimate resource base but rather the producibility constraints . . . that will determine how rapidly the world's nonrenewable resources will be exploited." The model presented in our article, therefore, covers a time span far beyond most of the models presented in that poll.

It is noteworthy that only a few of the responses in the Manne and Schrattenholzer poll were based directly on formal models. This indicates the extensive use of add factors in the interpretation of results originating from energy models, and the difficulties in carrying out a direct comparison between the results reported (especially those applied for short-term purposes) and the results formally generated by our model. The lack of robustness and the impact of add factors are illustrated by Manne and Schrattenholzer in commenting on the differences in price projections exhibited by the poll:

Cynics will be quick to point to other possible explanations for these differences. Long-

Between these two polls, the median oil-price projection for the year 2000 decli from 175 to 148 (in real terms, with 1980 = 100). The statistical significance of result is a bit doubtful, . . . Nonetheless, the cynics may be right. Just as in macro nomic forecasting, there is a strong herd instinct that operates within the commu of energy analysts. In any case, the workshop process is bound to lead to hea introspection—and more attention to minority viewpoints.

The lack of appropriate feedback in the energy models represented in the 1983 I poll caused a significant spread in the responses. G. W. Yohe (1984) commen "The statistically trained reader may be tempted to interpret these spreads as ref tions of the uncertainty with which we view the world's energy future," but he arg otherwise. He raised concern about the lack of economic consistency in much of modeling reported in the IEW poll and urged a more endogenous perspective of sort we have employed:

> In long-range energy modeling, for example, energy prices should be allowed to f back into endogenously determined rates of growth in energy consumption and G . . . Many of the projections reported . . . were based upon simple extrapolations of trends that allowed no feedbacks.

In 1983 the Energy Modeling Forum carried out another study of energy mod with a more specific purpose in mind—to study the U.S. macroeconomic impac energy shocks. The results were recently published (Hickman, Huntington, and Sw ney 1987), and a survey of the 14 models reviewed was presented. All but one econometric models, employing coefficients estimated from historical data samp from the time intervals 1946–1960 to 1975–1981. All but two are structural mod Most of them are general econometric models applied in economic forecasting policy analysis, which were only later expanded to incorporate energy detail.

The model presented in this article is structurally organized so as to facilitat comparison with the models surveyed by EMF. Note that these econometric moc contain considerably more detail about the macroeconomic impact of the ene sector than does our model. The survey, however, does not point out structu properties that characterize most econometric models but not system dynamics m els. For a review of fundamental differences in assumptions underlying these classes of models, see Meadows (1980) and Sterman (1985).

Two of the models in the EMF survey have no petroleum imports and an exogen import price. For three of the models, both import volume and price are determi exogenously. Five models generate import volume endogenously, based on an ex enous import price—which corresponds to our model. Finally, two models gene import volume as well as price endogenously. All but two of the models specify m than one petroleum price.

According to Hickman, Huntington, and Sweeney (1987),

> Although the remaining models provide greater energy price detail, they do not in porate interfuel substitution in a structural way, i.e., fuel demand and supply functi are not specified explicitly. Most models provide a linkage between the different and sectorial prices and the world oil price. When the latter increases, the other

In our model, only one natural petroleum price is provided. In addition, a synthetic petroleum price is introduced as a parameter. Thus, synthetic petroleum is an aggregate representation of any complete substitute for natural petroleum. Note that even though one energy form may substitute for natural petroleum within a specific sector of the economy, such as residential, the same energy form may be out of the question in another sector, such as transportation. In our model, the building of synthetic petroleum production capacity as well as the production of synthetic is represented structurally and endogenously in response to the natural petroleum price.

In major international energy journals (*Energy Economics*, *The Energy Journal*, *Energy Policy*, *Energy Systems and Policy*), no model with a purpose, scope, and endogenous complexity similar to ours has been presented over the last five years.

The remainer of this article contains a description of the structure of our petroleum life cycle model, followed by a discussion of the parametric assumptions, base case behavior, and potential applications.

Introduction to the model

The petroleum industry began in earnest in 1859 with Colonel Drake's famous well in Titusville, Pa. A model like the one described here, which portrays the full life cycle over 130 years of history and beyond, must meet certain requirements that a short-term forecasting model does not have to meet.

First, it must be a structural model. In contrast to a model based on historical correlations, it should represent the physical and causal structure of the processes modeled. Nonlinearities and constraints may alter the historical correlations in the future. Physical delays, such as the time required to develop an oil field or build a synfuel plant, should be represented explicitly.

Second, it should be a behavioral model, portraying the information available to actors and the procedures they use to process it and arrive at decisions. The petroleum system is characterized by imperfect information, uncertainty, and distributed decision making. If the model is to respond to changes in the environment in the same way that real actors do, this bounded rationality should be incorporated (Simon 1947; 1957; 1979; 1982; Hogarth 1980; Morecroft 1983; 1985).

Third, the model should generate its behavior endogenously. The exploration and production process is tightly interconnected with energy price, demand, imports, substitution, and technology. A change in one part of the system may have ramifications throughout. A model that relies on exogenous variables is likely to produce inconsistent results as the feedback effects are ignored. A model that generates the petroleum life cycle endogenously constitutes an internally consistent theory that is subject to analysis, refutation, and revision (Bell and Senge 1980).

In addition to these general considerations, a model of petroleum resources to be used in forecast evaluation should include the following specific features as endogenous components:

or "backstops" (Nordhaus 1973), such as synfuels will be stimulated. If the pr of domestically produced petroleum rises above the import price, imports indicated. The pattern of demand, imports, and substitution will have a str influence on production and investment in domestic exploration. Delays in response of demand and in the development of the backstop industry should made explicit.

- *Depletion through exploration and production.* The total quantity of petrole initially in place is finite. As it is discovered, produced, and consumed, the quant remaining inevitably declines, and the marginal cost increases, ceteris parib Though improving technology may offset depletion and cause the real price petroleum to decline, the limited nature of the resource base and its depleti should be treated explicitly.
- *Technology.* The ultimately recoverable reserve depends heavily on the recov factor. Only 30–40 percent of the oil in place can be recovered economically w current technology, but the fraction recoverable has been rising and may rise s stantially in the future. Similarly, there is a development of exploration technolo The effects of investment in technological development should be treated explici
- *Economic incentives; petroleum prices.* Economic incentives (primarily determin by the petroleum price) play a large role in determining proved reserves, explo tion, and production. Petroleum that is subeconomic at $10 per barrel may highly profitable at $30 per barrel. Regions that were not even considered exploration may be prime candidates for test wells at a higher price. Because price has a strong influence on the incentives for exploration and development should be modeled explicitly. The effects of production costs, supply and dema market imperfections, and imports should be incorporated.

The sectors of the model are exhibited in Figure 1.

The model

Exploration and production

The model divides the total quantity of oil in place into three basic categories: as y undiscovered petroleum, identified reserves, and cumulative production (Figure Within these broad categories, several finer divisions are portrayed (Figure 3). T disaggregation of the resource base follows the standard resource classification show in the McKelvey box, Figure 4. Successful exploration shifts the boundary betwe identified and undiscovered resources toward the right; improvements in technolo or increases in the real price of oil shift the boundary between economic and su economic resources toward the bottom. Production shrinks the reserve base.

In this section, the physical structure of exploration (discovery) and producti (recovery) of the resource are described. Of major concern are the determinants the productivity of investments in exploration and production.

The productivity of investment in exploration is negatively influenced by t

Fig. 1. The sectors of the model with their major characteristics

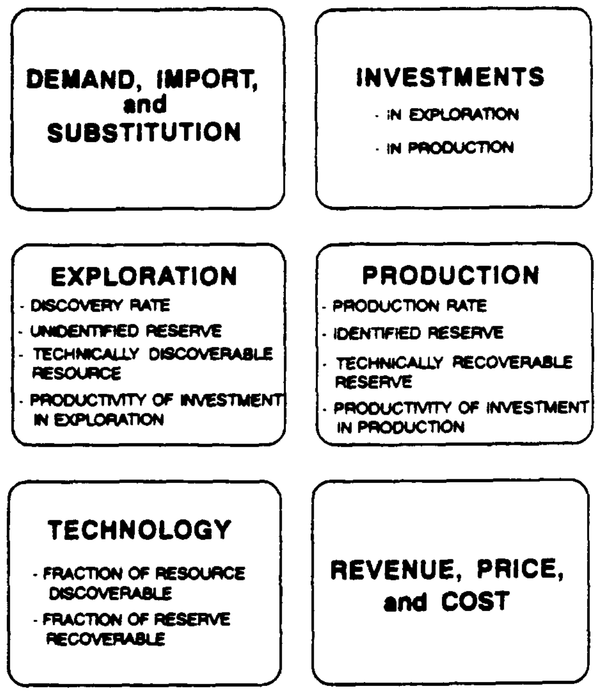


Fig. 2. Stocks and flows

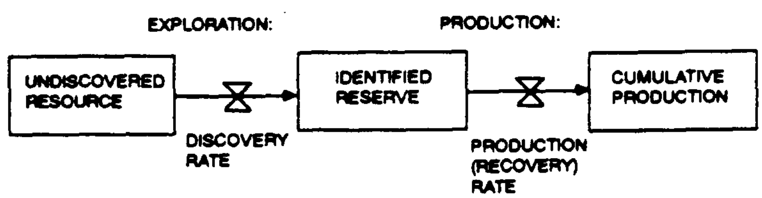
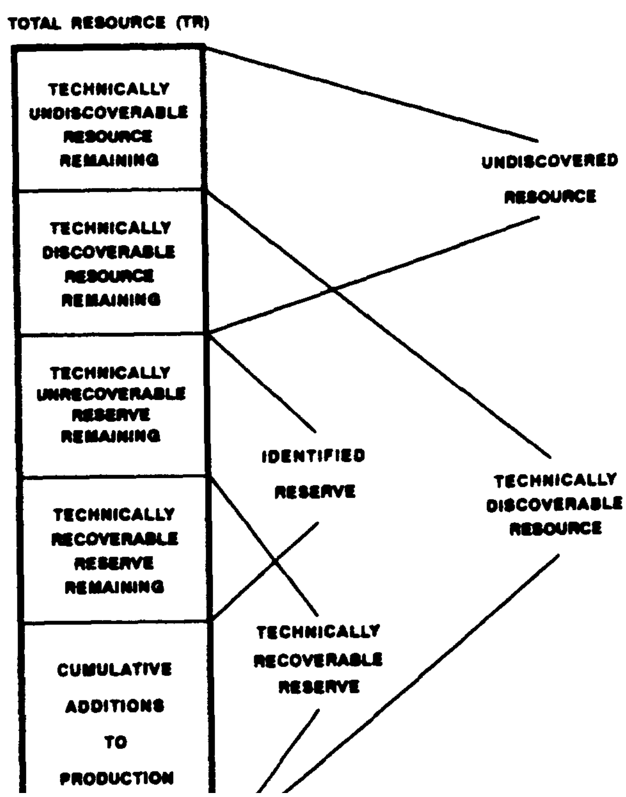


Fig. 3. The complete subdivision of the total resource applied to the model



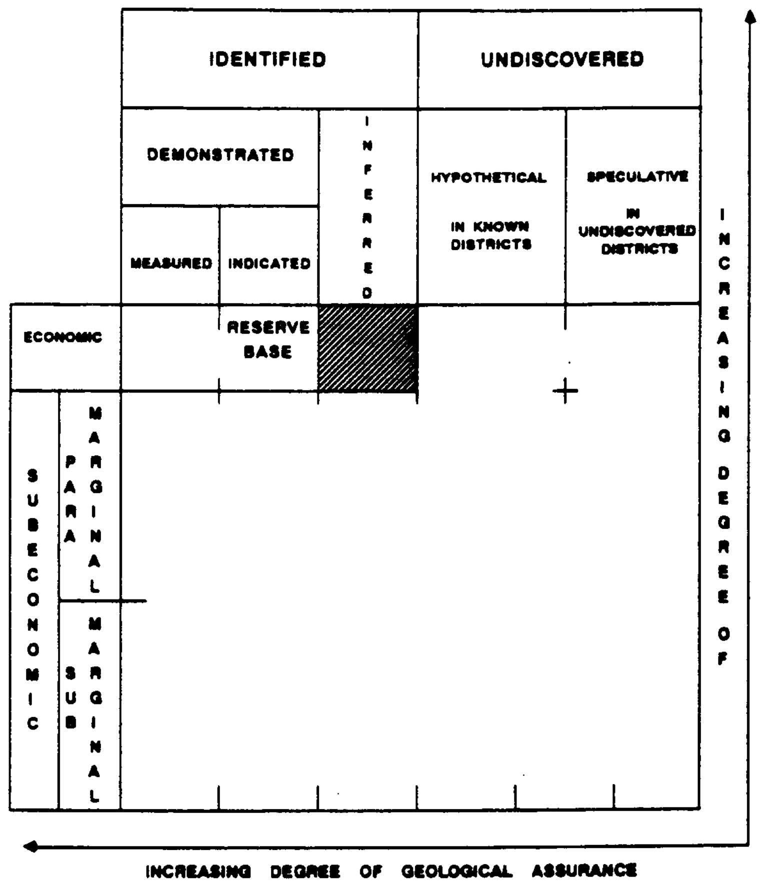


Fig. 4. The Mc-Kelvey box. Source: USGS 1976

in exploration is reduced. It is assumed that the yield from exploration is expoı tially decreasing with cumulative footage drilled, and that the footage drilled dollar invested is constant (Hubbert 1969; 1975; Hall and Cleveland 1981). reduction in productivity feeds back to the discovery rate, implying a reductioı the discovery potential provided by any given level of exploration activity.

The productivity of investment in production is influenced in a similar manne the rate of production (Figure 6). Suppose the production rate is increased. Then remains to be recovered. Thus, the productivity of investment in production is duced, feeding back to the production rate to reduce the production potential vided by the investment in production. The production potential constitutes an uı limit for the production rate, a rate that may thus be reduced. Note that the technic recoverable reserve remaining constitutes an upper limit for the rate of produc as well.

These underlying physical structures tend to stabilize the discovery and reco

Fig. 5. The physics of discovery

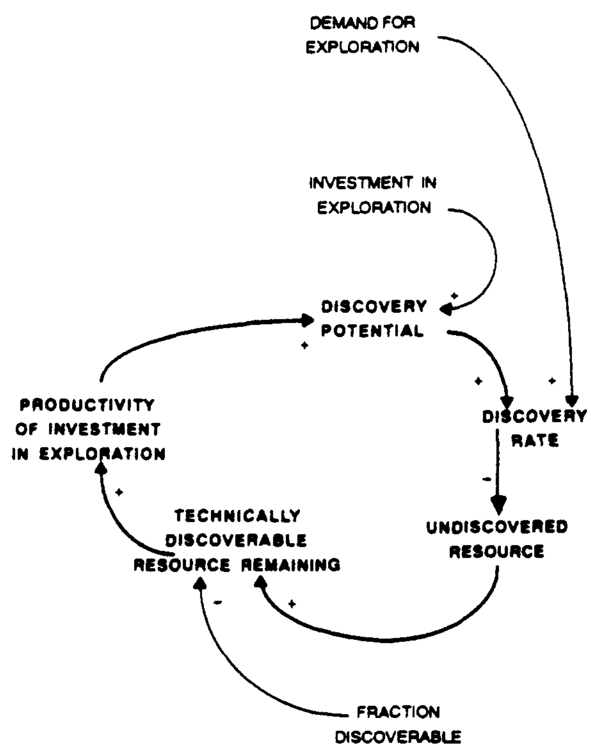


Fig. 6. The physics of recovery

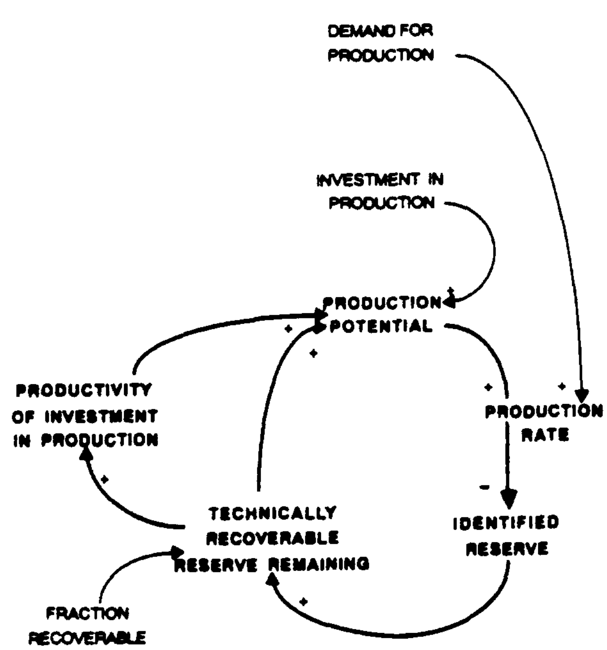
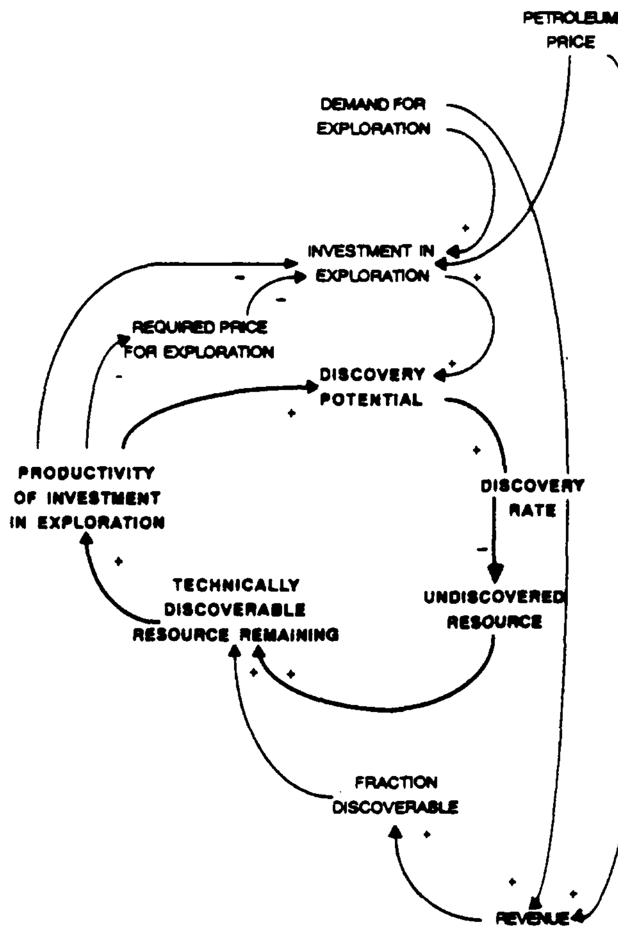


Fig. 7. Added: investment in exploration and its technology



of the identified reserve is recovered. The consequence is a tendency to slow c the rate of depletion. In addition to demand, there are only two more factors may help to achieve equilibrium in each sector: changes in exploration effort changes in technology. Increased investment in exploration increases the disc rate. Better technology improves the productivity of investment by making petroleum available, that is, discoverable and recoverable.

These two sectors are interrelated physically, since exploration provides the i tified reserve, which constitutes the basis for production. Progress in exploration has an impact on the productivity of investment in production. Suppose that remains undiscovered because of more extensive exploration. In that case, produ is allowed to take place in more demanding geostructures. Now, if production o where exploration has recently taken place, the productivity of production will correspond to the current productivity of investment in exploration. The recove

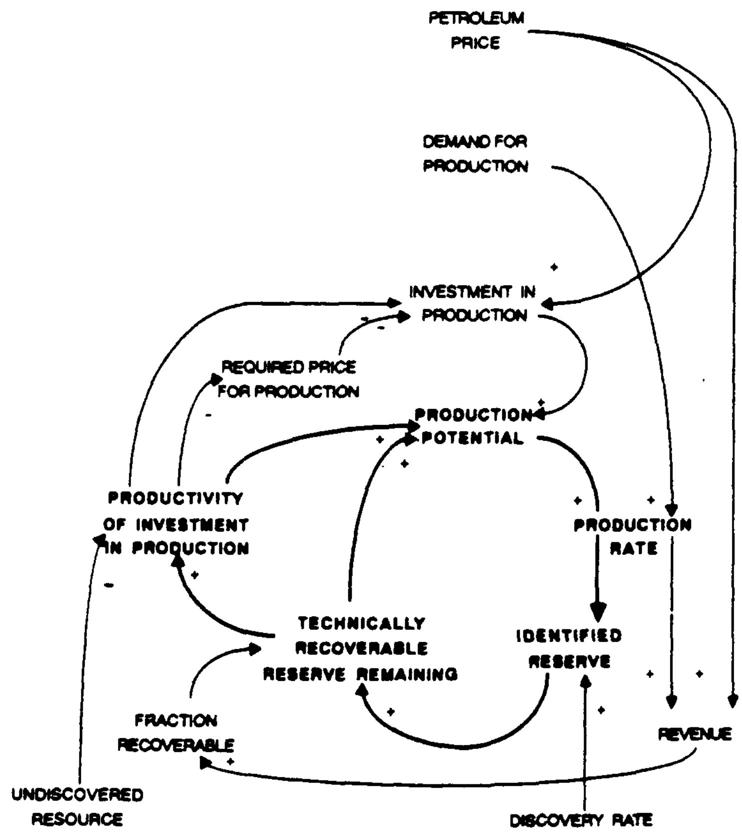


Fig. 8. Added: investment in production and its technology

Thus, the productivity of investment in production is lagging the productivity of investment in exploration that corresponds to this reserve.

Investments

Investments are made to build up an exploration potential (capacity) and a production potential (Figures 7 and 8). These investments are determined by the demand for petroleum and the petroleum price. In addition, the productivity of such investments, compared to the market price, plays an important role in investment decisions.

Investment augments the capital stock for exploration (drill rigs). The time required to allocate funds for, acquire, and conduct the exploration activity is represented explicitly. An average lag of four years is assumed. Once successful exploratory wells have been drilled, there is a further one-year average lag in the development of production wells. Investments in exploration and production are adjusted to the perceived productivity of such investments, though they must be justified by the market price. The break-even prices required to justify exploration and production investment in exploration is assumed to lag the real productivity by 15 years o average.

Technology

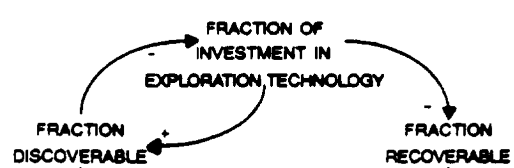
Petroleum technology may be divided into exploration and recovery technology ures 7 and 8). Technological improvements increase the availability of petro through exploration and production and thus improve the productivity of th vestments. The current level of sophistication in exploration technology is expr by the fraction of the total petroleum resource that can technically be discov The level of sophistication in production technology is expressed by the fracti the identified reserve that can technically be recovered. Both exploration and rec technology are endogenously improved by investment. As these fractions app their maxima, the marginal effect of further research and development dimin (technological saturation).

What may technically be discovered and recovered at any point in time, and the ratio between gross and net yield from exploration, is determined by technolc development. The net yield influences the demand for exploration and the calcul of the unit exploration expenditures, upon which the petroleum price is based.

The origin of technological progress lies in investment from revenues, that i product of petroleum price and production. A fixed fraction of the revenues sumed allocated to research and development. Because of the technological sa tion, the marginal productivity of this investment is declining. There is a six average third-order delay in technological research and development. The sp this investment between the two technologies is subject to changes over time (F 9). Of primary concern is the exploration technology, as exploration creates the for production. Gradually, as this technology approaches its maximum level c phistication, the emphasis is shifted from exploration to production technology to utilize the identified reserve.

Depending upon revenues, technological improvements allow for exploitatio cording to the petroleum demand, while compensating for the decline in the pr tivity of investments in exploration and production. Therefore, the stronger the nological progress, the more aggressively the depletion effect is compensatec further investment made in technology. When, on the other hand, producti falling, less is contributed to technological development. Therefore, the fall in

Fig. 9. Shift in technology investment



ductivity is compensated less aggressively, promoting a further decline in the production rate.

As long as production is growing, and the price is kept relatively stable by investment in technology, the production rate predominantly determines revenues and investment in technological research and development. If production levels off, this may be compensated by an increase in petroleum prices, in which case technological progress is dominated by the changes in price. Should production decline, amplified by technological stagnation, then there is a call for a substantial increase in price to sustain revenues and investment in technology.

Note that if production actually levels off and starts declining, then the impact of a change in technological compensation is determined by the timing of the peak in production. A large impact may result from production peaking at an early stage in technological development, because then the contribution from technological development is relatively dominating. When technological saturation sets in, the effect of such a change will be less. Note also that progress in exploration technology generally diverges from progress in production technology and that exploration costs and production costs are not the same (exploration costs generally being substantially higher than production costs), so that the contribution from each may differ significantly.

Price and demand

The U.S. economy is petroleum-intensive. Consequently, demand for petroleum is largely determined by the exponential growth of GNP (Figure 10). Domestic exploration and production are demanded to the extent that substitutes, provided by imports of natural petroleum or production of synthetic petroleum, are not available at lower than break-even costs.

Demand for domestic production is complemented by the tendency to import (the indicated import). A rising tendency reduces production pressure. The tendency to import is determined by the ratio between the international (import) price and exploration and production expenditure. Note that the unit exploration expenditure is the average exploration cost per barrel associated with the recoverable reserve. Thus, the tendency to import is smoothly affected by changes in the productivity of investment in exploration. Actual imports endogenously cover residual demand, that is, demand not satisfied by domestic production.

There are two ways in which the demand for petroleum may be influenced by the petroleum price over time. First, demand is reduced by rising prices, causing the energy intensity of GNP to decline. Second, a synthetic petroleum industry may be justified by higher prices. Substantial delays are associated with the impact of price on demand. It takes 15 years on the average to adjust the energy intensity, when the potential for retrofitting existing capital is taken into consideration, as the life of energy-consuming capital is 20 years on the average (Coen 1975; Sterman 1981). To build a synthetic petroleum industry takes nine years on the average. Synthetic petroleum, which represents a perfect petroleum substitute, is assumed to cost $50

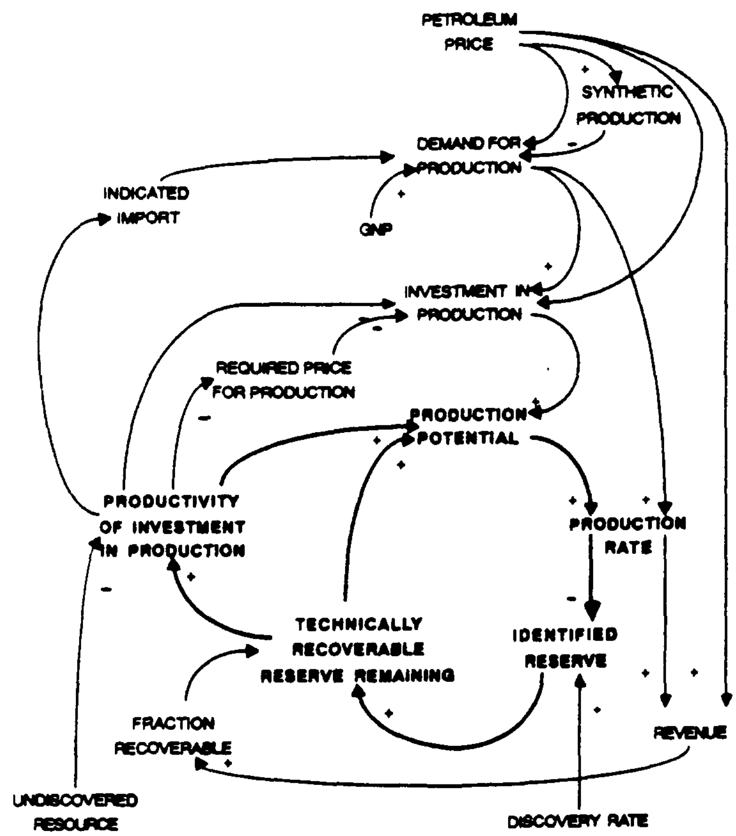


Fig. 10. Added: demand for production

As long as the domestic petroleum price is not dominated by the intern price or the price of synthetics, three factors determine the price (Figure 11):

- Costs associated with the exploration and production of petroleum
- Demand for petroleum
- Supply of petroleum

Before 1953 the U.S. domestic price dominated the international market, so th is endogenously determined by the cost of exploration and production. Fro on, domestic production is protected by import quotas until 1972. Yet the gradually influenced by the fall in the international price. In 1971 a price co introduced. This control is effective until 1981, contributing to the avoid windfall profits from a dramatically rising international price. During this per domestic price approaches the international price from its base level, which dominantly determined by costs. After 1981 no controls are in effect, and the do price is completely determined by the international price.

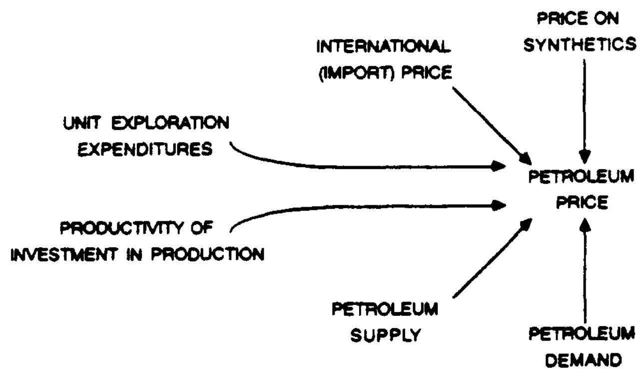


Fig. 11. Factors that determine the petroleum price

market is characterized by short-term adjustments of potential production (supply) according to demand and market price. It is therefore not very common that price is affected by an abundant supply. Shortages are primarily a result of depletion, insufficient investment in exploration, and insufficient supply of imports or substitutes. Under a dramatic upward pressure on price, there is a tendency to introduce price controls to protect the petroleum-consuming industry and to avoid windfall profits.

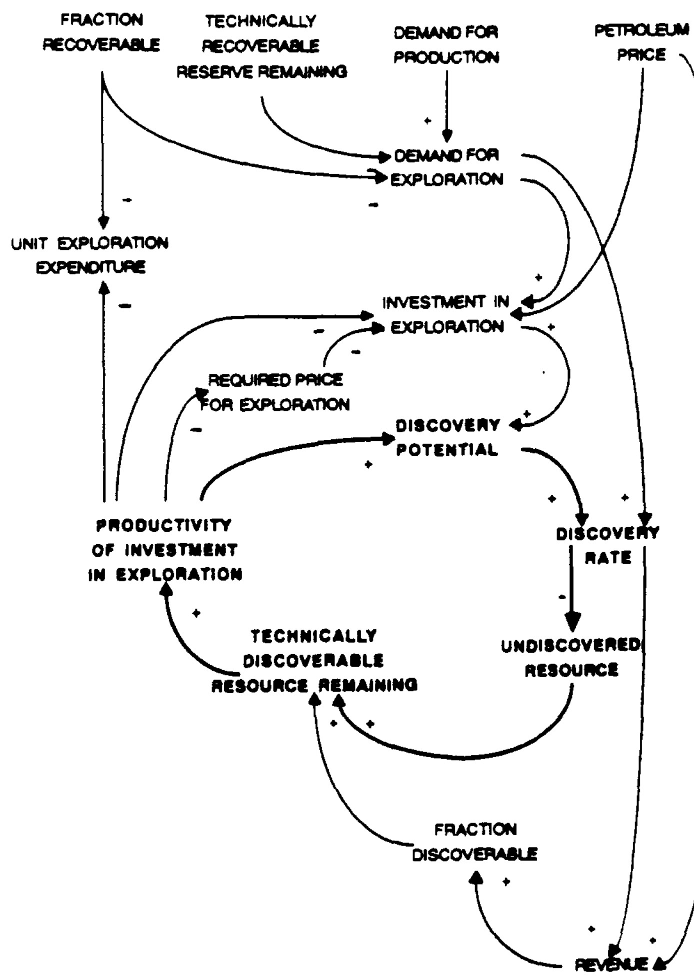
Demand for petroleum exploration originates from three different requirements (Figure 12):

- Keeping up with current production
- Maintaining a recoverable reserve adequate to keep up with production
- Adjusting the current recoverable reserve in accordance with the expected growth in demand

Production reduces the recoverable reserve, which must then be corrected to an adequate level corresponding to the current rate of production. Discrepancies from this level tend to be phased out over a relatively long period of time (15 years on the average). Furthermore, an adjustment must be made according to the expected growth in demand. This adjustment is based on the forecast of a recognized trend in growth. A five-year average delay is assumed, representing the time to observe, perceive, and recognize this trend, and an additional five years to average the trend as a basis for forecasting (Sterman 1988). As the growth trend is calculated from past demand, these adjustments of the reserve are based upon demand for production and the current technically recoverable reserve.

Demand for domestic production, when transformed into demand for exploration, is amplified for two reasons. First, the recoverable reserve must be established and maintained. Second, the gross yield from exploration must be considerably larger than the required net yield because of the inadequacy of the production technology.

Fig. 12. Added: demand for exploration



the effects of supply and demand on price, and the short-term adjustments of ment according to productivity and price are all left out). The bold part of thi represents the system considered without a technology sector. The remainde sents the impact of technology. Two major feedback processes tend to stabi system:

- Influence of exploration and production costs on the petroleum price
- Impact of import tendencies on demand for domestic production

As the unit costs increase because of depletion, these processes cause dem petroleum to stagnate. Thus, the rates of discovery and production are moc Because of the delayed, exponential nature of this effect, its impact is initiall

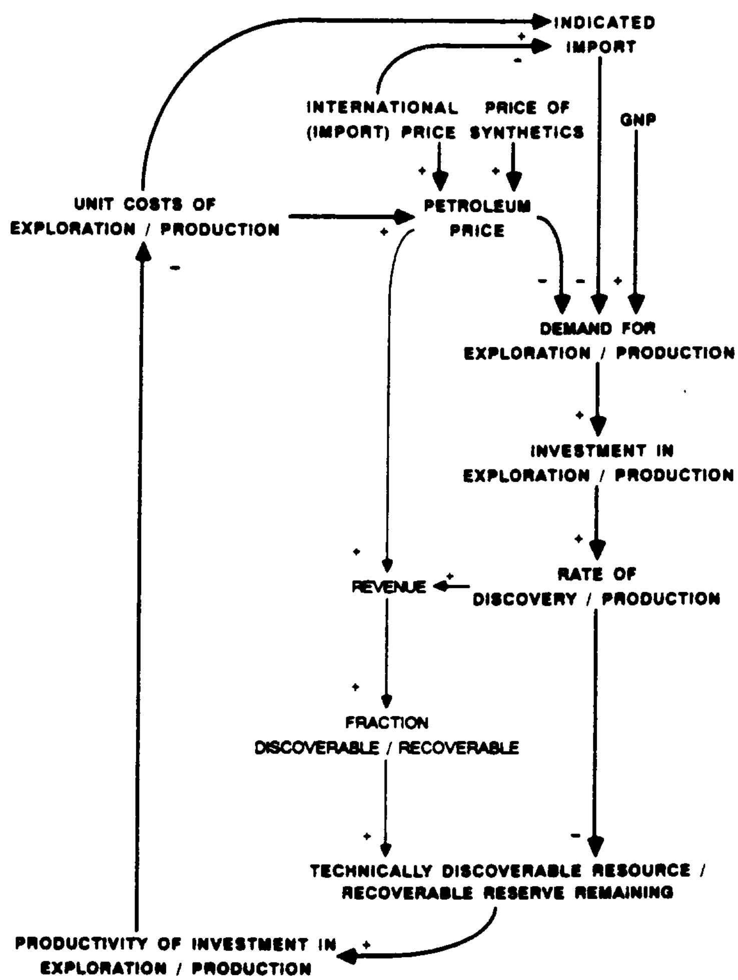


Fig. 13. The influence of the petroleum price

and progress. Provided this progress more than offsets the impact of depletion on productivity, the petroleum price will fall. This amplifies the rise in demand, production, and technological progress through positive feedback. When technological saturation sets in, progress can no longer offset depletion. The rise in costs, price, and imports forces the demand for domestic production into decline. This reverse tendency is again amplified by positive technological feedback. (Note that there is a negative feedback, impact of the petroleum price on revenues, that may dominate technological progress during a transition period as production levels off.)

The dynamic modes of the system

In this section, the dynamic behavior of the model will be explained and rel historical records. The system exhibits two quite different dynamic modes of be both driven by the exponential growth in the GNP.

One of these modes originates from the physical consequences of petrole ploitation, that is,

- Discovery of petroleum, leaving less of the total resource to be identifie reserve for the future
- Recovery of petroleum, leaving less of the identified reserve for future reco

The result is an exponential decline in the productivity of exploration and prod If investment were kept constant, and if there were no technological innovati discovery rate and the production rate would approach zero exponentially. case, the mode of behavior is an effective contraction of exploration and prod Under such circumstances, and provided there are no price constraints, the pet price would rise according to declining productivity. Thus, demand would no follow the exponential growth in GNP but gradually level off.

To the extent that the price mechanism does not offset the growth in GNI are two ways to compensate for the contraction of exploration and produc order to accommodate the residual growth in demand created by GNP:

- Increasing investment in exploration and production
- Increasing investment in research and development of the two technologie

Note that these compensating measures act through very different processes. investment tends to increase the volume of exploration and production activi is, the rate at which the exploration and production frontier is extended i geostructure. Larger investment therefore tends to reinforce the contraction. ment in research and development tends to make exploration and productio efficient. Technological progress may allow for the frontiers to be extended at rate, still with the same net yield. Thus, to compensate for deteriorating produ investment in technology may complement and even substitute for investme moting depletion.

Even stronger technological investment may more than cancel out the e depletion and actually cause productivity to increase. In that case, we are fa expanding mode of behavior with the following characteristics. The petroleu will fall as long as technological development dominates depletion. This, i will reinforce petroleum demand, a development that will amplify the press technological progress. To the extent that there is adequate response to this p exploration and production may continually satisfy demand without increasi costs. If technological response turns out to be inadequate, contraction ensue

The life cycle of the U.S. petroleum resource is characterized by expansion fo by contraction. Certain factors tend to modify this behavior, however. Fou most prominent ones are the following:

- The identified reserve, acting as a buffer between exploration and production
- Delay in recognizing the marginal exploration cost, acting as a buffer between cost and investment
- Delay in averaging the exploration expenditures, acting as a buffer between cost and price
- Regulations, acting as the buffer between the U.S. and the international petroleum economy

These buffers may mask the transition from expansion to contraction and tend eventually to amplify the contraction. Because of its significance, the transition will be designated as a particular mode of behavior.

The expansion (1870–1945)

The initial dynamic mode of the U.S. petroleum life cycle is a typical expansion with the following properties (Figures 14–20). Historically, the petroleum price varied substantially in the beginning. But, by and large, it declined with a decreasing margin and was fairly stable thereafter (until after World War II). Demand for petroleum was determined by the fact that it was predominantly used as a source of light, only later to be recognized as an energy source suitable for heating, production, and transportation. Gradually, petroleum was established as a mature source of energy with a relatively stable market share (1950–). With the increasing market penetration of petroleum during the first part of this century, the growth in demand (Figure 19), exploration, and production exceeded the growth in GNP. Production exhibited a growth pattern corresponding to demand (Figure 20) and allowed in addition for export. Note that during most of this time the United States was a net exporter of petroleum.

Fig. 14. Petroleum production in the U.S. lower 48 states, the contribution from imports, production in Alaska, and production of synthetic petroleum

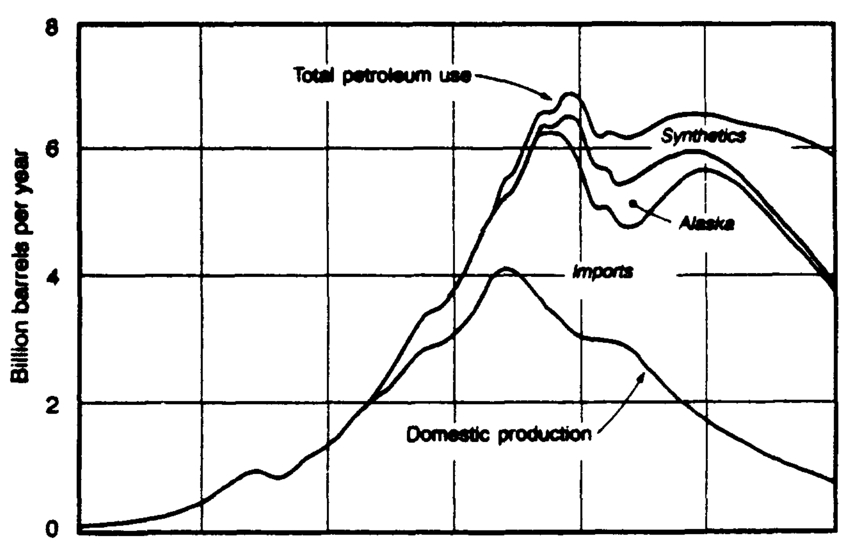


Fig. 15. Cumulative production, undiscovered resource, identified unrecovered reserve, technically discoverable resource remaining, and technically recoverable reserve remaining

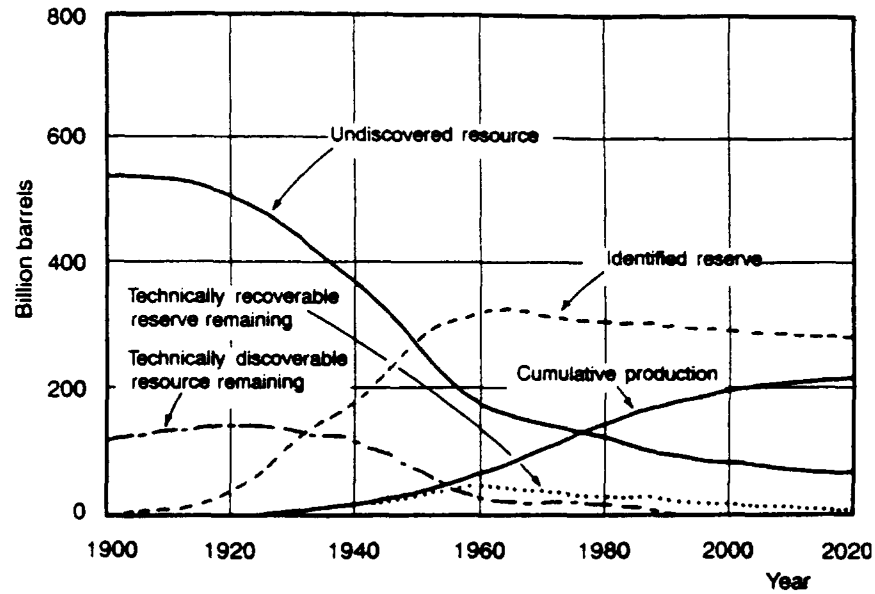


Fig. 16. Fraction discoverable, fraction recoverable, technically discoverable resource remaining, and technically recoverable reserve remaining

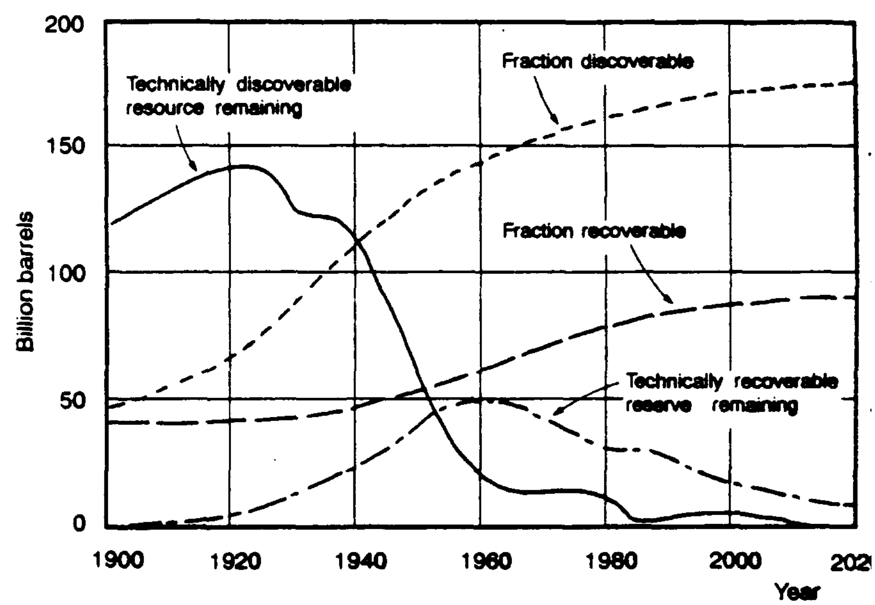


Fig. 17. Petroleum production in the U.S. lower 48 states, potential production from reserves, and additions to identified reserve

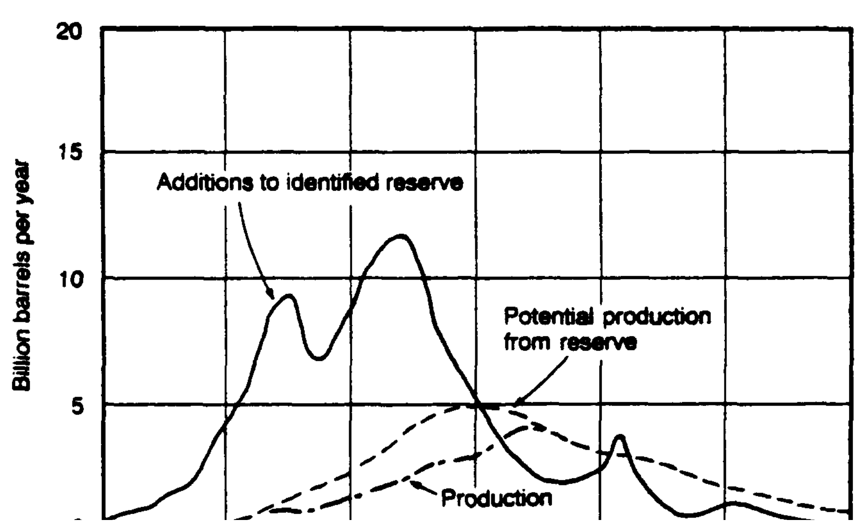


Fig. 18. Petroleum price, import price, and price of synthetic petroleum

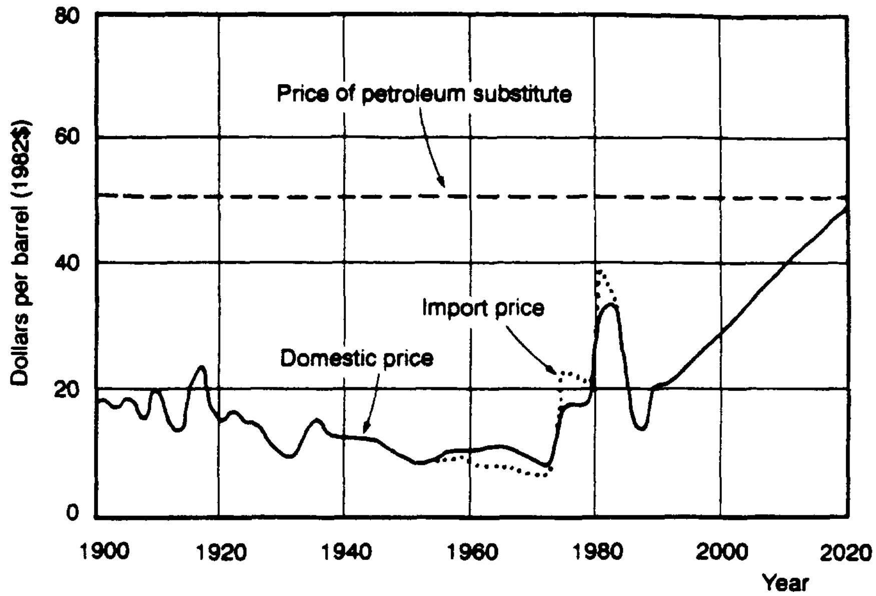


Fig. 19. Historical natural petroleum demand and simulated demand

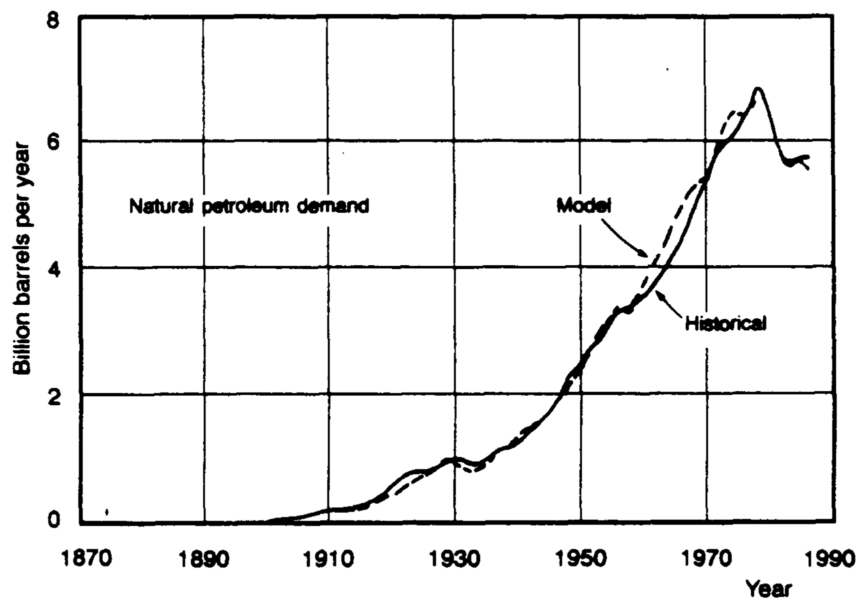
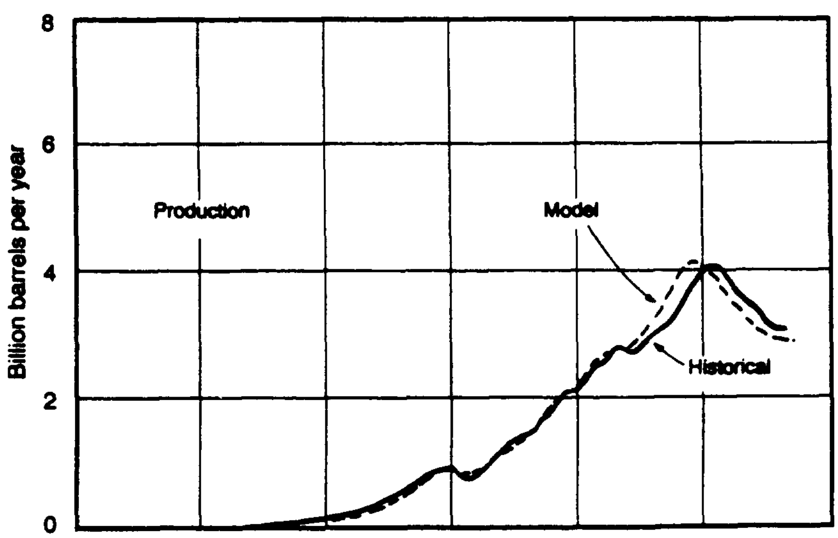


Fig. 20. Historical petroleum production and simulated production



The energy intensity in the model is calibrated to represent the prevailing ir during the last 35 years. Therefore, an exogenous factor represents the smoo sition from other sources of energy to petroleum. This causes petroleum den grow according to historical demand (Figure 19), that is, faster than economic for most of this period. In addition, this growth is endogenously amplifie declining petroleum price.

In the model, production grows exponentially (Figures 14, 17) and satisfies tic demand and the petroleum export. The growth in net yield from explor also exponential and adequate during this period (Figure 17). The technicall erable reserve is developing normally (Figure 16), according to the growing production, until 1928. Thereafter, excess reserves accumulate over time, b potential production from reserves well above actual production (Figure 17) of the fact that investment in exploration is adjusted to changes in costs. Th mulation originates from the substantial delay in recognizing the decline exploration expenditure, causing overinvestment. Both kinds of technology veloped at an exponential rate, more than offsetting the impact of deple productivity (Figure 16). The progress in discovery technology reaches its ma effect (the inflection point of the fraction discoverable) in 1931. The effect nological progress in production is considerably more moderate. Technologic ress accounts for an increasing productivity of investment, causing the pe price to decline from its initial value until 1930, when it levels off (Figure 18

In order to sustain technological development, ever larger investment is re Because technological investment is financed as a fraction of revenues, and th is declining asymptotically, it is the exponential growth in production that fa further growth through the positive feedback process previously described.

The transition (1945–1981)

There are upper limits to how much petroleum may be discovered and recove these limits are approached, technological progress is characterized by sat and the marginal effects of investment in technology are reduced. Thus, the r investment in technology, just to compensate for this decline, increases expone Recall, in addition, that the partial effect of constant exploitation is to red productivity exponentially and that the growth in petroleum demand is als nential. The growth in technology investment should therefore compensa decline in the return on this investment. Sooner or later, however, techn innovation is not adequate to withstand the effects of exploration and proc Thus, we approach a contraction, primarily characterized by declining prod But before the contraction is fully established as a mode of behavior (from 19 a lot happens, both historically and in the model.

It is not surprising that the historical records on price, demand, and pro hardly show any signs of the oncoming contraction during the transition m already pointed out, this transition is masked by internal and external buffers are the only ones that may be traced empirically. Note that the effects of the oil embargo (1973) and the Iran-Iraq war (1978) with respect to import and price cannot be claimed to reflect domestic exploration and production realities. It is important to notice, however, that these events coincide with the final stages of the domestic transition from expansion toward contraction.

After World War II, the domestic petroleum price rose by more than $4 per barrel (Figure 20). The price was then fairly stable but drifted during the import regulation towards the international price, which fell below the domestic price in 1950, and reached a local minimum around $6 per barrel in 1972. Price control then prevented the domestic price from rising as dramatically as the international price during the two crises in the 1970s. As petroleum reserves were being depleted, pressure from the international market forced the domestic price up towards the international price (which was practically attained in 1981).

The growth in petroleum demand was exponential until 1973, stagnating only slightly (Figure 19). It was then inflected significantly, leveled off, and started falling.

Domestic production initially followed the same trend as demand but was supplemented by a substantial growth in imports during the import regulation period (1953–1973) as the United States turned from being a net exporter to become a net importer of petroleum (Figure 20). Domestic production was also supplemented by Alaskan production, which gradually grew and amounted to more than 11 percent of the total domestic supply in 1986. Consequently, the production in the lower 48 states contracted more significantly than petroleum demand during this period and fell substantially during the period 1973–1981.

It is convenient to start the description of the transition mode of behavior, as portrayed in the model, by pointing out the early warning indicated by the inflection of the fraction discoverable in 1931 (Figure 16). This is the first sign that the positive, compensating feedback loop promoting technological development loses its dominance. Note, however, that progress in production technology has an accelerating effect until 1967, when also the fraction recoverable inflects because of saturation. But because the unit exploration expenditure at this point in time is considerably larger than the production costs, the contraction is triggered. One could then expect a contraction scenario with lower productivity, higher costs and price, reductions in demand and investment, and a decline in exploration and production. But it takes a very long time to establish this mode of behavior.

The petroleum price is relatively stable until 1973 (Figure 18). It does not reflect the postwar increase, as the model does not represent the price regulations prevailing during the war. The subsequent import and price regulations are, however, represented exogenously in the model. They are considered to be imperfect in the sense that the domestic price in each case gradually adjusts towards the international price.

The growth in petroleum demand follows the historical pattern accurately (Figure 19), that is, it develops exponentially until 1973. There is, however, a slight stagnation during this period, representing the stabilization of the petroleum market share. As the petroleum price increases dramatically during the 1970s, demand inflects accord-

Petroleum production satisfies demand until 1950 (Figure 14). Gradually (supply becomes insufficient, even with Alaskan production. There are two for this. First, the import price becomes competitive in the 1950s, so that the t to import petroleum is reinforced. In spite of the import regulation, this red pressure to explore domestically. Second, there is a masked transition into a in productivity of investment in exploration. This results from the inflectic fraction discoverable, that is, the declining effect of technological progre though this transition initially (1931–1953) is very smooth, there is a r dramatic fall in the net yield from exploration (Figures 16, 17), partly du delay in recognizing current exploration expenditure. So far, productivity l rising, and exploration activity has been oversized. But now, when produc falling, investment is systematically too low. Gradually the effects of techr investment are deteriorating, only to amplify the contraction. However, beca

- Excess exploration
- The large reserve that has been built up (Figure 17)
- The relatively strong progress still characterizing production technology

the technically recoverable reserve is inflected at only a moderate rate (Fig And the dramatic fall in the yield from exploration has no effect on pro Eventually, though, there is a dramatic decumulation of the technically rec reserve, and this reserve becomes an effective constraint on production, demand can no longer be satisfied. Thus, additions to the identified reserv longer sufficient to maintain required production.

When it eventually turns out that production does not yield revenues suff allow technological progress to keep up with depletion, the productivity o ment in exploration declines. This calls for a higher price to cover increase diture and possibly to counteract technological stagnation. At this point in t international price is increased, the domestic price is allowed to follow, and market price stimulates investment and revitalizes exploration. The large inv is justified also because petroleum demand responds very slowly to the cl price. This creates a shortage, previously covered by imports. But now, as tl national price goes up, there is an incentive to discontinue this import (se 14, where the wedge representing imports narrows around 1980). It finally t that in spite of a boost in Alaskan production, domestic supply remains insu and one may recognize that a contraction is in progress.

Several factors cause the massive investment in exploration not to pro required reserve and therefore may explain the subsequent contraction. Inv is not large enough because exploration expenditure is underestimated. The investment is delayed and distributed over time. The productivity of inves deteriorating exponentially along with exploration, an effect that is no lon quately matched by technological development. Although technological pro far has acted to amplify the expansion of exploration and production through feedback processes, it now promotes the contraction through the same kind cesses. The declining rate of production causes the revenues to decrease significant delay characterizing how demand responds to a change in price.) Even though the price is rising significantly after 1973, contributing to revenues, the technological consequences are far from sufficient. Therefore, productivity is still declining exponentially and is effectively slowing down technological progress even further.

The contraction (1981–)

Historically, the contraction did not manifest itself in terms of the petroleum price or the demand for petroleum (Figure 20). The petroleum price was determined internationally and fell suddenly after 1982. Because of this development, demand slowly recovered from the price shock of the 1970s, after having fallen significantly for a couple of years. The only contraction characteristic within the historical time frame was thus the production trajectory. Production decreased substantially for about ten years. It then leveled off slightly for the last couple of years (Figure 20).

The model reveals what is happening. Investments in exploration and production will be made as long as the petroleum price may be raised to cover the additional expenditure associated with exploitation. As long as the price required to justify investments in exploration and production is well below the international (import) price and the price on synthetics, such investments will be made, and the domestic price will be adjusted accordingly. Now, however, a double price ceiling is in effect, determined by the competing petroleum sources: imports and synthetics (Figure 18). When approaching this ceiling, domestic investment is curtailed, exploration and production are gradually shut down, and exploitation is substituted by natural petroleum imports and later on by the production of synthetics (Figure 14). With a stable international price, we would have seen this scenario play out in the 1970s. But because of the price increase, a large investment in exploration is still justified in the shadow of the rising international price. The slight recovery of petroleum production after 1981 (Figure 20) is explained only as a delayed response to this large investment. As it turns out, however, this investment is insufficient in the long run, and as exploration is extended, the productivity of this investment declines. Consequently, the net yield rapidly diminishes and does not support the required production (Figure 17).

Note that some of the major regulating feedback processes in the system deteriorate after 1953 and completely disappear in 1981. This is because there are no longer regulations that effectively preserve the relation between exploration and production expenditures on the one hand and the domestic price on the other. The price is not allowed to follow increasing expenditure, and demand remains high.

The substantial increase in the fraction of the reserve technologically recoverable (Figure 16) contributes significantly to production, because the identified reserve that remains unrecovered at this point in time is relatively large (Figure 15). But the contribution is far from sufficient to counteract depletion. This technological progress hardly affects costs because exploration expenditure dominates until the end of the

Predictions must be based upon two assumptions: one about future e growth, and one about price development on the international petroleum ma base case growth in GNP exhibited here is the moderate economic growth case by the U.S. Department of Energy (EIA 1985). (The model contains the extre as well.) After 1995 linear extrapolations of the Department of Energy projec applied. In the base case the international price is assumed to reach $20 p by 1990 (Figure 18). From then on, the price in this simulated scenario is to increase linearly by $10 per barrel per decade. Many other price scenario projected, but they have little effect at this late stage of the exploitation of petroleum resource. The termination of the petroleum life cycle is characte a rapidly growing difference between unit exploration expenditure and the pe price. The incentive to invest in exploration is thereby eroded. The reserv being depleted (Figure 15), until the unit production cost has increased be petroleum price, thus no longer justifying production. Imports grow rapidl this period (Figure 14), and one may find it realistic to assume a more si increase in the international petroleum price in response to the massive U.S pressure. In that case, U.S. natural petroleum demand will be more mode there will be a stronger incentive for domestic production of both natural thetic petroleum. The model runs until 2050, but by 2020 most of the dyna over.

Applications of the model

The most straightforward use of this model is as a tool for projecting the charac of the petroleum life cycle. This may be done under different scenarios with to uncertainties, such as

- Domestic economic growth, i.e., the development of U.S. GNP
- Additions to the identified reserves from the North Slope in Alaska
- Technological breakthroughs in discovery and recovery technology
- Alternative petroleum substitute development capabilities, costs, and p response to the natural petroleum price

The model may also be used as a framework for estimating the effects of and domestic resource policies, such as

- OPEC and non-OPEC supply and pricing policies
- Import fees
- Import restrictions (e.g., quotas)
- Petroleum taxes, on imports only or on domestic production as well
- The buildup of the strategic petroleum reserve
- Conservation strategies

The purpose of such projections would be to understand how the petroleum life cycle terminates under different environmental circumstances. In particular, they would show how rapidly the United States develops a dependence on import and synthetic production, and how large a part of the total resource is economically recoverable. For example, by changing the price module, the effects of alternative pricing policies could be tried out. Such a policy could include taxation or import fees intended to stimulate energy conservation and build up production capacity for synthetic petroleum. By changing the investment module of the model, the effects of different investment policies may be evaluated, for instance, limiting current exploration and production, and yielding to import pressure in the short run in order to maintain a recoverable reserve (corresponding to a strategic reserve) in an attempt to smooth the long-run consequences of future import constraints.

Note that the model is based on the assumption that there is a finite total petroleum resource. The volume of the true resource base is continually subject to estimation. So is the economically recoverable part of this resource. The model suggests a way to estimate the resource. Provided one by and large can agree upon the other assumptions represented by the model, it may be possible to identify a relatively narrow range of values within which we find the actual total volume of the resource. In fact, one may interpret our effort to tune the model to data as having done that already. Our best guess/estimate is therefore a total petroleum resource of 550 billion barrels.

Moreover, the model may be used to test out alternative techniques applied to acquire the information necessary to implement various policies. It was indicated that the volume of the petroleum resource is subject to estimation. Estimation techniques actually applied can be described by a set of formal models, each compatible with the one discussed in this article. In that way, we can carry out synthetic data experiments, in which the real data, acquired from the petroleum life cycle model, constitute a consistent basis for resource estimation represented by the additional models. Such experiments may provide a better understanding of the dynamics of estimates and stimulate discussion concerning the design and utilization of estimation techniques. The Geological Analogy Method and the Hubbert Life Cycle Method have been exposed to such experiments, based on the current model (Sterman and Richardson 1985; Sterman, Richardson, and Davidsen 1988).

Both the petroleum model described in this article and generalizations made to encompass other depletable resources may turn out to be promising tools for teaching resource management. Such generic models will provide an understanding of how the life cycle dynamics of a resource are related to the physical, technological, and economic characteristics of the underlying feedback structure. Models of this kind may be used to study the particular behavioral modes characterizing the life cycle and the transitions between these modes due to shifts in feedback loop dominance. Based on this understanding, appropriate policies can be suggested and evaluated through synthetic experiments, as can managerial information systems designed to support the implementation of such policies.

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