A Petroleum Life Cycle Model for the United States with Endogenous Technology, Exploration, Recovery, and Demand.

BY

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ABSTRACT

This paper describes a model of the life cycle of the petroleum resource in United States. Expanding on prior system dynamic models of petroleum resources, the model endogenously generates the complete life cycle of the resource. The model treats endogenously the petroleum demand, the development of technology for and investment in exploration and recovery, the discovery and production of petroleum and the development of petroleum substitutes. With only two exogenous variables (GNP and the international petroleum price), the model is able to portray the evolution of the 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 interplay of technological progress, depletion, and the development of substitutes create the lifecycle by altering the dominance of the feedback processes in the system. A full documentation may be found in (Davidsen, 1987).

The model constitutes the basis for more comprehensive studies in the following areas of concern, all related to the management of depletable resources:

1. Adaptation of the model to different kinds of depletable resources, and generalizations to obtain a model portraying the generic structure of the life cycle of a depletable resource.
2. Analysis and evaluation of current practices in the management of depletable resources.
3. Design and evaluation of alternative strategies for the management of such resources.

The model seems furthermore to be a promising tool for teaching resource management.

PURPOSE AND OVERVIEW

This paper describes a model of the life cycle of petroleum resources in the United States. Expanding on prior system dynamic models of fossil fuel resources (Naill, 1973; Naill, 1977; Backus et. al., 1979; Choucri, 1981; Sterman, 1981; Sterman and Richardson, 1985) the model endogenously generates the complete life cycle of this resource. The model synthesizes the perspective of several specific diciplines, such as geology, technology and economics. It integrates exploration, production, pricing, demand, imports, and the development of substitutes. Finally, the model emphasizes the impact of delays in both the physical processes and the information / decision making processes of the system.

With only two major exogenous variables (GNP and the international petroleum price), the model is able to portray the evolution of the 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 interplay of technological progress, depletion, imports and the development of substitutes, creates the lifecycle by altering the dominance of the feedback processes in the system. The life cycle is characterized by exponential expansion of the petroleum industry, driven by economic growth, developing geological knowledge, and technological progress, followed by a transition to decline, driven by depletion, rising real costs of exploration and production, and ultimately to the development of substitutes.

The model is intended to provide a realistic "micro world" in which the geological and technical parameters are known and can be varied to portray alternative scenarios. The model can then be used for a variety of puposes:

1. The model will be used to generate synthetic data for the modeling and evaluation of resource estimation methods (Sterman and Richardson, 1985; and Sterman, Richardson, and Davidsen 1987).
2. Integrated and mutually consistent forecasts of production, exploration activity, and costs can be developed.
3. Policies regarding e.g. price controls, taxes and import fees can be evaluated in a rich dynamic environment which represents the feedbacks important in the real system.
4. The model is reasonably transparent and offers opportunities to teach resource management, dynamic modelling, and principles of feedback.

The structure of the model is described, followed by a discussion of the parametric assumptions, base case behavior, and potential applications.

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

First, it must be a structural model. It should represent the physical and causal structure of the processes modeled, as opposed to a model based on historical correlations. Non-linearities and constraints may alter the historical correlations in the future. Physical delays, such as the time required to develop an oilfield or build a synfuel plant, should be represented explicitly.

Secondly, it should be a behavioural 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, -57, -79, -82; Hogarth, 1980; Morecroft, 1983, -85).

Thirdly, the model should generate its behavior endogenously. The exploration and production process is tightly interconnected with energy price, demand, import, 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, 1978).

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:

1. **Demand, import, and substitution.** Petroleum demand is sensitive to price. As the prices rise, the demand for petroleum will be depressed, and the production of substitutes ("backstops" [Nordhaus, 1973]), such as synfuels, will be stimulated. If the price on domestically produced petroleum rises above the import price, import is indicated. The pattern of demand, import and substitution will have a strong influence on production and investment in domestic exploration. Delays in response of demand and in the development of the backstop industry should be made explicit.
2. **Depletion through exploration and production.**. The total quantity of petroleum initially in-place is finite. As it is discovered, produced, and consumed, the quantity remaining inevitably declines, and the marginal cost increases, ceteris paribus. Though improving technology may offset depletion and cause the real price of petroleum to decline, the limited nature of the resource base and its depletion should be treated explicitly.

3. **Technology**. The ultimately recoverable resource depends heavily on the recovery factor. Only 30 -40 per cent of the oil in place can be recovered economically with current technology, but the fraction recoverable has been rising, and may rise substantially in the future. Similarly there is a development of exploration technology. The effects of investments in technological development should be treated explicitly.
4. **Economic incentives; petroleum prices**. Economic incentives (primarily determined by the petroleum prices) play a large role in determining proved reserves, exploration, and production. Petroleum that is subeconomic at $10 per barrel may be highly profitable at $30 per barrel. Regions that were not even considered for exploration may be prime candidates for test wells at a higher price. Because the price has a strong influence on the incentives for exploration and development, it should be modeled explicitly. The effects of production costs, supply and demand, 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 yet undiscovered petroleum, identified reserves and cumulative production (figure 2). Within these broad categories, several finer divisions are portrayed (figure 3). The disaggregation of the resource base follows standard resource classification shown in the McKelvey box (USGS, 1976) (figure 4). Successful exploration shifts the boundary between identified and undiscovered resources to the right; improvements in technology or increases in the real price of oil shifts the boundary between economic and subeconomic resources towards the bottom. Production shrinks the reserve base.

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

The productivity of investment in exploration is negatively influenced by the discovery rate (figure 5): Suppose the discovery rate is increased. Then less remains to be discovered with current technology, and the productivity of further investment in exploration is reduced. It is assumed that the yield from exploration is exponentially decreasing with the cumulative footage drilled, and that the footage drilled per $ invested is constant (Hubbert, 1969, - 75; Hall and Cleveland, 1981). The reduction in productivity feeds back to the discovery rate implying a reduction in the discovery potential provided by any given level of exploration activity.

The productivity of investment in production is influenced in a similar manner by the rate of production (figure 6): Suppose the production rate is increased. Then less remains to be recovered. Thus the productivity of investment in production is reduced, feeding back to the production rate to reduce the production potential, provided by the investment in production. The production potential constitutes an upper limit for the production rate, a rate which may thus be reduced. Note that the technically recoverable resource remaining constitutes an upper limit for the rate of production as well.

These underlying physical structures tend to stabilize the discovery and recovery of petroleum. As long as there is a demand for petroleum, the productivity of the investments will be exponentially reduced as more of the resource is discovered and more of the identified reserve is recovered. The consequence is a tendency to slow down the rate of depletion, i.e the rate at which the system approaches its equilibrium. In addition to demand, there are only two more factors that may influence the development towards equilibrium in each sector, changes in exploration effort and changes in technology. Increased investment in exploration increases the discovery rate. Better technology improves the productivity of investments by making more of the petroleum available, - i.e. discoverable and recoverable.

These two sectors are interrelated physically since exploration provides the identified reserve, which constitutes the basis for production. Progress in exploration also has an impact on the productivity of investment in production: Suppose that less remains undiscovered due to more extensive exploration. In that case, the production is allowed to take place in more demanding geostructures. Now, if production takes place where exploration has recently taken place, the productivity of the production will then correspond to the current productivity of the investment in exploration. The recovery of a field however, normally takes place somewhat after the field has been discovered. As exploration progresses, the technically recoverable reserve discovered accumulates. Thus the productivity of investments in production is lagging the productivity of investment in exploration, corresponding to this reserve.

INVESTMENTS

Investments are made to build up an exploration potential (capasity) and a production potential (figure 7 and 8). These investments are determined by the demand for petroleum and the petroleum price. In addition, the productivities of such investments, as they compare to the market price, play an important role in the 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 4 years is assumed. Once successful exploratory wells have been drilled, there is a further 1 year average lag in the development of production wells.

Investments in both exploration and production are adjusted to the perceived productivities of such investments, - though have to be justified by the market price. The breakeven prices required to justify exploration and production are therefore compared to the prevailing market price. If the market price falls below the required prices, investments will be curtailed. The perceived productivity of investments in exploration is assumed to lag the real productivity by 15 years on the average.

TECHNOLOGY

Petroleum technology may be divided into exploration and recovery technology (figures 7 and 8). Technological improvements increase the availability of petroleum through exploration and production, and thus improves the productivity of the investments. The current level of sophistication in exploration technology is expressed by the fraction of the total petroleum resource that can technically be discovered. The level of sophistication in production technology is expressed by the fraction of the identified reserve that can technically be recovered. Both exploration and recovery technology are endogenously improved by investments. As these fractions approach their maxima, the marginal effect of further research and development diminishes (technological saturation).

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

The origin of technological progress lies in investments from revenues, i.e. the product of petroleum price and production: A fixed fraction of the revenues is assumed allocated to research and development. Because of the technological saturation, the marginal productivities of these investments are declining. There is a 6 years average third order delay in technological research and development. The split of this investment between the two technologies is subject to changes over time (figure 11). Of primary concern is the exploration technology, as the exploration creates the basis for production. Gradually, as this technology approaches its maximum level of sophistication, the emphasis is shifted from exploration to production technology so as to utilize the identified reserve.

Depending upon the revenues, technological improvements allow for exploitation according to the petroleum demand, while compensating for the decline in the productivities of investments in exploration and production. Therefore, the stronger the technological progress is, the more aggressively the depletion effect is compensated, - and further investments made in technology. When, on the other hand, the production is falling, less is contributed to technological development. Therefore the fall in productivity is compensated less aggressively, promoting a further decline in the production rate.

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

Note that if the 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 the technological development, because then the contribution from technological development is relatively dominating. When the technological saturation sets in, the effect of such a change will be less. Note also that the progress in exploration technology generally diverges from the progress in production technology and that the exploration costs and the production costs are not the same (exploration costs generally being substantially higher than production costs), so that the contribution from each of them may differ significantly.

PRICE AND DEMAND

The demand for petroleum is caused by our economy being petroleum intensive and is determined by the exponential growth of GNP (figure 10). Domestic exploration and production is in demand to the extent that substitutes, provided by import of natural petroleum or production of synthetic petroleum, are not available at lower that breakeven costs.

The demand for domestic production is complemented by the tendency to import (the indicated import). A rising tendency, reduces the production pressure. The tendency to import is determined by the ratio between the international (import) price and the exploration and production expenditures. 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 effected by changes in the productivity of investments in exploration. The actual import endogenously covers the residual demand, i.e. the demand not satified by domestic production.

There are two different ways in which the demand for petroleum may be influenced by the petroleum price over time: First of all the demand is reduced by rising prices causing the energy intensity of GNP to decline. Furthermore, a synthetic petroleum industry may be justified by higher prices. There are substantial delays associated with the impact of price on demand: It takes 15 years on the average to adjust the energy intensity, considering the potential for retrofitting existing capital, as the life of energy consuming capital is 20 years on the average (Coen, 1975; Sterman 1981). To build a synthetic petroleum industry takes 9 years on the average. Synthetics, which represents a perfect petroleum substitute, is assumed to cost $50 per barrel.

As long as the domestic petroleum price is not dominated by the international price or the price of synthetics, three factors determine the price (figure 12);

- the costs associated with the exploration and production of petroleum;
- the demand for petroleum; and
- the supply of petroleum.

Before 1953, the US domestic price is considered dominating the international market, so that the price is endogenously determined by the cost of exploration and production. From then on, the domestic production is protected by import quotas until 1972. Yet the price is gradually more influenced by the fall in the international price. In 1971 a price control is introduced. This control is effective until 1981 contributing to avoid a windfall profit from dramatically rising international prices. During this period the domestic price approaches the international price from its base level which is predominantly determined by costs. After 1981, no controls are in effect, and the domestic price is completely determined by the international price.

The impact of the demand on price is relatively straightforward: Suppose the demand for domestic production increases. Then so does the petroleum price because the petroleum market tends to develop towards a sellers' market. The impact of the petroleum supply is the opposite one: Suppose the supply is increased. The price is then reduced because the petroleum market tends to develop towards a buyers' market. The supply of petroleum is represented by the production potential. Note that the effect of supply and demand on price is relatively limited: The oligopolistic petroleum market is characterized by short term adjustments of the potential production (supply) according to the demand and the market price. It is therefore not very common that the 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 avoid windfall profits. As the price approaches the international level, such regulations are abolished.

The demand for petroleum exploration originates from three different requirements (figure 9), i.e. to;

- keep up with current production;
- maintain a reserve recoverable, adequate to keep up with production; and
- adjust the current recoverable reserve in accordance with the expected growth in demand.

The amount to be produced is simultaneously required substituted by recoverable petroleum. The reserve must be corrected to an adequate level, corresponding to the current rate of production. Any discrepancies from this level is 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 immediate, but is based on the forecast of a recognized trend in growth. There is assumed to be a 5 years average delay representing the time to observe, perceive, and recognize this trend, and an additional 5 years to average the trend as a basis for forecasting. As the growth trend is calculated from past demand, these adjustments of the reserve are both based upon the demand for production, and the current reserve technically recoverable.

We may conclude that the demand for domestic production, when transformed into a demand for exploration, is amplified for two different reasons: First of all the recoverable reserve must be established and maintained. Secondly the gross yield from exploration must be considerably larger than the required net yield, due to the inadequacy of the production technology.

The price on and demand for petroleum is determined as summerized in figure 13 (where the amplifying effect of the inadequate recovery technology on exploration, the effects of supply and demand on price, and the short term adjustments of investments according to productivity and price, are all left out). The bold part of this figure represents the system considered without a technology sector. The remaining represents the impact of technology. Two major feedback processes tend to stabilize the system, respectively via;

- the influence of exploration and production costs on the petroleum price; and
- the impact of import tendencies on the demand for domestic production.

As the unit costs increase due to depletion, these processes cause the demand for petroleum to stagnate. Thus the rates of discovery and production are moderated. Due to the delayed, exponential nature of this effect, its impact is initially insignificant. Therefore exploration and production may increase with the exponential demand created by the growth in GNP. This gives rise to technological investments and progress. Provided this progress more that offsets the impact of depletion on productivity, the petroleum price is falling. This amplifies the rise in demand, production and technological progress through positive feedback. When the technological saturation sets in, the progress can no longer offset the depletion. The rise in costs, price and imports, forces the demand for domestic production into decline. This reverse tendency is again amplified by the positive technological feedback. (Note that there is a negative feedback, via the impact of the petroleum price on revenues, that may dominate the technological progress during a transition period as the production levels off).

THE DYNAMIC MODES OF THE SYSTEM

INTRODUCTION

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

One of these modes originates from the physical consequences of petroleum exploitation, - i.e.;

- the discovery of petroleum, leaving less of the total resource to be identified as a reserve in the future; and
- the recovery of petroleum, leaving less of the identified reserve for future recovery.

The result is an exponential decline in the productivities of exploration and production. If the investments were kept constant, and there was no technological innovation, this would cause the discovery rate and the production rate to approach zero exponentially. In this case the mode of behavior is an effective contraction of exploration and production. Under such circumstances, and provided there are no price constraints, the petroleum price would rise according to the declining productivity. Thus the demand would no longer follow the exponential growth in GNP, but gradually level off.

To the extent that the price mechanism does not offset the growth in GNP, there are two different ways to compensate for the contraction of exploration and production, in order to accomodate the residual growth in demand created by GNP. That is to increase investments in;

- exploration and production; and in
- research and development of the two technologies.

Note that these two kinds of compensating measures act through very different processes. Direct investments tend to increase the volume of the exploration and production activity, i.e. the rate at which the exploration and production frontier is extended into the geo-structure. Larger investments therefore tend to reinforce the contraction. Investments in research and development tend to make exploration and production more efficient. Technological progress may allow for the frontiers to be extended at a lower rate, still with the same net yield Thus to compensate for deteriorating productivities, one may invest in technology to complement, and even substitute for investments promoting depletion.

Even stronger technological investments may more than cancel out the effect of depletion and actually cause the productivities to increase. In that case, we are facing an expanding mode of behavior with the following characteristics: The petroleum price will be falling as long as the technological development is "on top of" depletion. Note that this in time will reinforce the petroleum demand, - a development that will amplify the pressure for technological progress. To the extent that there is an adequate response to this pressure, the exploration and production may continually satisfy the demand without increasing unit costs. If the technological response turns out to be inadequate, then we experience the contraction.

The dynamics of the life cycle of the US petroleum resource is characterized by expansion followed by contraction. There are however a set of factors that tend to modify this behavior. Four of the most prominent ones are;

- the identified reserve, acting as a buffer between exploration and production;
- the delay in recognizing the marginal exploration cost, acting as a buffer between cost and investment;

- the delay in averaging the exploration expenditures, acting as a buffer between cost and price, and
- the regulations, acting as buffers between the US's and the international petroleum economy.

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

THE EXPANSION (1870 -1945)

The dynamic mode of the petroleum life cycle is a typical expansion, and has the following properties (figures 14 to 23): Historically the petroleum price varied substantially in the beginning (figure 23). But by-and-large it declined with a decreasing margin until and was fairly stable thereafter (until after World War II). The 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 that petroleum had during the first part of this century, the growth in demand (figure 21), exploration and production exceeded the growth in GNP. The production exhibited a growth pattern corresponding to the demand (figure 22), - and allowed in addition for export. Note that during most of this time, USA was a net exporter of petroleum.

The energy intensity in the model is calibrated to represent the prevailing intensity during the last 35 years. Therefore an exogenous factor represents the smooth transition from other sources of energy to petroleum. This causes the petroleum demand to grow according to the historic demand (figure 21), - i.e. faster than the reference growth for most of this period. In addition to that, this growth is endogenously amplified by a declining petroleum price.

In the model, the production grows exponentially (figure 14, 16) and satisfies the domestic demand and the petroleum export. The growth in net yield from exploration is also exponential and satisfying during this period (figure 18). The technically recoverable reserve is developing normally (figure 17), according to the growing rate of production, until 1928. Thereafter, an excess reserve accumulates over time bringing the potential production from reserves well above the actual production (figure 16), in spite of the fact that the investments in exploration are adjusted to changes in costs. The accumulation originates from the substantial delay in recognizing the decline in unit exploration expenditures, causing overinvestments to be made. Both kinds of technology are developed at an exponential rate so as to more than offset the impact of depletion on productivities figure 17). The progress in discovery technology reaches its maximum effect (the inflection point of the fraction discoverable) in 1931. The effect of the technological progress in production is considerably more moderate. The technological progress accounts for an increasing productivity of investments, causing the petroleum price to decline from its initial value until 1930, when it levels off (figure 20) (The price exhibits a fluctuation which is a little more moderate than what was experienced historically, and is systematically slightly higher after 1930 (figure 23)).

In order to sustain the technological development that makes it possible to satisfy demand, ever larger investments must be made. Because the technological investments are financed as a fraction of the revenues and the price is declining assymptotically, it is the exponential growth in production that facilitates further growth through the positive feedback process described under "Technology".

THE TRANSITION (1945 - 1981)

There are upper limits as to how much of the petroleum that may be discovered and recovered. As these limits are approached, the technological progress is characterized by saturation, and the marginal effects of the investments in technology are reduced. Thus the need for investments in technology, just to compensate for this decline, is increased exponentially. Recall in addition, that the partial effect of a constant exploitation is to reduce the productivities exponentially, and that the growth in petroleum demand is also exponential. The growth in technology investments should therefore compensate for a hyper (tripple) exponential decline in the return on these investments. Sooner or later, we may conclude, the technological innovation are not adequate to withstand the effects of exploration and production. Thus we approach a contraction, primarily characterized by declining productivities. But before the contraction is fully established as a mode of behavior (from 1981 on), a lot happens, - both historically and in the model:

It is not surprising that the historic records on price, demand and production hardly show any signs of the oncoming contraction during the transition mode. As already pointed out, this transition is being masked by internal and external buffers (delays, reserves and regulations). The import (195 - 73) and price (1971 - 81) regulations are the only ones that may be traced empirically. Note that the effects of the oil-embargo (1973) and the Iran - Irak 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 towards contraction. What historically happened was the following:

After World War II, the domestic petroleum price rose by more than $ 4 per barrel (figure 23). 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 in 1972. The price control then prevented the domestic price from rising as dramatically as the international price during the two crises in the '70s. As the produced and imported petroleum reserves were being depleted, the 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 21). It was then inflected significantly, leveled off, and started falling.

The domestic production initially followed the same trend as the demand, but was supplemented by a substantial growth in imports during the import regulation period (1953 - 73) as USA turned from being a net exporter to become a net importer of petroleum (figure 22). The domestic production was also supplemented by the Alaskan production which gradually grew and amounted to more than 11% of the total domestic supply in 1986. Consequently, the production in the lower 48 states contracted more significantly than the petroleum demand during this period, and fell substantially during the period 1973 - 81.

It is convenient to start off 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 17). This represents the first sign that the positive, compensating feedback loop, promoting the technological development, looses its dominance. Note however that the progress in production technology has an accellerating effect up until 1967, when also the fraction recoverable inflects due to saturation. But because the unit exploration expenditure at this point of time is considerably larger than the production costs, the contraction is triggered. One could then expect a contraction scenario; - with lower productivities, higher costs and price, reductions in demand and investments 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 20). It does not reflect the post-war 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 the petroleum demand follows the historic pattern accurately (figure 21): I.e. 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 '70s, the demand inflects accordingly, and drops off with a substantial delay during the '80s.

The petroleum production satisfies the demand until 1950 (fig 14). Gradually the domestic supply is less sufficient, even if the Alaskan production comes into play. There are two reasons for this: First of all, the import price becomes competitive in the 50's, so that the tendency to import petroleum is reinforced. In spite of the import regulation, this reduces the pressure to explore domestically. Secondly, there is a masked transition into a decline in the productivity of the investment in exploration. This is due to the inflection of the fraction recoverable, - i.e. the declining effect of technological progress. Even though this transition initially (1931 - 53) is very smooth, there is a relatively dramatic fall in the net yield from exploration (figures 17, 18), partly due to the delay in recognizing the current exploration expenditures: So far, the productivity has been rising, and the exploration activity has been oversized. But now, when the productivity is falling, the investment is systematicly too low. Gradually the effects of technological investments are deteriorating, only to amplify the contraction. However, due to;
- the excess exploration;
- the large reserve that has been built up (figure 16); and
- the relatively strong progress still characterizing production technology,

the technically recoverable reserve is inflected at only a moderate rate (figure 17). And the dramatic fall in the yield from exploration has no effect on production. Eventually though, there is a dramatic decumulation of the technically recoverable reserve, and this reserve becomes an effective constraint on production, so that the demand can no longer be satisfied. Thus additions to the identified reserve are no longer sufficient to maintain the required production.

When it eventually turns out that the production does not yield revenues, sufficient to allow the technological progress to keep up with the depletion, then the productivity of the investments in exploration declines. This calls for a higher price to cover the increased expenditures, and possibly counteract the technological stagnation. Incidentally this is exactly what happens: At this point of time, the international price is increased, the domestic price is allowed to follow, and the high market price stimulates investments and revitalizes the exploration. The large investments are justified also because the petroleum demand responds very slowly to the change in price. This creates a shortage, previously covered by imports. But now as the international price goes up, there is an incentive to discontinue this import (figure 19). It finally turns out, that in spite of a boost in Alaskan production, the domestic supply remains insufficient and one may recognize that a contraction is in progress. There are several factors which cause the massive investment in exploration not to provide the required reserve, and therefore may explain the subsequent contraction:

The investment is not large enough, because the exploration expenditures are under-estimated. The effect of the investment is delayed and distributed over time. The productivity of the investment is deteriorating exponentially along with the exploration, - an effect which is no longer adequately matched by the technological development: While as the technological progress so far acted to amplify the expansion of exploration and production, through positive feedback processes, it now promotes the contraction, through the same kind of processes: The declining rate of production, causes the revenues to decrease, - while as the demand for technological investments is still growing hyper-exponentially. (Recall the significant delay cerecterizing how demand responds to a change in price). Even though the price is rising significantly after 1973, so as to contribute to the revenue; the technological consequences are far from sufficient. Therefore the productivities are still declining exponentially, and effectively slowing down the 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 (figures 22, 23): The petroleum price was determined internationally, and fell suddenly down to a 1986 level that could only be justified by the costs of the largest producers in OPEC. Because of this development, the demand slowly recovered from the price shock of the '70s, after having fallen significantly during a couple of years. The only contraction characteristic within the historic timeframe was thus the production trajectory: The production decreased substantially for about 10 years. It then levelled slightly off for the last couple of years (figure 22).

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 expenditures associated with the exploitation. As long as the price considered 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 20). When approaching this ceiling, domestic investments are curtailed, exploration and production is gradually shut down, and the 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 '70s. But due to the price increase, a large investment in exploration is still justified in the shadow of the rising international price. The slight recovery of the petroleum production after 1981 (figures 16, 22) is explained only as a delayed respons to this large invest- ment. As it turns out however, this investment is insufficient in the long run, and as the exploration is extended, the productivity of this investment is declining. Consequently the net yield is rapidly diminishing, and does not support the required production (figure 18).

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

The substantial increase in the fraction of the reserve technologically recoverable (figure 17), contribute significantly to the production, because the identified reserve that remains unrecovered at this point of time, is relatively large (figure 15). But the contribution is far from sufficient to counteract the depletion. This technological progress hardly effects costs because the exploration expenditures are very dominating until the end of the petroleum life cyle. Gradually also the marginal effect of this progress diminishes.

Predictions must be based upon two assumptions; one about the future economic growth and one about the price development on the international petroleum market. The base case growth in GNP exhibihed here, is the middle economic growth applied by the U.S. Department of Energy (EIA, 1985). (The model contains the extreme DOE cases as well). After 1995, linear extrapolations of the DOE projections are applied. In the base case, the international price is assumed to reach $ 20 by 1990 (figure 20). From then on, the price is assumed to increase linearly by $ 10 per decade. The termination of the petroleum life cycle is characterized by a rapidly growing difference between the unit exploration expenditure, and the petroleum price. The incentive to invest in exploration is thereby eroding. The reserve is still being depleted (figure 15), until the unit production cost has increased beyond the petroleum price, so as to no longer justify production. Imports are growing rapidly during this period (figures 14,19), and one may find it realistic to assume a more significant increase in the international petroleum price in response to the massive U.S. import pressure. In that case the U.S. natural petroleum demand will be more moderate, and there will be a stronger incentive for the domestic production of both natural and synthetic petroleum. The model runs until 2050, but by 2020 most of the dynamics are over.

APPLICATIONS OF THE MODEL

The most straightforward use of this model is as a tool for projecting the characteristics of the petroleum life cycle into the future. This may be done under different scenarios with respect to the development of the GNP, the international petroleum price, and the price on synthetic petroleum.

The pupose of such projections would be to understand how the petroleum life cycle terminates under different environmental circumstances. In particular, it will show how rapidly USA develops a dependency on import and synthetic production, and how large part of the total resource that is economically recoverable. By changing the investment module of the model, the effects of different investment policies may be evaluated, e.g. to limit the current exploration and production, and yield to the 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. By changing the price module, the effects of alternative pricing policies could be tried out. Such a policy could include a taxation or import fees intended to stimulate energy conservation, and build up the production capasity for synthetic petroleum.

Note that the model is based upon the assumption that there is a finite total petroleum resource. The volume of this resource is continuously 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.

Moreover, the model may be used to synthetically test out alternative techniques applied to acquire the information neccessary 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 of them compatible with the one discussed in this paper. 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 the resource estimation, represented by the additional models. Such experiments may provide a better understanding of the dynamics of estimates, and stimulate the discussion concerning the design and utilization of estimation techniques. Experiments of this kind, focusing on the Geological Analogy Method and the Hubbert Life Cycle Method, has been carried out at MIT by J. Sterman, G. Richardson, and P. Davidsen (Sterman and Richardson, 1985) and (Sterman, Richardson, and Davidsen, 1987).

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

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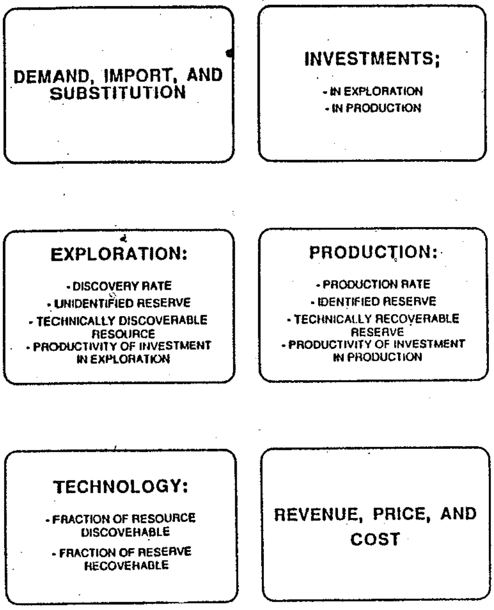

Figure 1: The sectors of the model.

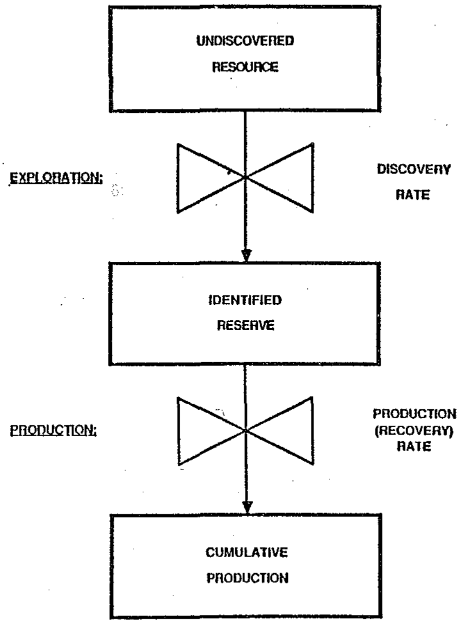

Figure 2: Stocks and flows.

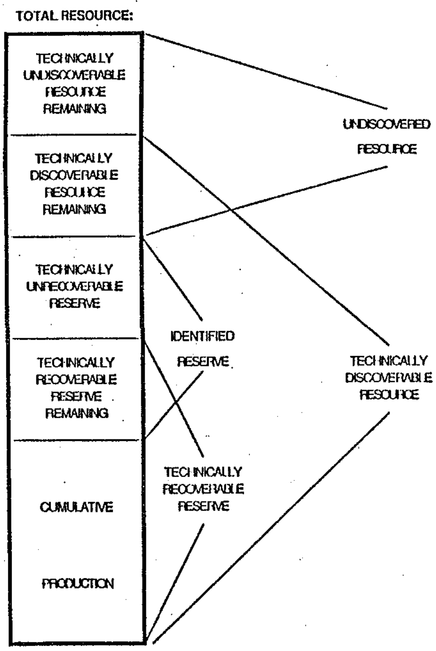

Figure 3: A resource classification.

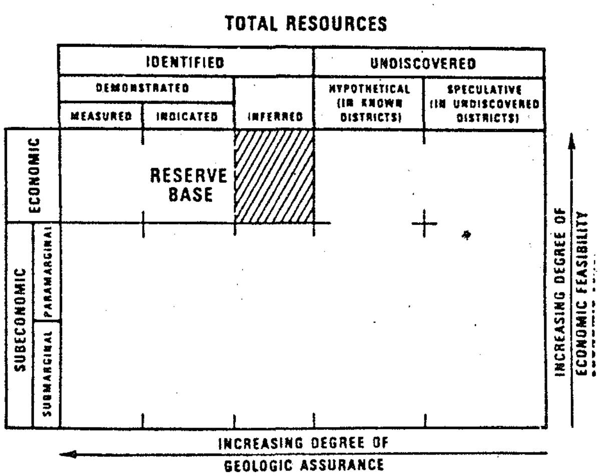

Figure 4: The McKelvey Box (Source:USGS,1976).

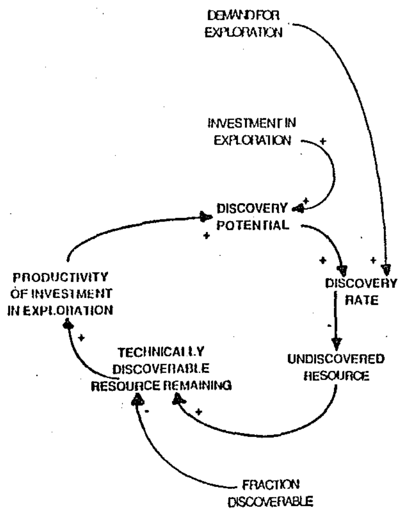

Figure 5: The physics of discovery.

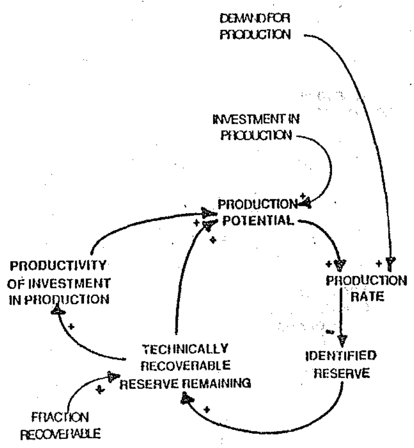

Figure 6: The physics of recovery.

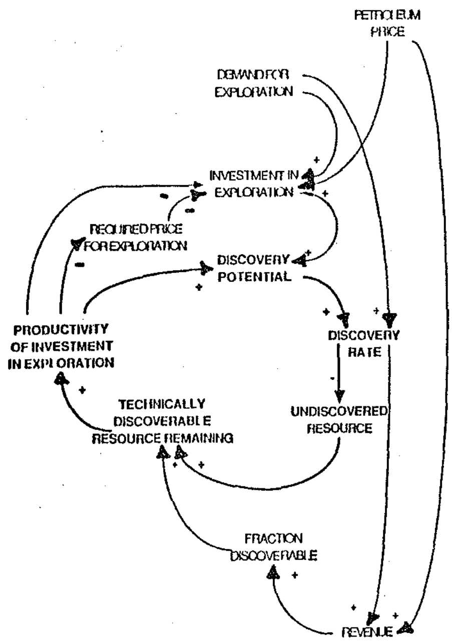

Figure 7: Investments in exploration
and its technology added.

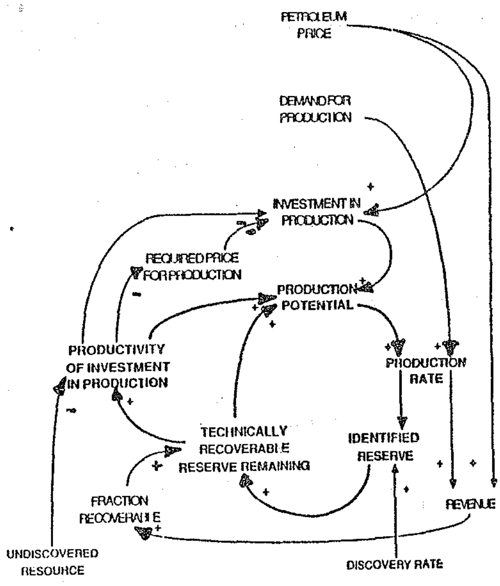

Figure 8: Investments in production
and its technology added..

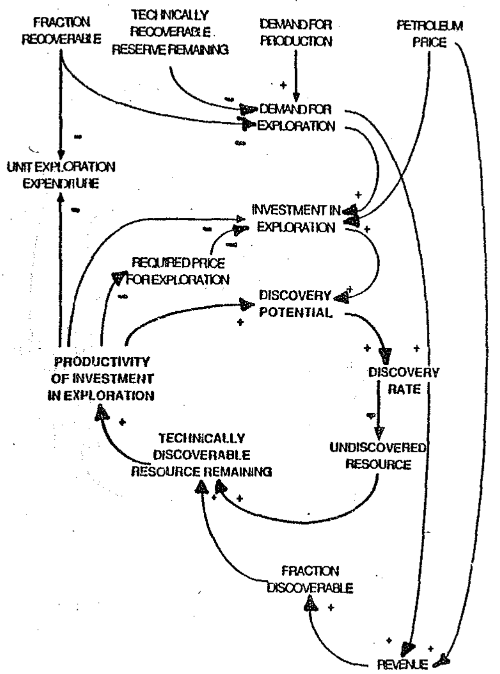

Figure 9: The demand for exploration added.

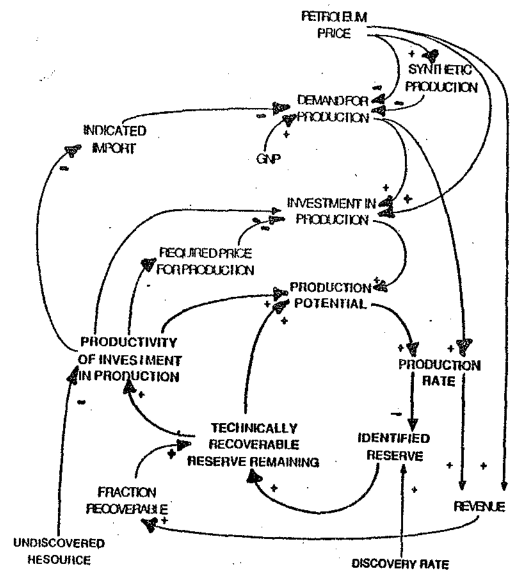

Figure 10: The demand for production added.

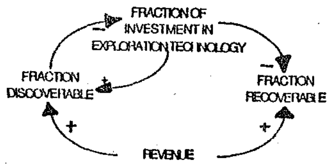

Figure 11: Shift in technology investments.

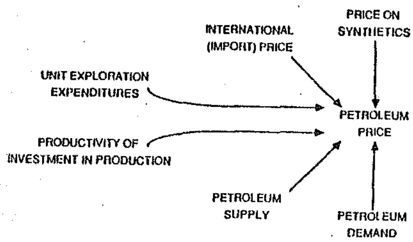

Figure 12: Factors that determine the Petroleum price.

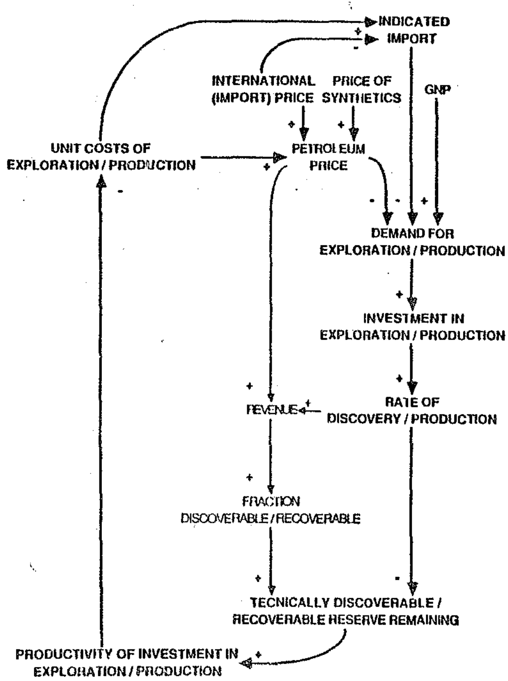

Figure 13: The influence of the petroleum price.

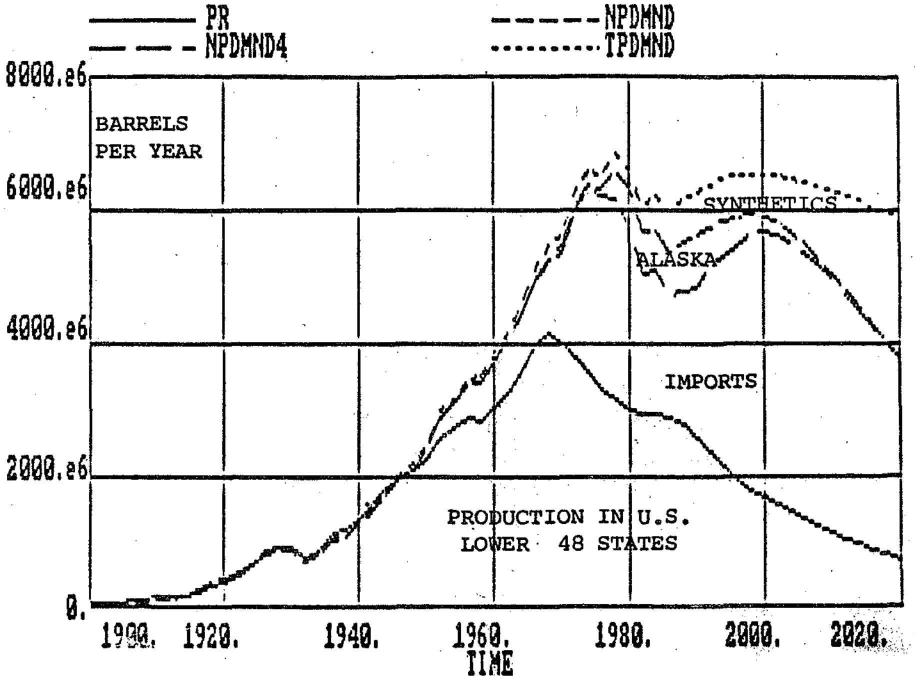

Figure 14: Petroleum Production (PR) and the contributions from Imports, Production In Alaska, and the production of Synthetic Petroleum.

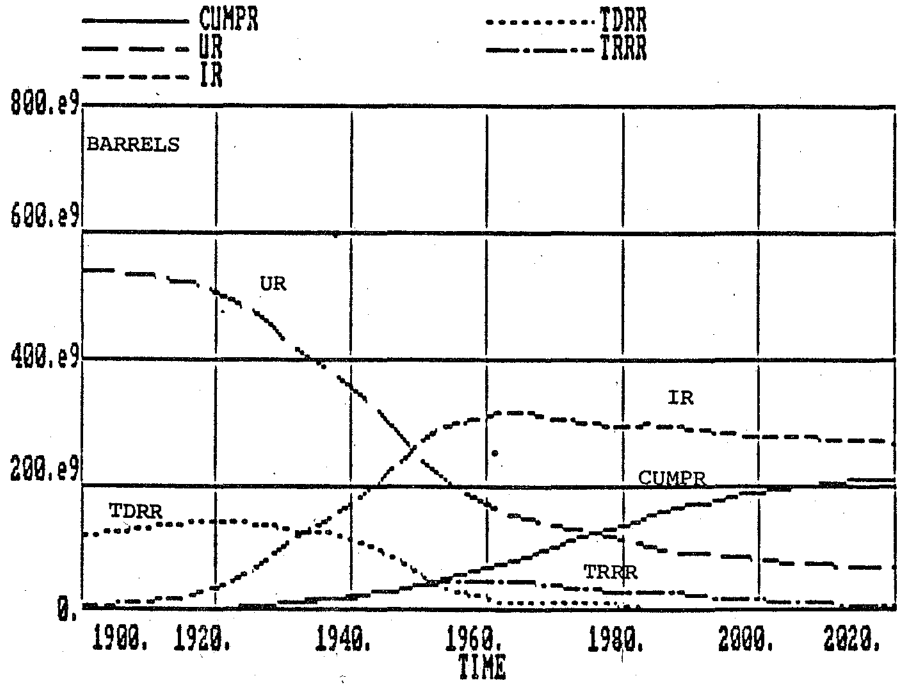

Figure 15: Cumulative Production (CUMPR), Undiscovered Resource (UR), Identified Unrecovered Reserve (IR), Technically Discoverable Resource Remaining (TDRR), and Technically Recoverable Reserve Remaining (TRRR).

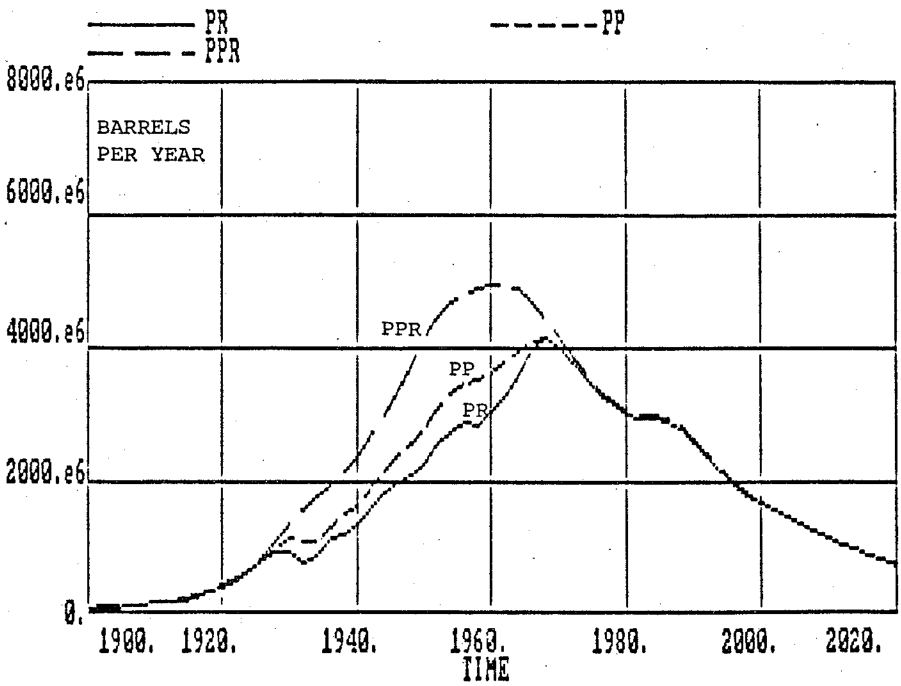

Figure 16: Petroleum Production in the lower 48 states(PR), Potential Production from Reserves (PPR), and Potential Production (investments taken into consideration) (PP).

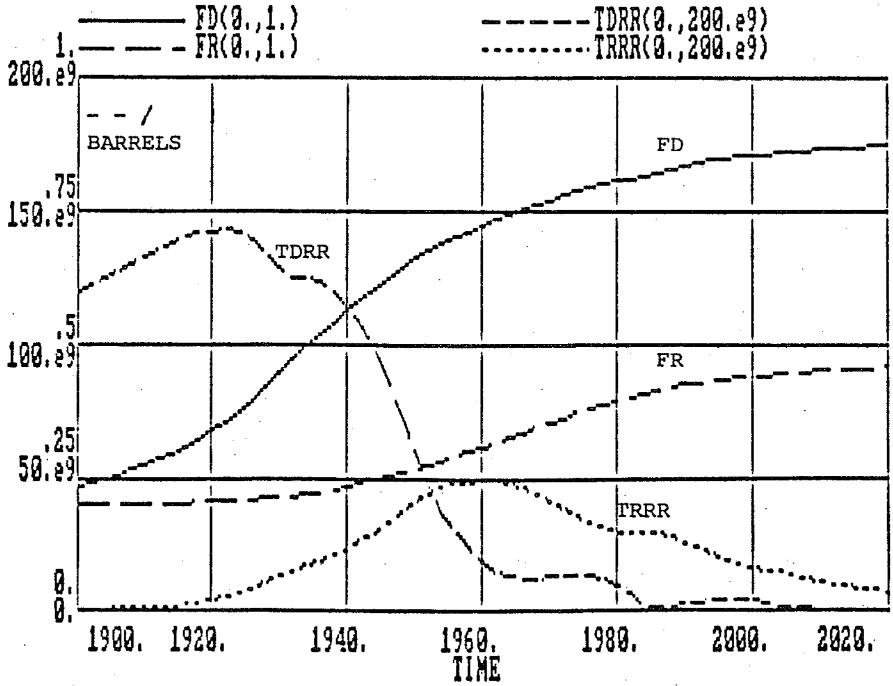

Figure 17: Fraction Discoverable (FD), Fraction Recoverable(FR), Technically Discoverable Resource Remaining (TDRR), and Technically Recoverable Reserve Remaining (TRRR).

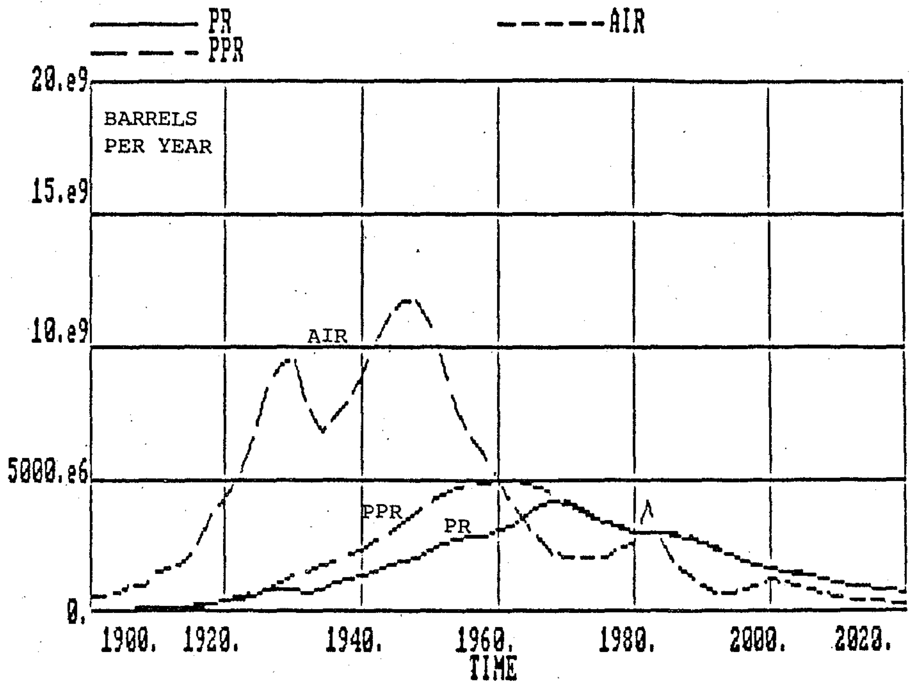

Figure 18: Petroleum Production (PR), Potential Production from Reserves (PPR), and Additions to Identified Reserves (AIR).

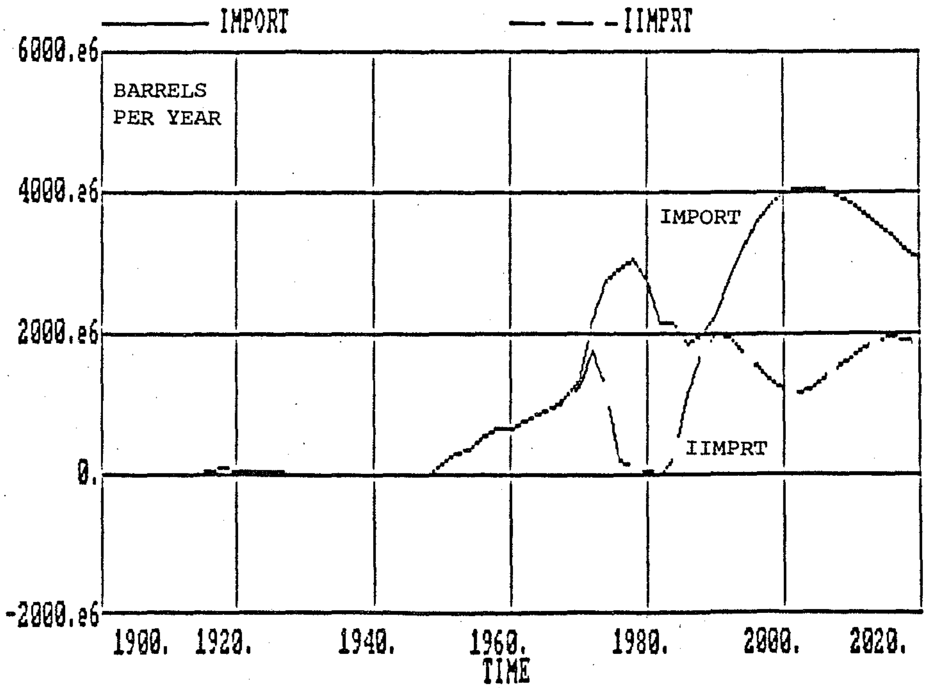

Figure 19: Imports (IMPORT) and (Price-) Indicated Import (IIMPRT).

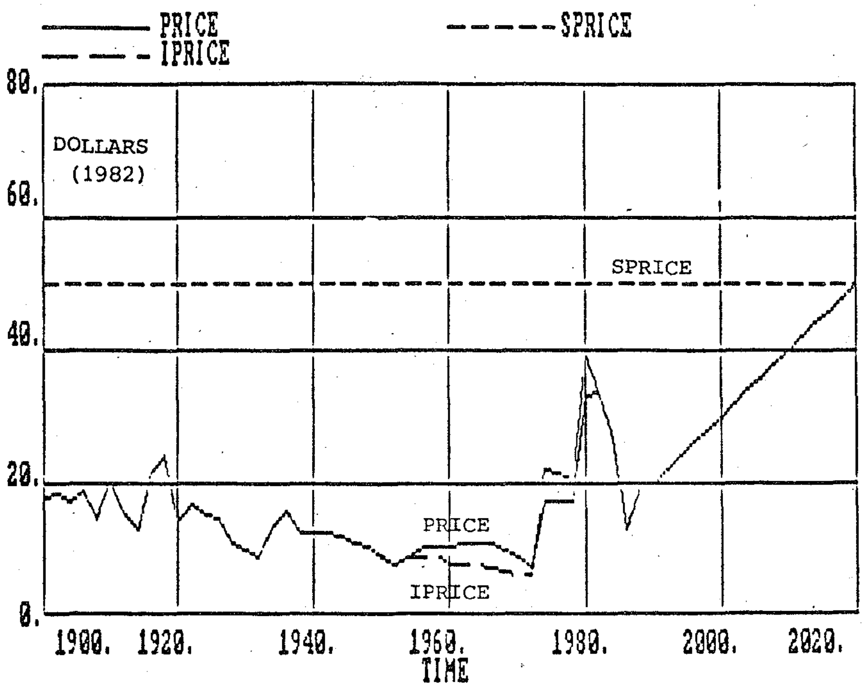

Figure 20: Petroleum Price (PRICE), Import Price (IPRICE), and Price on Synthetic Petroleum (SPRICE).

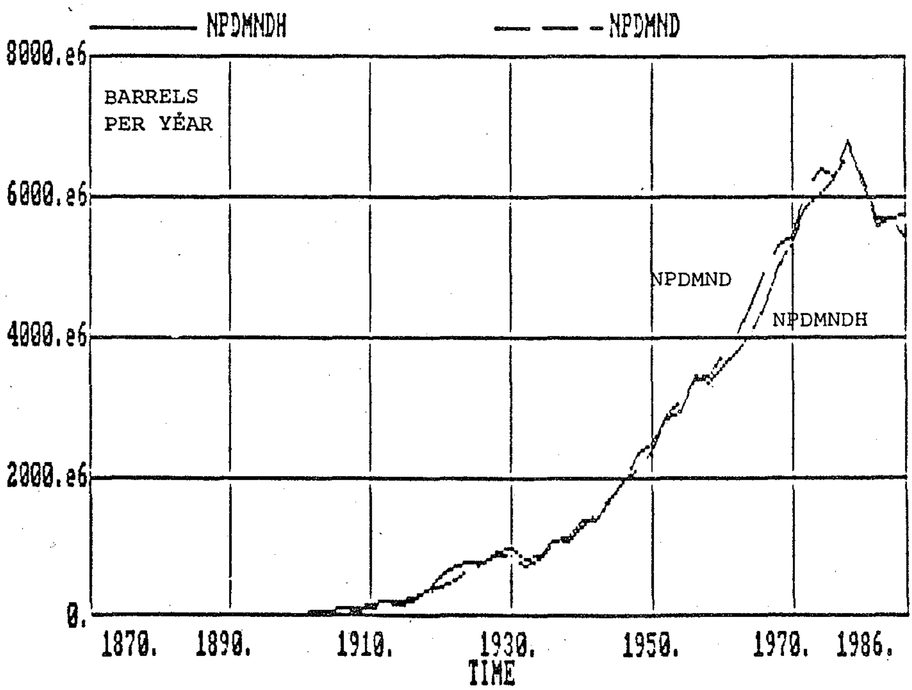

Figure 21: Historic Natural Petroleum Demand (NPDMNDH) versus Simulated Demand (NPDMND).

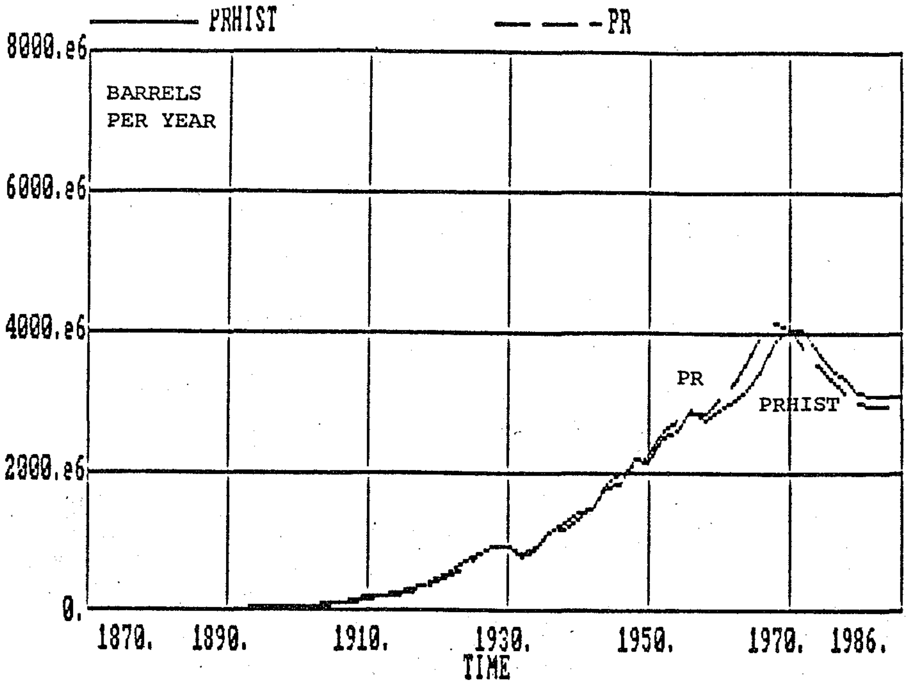

Figure 22: Historic Petroleum Production (PRHIST), versus Simulated Production (PR).

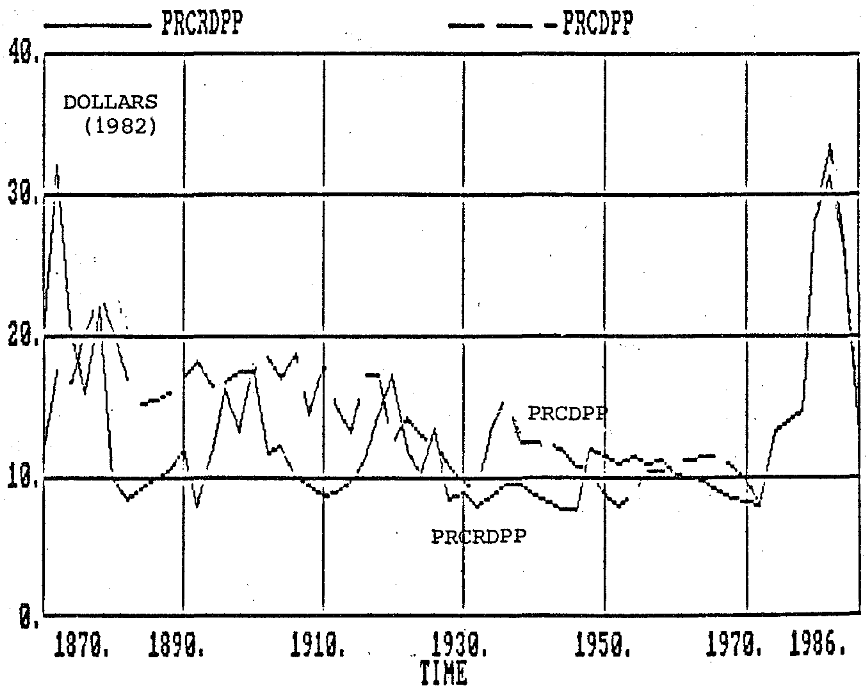

Figure 23: Historic Real (1982 USD) Price on Domestically Produced Petroleum (PRCRDPP) versus Simulated Price (PRCDPP).