The Dynamics of Energy Systems and the Logistic Substitution Model

Volume 1: Phenomenological Part

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RESUME

This is a report on the work done at the International Institute for Applied Systems Analysis in 1976 to 1977 under a grant from Volkswagenwerk Foundation, whose objective was to explore the potential and the mechanisms of logistic analysis to describe the structure and the evolution of energy systems.

Volume One contains the phenomenological part. About 300 cases were examined, some of which are reported in detail.

The quality of the logistic description is generally excellent, even for cases extending 150 years into the past and with all the perturbations such a long time span entails, and consequently we thought it appropriate to extend the description into the future and use it for prediction.

This was not really the objective of the grant but it naturally arises from the work and provides food for thought. Projections in the current literature appear to be in fact strongly inconsistent with the past, which cast doubts on their realizability, and are even internally inconsistent, which reinforces these doubts.

The fact that numerous "free" choices at the social level lead to very regular overall patterns should perhaps temper the feeling of being caught in a deterministic clockwork.

In *Volume Two*, devoted to the theoretical work, F. Fleck deals specifically with this problem showing the final regularity derived from a set of stochastic, i.e. "free", decisions. V. Peterka, on the other hand, operates at a more aggregated level, where one can start to speak of economic determinism. He describes a form of fate we are more ready to accept, if only grudgingly.

Our exploration has generated more problems than we have solved; thus the field appears very fertile for future research.

CONTENTS

The Dynamics of Energy Systems and the Logistic Substitution Model

C. Marchetti and N. Nakicenovic

1. INTRODUCTION

Four years ago the International Institute for Applied Systems Analysis, Laxenburg, Austria, initiated a study of energy systems using the techniques of market penetration analysis.

The basic hypothesis--which has proved very fruitful and powerful--is that *primary energies, secondary energies, and energy distribution systems are just different technologies competing for a market* and should behave accordingly.

Previous analysis of market competition had always been performed looking at only two competitors. But it is the peculiarity of energy systems over the last hundred years that most of the time more than two competitors took important shares of the market. Thus we had to modify the original rules by introducing new constraints that permitted to deal with the more complicated case. These constraints were defined empirically based on the observation of a few cases, but proved very successful in dealing with practically all the cases analyzed to date. The constraints in our study basically restrict the competition between the youngest and the oldest technology still expanding its market.

A mathematical formulation of the substitution process is given below and the manual for the software package is given at the end.

2. LOGISTIC FUNCTION AND SUBSTITUTION DYNAMICS

Substitution of a new for the old way of satisfying a given need has been the subject of a large number of studies. One general finding is that almost all binary substitution processes, expressed in fractional terms, follow characteristic S-shaped curves, which have been used for forecasting further competition between the two alternative technologies or products, and also the final takeover of the new competitor.

One of the most notable models of binary technological substitution was formulated by Fisher and Pry (1970). This model uses the two-parameter logistic function to describe the substitution process. The basic assumption postulated by Fisher and Pry is that once a substitution of the new for the old has progressed as far as a few percent, it will proceed to completion along a logistic substitution curve:

$$\frac{f}{1-f} = \exp\ (\alpha t+\beta) \quad ,$$

where t is the independent variable usually representing some unit of time, α and β are constants, f is the fractional market share of the new competitor, and 1-f that of the old one.

The coefficients α and β are sufficient to describe the whole substitution process.

They cannot be directly measured; they can however be estimated from the historical data.

Two sets of examples are shown here (Figures 1 and 2) from Fisher and Pry's original papers, Fisher and Pry (1970), Pry (1973). The logistic functions appear to give an excellent description of substitution, not only for very different products and technologies, but also for different types of economies.

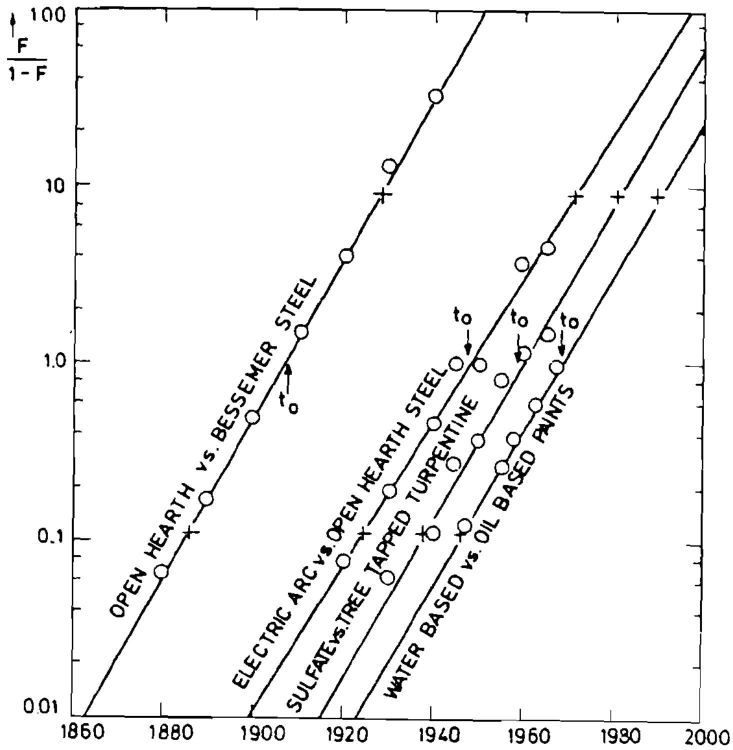


Figure 1. Technological substitution in the production of steel, turpentine, and paints.
Source: Fisher and Pry (1970).

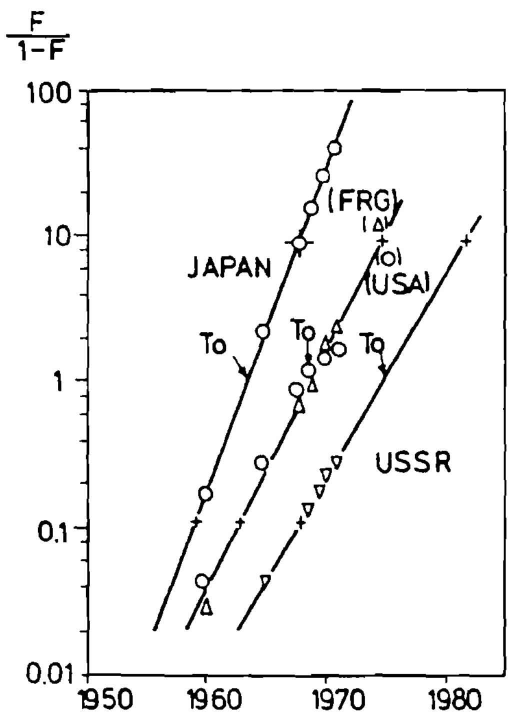


Figure 2. Substitution of B.O.F. for open hearth and Bessemer steel production.
Source: Pry (1973).

In dealing with more than two competing technologies we have had to introduce additional constraints into the system since in this case logistic substitution is not preserved in all phases of the substitution process. Every given technology undergoes three distinct substitution phases: growth, saturation, and senescence. The growth phase is similar to the Fisher-Pry binary logistic substitution, but it usually terminates before full substitution is reached with the saturation of the market. The saturation phase is not logistic. After the saturation phase the market shares of the technology proceed to decline (i.e. the technology is substituted from the market) logistically. This is so because new technologies enter the market and grow at logistic rates forcing the older technology to take what is left, the residual. After this older technology starts declining at a logistic rate the next technology starts saturating. This process is repeated until all but the newest technology are senescending.

In practice we deal with discrete time intervals, say one year; thus the formulation of this generalized model has an algorithmic character which facilitates computer implementation.

3. SIMPLIFIED ANALYTICAL TREATMENT

Let us assume that there are n competing technologies ordered chronologically in the sequence of their appearance in the market. Over a certain historical interval we estimate the coefficients of the logistic functions for the technologies in the logistic substitution phases. Typical historical periods we have investigated range from 130 to 20 years. The substitution process can be simulated, however, over any desired time interval which need not overlap the historical period. Let us call the beginning of this interval t_B and the end point t_E.

After the coefficients have been estimated, either by the ordinary least squares or by some other method, we have n equations:

$$\frac{f_i(t)}{1-f_i(t)} = \exp\ [\alpha_i t+\beta_i],\ i=1,\ldots,n \quad ,$$

where α_i and β_i are the estimated coefficients. Now we choose the oldest technology, j, still substituting the market, i.e. $\alpha_j>0$, $\alpha_{j-1}<0$, and $\alpha_{j+1}>0$, to enter the residual phase. The market shares are then defined by:

$$f_i(t) = 1/[1+\exp(-\alpha_i t-\beta_i)] \quad , \qquad i\neq j \quad ,$$

and

$$f_j(t) = 1-\sum_{i\neq j} 1/[1+\exp(-\alpha_i t-\beta_i)] \quad .$$

Let us call this time point t_j, so that $t \geq t_j$. I.e., technology j is in its residual phase and all other technologies are either growing or declining logistically. The transition from the saturation region of the residual phase to logistic senescence will take place when function $f_j(t)$ becomes logistic again on its way down. However, since we usually deal with discrete time intervals, this will be the case when function $f_j(t)$ approaches the curvature of some logistic function.

Using the transformation of the logistic function:

$$y_j(t) = \log\ [\frac{f_j(t)}{1-f_j(t)}] \quad ,$$

we can define a very sensitive measure of the curvature of $y_j(t)$, $t>t_j$ to decide whether the saturation phase of technology j has been completed. The following criterium is used: technology j has completed the saturation phase when the relative rate of change of the slope of $y_i(t)$ is minimal:

$$y_j''(t)/y_j'(t) \xrightarrow[t_E>t>t_j]{} \text{Min! and } y_j'(t)<0 \quad .$$

Once this condition is satisfied let us call this time point $t_{j+1} > t_j$; we determine the new coefficients for technology j:

$$\alpha_j = y_j'(t_{j+1}) \quad , \text{ and}$$

$$\beta_j = y_j(t_{j+1}) - y_j'(t_{j+1}) \cdot t_{j+1} \quad .$$

Technology j+1 enters its residual phase, and the process is repeated until the last technology, n, enters its residual phase, or the end of the time period, t_E, is encountered.

These expressions determine the temporal relationships between the competing technologies. Only time t and the estimated coefficients α_i and β_i extracted from historical data have been treated as independent variables.

4. COMMENTS AND WARNINGS ON USING THE CHARTS FOR PREDICTION

Logistic analysis has shown an unexpected capacity in organizing historical data, in that the information relevant to the evolutionary behavior of energy systems is contained in very restricted time series. This provides a very sound basis for using it for prediction. However, a certain number of precautions should be taken, or at least be kept in mind when using the results.

First of all, a new primary energy, like any new technology, is introduced first by drawing capital and resources from the industrial and economic environment. This "investment in faith" shows up with, usually, very fast rates of market penetration right at the beginning followed by a reflection period after which speed is resumed in compliance with the market. As a new technology, now a new industry, has to walk on its legs, its speed of penetration is always lower. This transition point, or kink in the curve, usually occurs when penetration has reached 2% or 3% of the market. If this kink does not show up, one is left with the suspicion that it will occur later, so that the final rate of penetration has to be guessed from other indicators. The most useful is the time constant prevalent for other substitutions in the same system, and this is what we often use for our scenarios.

In the energy field, natural gas has the tendency to keep the boosted track up to even 10% of market penetration. This behavior merits further study as it may permit a better insight into the introduction period of a new technology. One of the possible explanations is that at the beginning natural gas can fill an existing distribution infrastructure so that only trunk transportation has to be provided during the initial phase.

Secondly, the model does not predict the introduction of a new technology. This limits the time horizon of forecasting. Analysis of numerous cases has shown that each system has a fairly stable time constant. For example, the time constant (time to go from 1% to 50% market share) for the introduction of a new energy source in the world is 100 years. Consequently, from the point of view of the competitors not very much is going to happen during the first fifty years of the introduction of a new technology. This offers much breathing space when we discuss about the world, but advises prudence with a time constant of 20 or 30 years, as is for the F.R.G.

The weakest point for the predictions over the next 50 years is the role of nuclear energy, for which we have a starting point, but still cannot determine the slope. For that reason we intentionally took prudent values, e.g. penetration of only 6% for the world in the year 2000, backed by a slightly more optimistic 10%.

In both cases it is clear that the predictions of the future roles of the various sources of energy based on this model contradict most of the predictions in the current literature, which are mainly controlled by the much looser constraints of resource availability and political opportunity.

The causal importance of resource availability is weakened by the fact that coal and oil successfully penetrated the energy market when wood and also coal still had an enormous potential as energy sources. The causal importance of the political argument is weakened by smooth substitution observed over a period of more than one century, when political moods changed quite frequently and drastically.

Furthermore, the drastic changes in energy prices after 1973, even if of monopolistic origin, do not appear a sufficient cause to change the rates of substitution; similar changes in the prices in the past did not affect them either. This has been so at least for the medium- and long-run, presumably because of rapid relative price readjustments between various sources. While this is only a hypothesis, which merits a deeper study, the very rapid price adjustments after recent oil price increases, however, are well in tune with it.

The most important differences that mark the predictions issuing from our model with respect to ones in the current literature, are:

- the relatively rapid phase-out of coal as a primary energy;
- a quite important role natural gas should have in the next 50 years;
- the negligible role during that period of satellite sources, such as geothermic, solar, fusion, on the basis of the very long lead times *intrinsic* to the system.

The curious fact about the last point is that the flourish of very expensive research on these sources implies a fairly low discounting factor in decisions on the allocation of funds. This appears very wise, if not self-consistent, as the lead times of the systems are so long, and nothing could be started properly if the high discounting rates were used.

These, and many other predictions, like the compatibility of resources with demand, although extremely interesting, are not really part of our research task, which is centered in the past and which tries to find order and make it rationally understandable.

5. THE EXAMPLES

The scope of the experimental part is to show the breadth and power of the method by taking as many examples as possible from three different levels of aggregation:

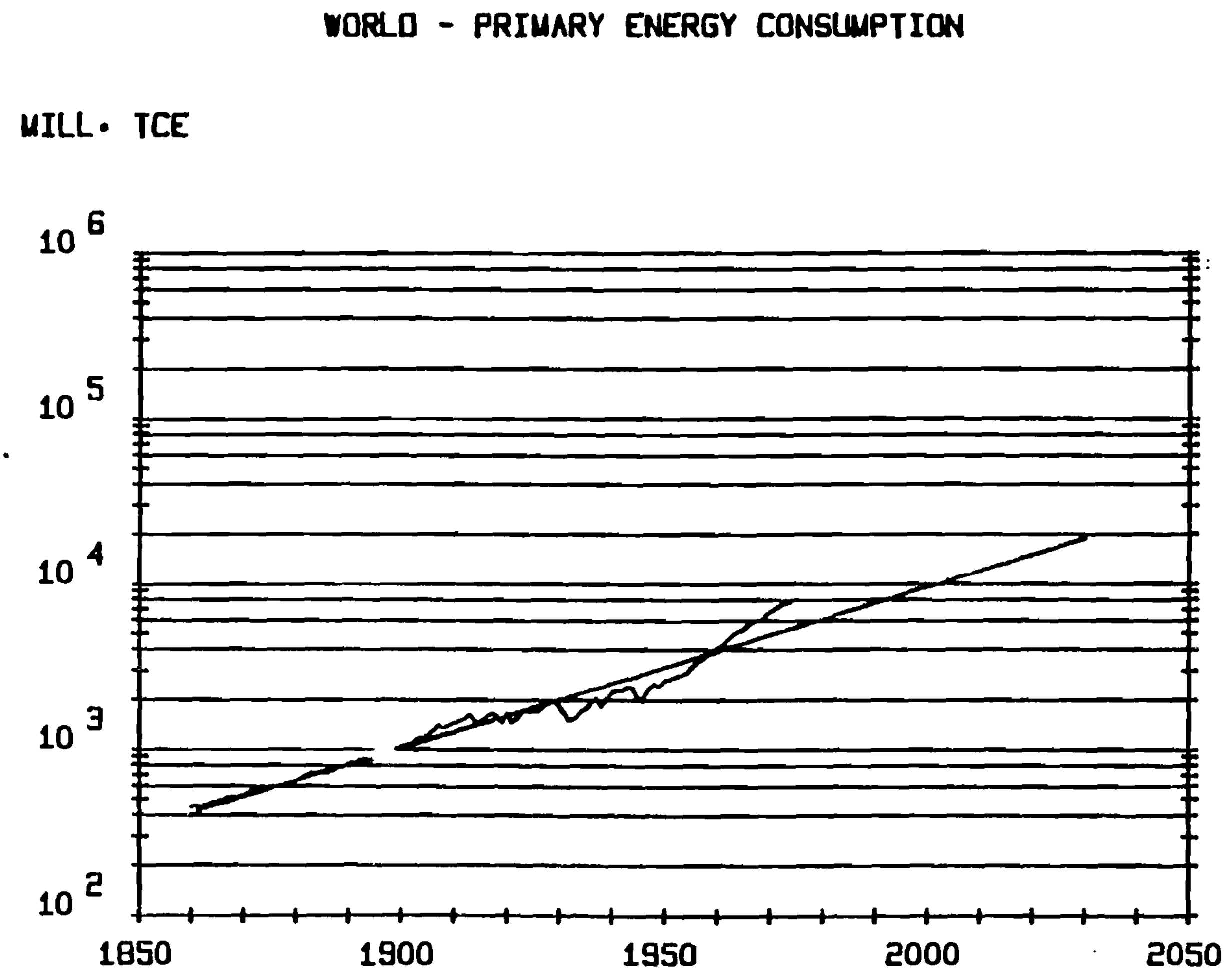
- primary energy inputs for the world as a whole;
- primary energy inputs for single nations or a cluster of nations;
- energy subsystems, such as electric utilities.

In total, we used 60 data bases to generate 300 examples for 30 different spatial and structural subsets of the world energy systems. The quality of fitting being consistently high in all examples, the cases reported here have been chosen mainly for didactic reasons.

The United States are particularly well represented, largely because of the quality, detail, and readability of their statistics. We also made an effort to have a good representation for the FRG. If this research sould be continued, collaboration with an institute for statistics would have a multiplicative effect.

For optical reasons the substitution graphs are preferably drawn using as the historical function $\log[f/1-f]$ versus time, f being the market share. This makes the top and bottom part of the graph very sensitive and this fact should be kept in mind when drawing conclusions from visual inspection. The graphs showing the total energy consumption are drawn on both logarithmic and linear axes depending on the dispersion of the data.

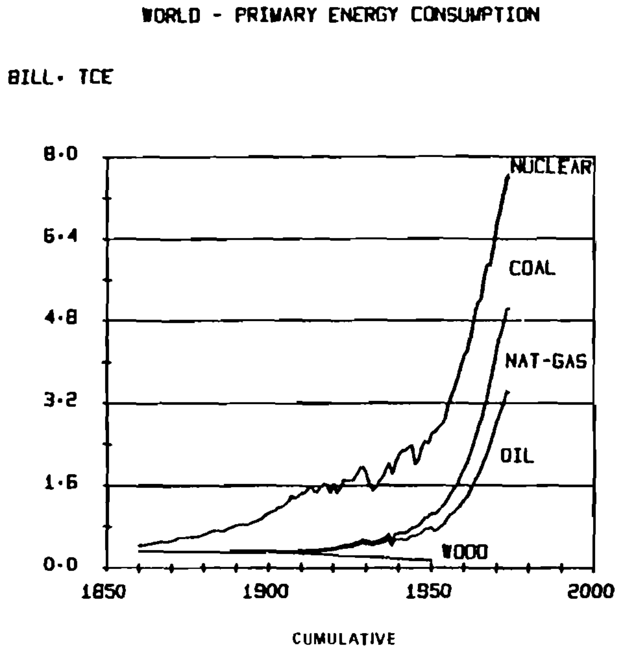
LIST OF EXAMPLES

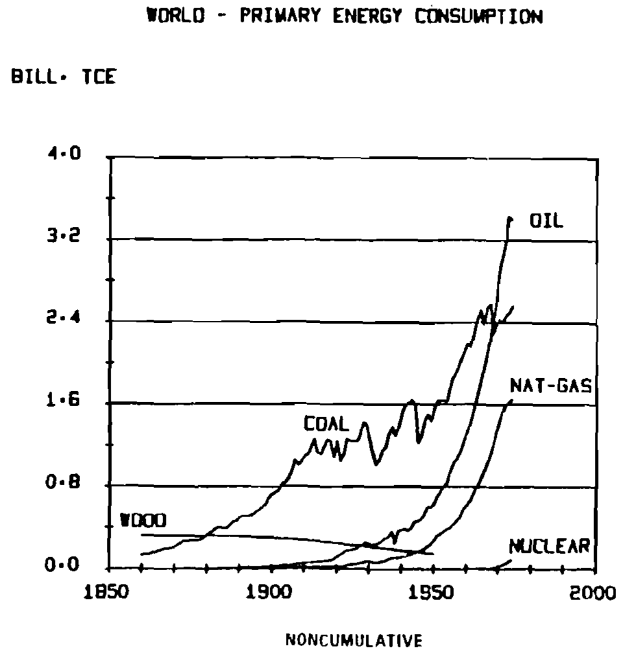


Our statistical base is reported first in various forms to help visualizing details. When noncommercial sources are included, the development of the world energy consumption appears fairly regular until World War II, with a growth of 2.3% per year. After 1950 not only were the losses reabsorbed that occurred as a consequence of the great recession, but some overshooting did occur with respect to the trend line. This may have been caused by an increase in the rate of population growth after the War. The increase in energy costs may well temper this rate again.

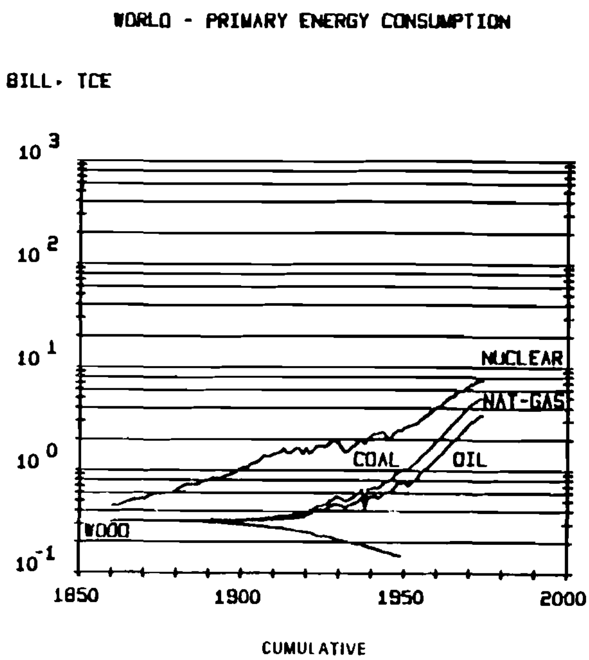
Historical data on the consumption of coal, oil, natural gas, and nuclear energy from 1960 to 1974 have been taken from Schilling and Hildebrandt [1977]; the time series on fuel wood consumption were taken from Putnam [1953]. Fuel wood consumption levels for the years 1950 to 1974 were not available; during this period the commercial use of fuel wood was not very large so that any error thus introduced is not significant. These data were also converted to million tce.

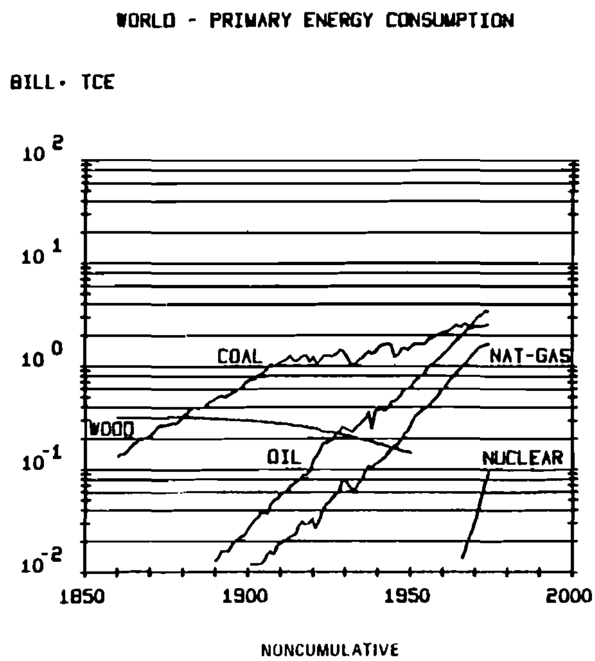
Nuclear energy was not available directly as primary equivalent but in GWh electric. We have converted the nuclear energy into million tce on the basis of an overall thermal to electric conversion rate of 33%.



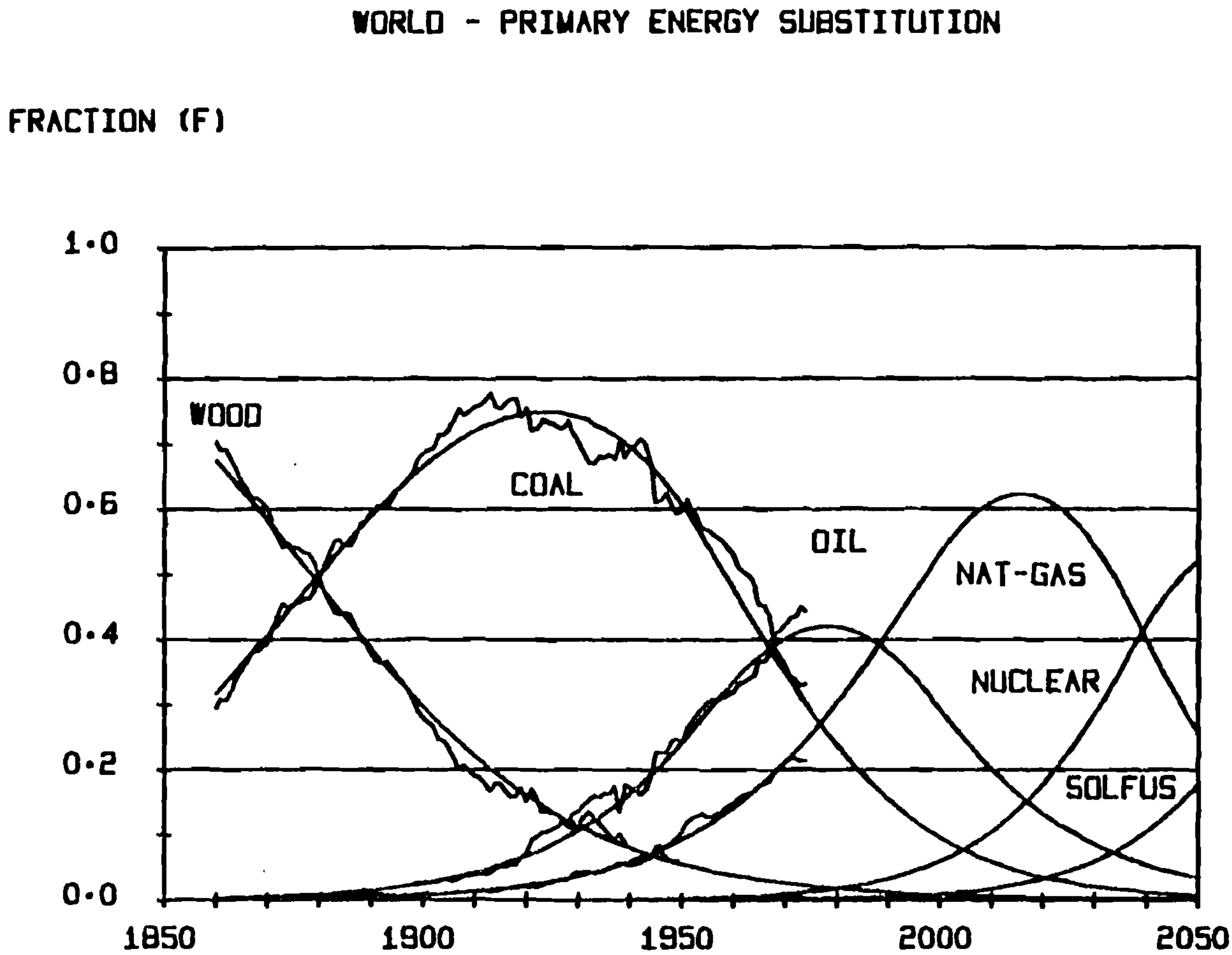


The energy inputs for the world according to primary energy form are plotted linearly in cumulative and noncumulative form. Many features related to economic or political events appear in the figure, but no consistent patterns are visible. Initial growth of new sources appears to be exponential: The smoothness of the line for wood raises suspicion and points to artificial estimation methods.





New sources appear to grow with exponential trends. Therefore we plotted them in semi-log form. The presence of some stright lines indicates that we are moving in the right direction, but we still do not find consistent general trends allowing a precise mathematical description of the evolution in the use of the various primary energy sources.



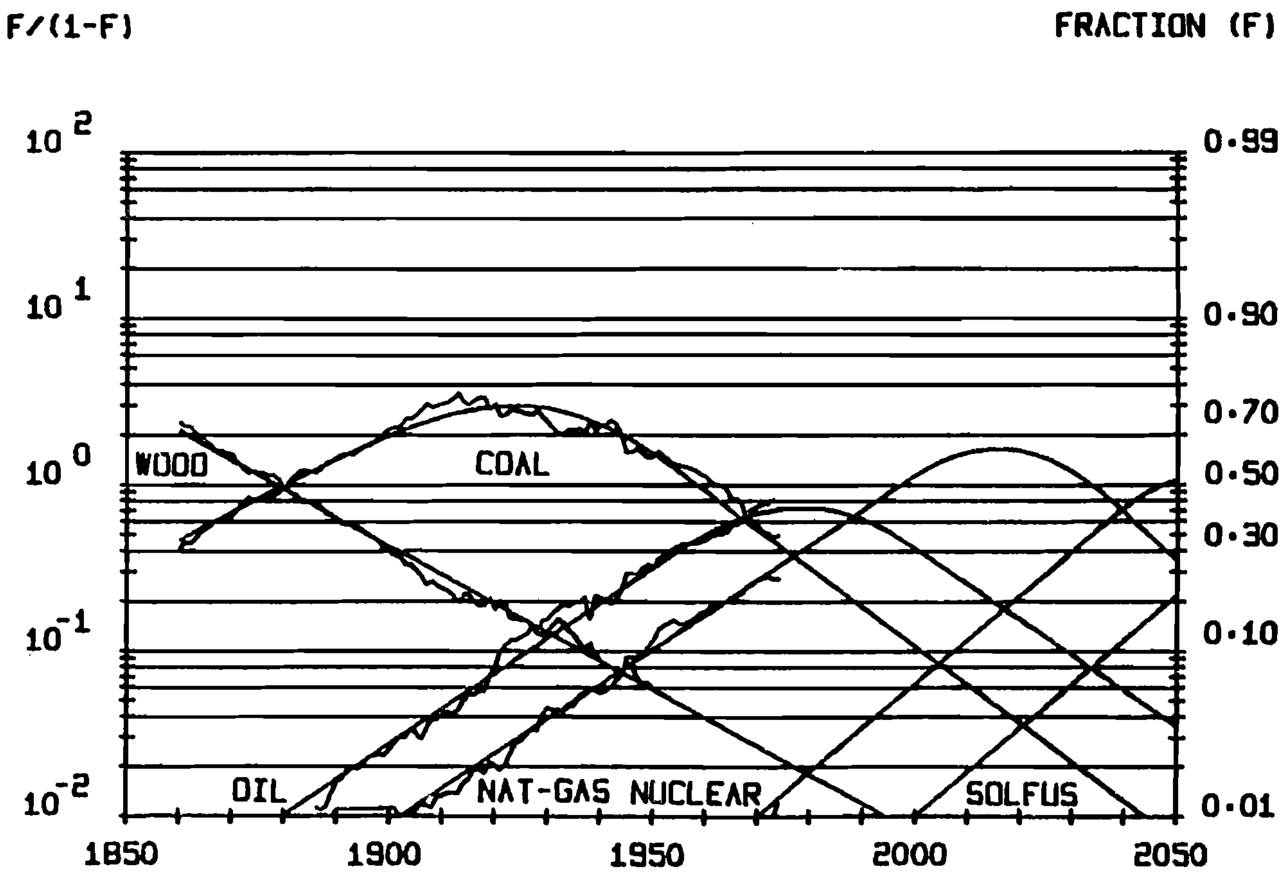
Here the contribution of the various primary sources are reported as fractions of the total market. The smooth curves are two parameter logistics assembled in a system of equations as described in the text. The fitting appears perfect for historical data.

The figure however contains two primary energy sources for which a complete fitting of the parameters was not possible. For nuclear energy the present rate of penetration is still too low to determine the slope of the penetration.

For SOLar or FUSion, the scenario is completely hypothetical. As rates of penetration where almost the same for coal, oil and gas, we assumed an equal rate for nuclear and SOLFUS, in a spirit of "business as usual".

The unexpected dominance of natural gas over the next 50 years will be discussed below.

WORLD - PRIMARY ENERGY SUBSTITUTION



W o r l d : Primary energy substitution; the log-logistic plot.

The same curves of the preceding figure are now plotted as log f/(1-f) which makes logistics appear as straight lines, greatly helping visual inspection and formal considerations.

The first fact to be observed is the extreme regularity and slowness of the substitution. It takes about 100 years to go from 1% to 50% of the market. We call this length of time the time constant of the system.

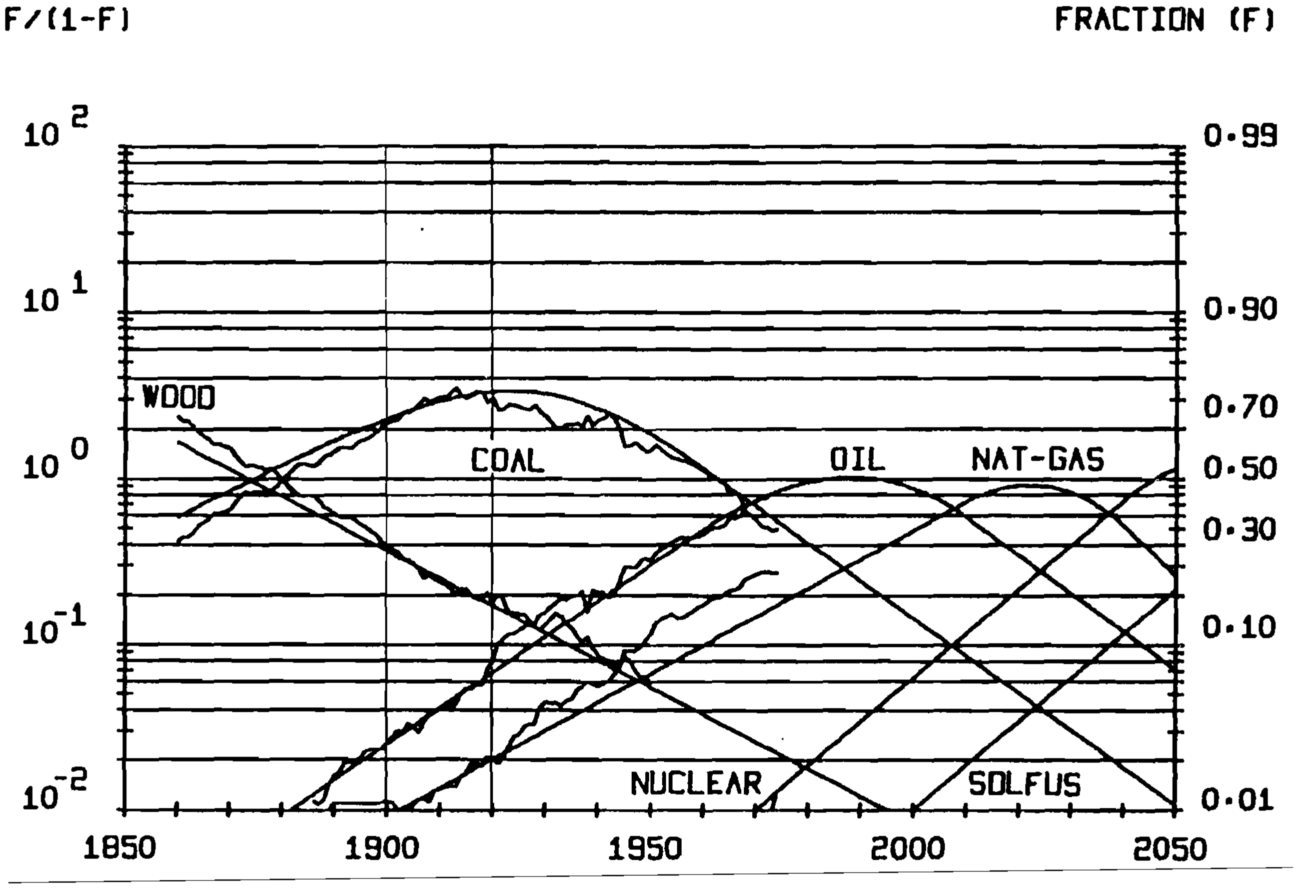
The regularity refers not only to the fact that the rate of penetration (defined as constant α in the equation and corresponding to the slope of the curves) remains constant over such very long periods when so many accelerating processes seem to take place, but also to the fact that all perturbations are reabsorbed elastically without influencing the trend. One is led to suspect that the system has a schedule, a will, and a clock.

It is also interesting to note that no source finally saturates the market. The dynamics of the introduction of new sources and the high time constant lead to maximum penetrations of 60% to 70%. This is also true for most smaller systems as will be shown later.

Nuclear achieved only a 1% share of primary energy in the 1970s; thus its future penetration rate cannot be distilled from the historical data. In 1977, 88.25 GW(th) nuclear capacity were installed, IAEA [1977]. Taking an overall utilization factor of 75% the nuclear share in primary energy consumption is about 2%.

By 1990, power plants presently under construction and planned should be in service according to IAEA [1977]; thus the total installed capacity should be at least 430 GW(th). With a rough utilization factor of 75% this corresponds to a 5% to 10% share in 1990, depending on whether we use a 2% or 3% growth rate of primary energy during the next 12 years. We have chosen a more modest nuclear share to account for possible delays in the construction of the planned power plants: Our nuclear scenario prescribes a 6% nuclear share in year 2000.

WORLD - SHORT DATA BASE



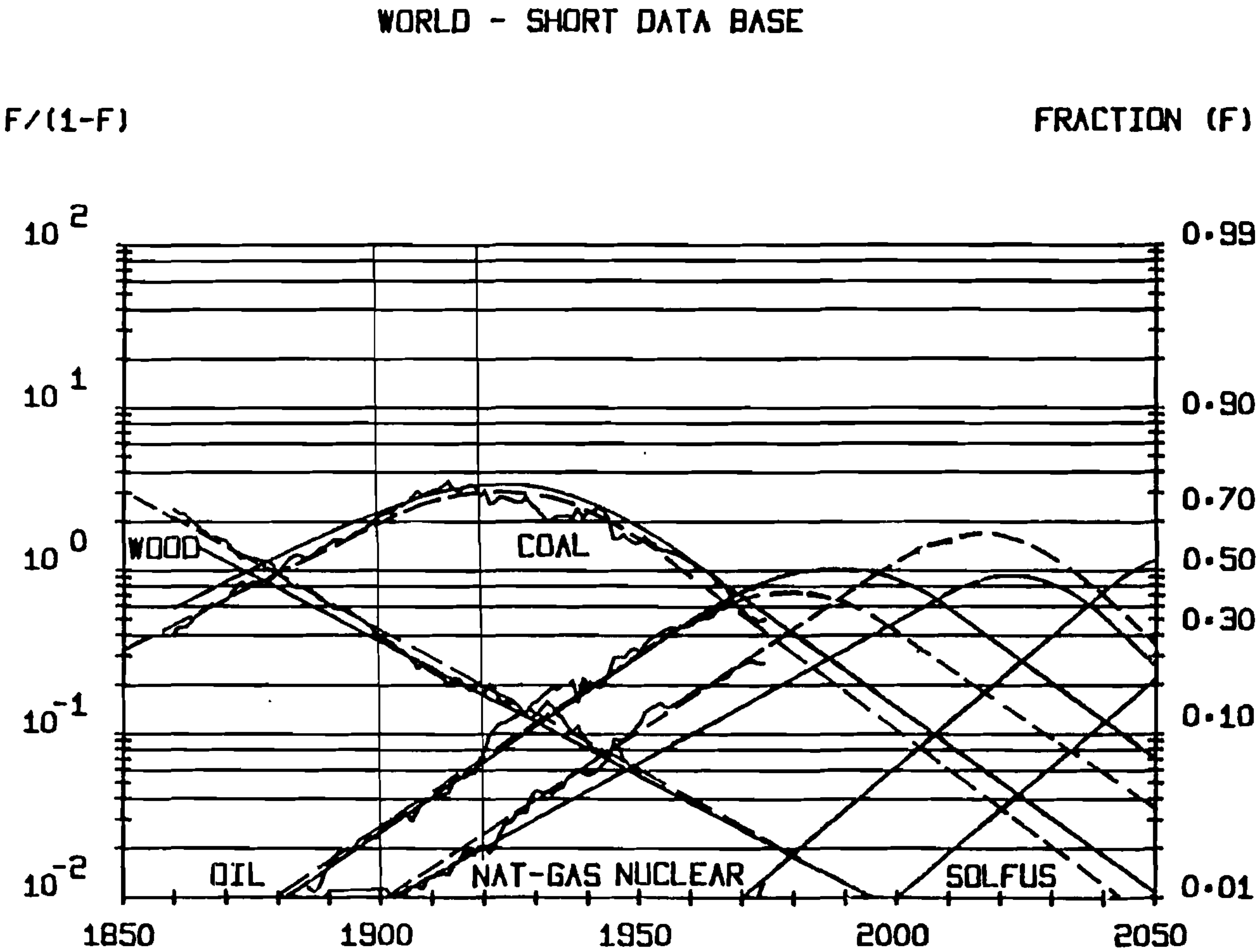
W o r l d : Primary energy substitution; short data base.

As available statistics are sometimes unreliable, have gaps lasting for long periods of time, refer to certain energy sources and not to others etc., we have tried to check the stability of the fitted functions and of the forecasts in respect to restrictions in the information base. The results are very encouraging showing that the relevant information can be extracted from relatively short data swaths.

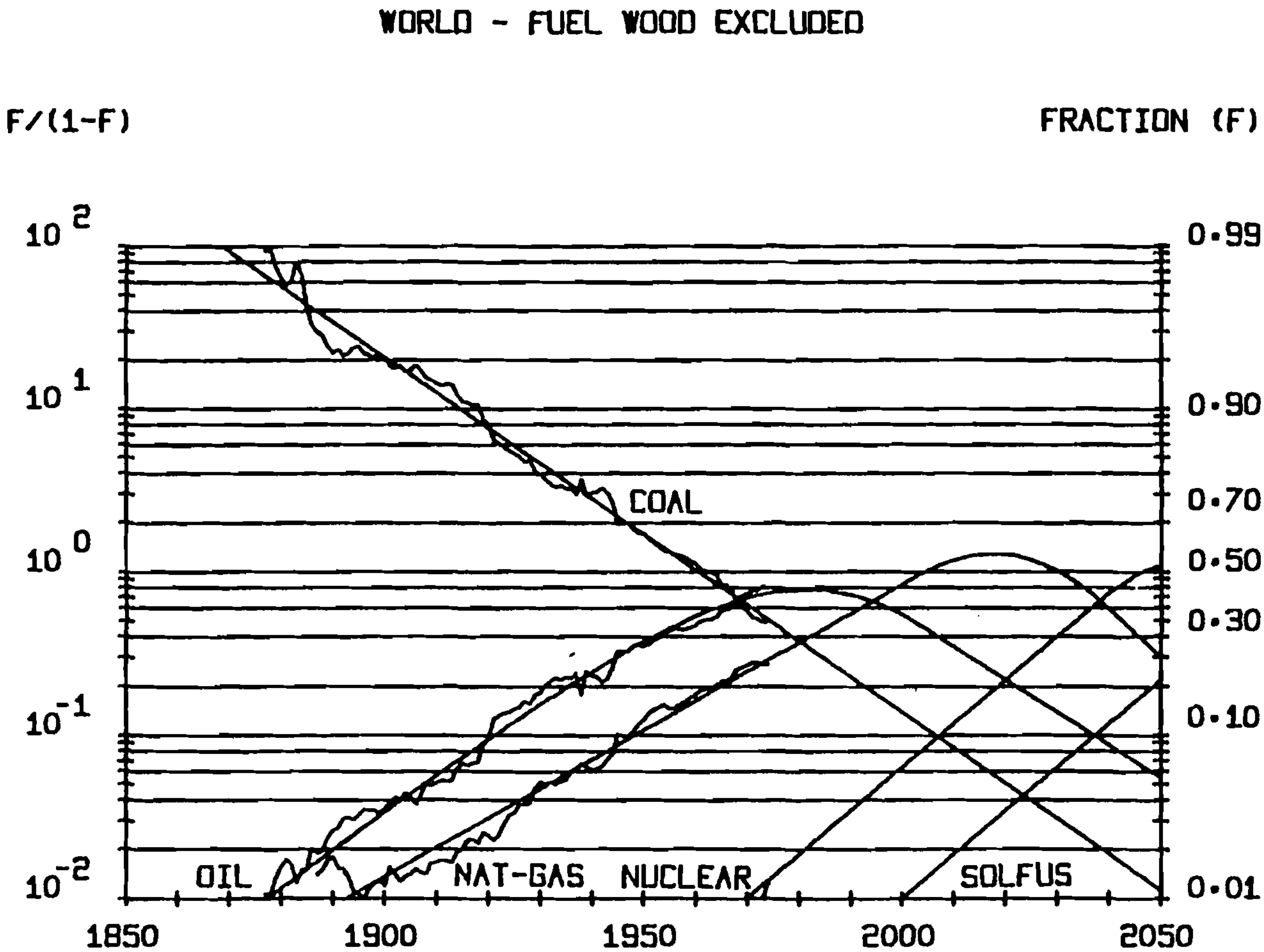
Each curve in our system can be fitted with only two points. Consequently, the large number of statistical data used serve only to reduce noise. However, 20 years of data already constitute an excellent base. We have tried then to reconstruct all the periods under examination, using only a time series of 20 years, between 1900 and 1920. This base has the disadvantage that gas has reached only a 2% share and consequently its rate is still subject to some change.

The smooth curves fitted that way still show an extraordinary agreement with the data outside the historical period. Natural gas deviates somewhat and there is an error in the "prediction" of about 7% at the end of the period. This may seem relatively large, but it is a prediction made 50 years ahead, and with a depression and a war in between!

This fact is of the greatest importance since it gives a logical support to the use of our system of equations for projections into the future, or at least serves to establish the internal consistency of the scenarios. Superposing the curves fitted on a short data base with those fitted on the complete data base shows the relatively small differences.

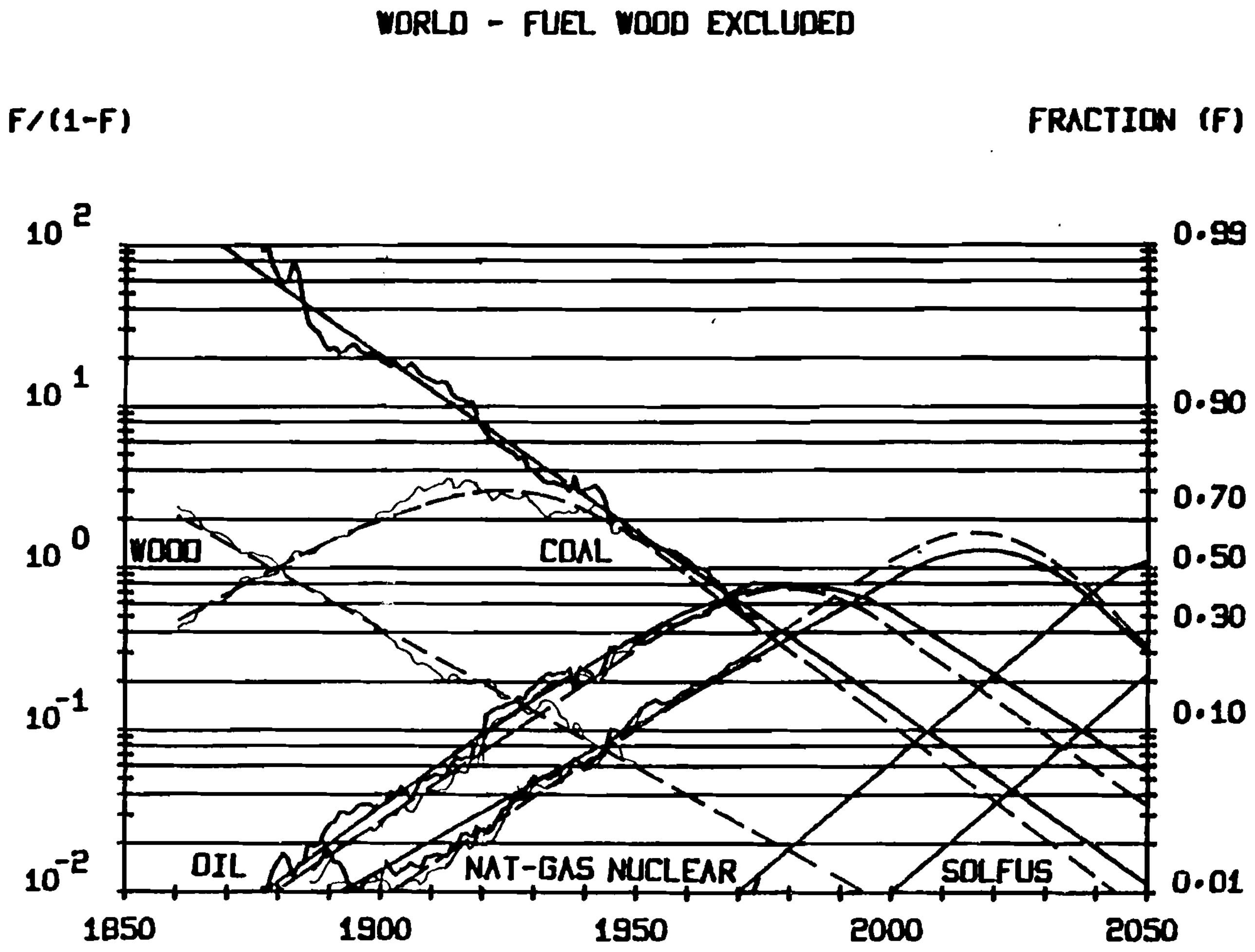


The superposition of the curves calculated with both the reduced and the extended data base, permits to better appreciate the accumulation of errors.



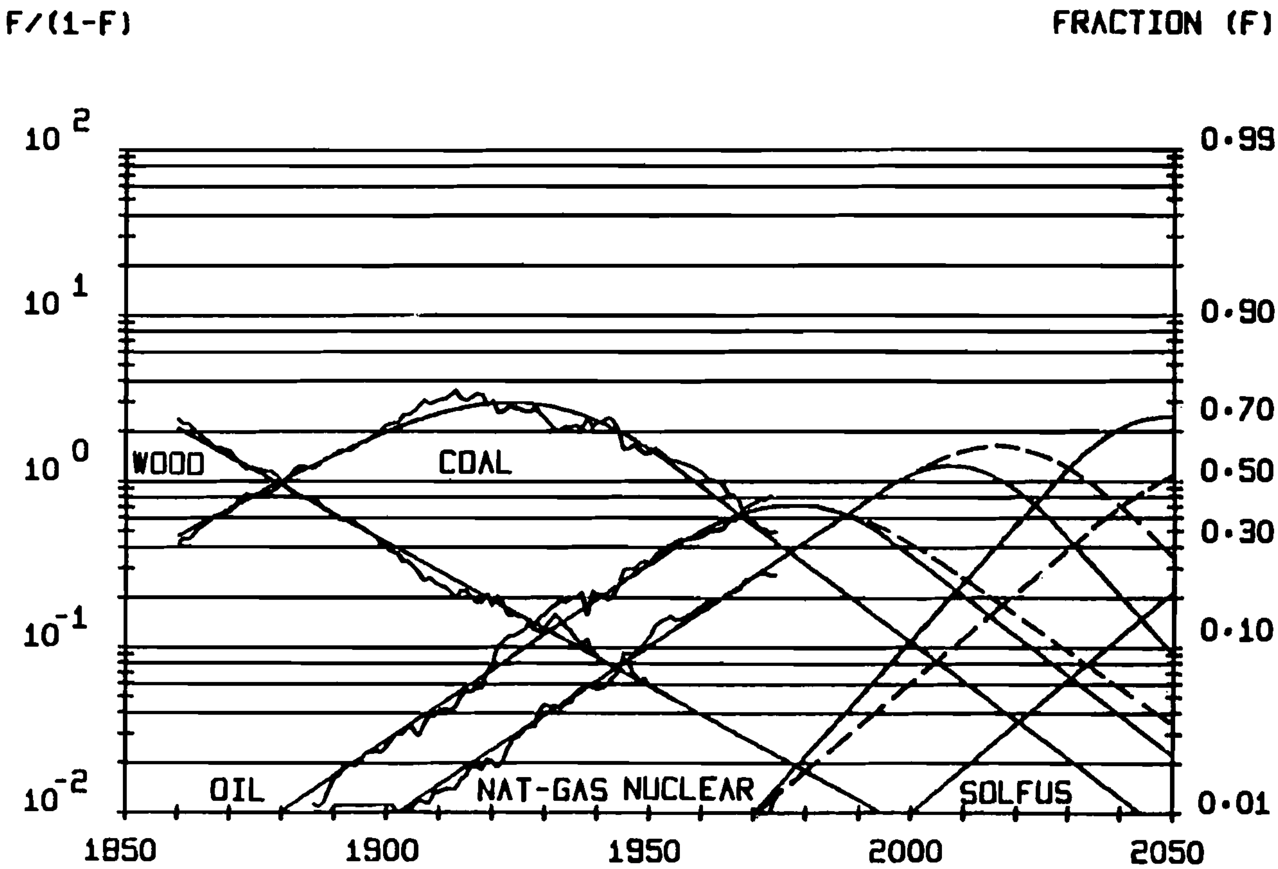
This experiment shows how much information about the total system can be extracted from structural subsets. From the complete data base we had the impression that wood statistics were too smooth to be accurate, and in a certain measure represented educated guesses of the statistical offices.

Consequently we suppressed them analyzing the competitive behavior of the other primary sources left in the market. As the figure shows the logistic description perfectly fits the subset. In the following one the curves with and without wood are superposed, to show that little information is lost when wood statistics are eliminated.



To better appreciate the level of the errors made by eliminating fuel wood data, we superposed the two sets of curves. The differences never went beyond a few percents of the market. This proves that the key information about the dynamics of the market is contained in and can be extracted from quite restricted subsets of the original data base.

WORLD - FAST AND SLOW NUCLEAR ENERGY



W o r l d : Primary energy substitution; sensitivity analysis; fast and slow nuclear penetration.

The penetration rate of nuclear energy is too uncertain if it is determined from actual statistical data. Thus we made a sensitivity analysis to see the consequences of this uncertainty.

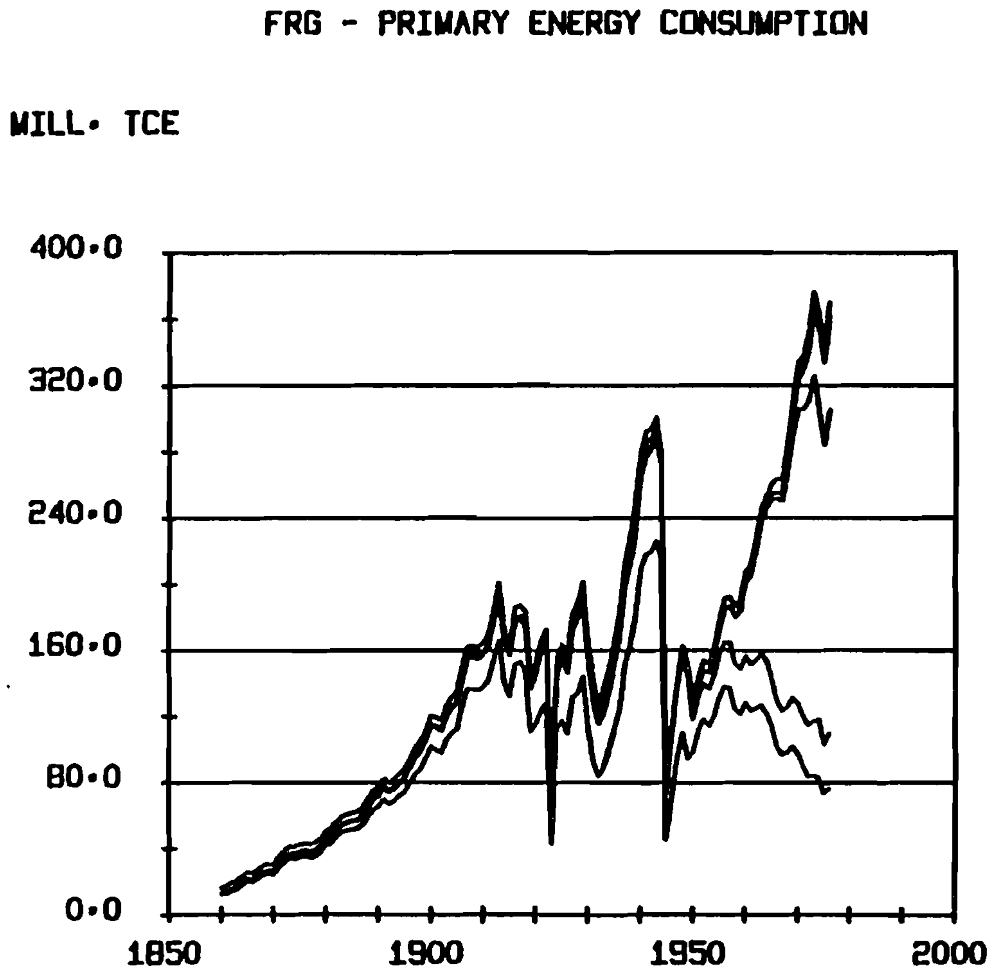
A plot with a nuclear energy share of 6% in the year 2000 and one with a 10% share in the year 2000, thus almost doubling the rate, are superposed. This graph reveals very interesting properties of the logistic competition.

Primary fuels in their way down are insensitive to a change in the rate of newcomers. They would also be insensitive to the introduction of other new sources. After the great fuss about nuclear tramping into the garden of coal, and coal being a tool to stamp out nuclear, this appears very refreshing if unexpected.

Nuclear appears to interact strongly only with natural gas, presumably preempting the markets into which it could have expanded, and interacts only very marginally with oil, which may induce despair in those who install nuclear power stations to become independent of oil imports.

The problem of resources which automatically comes to mind is not dealt with here. It appears, however, that the substistution mechanism itself takes care of it. Actually, leftovers seem a stable characteristic of the operation.

Incidentally the introduction of SOLFUS in the year 2000 would influence nuclear only around 2050.

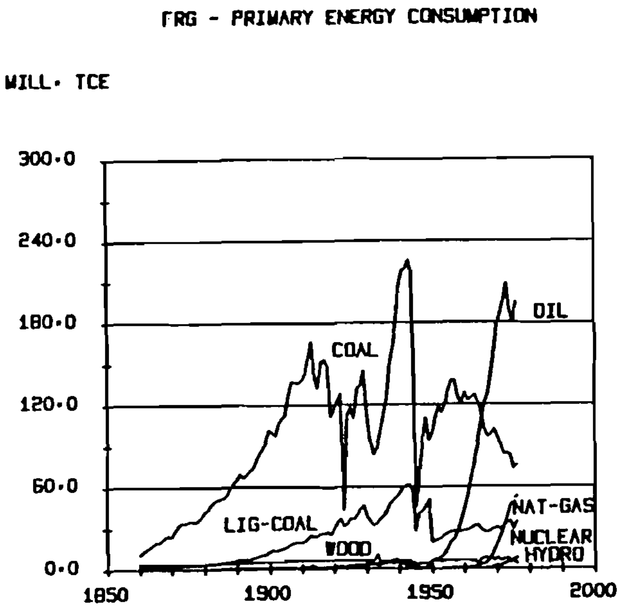


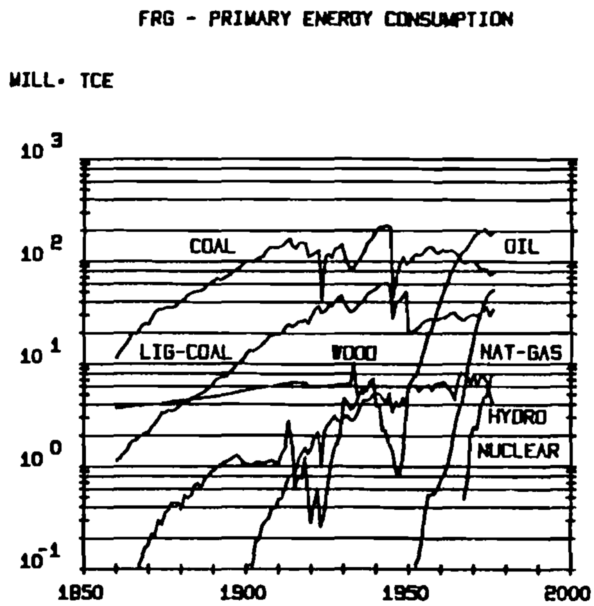
The evolution of energy consumption for Germany is reported here and in the next two figures, both in cumulative form and with the primary sources separated.

The fluctuations between the two world wars cover a perfect stagnation. It is interesting, if perhaps accidental, that the curve after 1950 matches exactly that before 1910 with the same values and the same growth rate of 4.3%. The data after 1950 however refer to the FRG only.

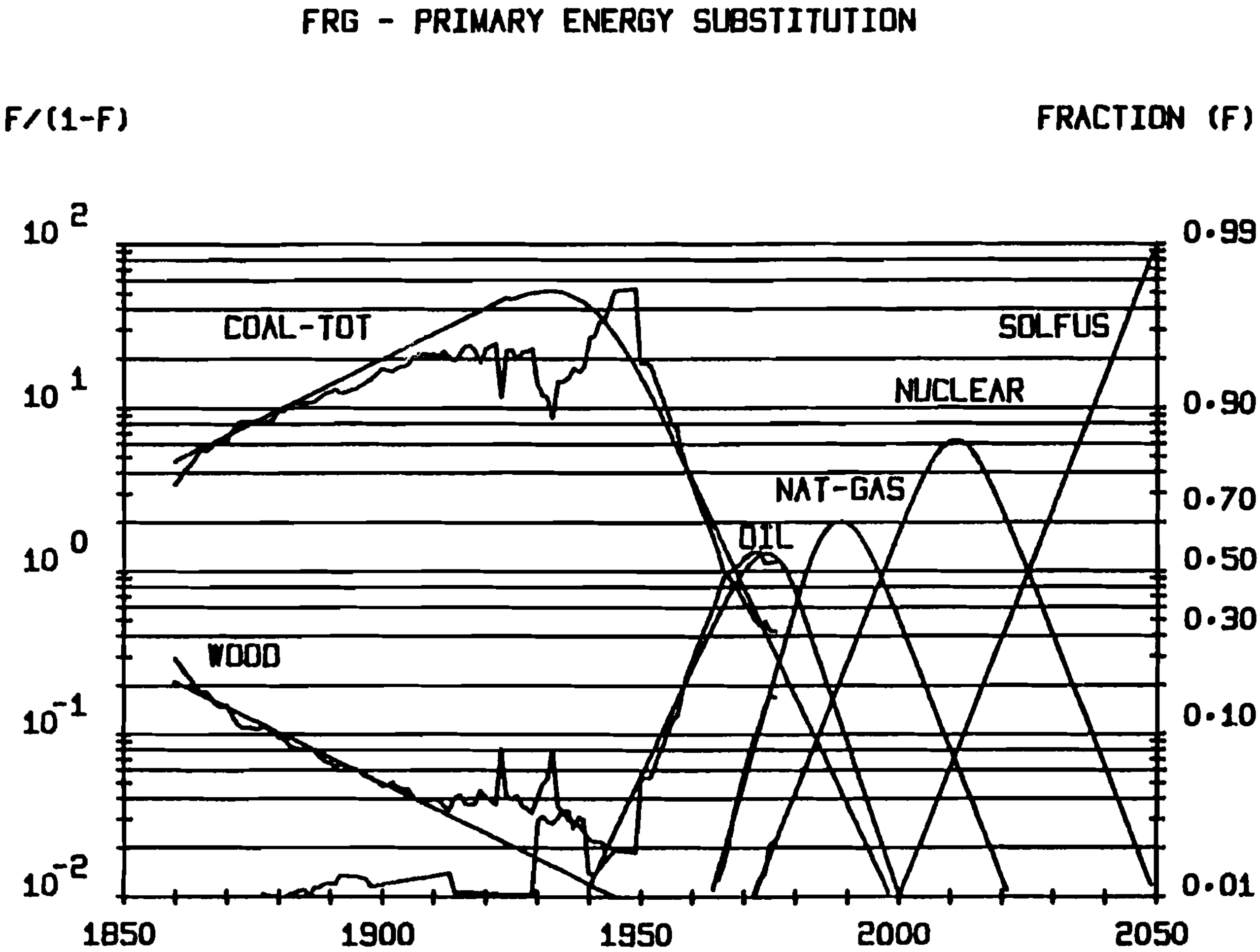
The original data for the period 1860-1974 are taken from Schilling and Hildebrandt [1977], and the data for 1975 and 1976 were calculated on the basis of energy flow diagrams for the FRG given in KFA [1977] for 1975 and by Voss [1978].

Fuel wood data were taken from Putnam [1953] and were converted from Btu into tce. No wood data were available for the FRG, but during the last three decades wood consumption had only a marginal share of primary energy. Nuclear energy inputs, given in GW(th) in IAEA [1977], were converted into tce, with a thermal to electric conversion efficiency of 33% and utilization factors of 75%.





The same data of the previous page for the various primary energy sources are reported here in linear and semilog form, which emphasizes the startup period.


FRG - PRIMARY ENERGY SUBSTITUTION
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
COAL-TOT
SOLFUS
NUCLEAR
NAT-GAS
OIL
WOOD
1850
1900
1950
2000
2050

F R G : Primary energy substitution; log-logistic plot.

The logistic analysis is reported here with wood and on the next page without it. As wood statistics tend to be unreliable, they are eliminated to avoid a source of perturbation. In both cases the scene appears fully dominated by coal before World War II. The nick for oil suddenly jumping to 3% in the thirties from a stationary 1% is unexplained and could merit further analysis. It may have something to do with the preparation of the war. Between 1945 and 1972, substitution proceeded very smoothly and logistically, with oil becoming dominant, with fairly short time constants of about 25 years, and gas promising the same performance in a suspiciously short period of 15 years. The peaking of oil consumption around 1973 in relative and absolute terms, could have been precisely predicted with data up to 1965. Thus it cannot be attributed to the oil crisis, but to forces internal to the German economy. After this crisis, however, energy consumption did not increase as before, and hydrocarbons were most affected. The swiggle in the coal curve does not seem to initiate a coal revival at the time.

There are, however, two uncertainties hidden in this straightforward projection. First, by analogy with the UK, Belgium, and up to a point France, natural gas can continue the fast initial trend beyond the usual 2% or 3%. No kink actually appears in its curve for the FRG. This means that the kink may appear later, so that we actually overestimated its rate of penetration.

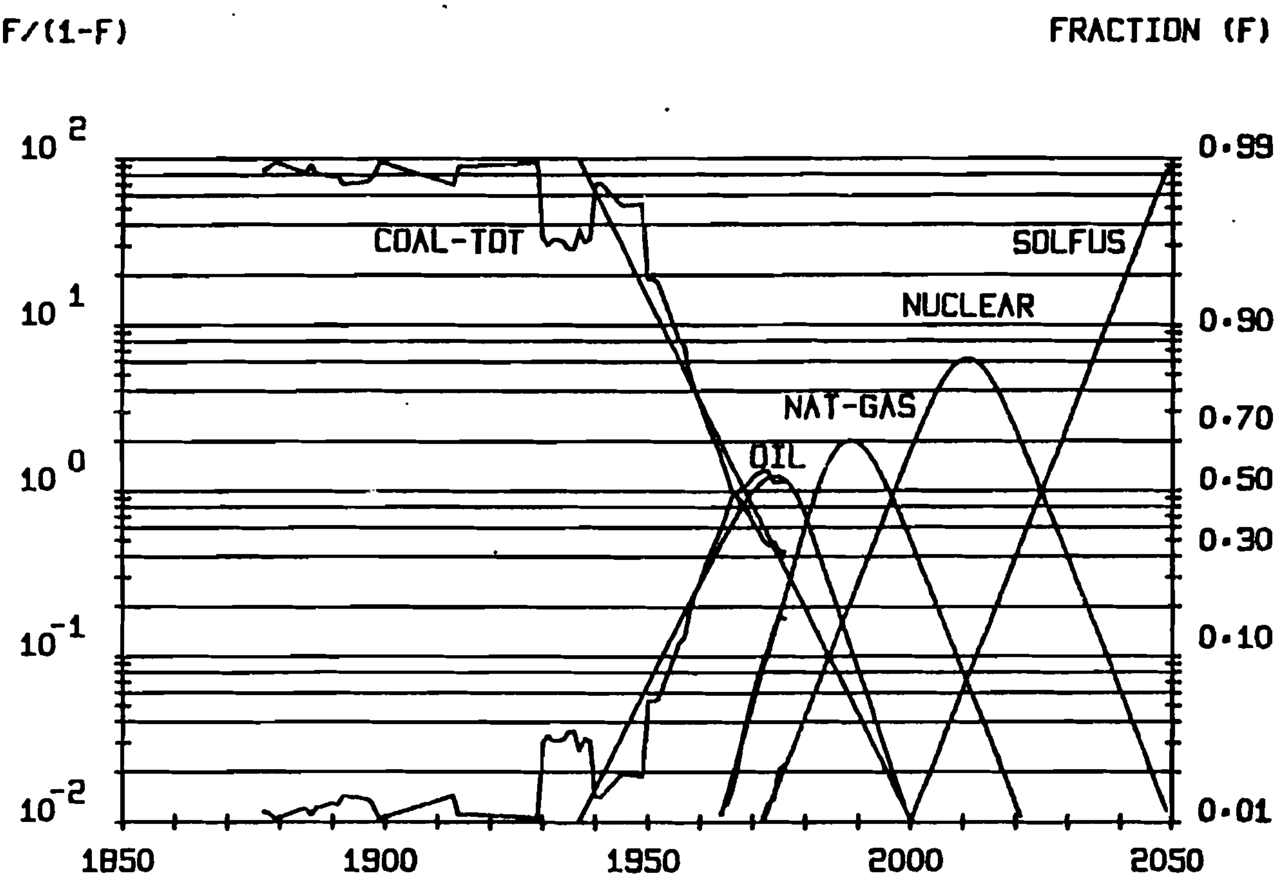
The nuclear penetration rate was estimated on the basis of historical data. However, due to its relatively low share of primary energy (2.2% in 1976) we have checked this penetration rate with the power plants presently under construction and those planned in the future.

IAEA (1977) gives a total installed capacity of 21 GW(th) in 1977 for the FRG; additional 34.3 GW(th) are now under construction and will be in commercial operation by 1982; and another 65.9 GW(th) are planned by 1985. Taking a rough utilization factor of 75% over this period, we would obtain approximately 40 million tce nuclear primary energy equivalent in 1982 and 90 million tce in 1985. Our nuclear penetration rate with a total primary energy consumption growth rate of 4.3% per year gives a nuclear primary share of 30 million tce in 1982 and of 50 million tce in 1985. Thus, our nuclear penetration rate can be characterized as being rather pessimistic on the basis of current information, and presumably realistic as a lower limit on the future role of nuclear energy in the FRG.

A SOLar or FUSion scenario has been introduced for the year 2000, with a penetration rate equal to that of nuclear energy. This keeps the system evolutionary and gives an idea about the effect of the next source on nuclear, whose fate will be sealed in the next ten years.

Altogether the FRG appears to behave normally but more dynamically than systems of similar size and structure like France or the UK.

FRG - PRIMARY ENERGY SUBSTITUTION

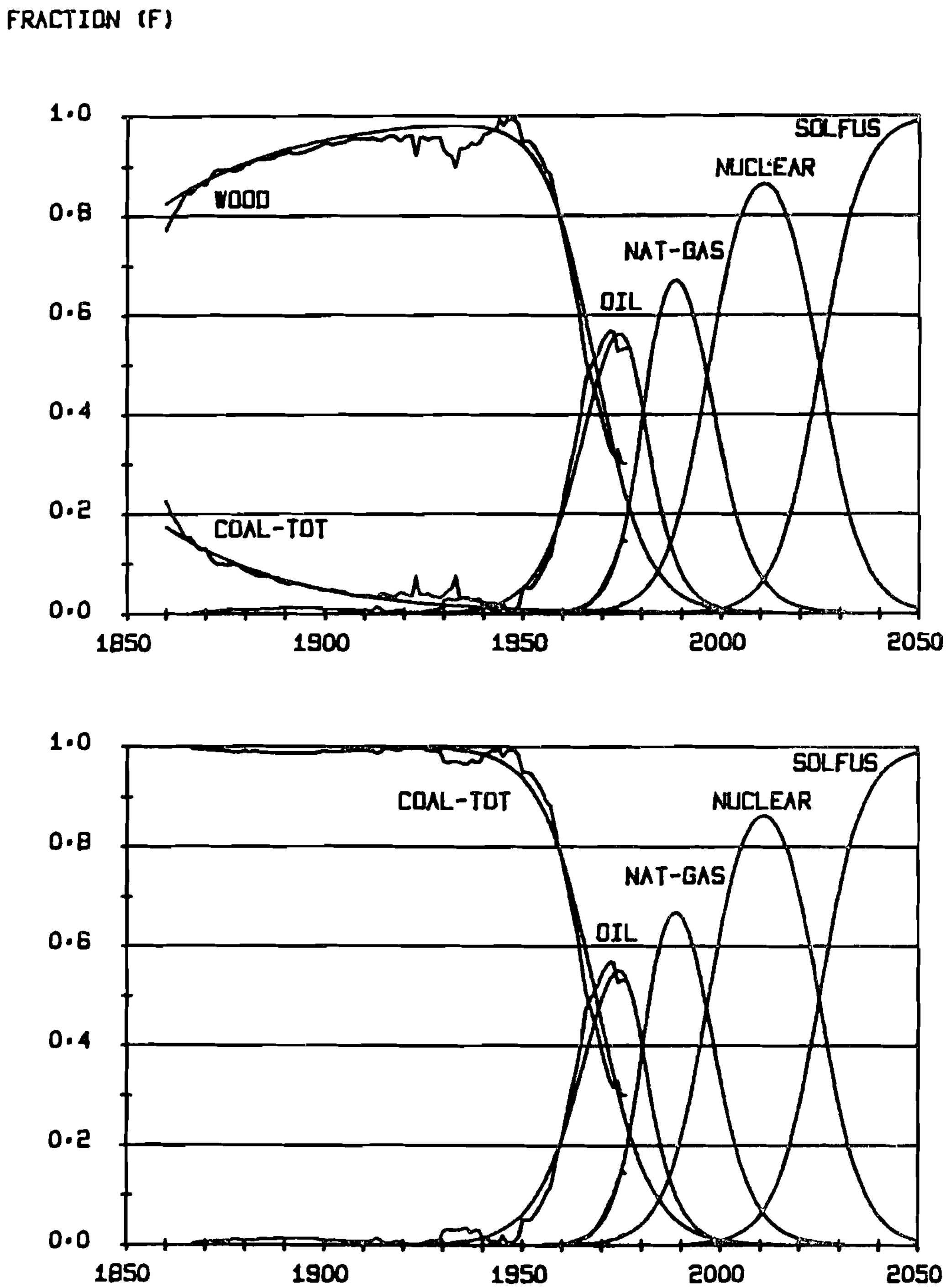


As the statistics on fuel wood are often unreliable, we have eliminated wood, and analyzed how the other fuels share the market between them.

Oil remains at a level of 1% for half a century and shows again that actual logistic market penetration starts when the market has been penetrated by a few percent.

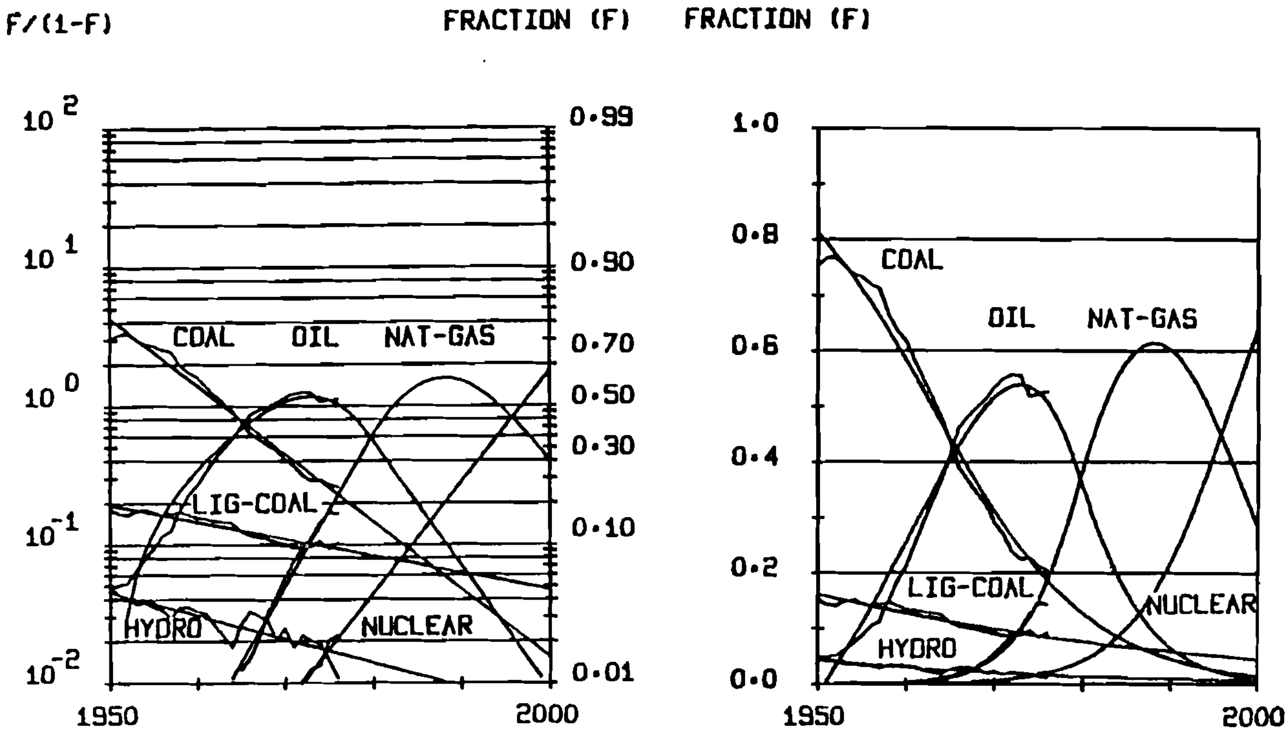
An extraordinary feature of the predictive side of the graph is that oil as a primary source of energy will practically disappear in the year 2000, a feature common to the UK, the Netherlands, and Belgium. If this happens to be true, what will cars run on by then? Perhaps on LNG, H_2, or methanol?

FRG - PRIMARY ENERGY SUBSTITUTION



These two graphs reproduce the same substitution process from the previous two pages on the linear-logistic plots with and without wood.

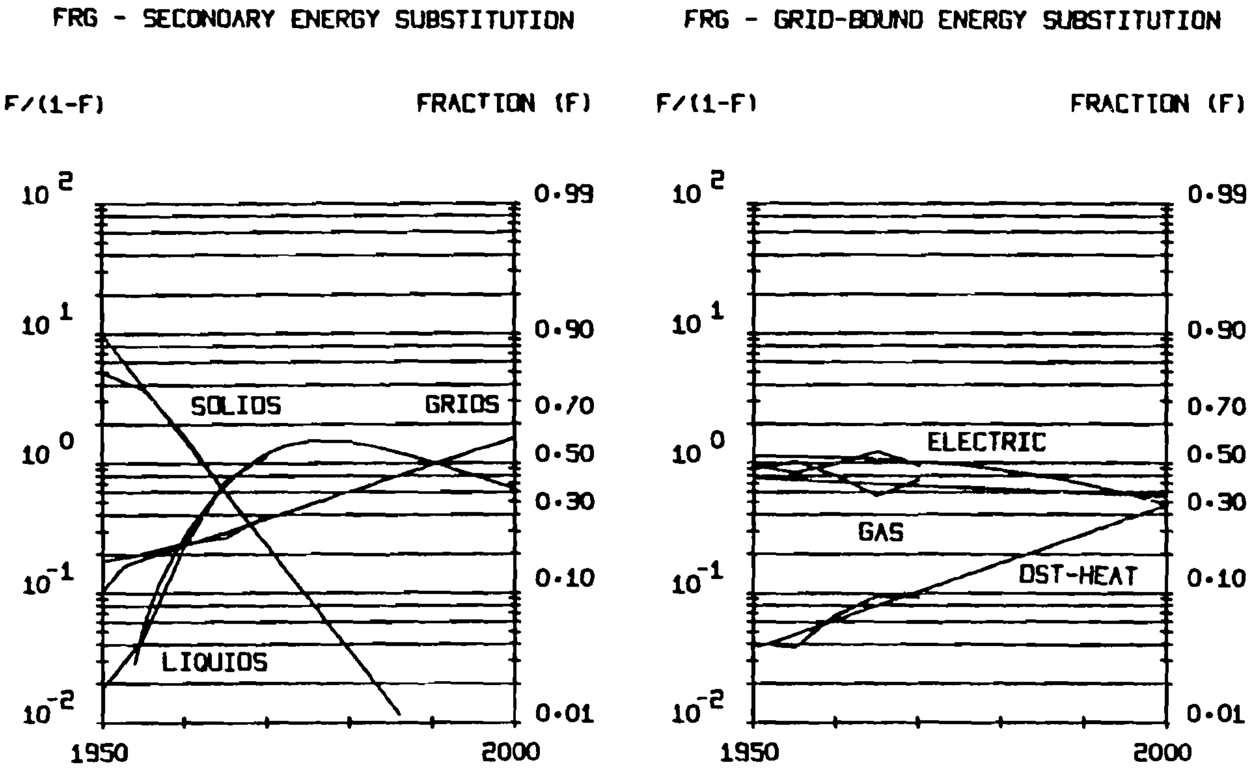
FRG - PRIMARY ENERGY SUBSTITUTION



Coal and lignite are usually lumped together in statistics, although like oil and gas they are technologically, logistically, and structurally different enough to be considered separately.

As in the past lignite production was much lower than that of coal, its trend could have been swamped into the background noise of coal statistics.

The separation of the data did appear fruitful. Lignite has its own precise trend and appears to overtake coal in the late eighties. Can it be a source of fuel for cars, e.g. via methanol?

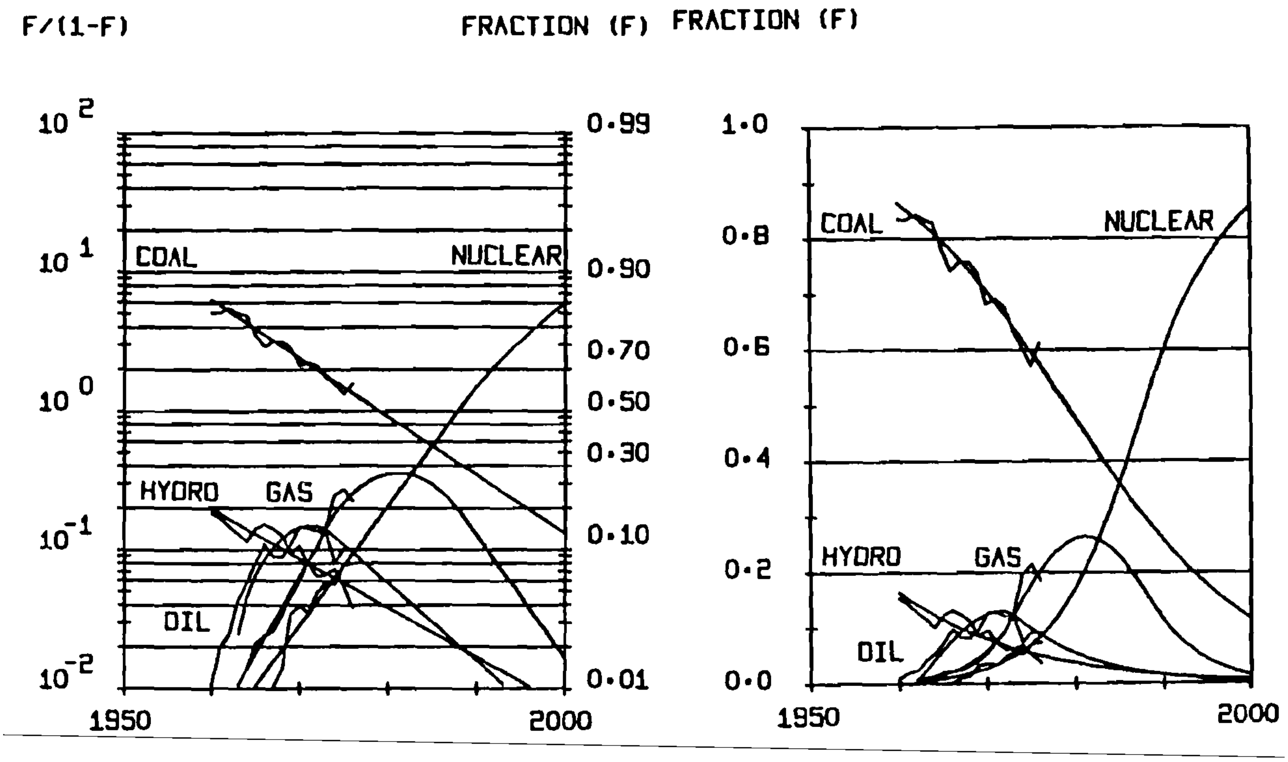


In the same way as we supposed that primary energies are technologies competing for a market, we also assumed that secondary energies behave in the same fashion.

As it could be expected, the evolution of the final energy market shares can also be described by logistic functions, showing a great future for district heating, unless a new system (perhaps H_2) is available in the next 20 years.

Historical data are from Sassin (1978).

FRG - ELECTRICITY GENRATION BY PRIMARY INPUTS



F R G : Electricity generation according to primary source.

The relatively short data base permits reasonable curves to be fitted. A longer time series would not really help since before 1950 electricity came almost exclusively from coal.

The visual impression from the garble of curves is that the German electric industry is undergoing a very fast transformation, with nuclear finally substituting coal in its dominant role with a time constant of about 20 years.

If we try to make predictions, oil and gas appear to fill a transitory gap. Hydropower is phased out of the market as a sheer effect of the market expansion.

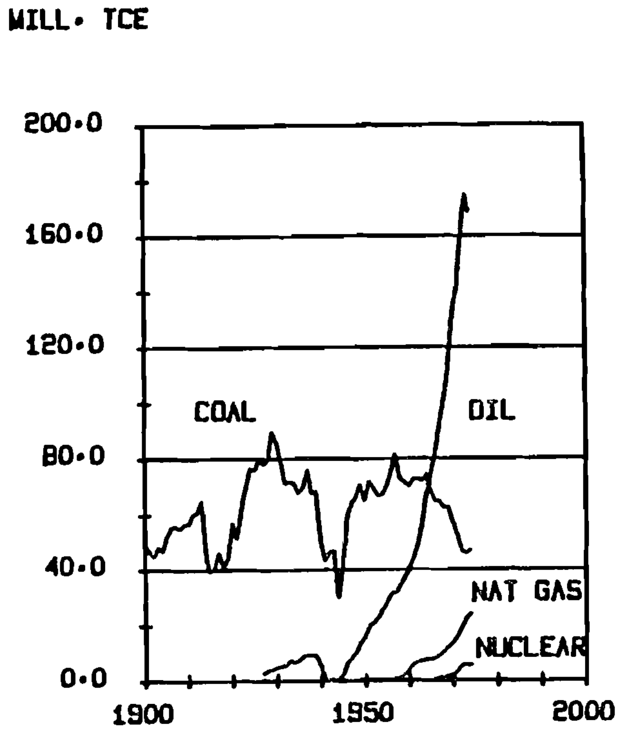
As nuclear is most suited to baseload, having very low marginal costs, a question arises about the utilization of part-time capacity available when this baseload will be saturated, which seems to occur in the mid-eighties. It is not improbable that this may spur the production of synthetic fuels from nuclear energy, and make the disappearance of oil a little more plausible.

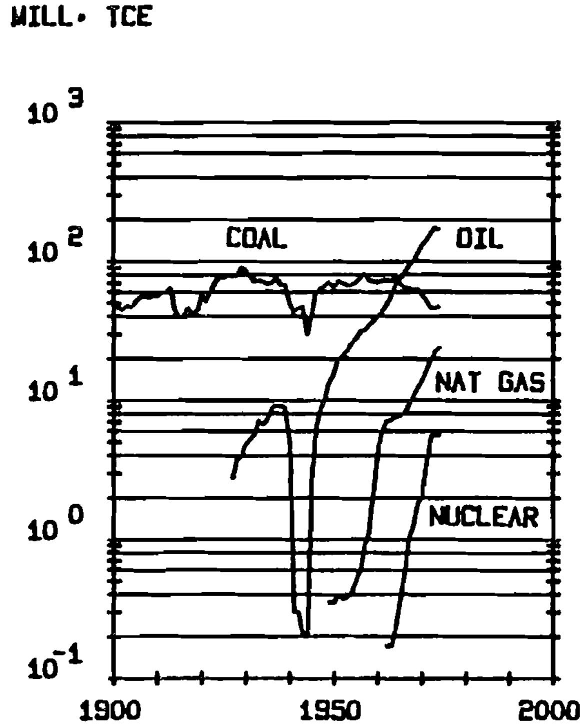
In order to crosscheck the selfconsistency of the relatively fast phase-out of coal and lignite in the primary inputs, and the relatively more sluggish disappearance in the electrical industry, we made a check with the assumption that the share of primary energy going into electricity production in the year 2000 will be less than 50%.

The electricity generation by primary energy source from 1950 to 1974 was taken from Atomwirtschaft [1976]. Data from 1950 to 1958 were only estimates; thus we did not use them. The original data are given in GW(th) electricity output. For the purpose of comparison with primary energy consumption we have converted the data into million tce. However, this conversion is not very exact since we did not account for different efficiencies of various fuels. Instead we have taken an overall average efficiency for all inputs.

Data for 1975 and 1976 were taken directly from Voss [1978] and KFA [1977] in million tce. The errors resulting from the approximate conversion to million tce are small.

FRANCE - PRIMARY ENERGY CONSUMPTION





Two sets of data were used for the generation of the substitution dynamics of primary energy for France.

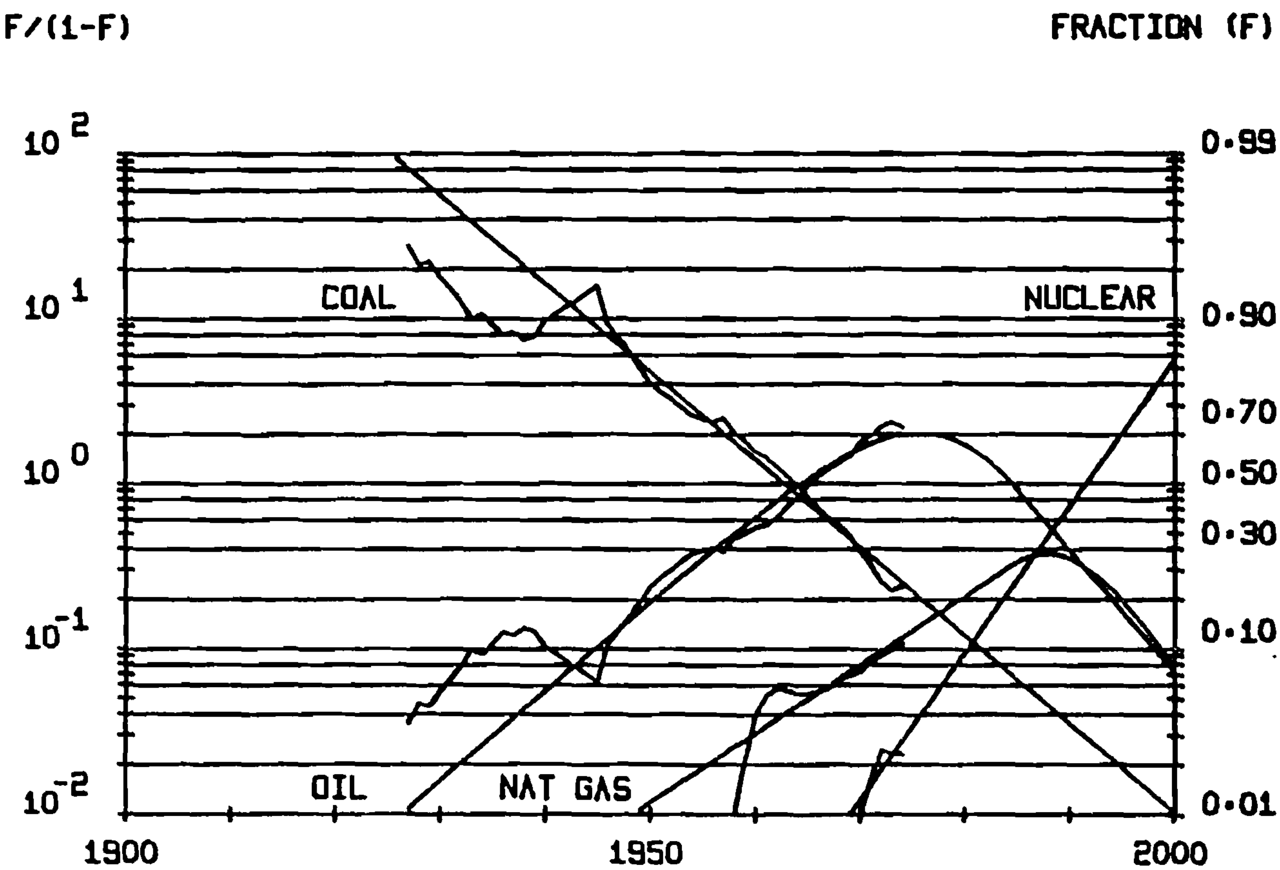
The first set is from Weitsch [1976] and was available as fractional shares of coal, oil, natural gas, and nuclear energy for the period of 1925 to 1974.

The second set comes from OECD [1976] and is reported below. The time series for coal, oil, natural gas, and nuclear are reported in million tce for the period of 1960 to 1974. Oil data contain crude oil and petro-chemical products.

The agreement of data for the overlapping period of 1960 to 1974 is very good.

The first data set is reported here in linear and semi-log form to amplify the starting period.

FRANCE - PRIMARY ENERGY SUBSTITUTION

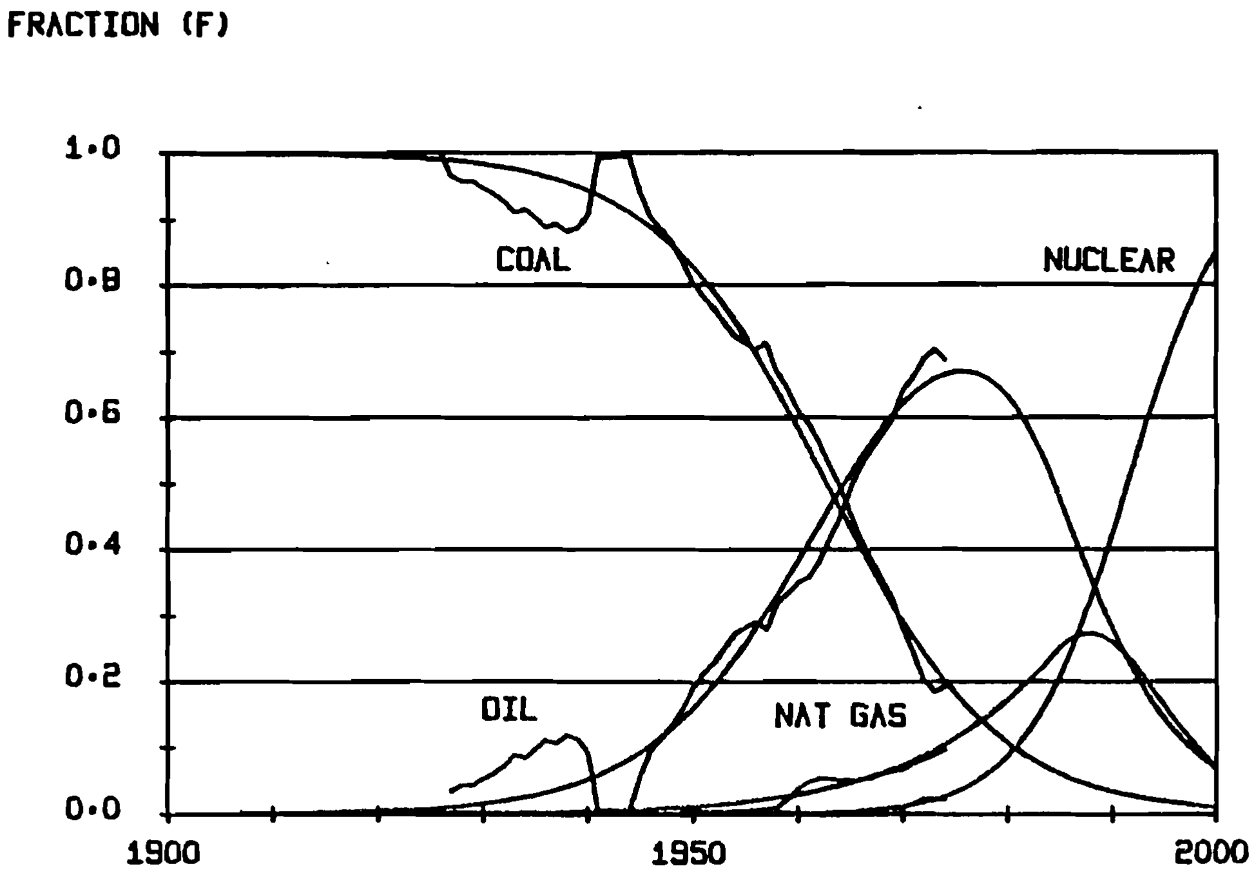


This example of the primary energy substitution indicates that France will manage a relatively smooth transition without the very problematic issues seen in the examples for the FRG.

Oil was introduced much earlier and will be phased out late. This leaves more breathing space for the question of car fuels, for instance. The dependence on oil has reached a maximum level of about two thirds of the total energy consumption. This presumably has greatly stimulated the decisions in favor of the nuclear option, whose penetration however seems to be slightly slower than in the FRG. Natural gas, which started its career at approximately the same time as in the FRG, may then last a little longer and play the same important role around the year 2000. The very fast growth up to about 7% of the market might be interpreted as the manifestation of an intensive external support (by the state?), a hypothesis that is to be verified.

A peculiarity of the curves is the twist corresponding to World War II. Everything would fit again if we assume that the French system hibernated during military occupation, and if we "cancel" the five years for which it lasted.

FRANCE - PRIMARY ENERGY SUBSTITUTION

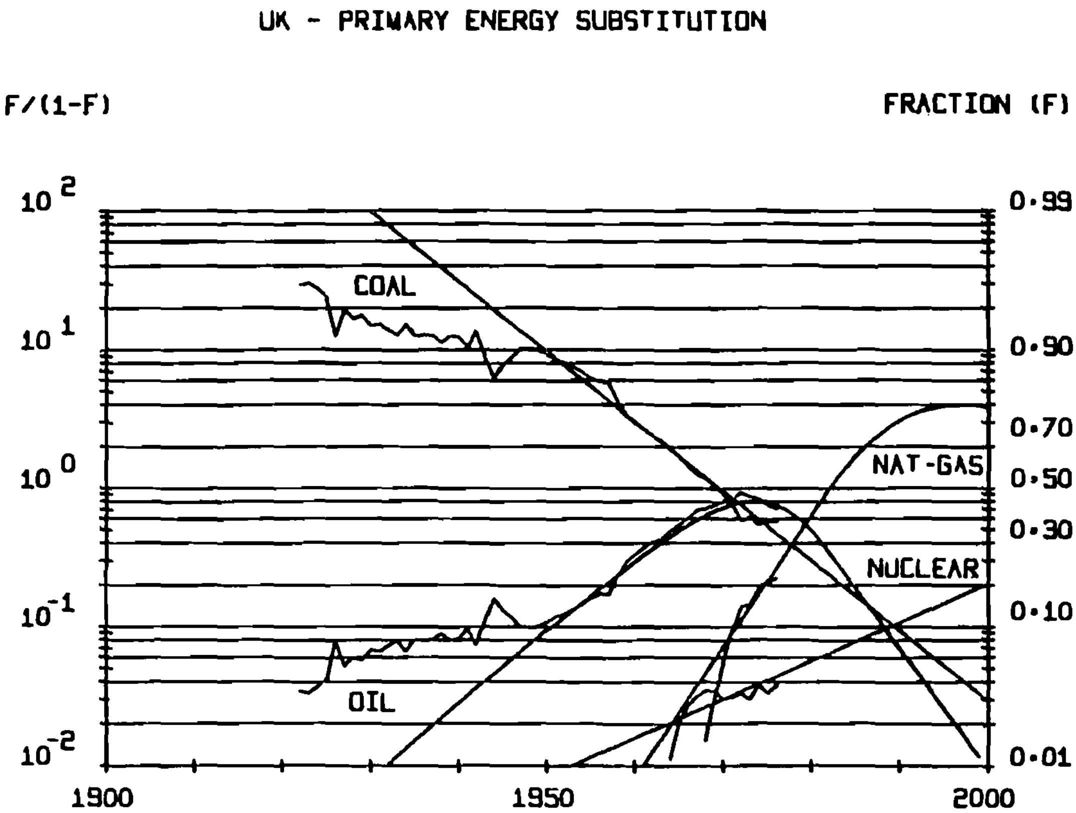


F r a n c e : Primary energy substitution; linear-logistic plot.

France seems a much less dynamic system than the FRG. Time constants are in fact about 50 years. As there are so many uncertainties facing the deployment of nuclear energy in the next decade, which is so critical for defining the pace for the rest of its penetration, we made a sensitivity study adopting two other plausible hypotheses. As expected penetration of gas is strongly related to that of nuclear, but even oil shows an important feedback. It can be deduced that nuclear is really a hot point in the energy policies of France.

Nuclear energy controlled more than 2% share of primary energy in 1972 after two years of very steep growth from a 1% share in 1970. This corresponded to 9.7 GW(th) installed capacity reported by IAEA [1977] for 1972. According to the same source, an additional 58.2 GW(th) installed capacity is under construction, whose commercial operation is expected by 1981. Together, this makes a total of 68 GW(th) installed capacity by 1981. Assuming a very high historical growth rate of energy consumption (1960 to 1974) of 5.6% per year and a power plant utilization factor of 75%, the nuclear share will be about 14% of primary energy in 1981.

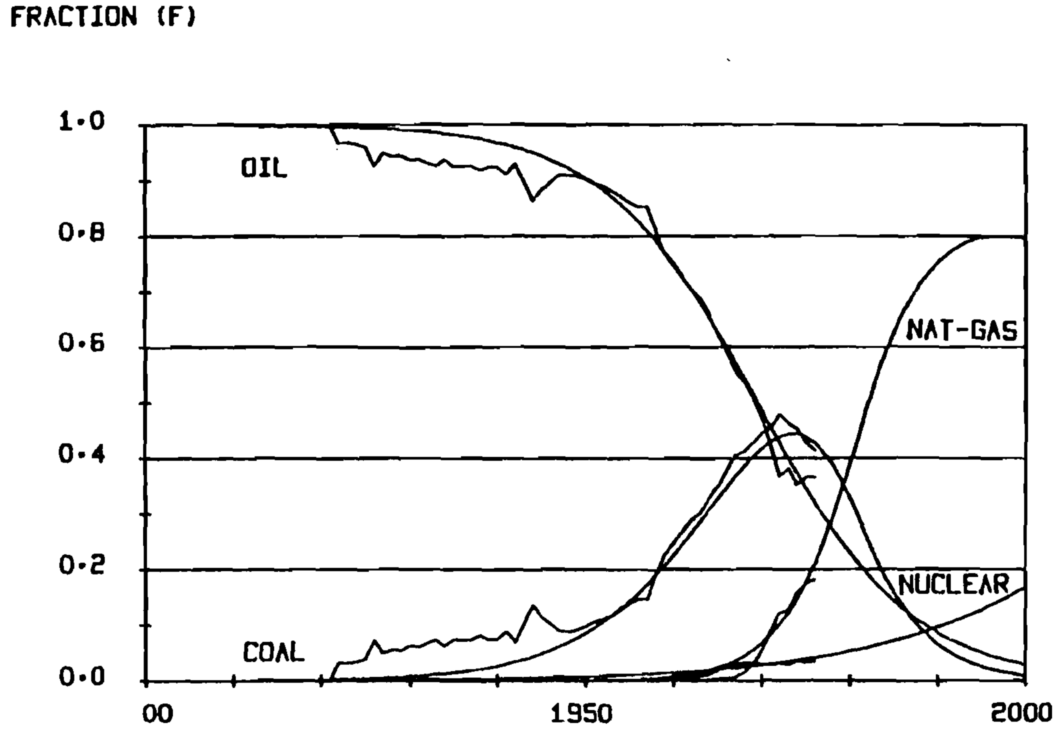
If we also include the planned power plants, we obtain a total of 94.6 GW(th) installed capacity by 1985, which also corresponds to a share of about 14% of primary energy. This calculation shows extremely rapid nuclear construction rates, and if we assume a lower energy demand during the next decade the nuclear share would be even higher. Assuming that historical rates for other substitutions also apply for nuclear its penetration would be much slower, 8% in 1980. We used that rate in our scenario, which therefore should be considered a very prudent one.



Historical data on consumption levels of coal, oil, natural gas, and nuclear energy come from three sources. The period of 1860 to 1950 has been taken from Putnam [1953], 1950 to 1974 from Ormerod, and 1975 and 1976 from the UK Department of Energy [1976] and [1977]. Data from Ormerod, however, are reported as fractional shares and therefore absolute levels are not plotted here. According to Putnam fuel wood has never been an important energy source in the UK except for some use of charcoal. It is not considered in our analysis.

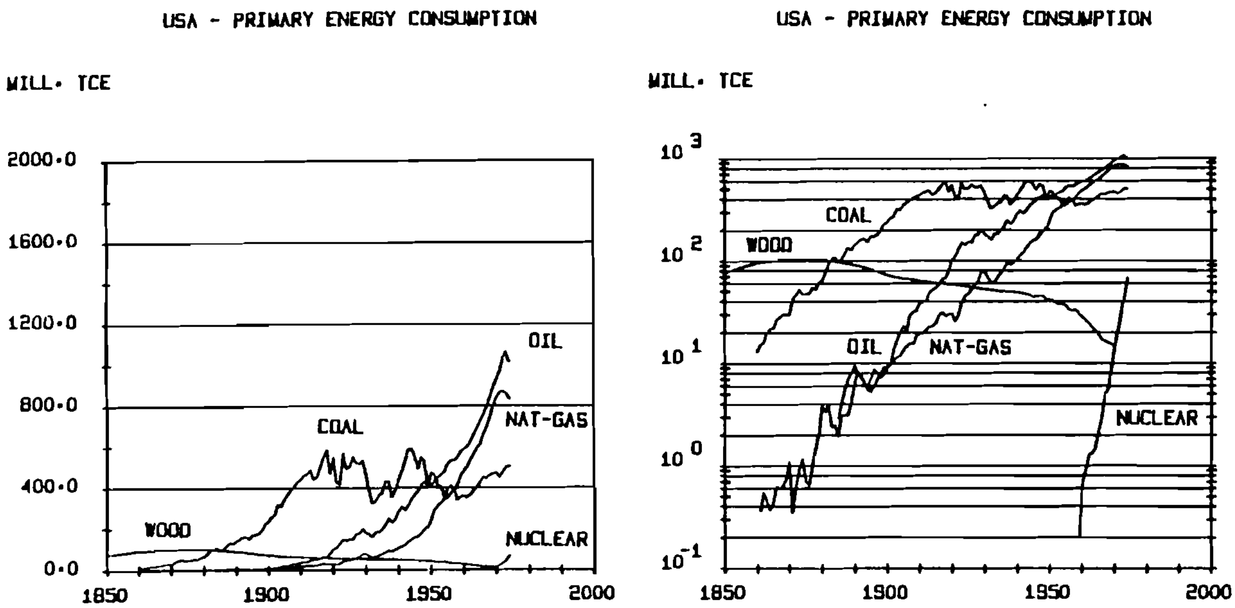
The primary energy substitution is marked by the dominance of coal on the energy market during the last century. Even in 1950 it still contributed 90% of primary energy consumption. From 1950 on, the substitution proceeded at high rates. By 1970 oil already controlled a 50% share and natural gas 10% starting at 1% in 1968. However, natural gas penetration rate has a kink in 1970 which we assume to be indicative of smaller substitution rates to be observed in the future. The very high pre-1970 trend could be explained by the already existing gas distribution net work being serviced by city gas (i.e. mainly coal), which natural gas simply took over and saturated by 1970 so that it did not face usual growth limitations of the new technologies. Therefore, we use only points after 1969 to estimate the natural gas penetration trend.

UK - PRIMARY ENERGY SUBSTITUTION



This plot shows that although nuclear energy had a very fast start in 1964, later it slowed down considerably. Today there are 24 GW(th) installed nuclear capacity, which at the current utilization rate is about 4% of primary energy consumption. Additional 9 GW(th) are under construction and expected to be in commercial operation by 1979. Another 3.23 GW(th) are planned by 1986. This makes a total of 36.3 GW(th) installed capacity to be in operation by 1986.

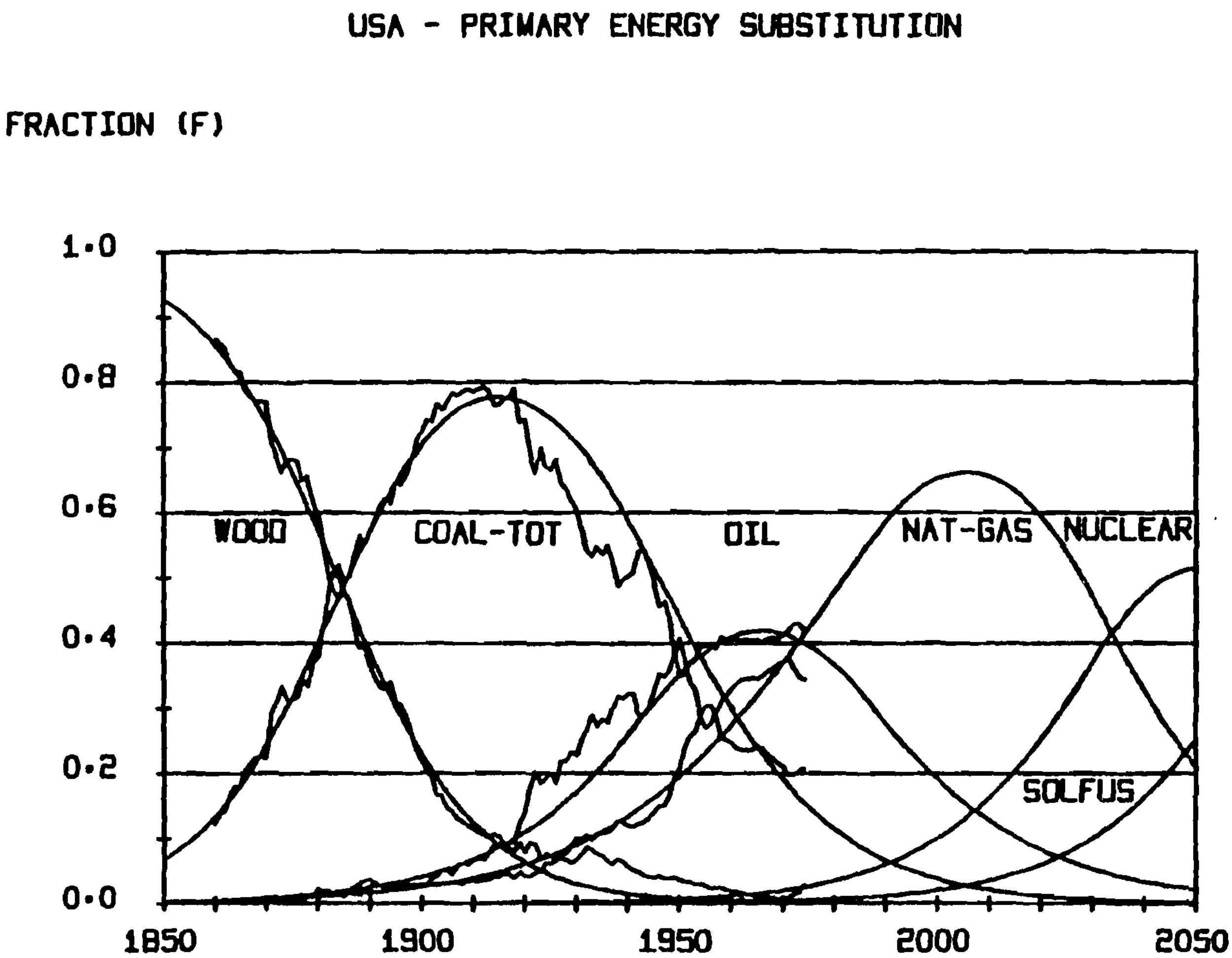
With a utilization factor of 75% and the current growth rate in energy consumption of 3% per year, this would give a 7% market share by 1986. We took 6%.



The historical data on primary energy consumption in the USA since 1860 were taken from Schilling and Hildebrandt [1977] for coal, oil, natural gas, and nuclear energy.

All data were reported in million tce except nuclear energy. Nuclear consumption rates were reported in million kWh, and we converted them to million tce.

Fuel wood time series come from the US Department of Commerce [1975] for the period of 1860 to 1970. The wood consumption after 1970 was negligible, thus it was not necessary to add the last few years. The actual source for the data on wood from 1860 to 1945 is Resources for the Future [1960], which in turn has used two different sources: 1850 to 1930 Reynolds and Pierson [1942], and 1935 to 1955 is based on USDA [1958]. Thus, the discontinuity in the penetration rate of fuel wood in the 1930s should be attributed to discrepancies between the two sources.

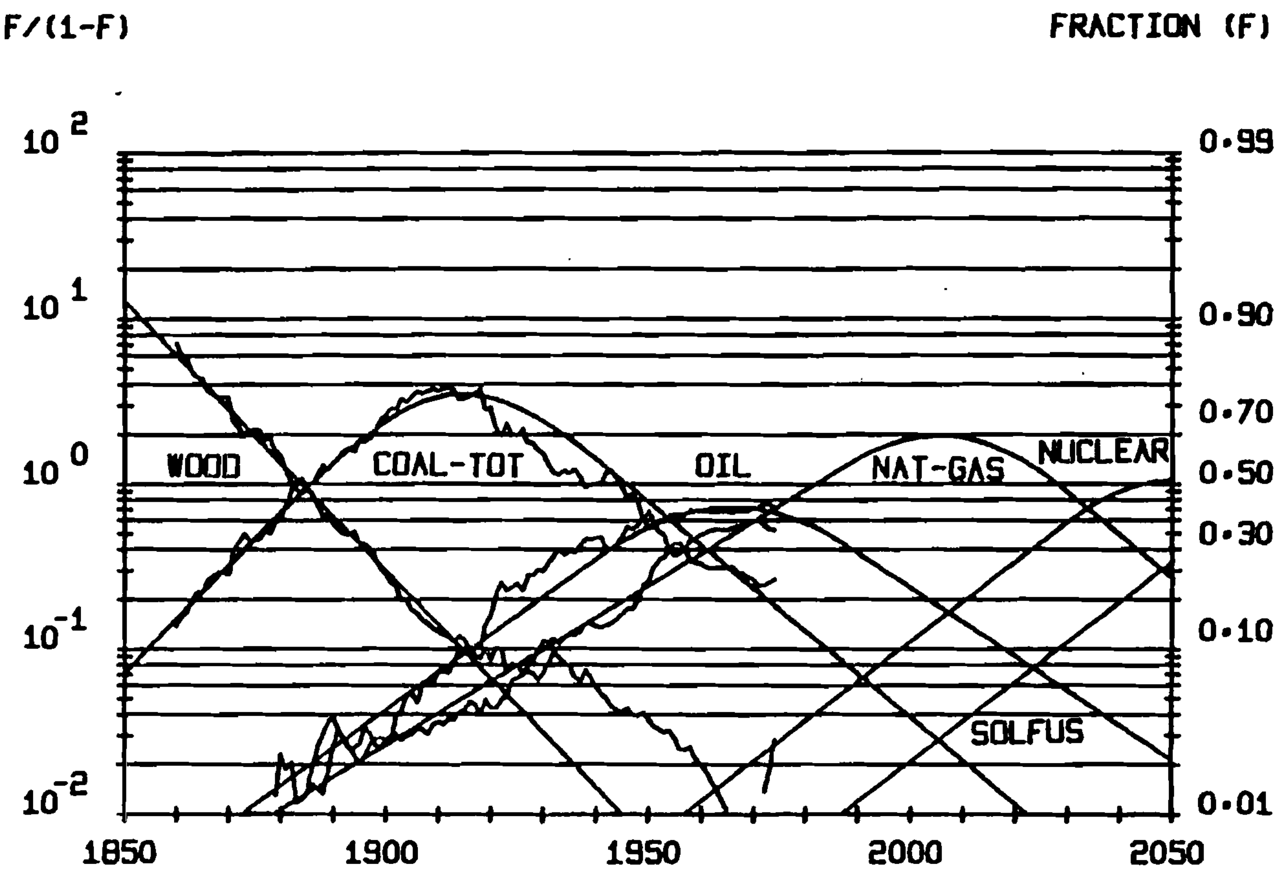


The logistic analysis again puts order in the mess of statistical data. Substitution appears to move extremely smooth until 1920, in agreement with other economic indicators. Coal peaks around that date and oil at the beginning of the sixties, namely 40 years later.

It must be clear that in 1900 both peaks could have been predicted with good precision; consequently they are not linked to forthcoming events like wars or embargos. Here, as in all the other cases examined, embargos and large price increases did actually produce disproportionately small dents in the curves.

The deviation in the lowest part of the wood curve is connected to a change in the statistical sources, and most probably due to a change in the accounting and estimating method.

USA - PRIMARY ENERGY SUBSTITUTION



U S : Primary energy substitution; log-logistic plot.

One thing left to be explained is the sudden drop in coal production, much below the trend line, essentially during the depression years. This drop induced a corresponding high share of oil, but it does not affect gas. The analysis should perhaps look deeper into the organization or reorganization of the coal industry. The striking fact in the process, however, is that after a while the perturbation is reabsorbed and the secular trend taken over again in 1940, 20 years later! This again points to system memory and clocks!

Contrary to all other predictions natural gas appears to be the dominating energy source for the next 50 years, which leads to the question whether the US will become a larger importer of natural gas from Canada, Mexico and via LNG, or whether the numerous "harder" sources, like geopressurized zones, will be put to work.

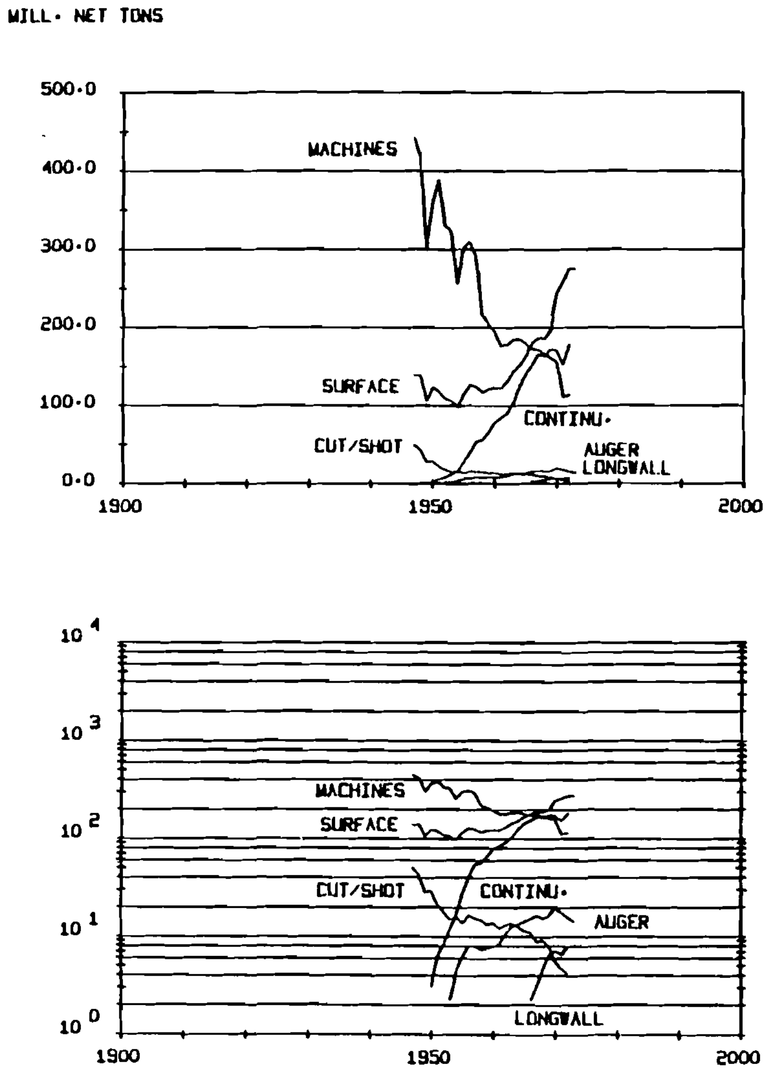
The nuclear market share in the US was about 3% of the primary energy in 1974 and about 5% in 1977. This, however, may still not be enough to determine the long-term trend of nuclear penetration rates. By 1990 there should be about 610 GW(th) installed capacity. This estimate is based on the power plants presently under construction and those planned to be in service by 1990, IAEA [1977].

With the long-term energy consumption growth of 3% per year this would imply a 15% share in 1990, assuming an overall utilization factor of 75%. To account for all possible delays in our nuclear scenario, we assumed a 10% share by the year 2000.

We have also included an alternative future energy source (SOLar-FUSion) to enter the market in 1990 with the same penetration rate as nuclear. There is no base whatsoever for this assumption, except that a new source would not reach a 1% market share before then.

As in the world case, a change in the rate of penetration for nuclear will not change the situation of oil, and only after year 2000, that of natural gas.

USA - COAL PRODUCTION BY MINING METHOD

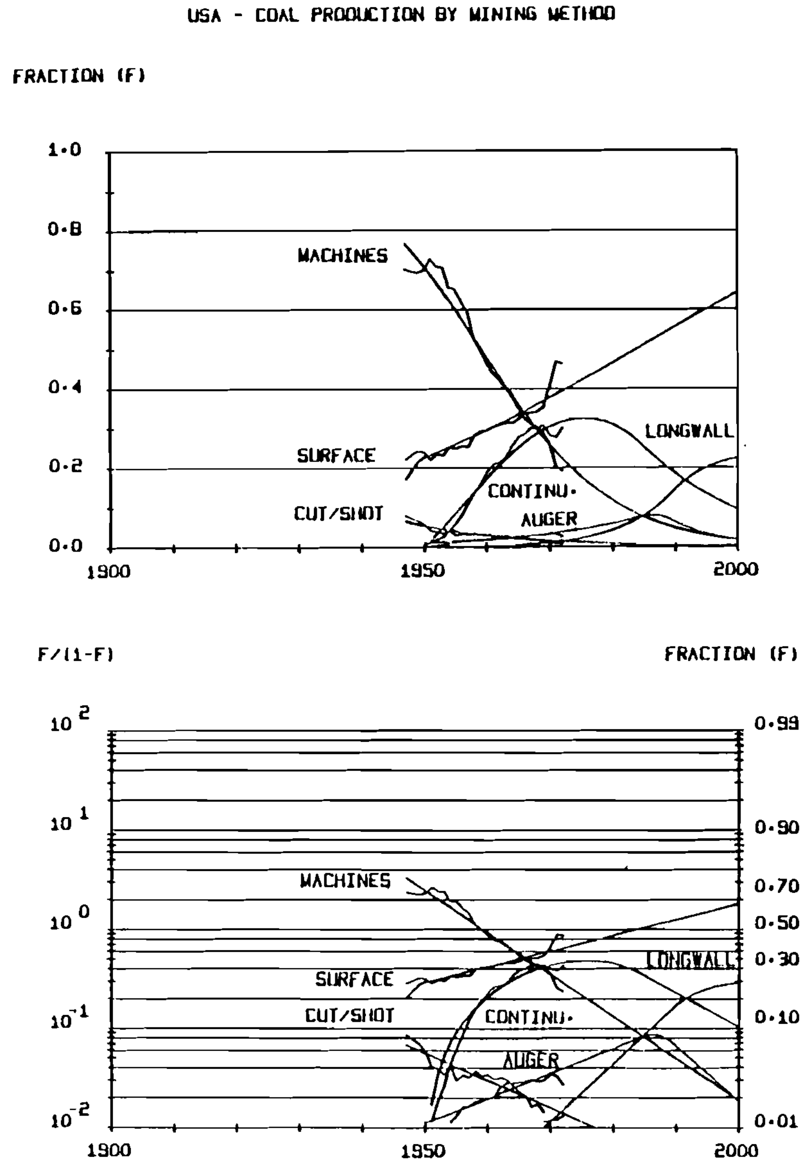


The evolution of mining techniques is examined here. It is a very appropriate field for logistic substitution analysis.

In these two figures the amount of coal extracted according to the various techniques are reported in linear and semilog coordinates. As usual, no simple patterns appear.

The various methods of mining are labeled on the plots according to the following list:

CUT/SHOT	-	cut by hand and shot from solid
CONTINU.	-	mined by continuous mining machines
LONGWALL	-	mined by longwall machines
MACHINES	-	cut by machines
AUGER	-	mined at Auger mines
SURFACE	-	from surface mines.

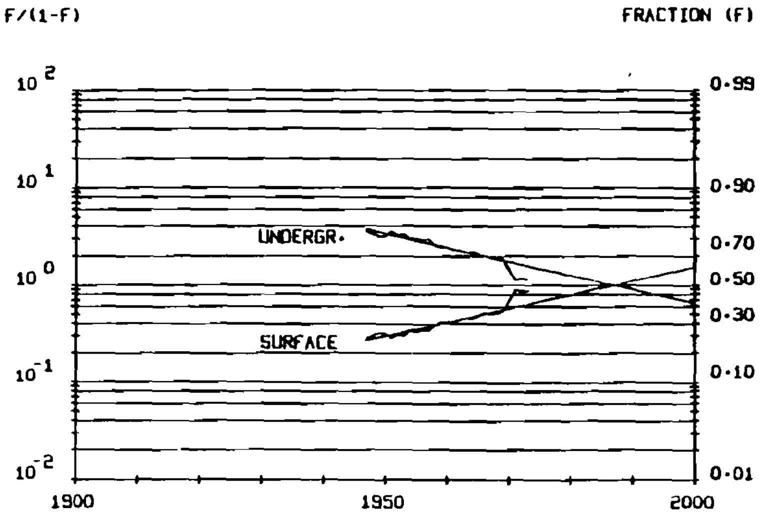


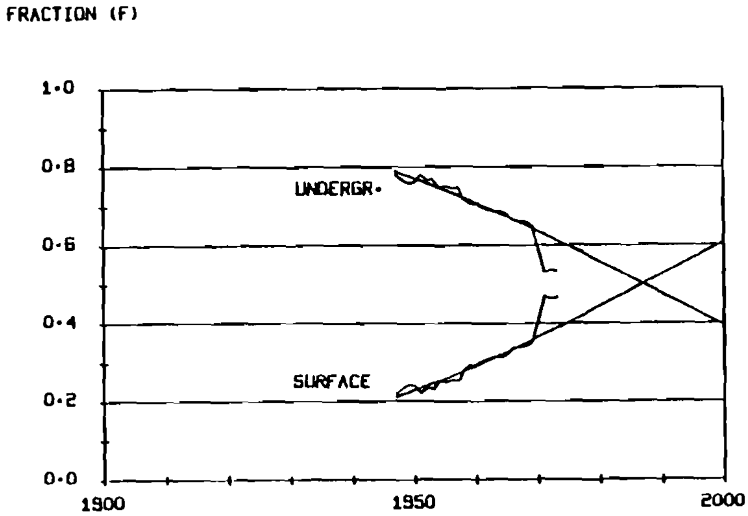
In these two figures the logistic substitution analysis is reported in the usual two presentations, linear and logarithmic. Very consistent patterns are revealed showing mining technologies competing as such in the usual way. It is also interesting that our methodology to treat multiple competition appears to work well even in this case where at times there are six different technologies in the market.

The various methods of mining are labeled on the plots according to the following list:

CUT/SHOT - cut by hand and shot from solid
CONTINU. - mined by continuous mining machines
LONGWALL - mined by longwall machines
MACHINES - cut by machines
AUGER - mined at Auger mines
SURFACE - from surface mines.

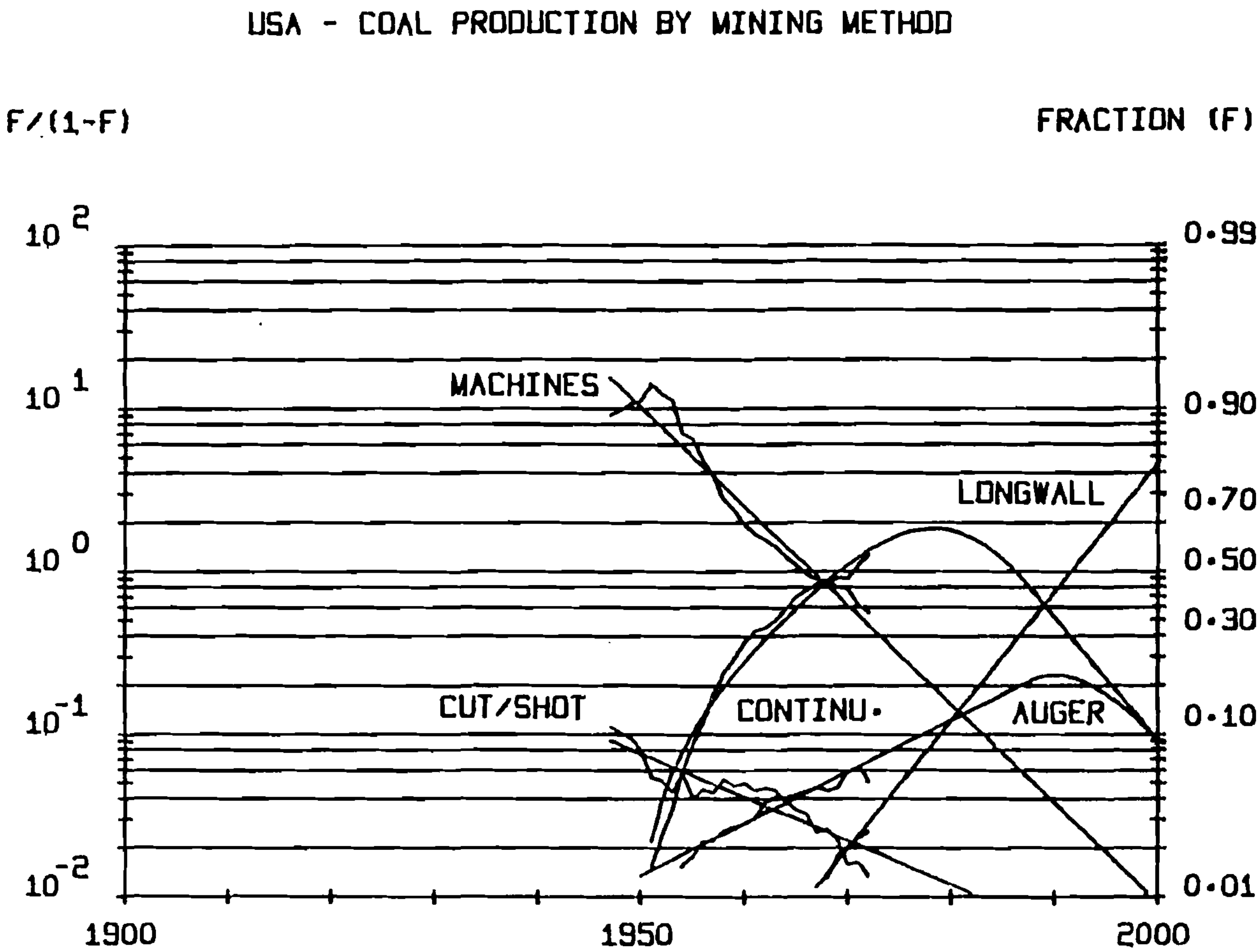
USA - UNDERGROUND AND SURFACE MINING





Due to the increasing dominance of strip mining, the competition between strip mining and underground mining is dealt with explicitly here. A control on the total amounts extracted shows that the sharp kink in the logistic plot is due to a sudden drop of deep mining production. These sudden drops are not new in a socially turbulent structure like US mining industry, but this time it may be due to the introduction of stringent safety rules in the mines.

Most probably the perturbation will be reabsorbed in a few years. If not, deep mining would disappear in the US in 1980, a very unlikely if not impossible occurrence. Passing the legislation about strip mining may bring the corrective action.



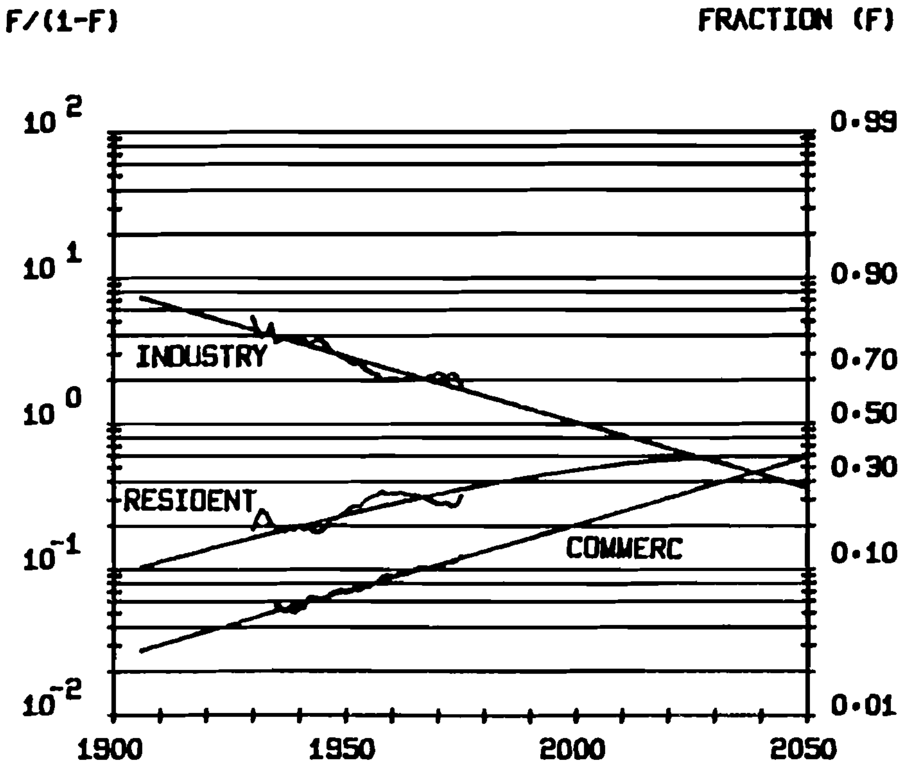
As deep mining presents such an array of competing technologies, it is interesting to analyze their struggle leaving out the surface mining techniques except Auger which could be considered as both underground and surface technology. The technology becoming dominant in the next twenty years will be the longwall, winning the last battle of a lost war as underground mining seems to be bound to disappear in about 50 years.

With ups and downs, coal production in the US did stay constant in the last 50 years to a level of about $0.5 \cdot 10^9$ tons/year. The phase-out of coal in the US being a slow process, during the next 20 years US mining industry should equip longwall mines with a production slightly larger than the total production of German coal mines now.

The various methods of mining are labeled on the plots according to the following list:

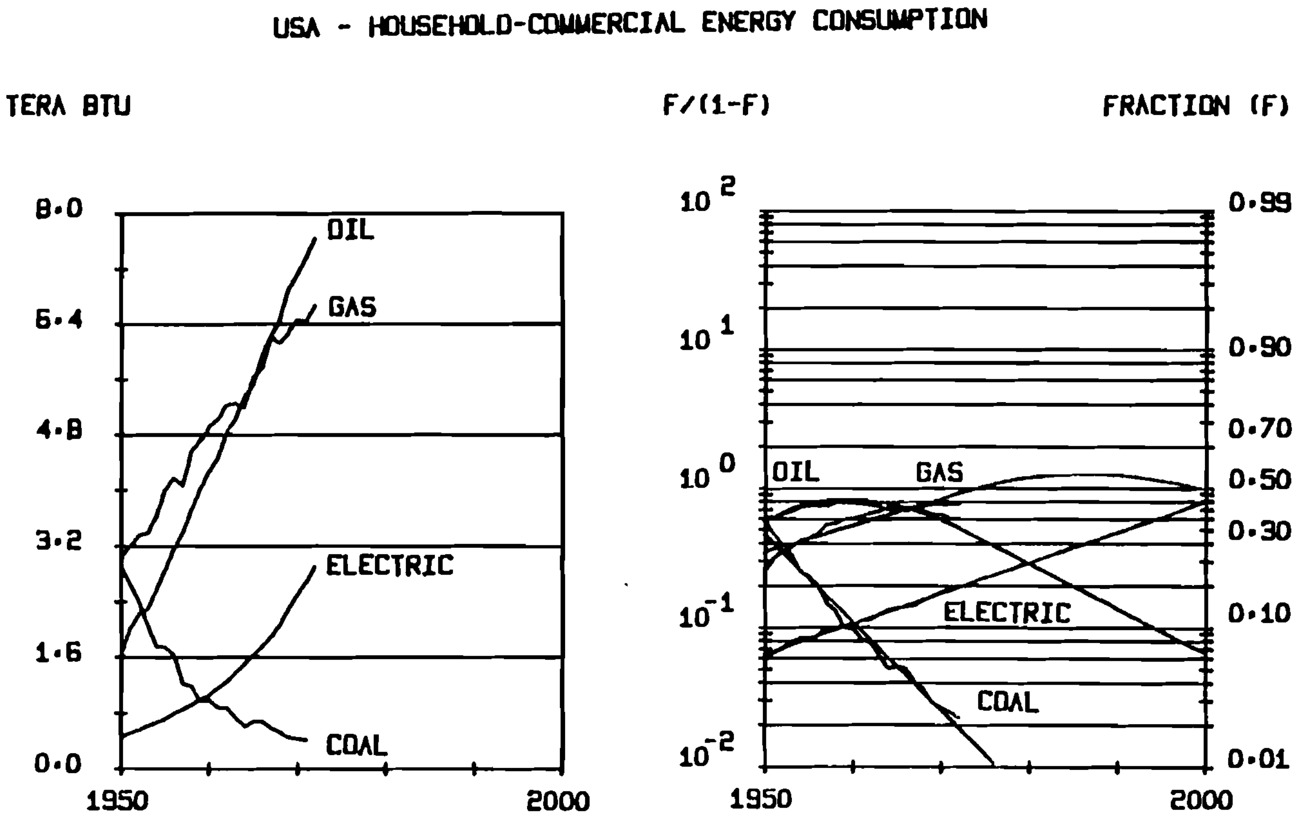
CUT/SHOT	-	cut by hand and shot from solid
CONTINU.	-	mined by continuous mining machines
LONGWALL	-	mined by longwall machines
MACHINES	-	cut by machines
AUGER	-	mined at Auger mines

USA - NATURAL GAS CONSUMPTION BY SECTORS

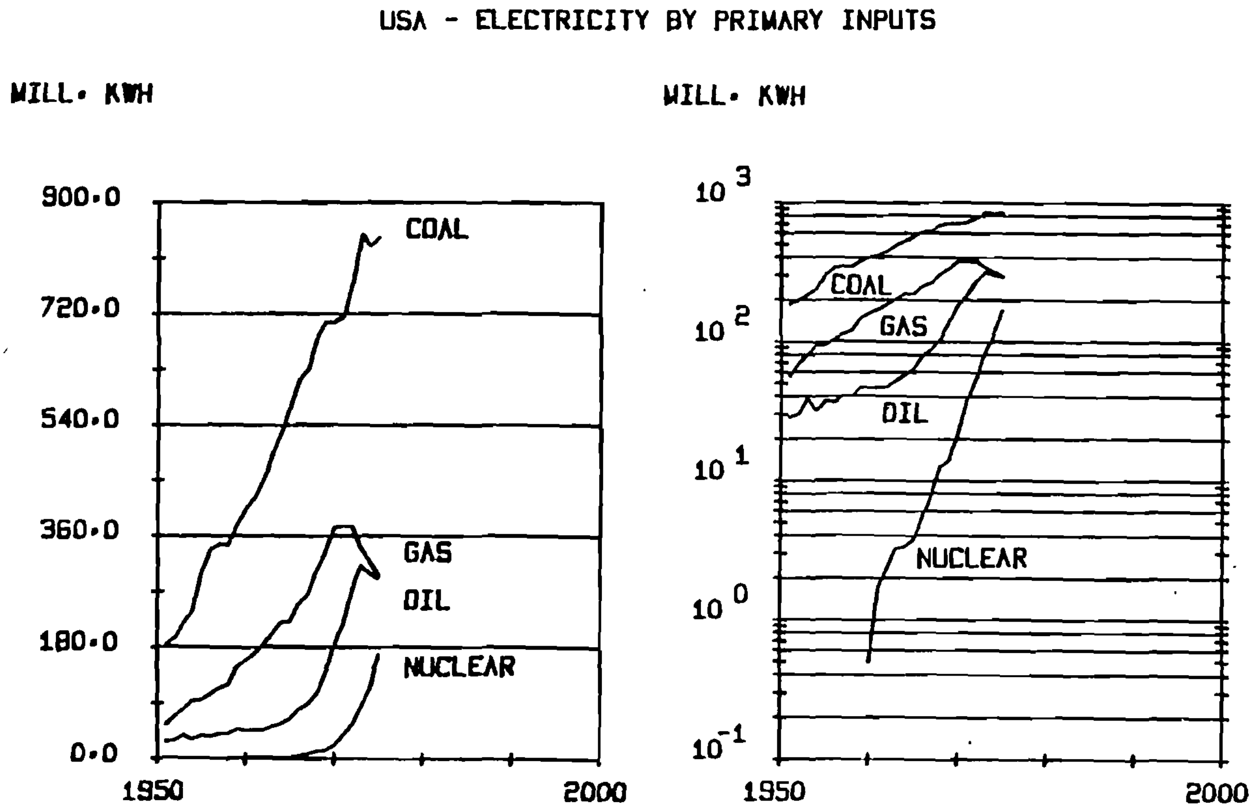


When we view the system through dynamically competing subsystems, we may think that different branches of the economy compete for the same resource, a statement much more in line with the Weltanschauung of economists and laymen. In this spirit we made a logistic analysis of the share of natural gas consumption between three large sectors of the economy, industry, residential, and commercial.

It appears that the small consumers are trying to get the larger share of natural gas which is quite rational in view of the extreme simplicity in its use and its non-polluting characteristics. The process of competition however appears to have long time constants, and only in the year 2050 the natural gas input will be equally distributed between the three competitors. Residential will decline mainly due to the inroads of electricity.



Reversing the previous reasoning one can think that the various forms of energy compete for a certain sector. In this case it is the household-commercial sector.

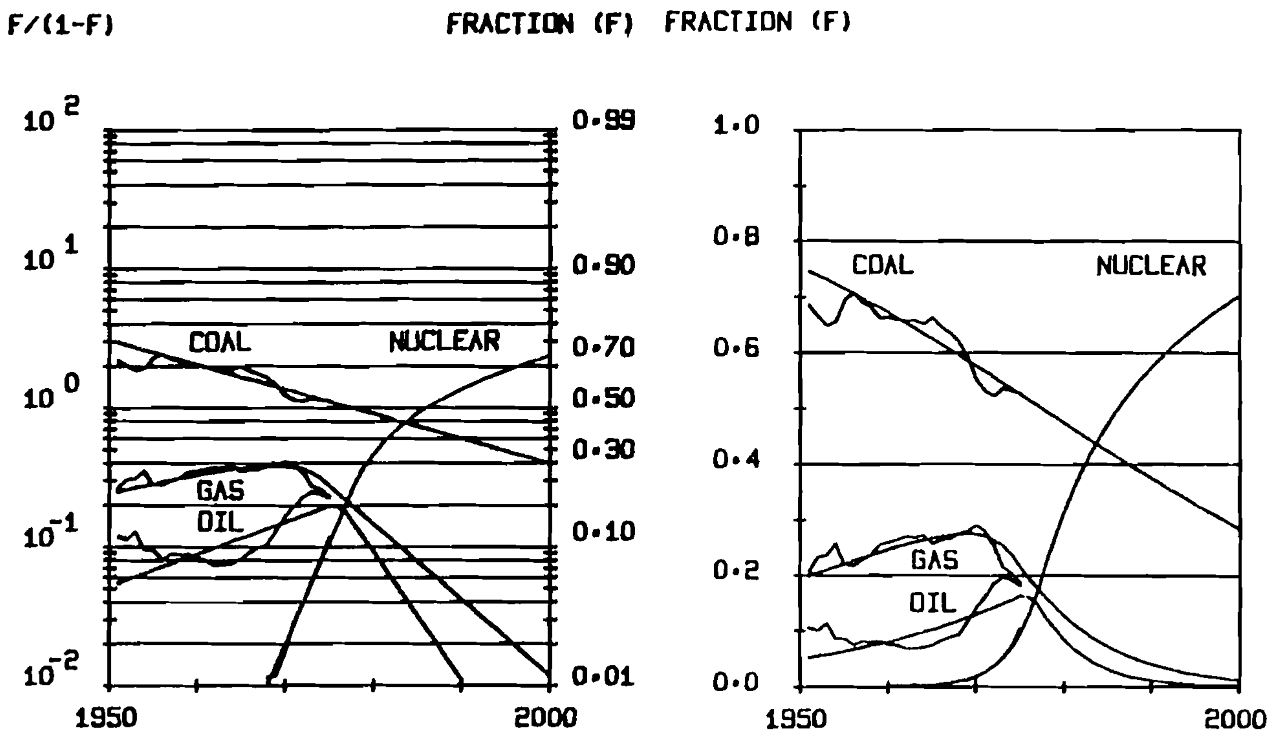


The electrical utility market is very important for primary energy producers, it is large, fairly homogeneous, highly technological, and rather profitable. Therefore it is a good testbed for observing the progress of new technologies.

In these two figures we plotted the evolution during the last 25 years of the production of electricity accoring to the various primary fuels, both in linear and semi-log form.

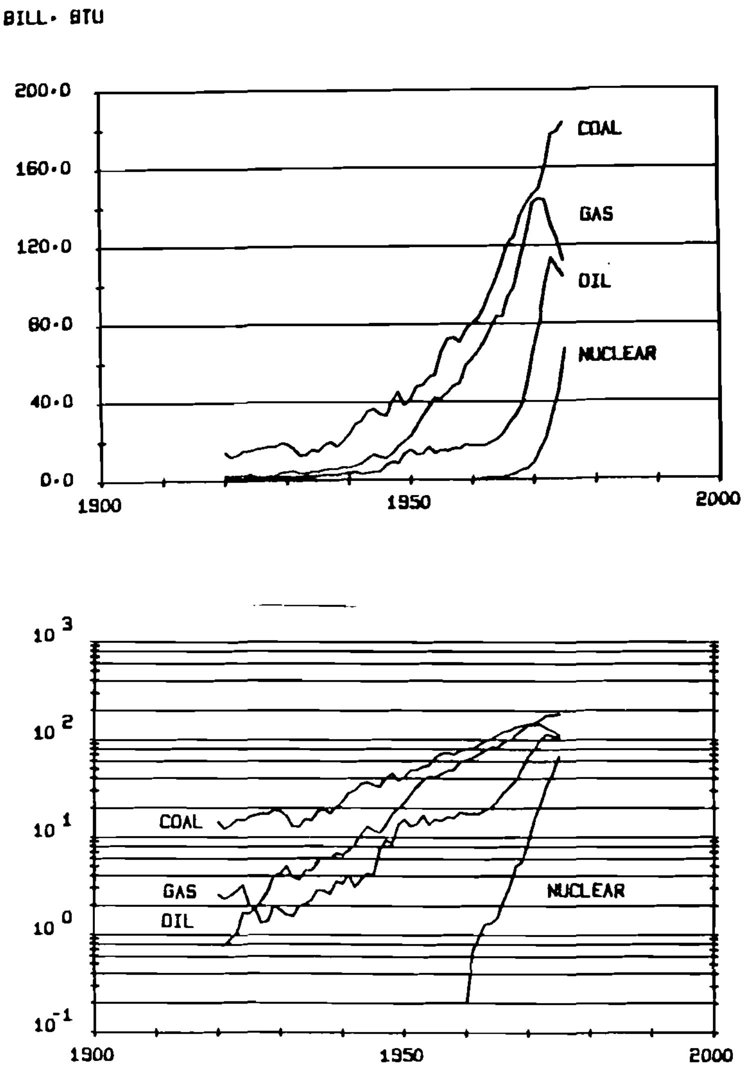
The historical data on the electricity generation according to primary energy fuels in million kWh and the data on primary energy consumption for electricity production in billion Btu have been all taken from the US Department of Commerce [1975], [1976], [1977]. The two data sets show implicitly relative conversion efficiencies for electricity generation according to the various energy inputs used.

USA - ELECTRICITY BY PRIMARY INPUTS



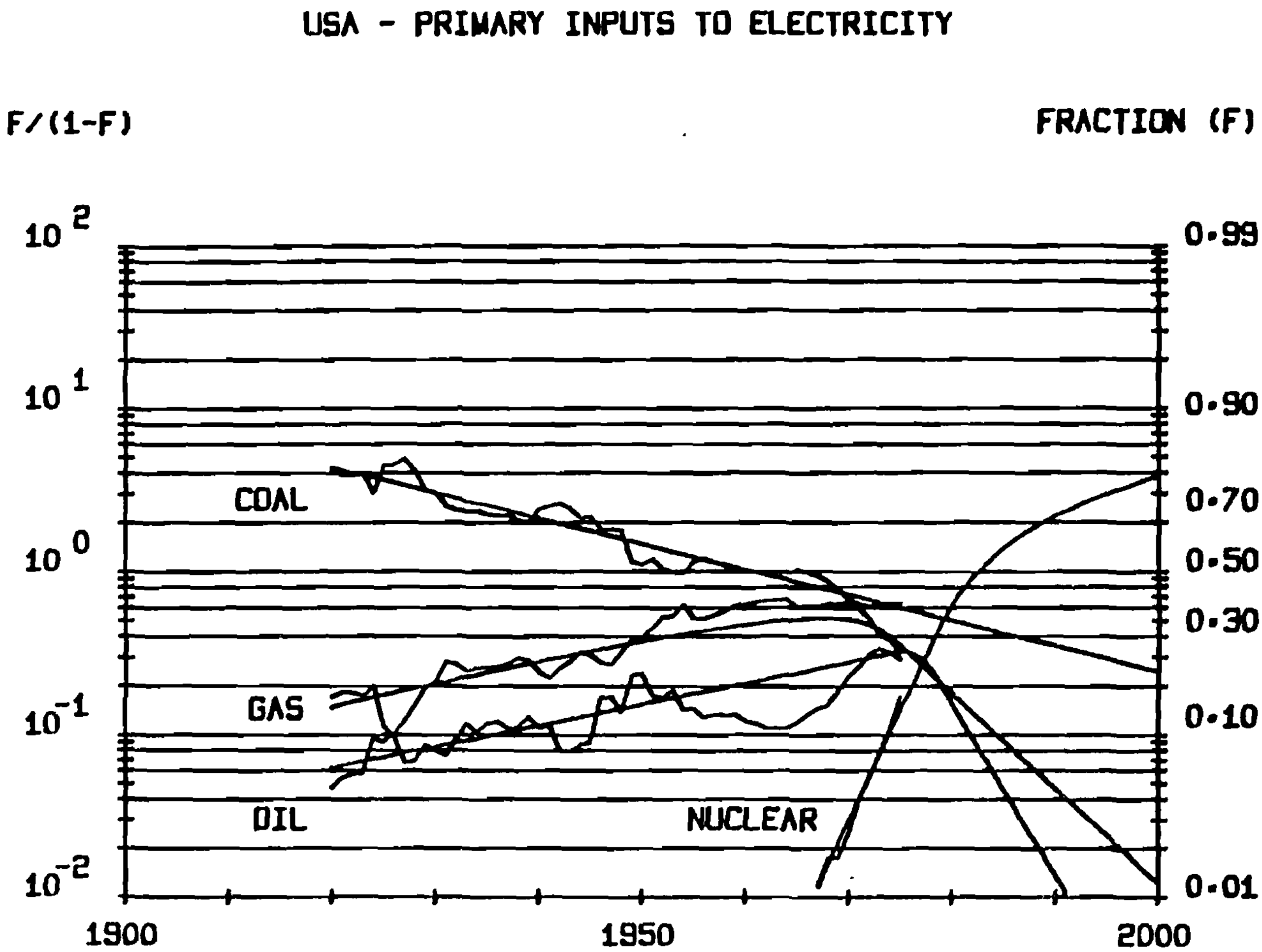
Electricity generated using coal, oil, or gas is shown here in logistic representation. This is an indirect way of showing the competition of the various primary energies.

USA - PRIMARY INPUTS TO ELECTRICITY



Here the competition is expressed more explicitly in terms of tce of different fuels entering the electric market.

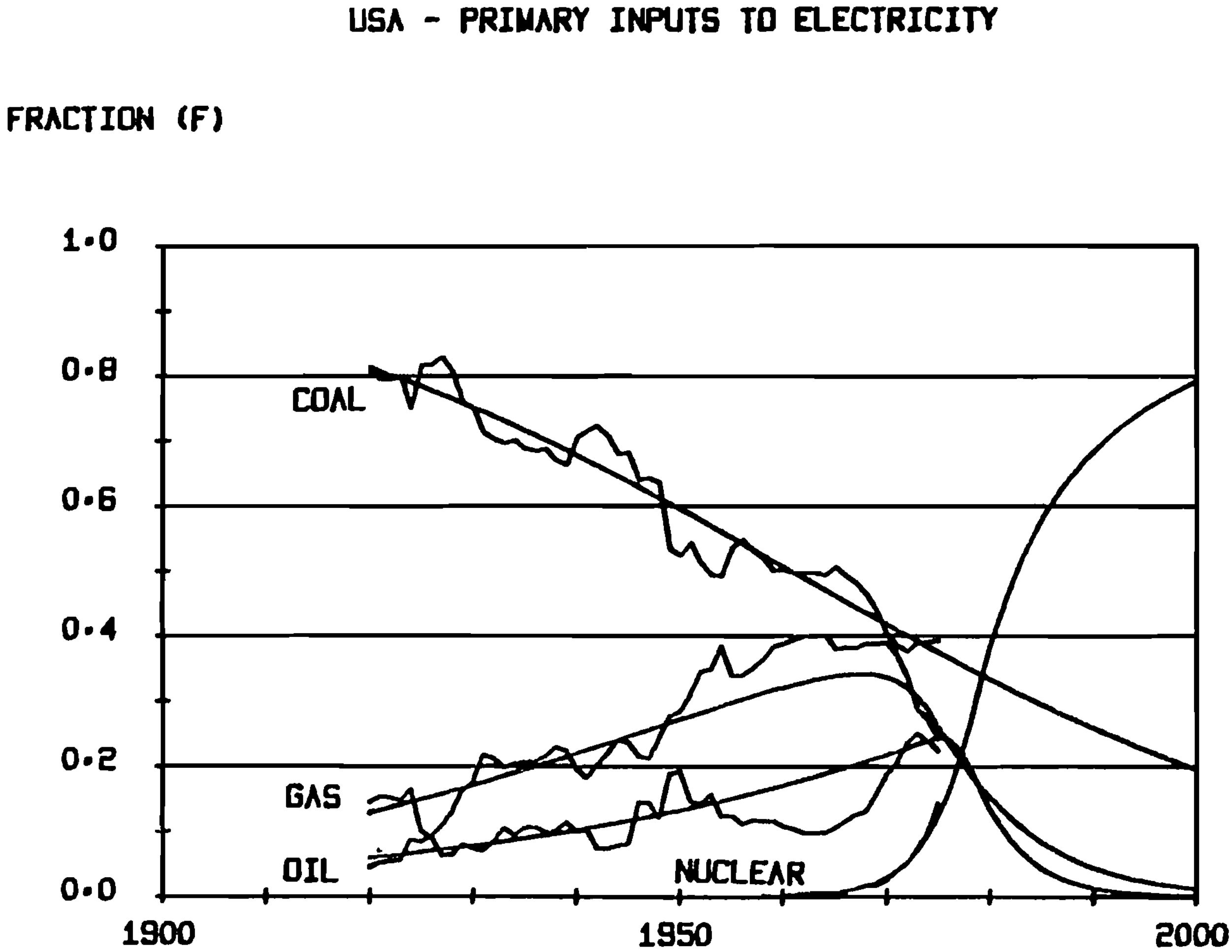
It is clear that coal has been under constant attack by oil and gas which has progressively eroded its position. A perturbation appears in the period of 1955 to 1970, showing an excessive consumption of gas with respect to oil if we take the logistic functions fitted with the 1920-1950 data. This may appear strange as during this period oil was "cheap and abundant". But in the US, gas was still cheaper due to stringent regulation. Oil however recovers and takes back its position in 1973 to 1974! Incidentally, no appreciable perturbation marks the period of World War II.



The substitution of different primary inputs to electricity generation is discontinuous when nuclear enters the market with a powerful drive and phases out oil and gas before the end of the century. Coal appears perfectly unperturbed and finally dictates the pace of introduction of nuclear from now on.

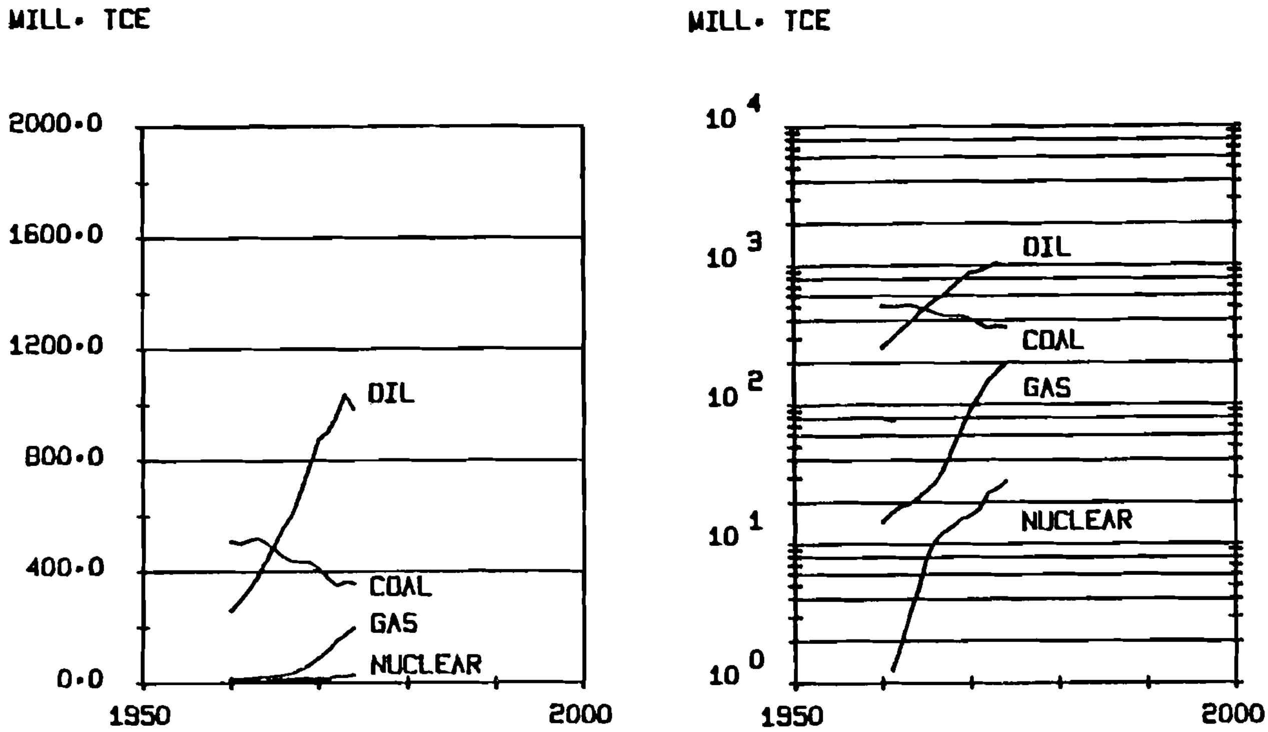
It is interesting, even if a little shocking, that this pace had been finally determined by the penetration rates of oil and gas in the twenties.

Many problems surface from the expected structure of the system in the next 20 years. For example: What kind of peaking system will be provided? Will it be through medium Btu gas from coal and gas turbines or through storage?



This figure reports the same results as the preceding one but in linear terms in order to facilitate visualization.

OECD EUROPE*- PRIMARY ENERGY CONSUMPTION



The data come from OECD [1976]. We made a logistic analysis for the European OECD states lumped together and for some of the states separately. The data base is relatively short, 15 years, but the curves appear very stable.

The lumped case is presented here. Coal and oil behave very regularly. Natural gas has prolonged the start-up vagaries up to 10% of the market. The fact that it shows a penetration rate practically identical with that of oil is a sign that tends to confirm the good quality of the projections. Nuclear has penetrated only to 2%, consequently the projection is still somehow uncertain. Any change in rate, however, would not change the projection for gas becoming the next dominant primary energy source. With 30% of the total in year 2000, nuclear appears to saturate the electric market around that year.

SOLFUS has not been included as a scenario. It would possibly make nuclear saturate during the first half of the next century.

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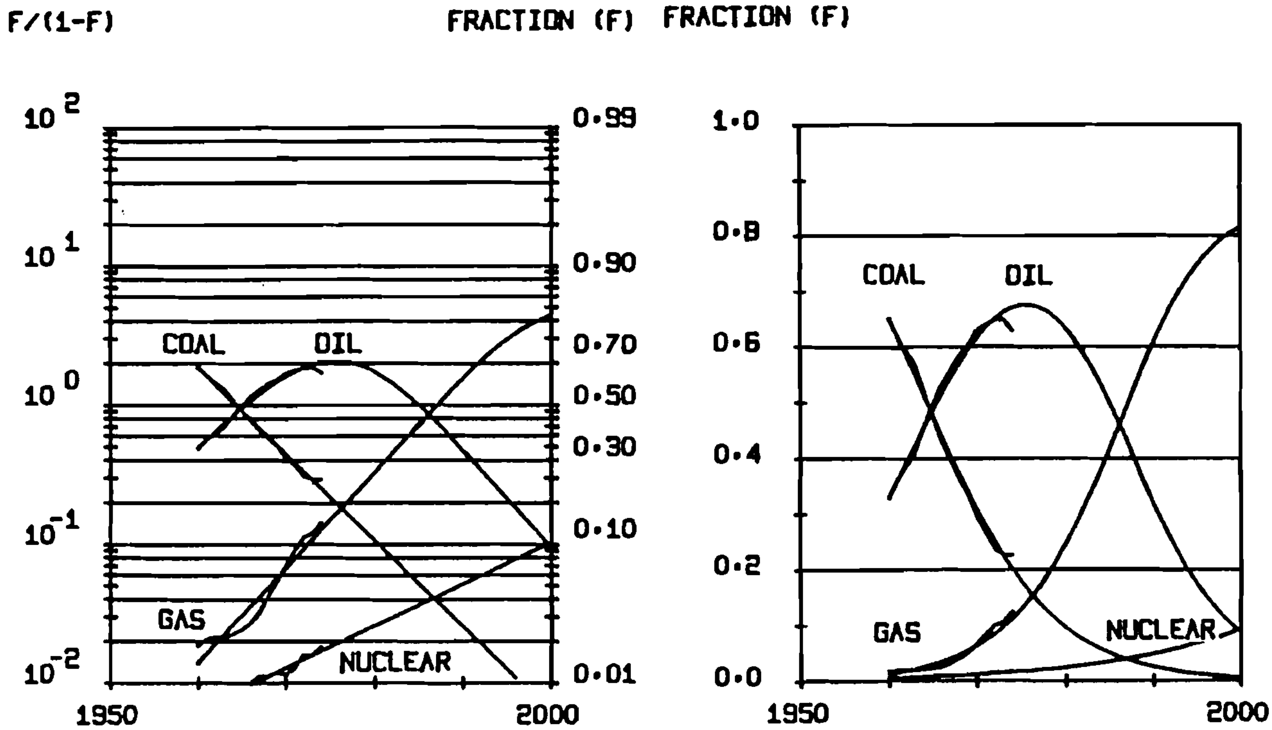
*Austria, Belgium, Luxemburg, Denmark, Finland, France, FRG, Greece, Iceland, Ireland, Italy, The Netherlands, Norway, Protugal, Spain, Sweden, Switzerland.

OECD EUROPE - PRIMARY ENERGY SUBSTITUTION



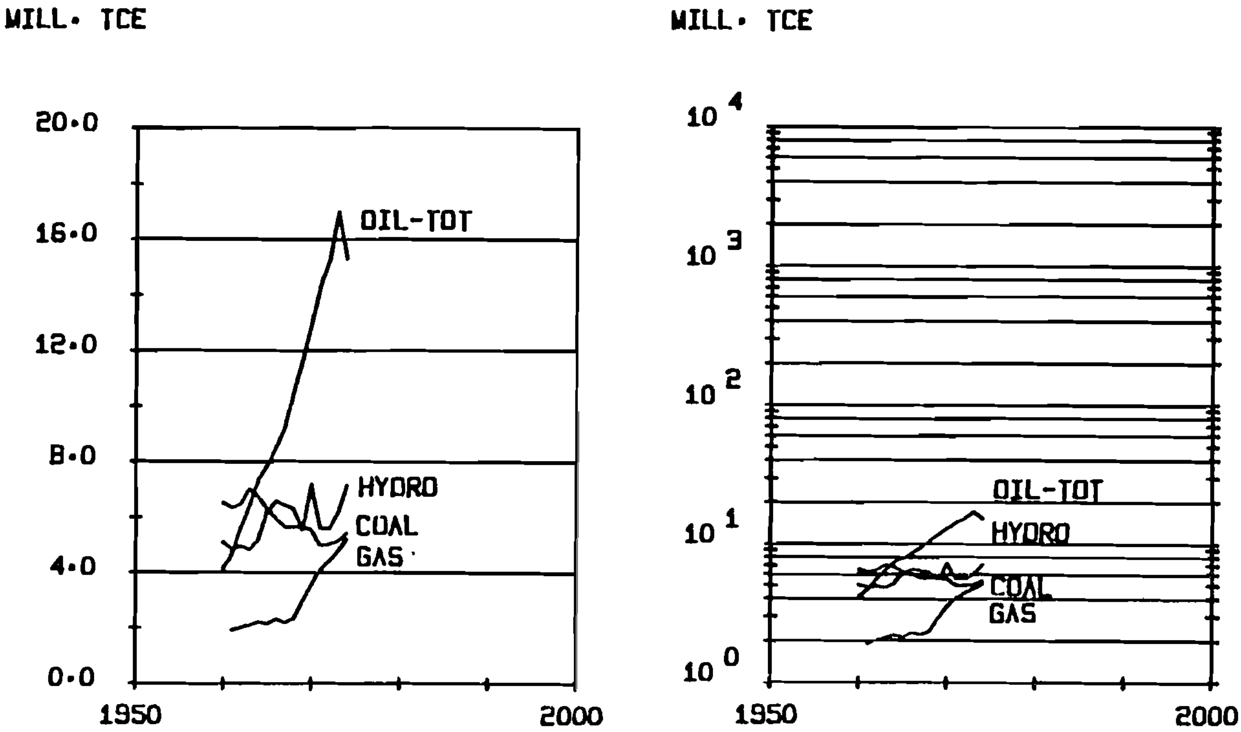
The logistic analysis is here presented in the log and linear form.

Two facts emerge, one is that natural gas, with a penetration rate much similar to that of oil, appears the great dominator of the year 2000. It appears to displace oil to an impressively low level of 10% in the year 2000.

The curve for nuclear seems quite regular, although the definition of the final substitution rate is still open due to the low level of penetration.

With the present rate nuclear would reach a not very impressive share of 10% of the market in the year 2000, leaving Europe completely dependent on hydrocarbons.

AUSTRIA - PRIMARY ENERGY CONSUMPTION

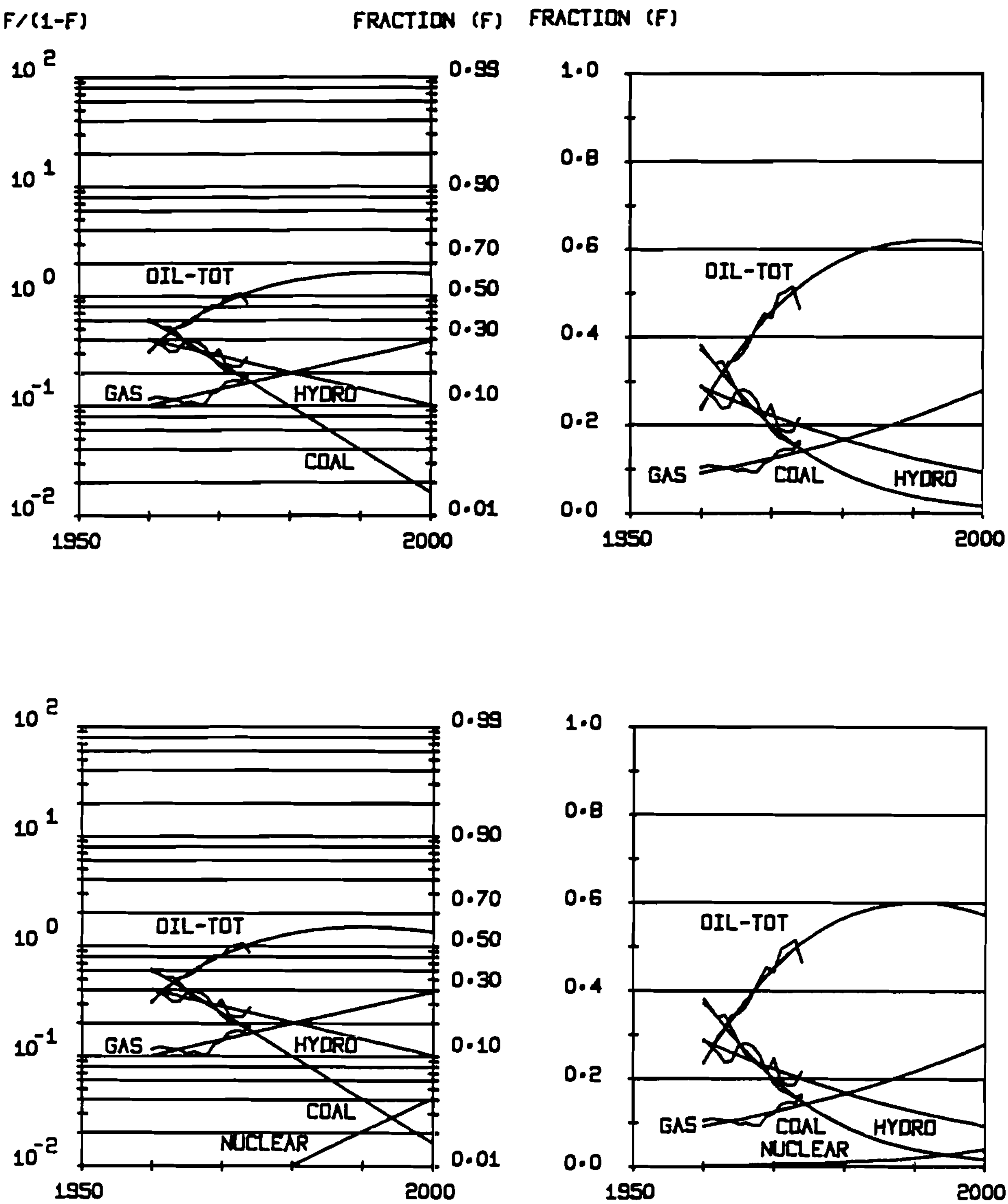


The primary energy consumption for Austria displays minimal dispersion except for rapid growth in oil consumption.

Hydropower has been included in the set of primary energies as it appears a quite important energy source for Austria.

The market appears dominated by oil, with natural gas still low but increasing fast.

AUSTRIA - PRIMARY ENERGY SUBSTITUTION



O E C D   A u s t r i a : Primary energy substitution.

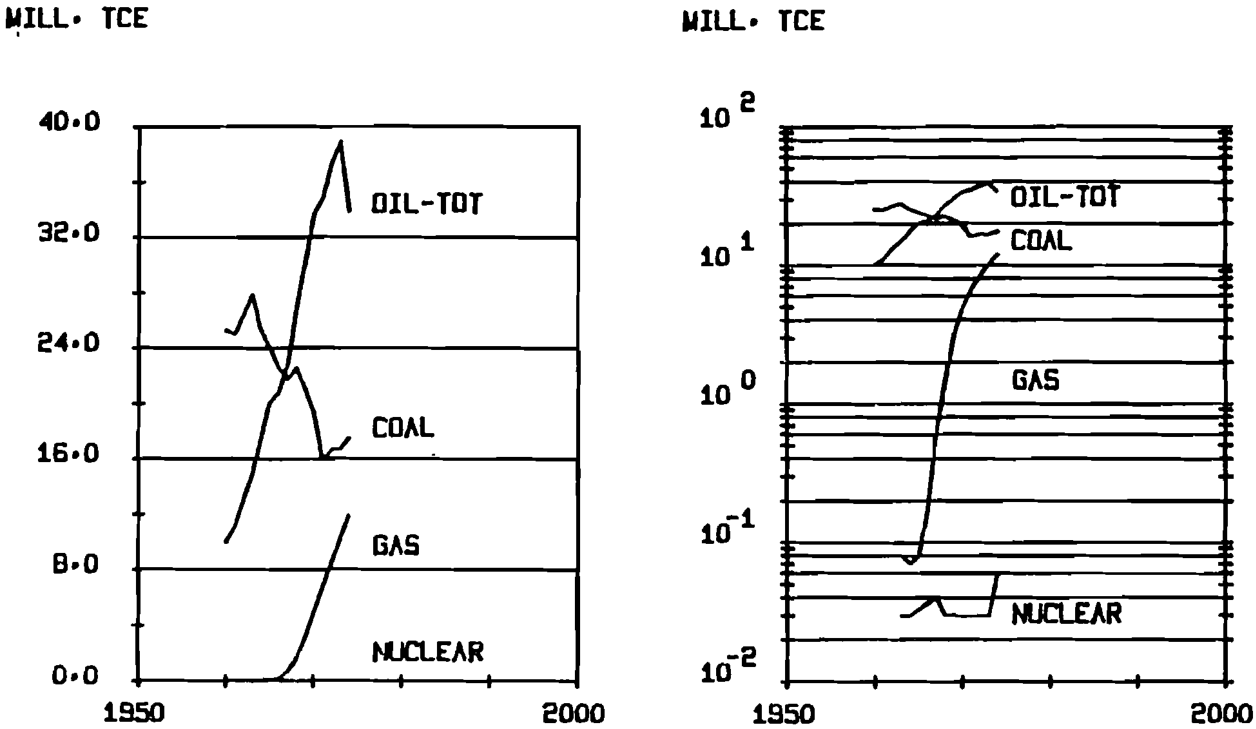
The data are presented in the log and linear logistic format. In the first row no new sources are introduced. This may not have many consequences before the year 2000 because the time constant of the country appears so large, about 100 years.

For what concerns nuclear in particular, the situation is in fact extremely confused. One power station is most probably going to be put into operation toward the end of 1978. No second power station is in sight, but nuclear electricity might be imported from neighboring states.

The figures in the second row should then be considered as a sensitivity analysis, indicating the effect of introducing nuclear energy on the other primary sources. The hypothesis is 4% penetration in the year 2000, the medium-term effect (30 years time horizon) would be reflected in a slight reduction of oil imports. Gas consumption would be affected only after 2020.

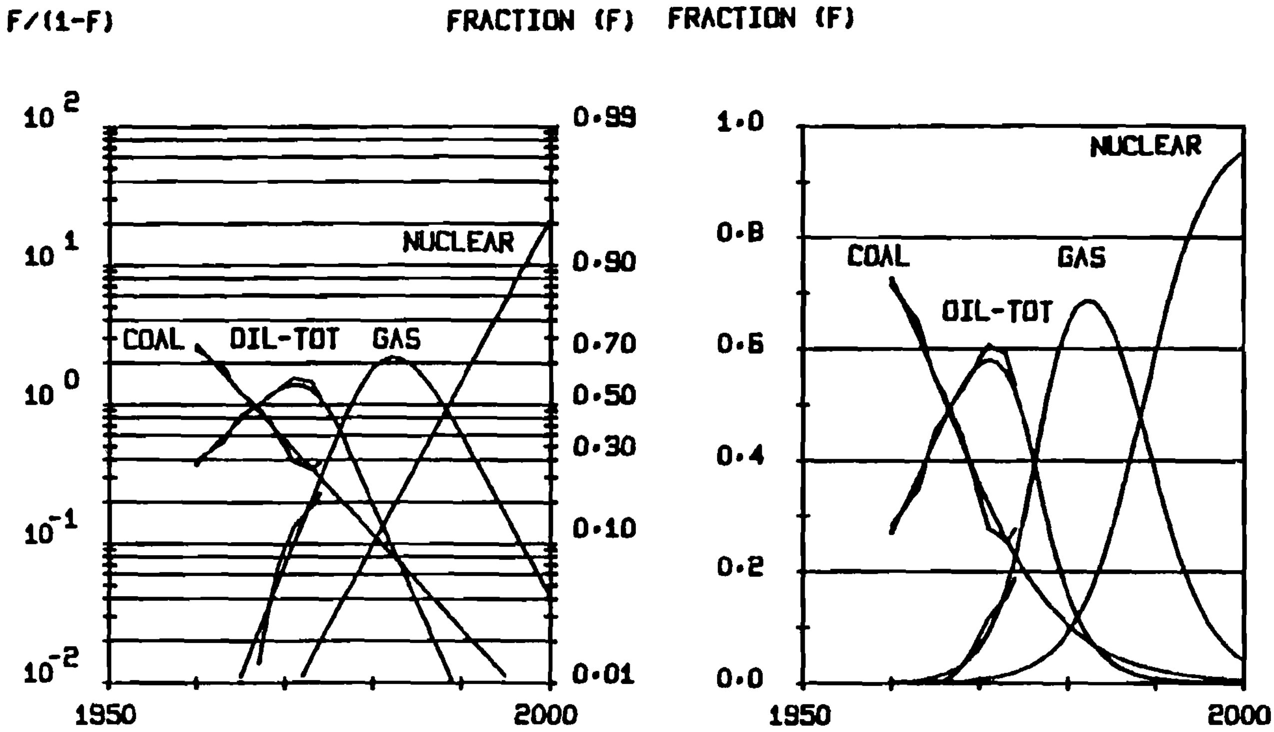
Only an improbable, very fast nuclear penetration could make Austria reasonably independent from oil in the next thirty years.

BELGIUM - PRIMARY ENERGY CONSUMPTION



The consideration that can be made from the straight presentation of the data on primary energy consumption in Belgium is that oil is the dominant primary energy, with no limits about its future. Coal is rapidly phasing out and gas is phasing in. Nuclear is barely perceptible (in 1974).

BELGIUM - PRIMARY ENERGY SUBSTITUTION



O E C D B e l g i u m : Primary energy substitution.

Logistic analysis reveals the hidden order. Although the data cover a short period of time, the good quality of the fitting gives weight to the following considerations.

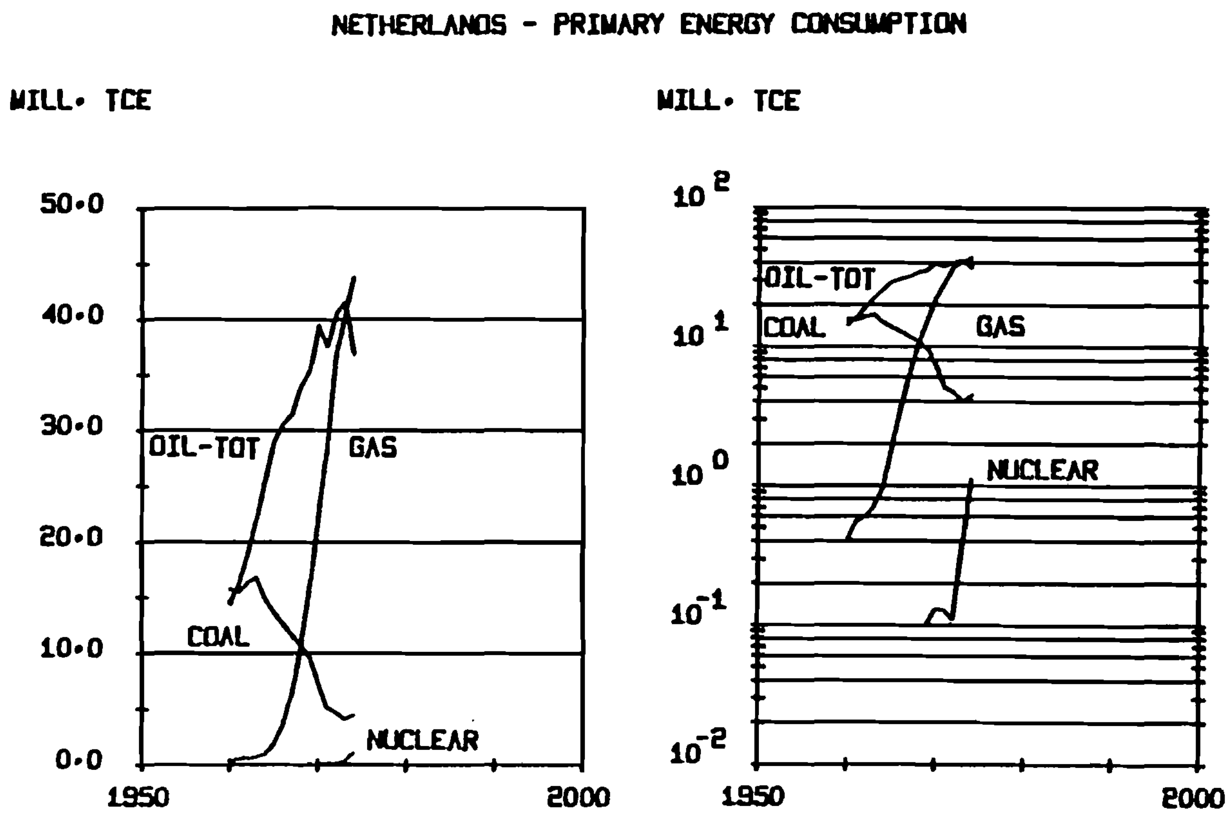
Coal seems to disappear around the year 2000 which is more or less in line with the ideas in the country. Oil including the trade balance in products peaks around 1973 and seems to phase out in 1990. This prediction, which by the way repeats itself in similar form for the Netherlands, the FRG, and UK, is a bit hard to swallow on technical grounds. How will cars run in 1995? Will they use increasing amounts of methanol produced from coal and natural gas? This would in fact preserve their compatibility with gasoline, necessary at least for long distance traveling. If coal is the primary source, a new curve should be started on the argument, e.g. of underground coal gasification, i.e. new coal.

Electric, hydrogen- or methanol-electric, and pure hydrogen cars are in principle possible, but do not seem very probable in this time horizon.

We could also have overestimated the rate of penetration for gas. External interests prop up the penetration of a new technology at very high rates, usually until it has penetrated some percent of the market. One could make the hypothesis that a particularly favorable environment, e.g. the pre-existence of an efficient distribution net for gas, and the spacial concentration of population, has prolonged this initial stage up to 10%. A change in the penetration rate from that point would only displace the disappearance of oil by a few years.

A similar tampering with the rate of penetration of nuclear, still fairly hypothetical bacause of many lingering doubts, shows other possible little gains, but is not really decisive.

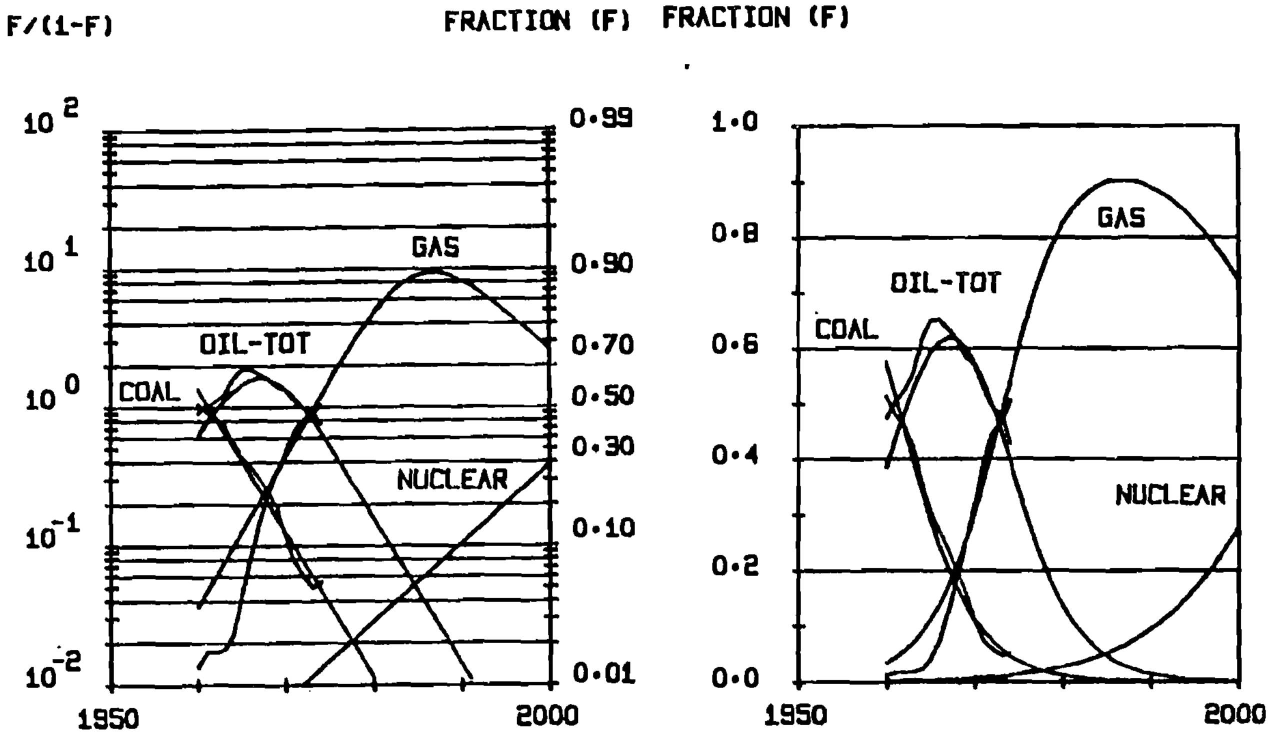
So the problem is substantially left open. If we believe in the predictive capacity of our methodology, something fairly drastic will occur in the car field during the next 20 years, and the nucleating area will be in Belgium, the Netherlands, or the FRG.



Primary energy consumption in the Netherlands is here reported by primary source, in linear and semi-log form to stress the starting period.

No particular tendency emerges, coal is phasing out and oil in. Gas has made a very fast inroad after the discovery of the Gröningen field. Nuclear is just emerging.

NETHERLANDS - PRIMARY ENERGY SUBSTITUTION



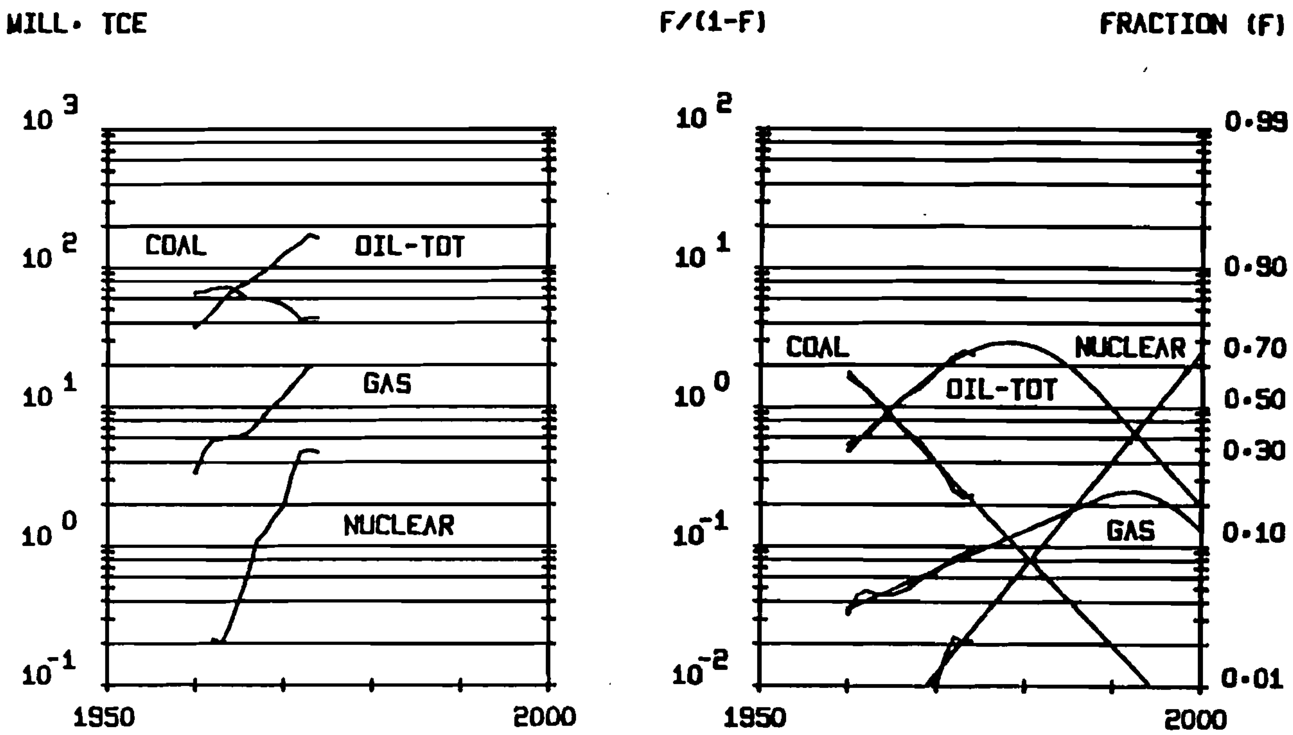
The logistic analysis shows here a quite precise structure. Coal is bound to disappear in 1980 and oil in 1990, opening the question about cars discussed already in the case of Belgium.

The problem of nuclear is perfectly open and our scenario is pure guessing. It must be clear that if nuclear electricity is imported in spite of anti-nuclear puritanism, nuclear should still be included in the energy budget.

Natural gas having such a dominating role, however, the rate of introduction of nuclear energy will have little influence on the fate of oil. Thus the car question is left open.

Seen in the light of our analysis, the Netherlands' alternative appears to be natural gas or nuclear, and in this light one understands better the nuclear opposition.

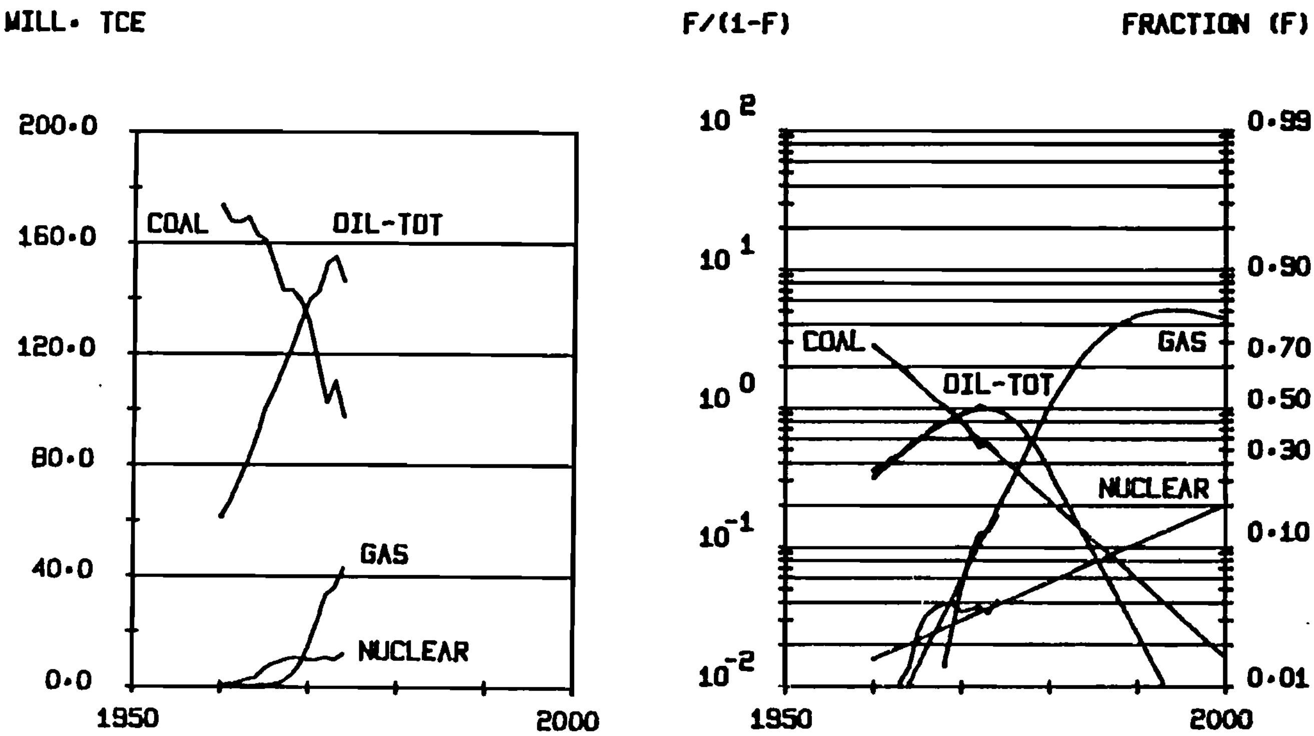
FRANCE - PRIMARY ENERGY CONSUMPTION



The primary energy substitution for France is repeated here using OECD data sources. The result is substantially the same, although different data and a shorter data base are used, which leads to minor discrepancies in the long run.

For the nuclear scenario we took 8% in year 1980, which comes from the fitting of the data, but with a market share still below 2%. However nuclear energy is growing fast in France and the situation should become clear in a few years.

UK - PRIMARY ENERGY CONSUMPTION

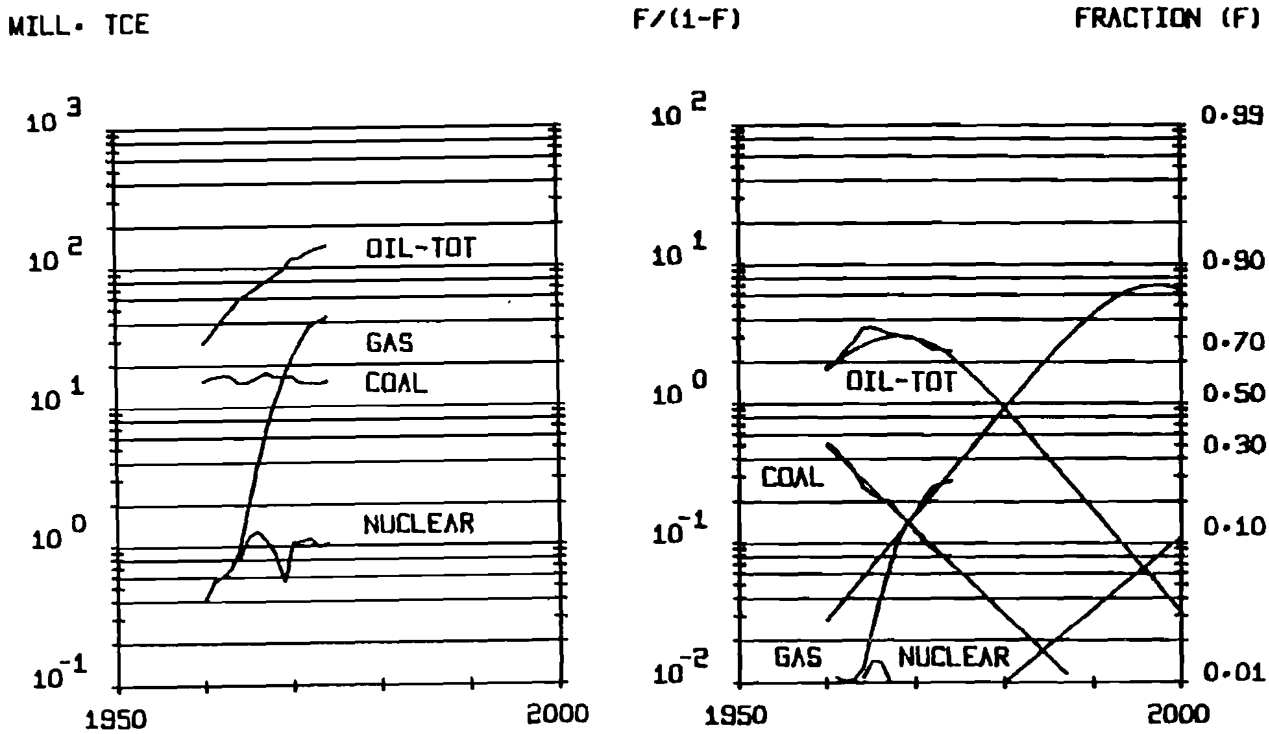


The primary energy substitution for the UK is repeated here using OECD data.

In spite of some discrepancy with other sources, the predictions differ only in relatively small details.

Even if nuclear resumes speed, it would produce only a small dent in the dominance of gas in the next decades.

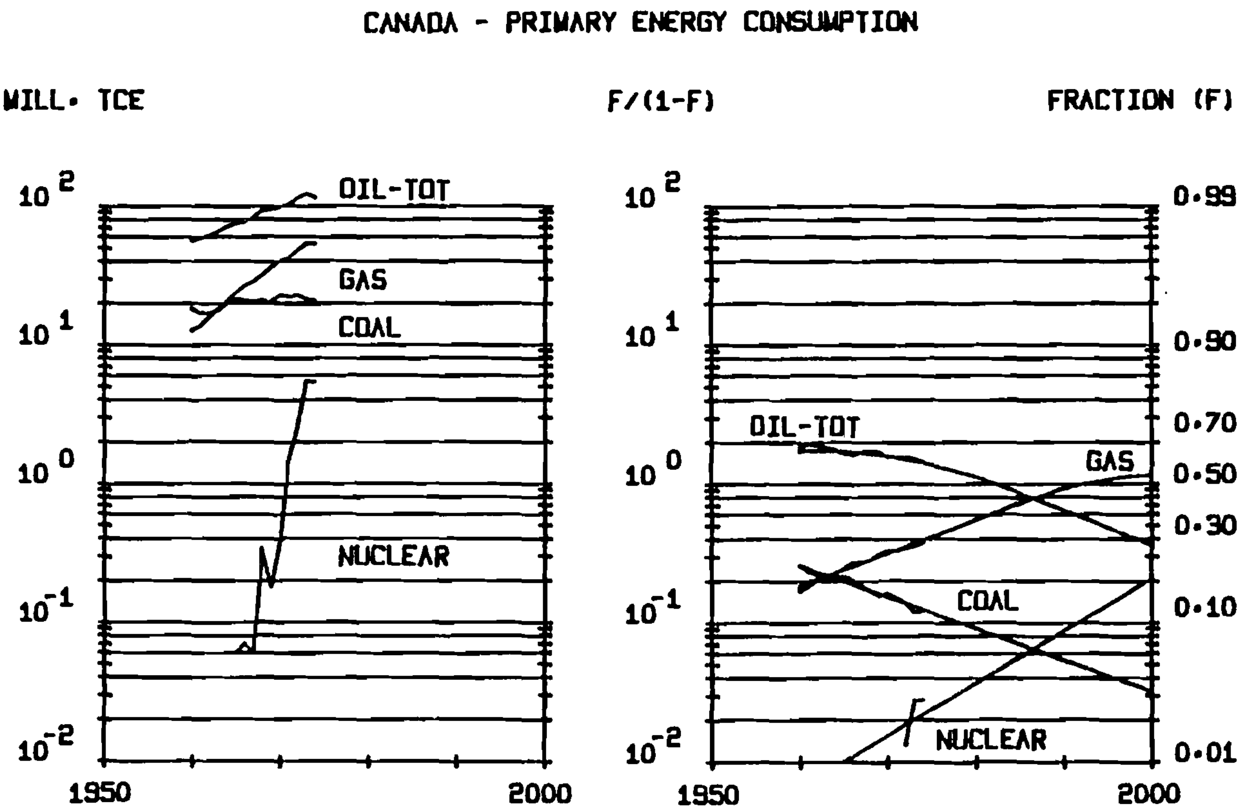
ITALY - PRIMARY ENERGY CONSUMPTION



The primary energy consumption and substitution for Italy is shown here with a 15 year OECD data base. The penetration of nuclear energy (10% by the year 2000) is hypothetical and based on the assumption that Italy will not be very different in that respect from other European OECD countries.

The future appears very bright for gas reaching dominance in the next decade. This is not contradictory with the efforts to link Italy with the Netherlands, the Soviet Union, and North Africa via a pipeline under the Mediterranean, but it is certainly beyond the rosiest plans of the gas industry.

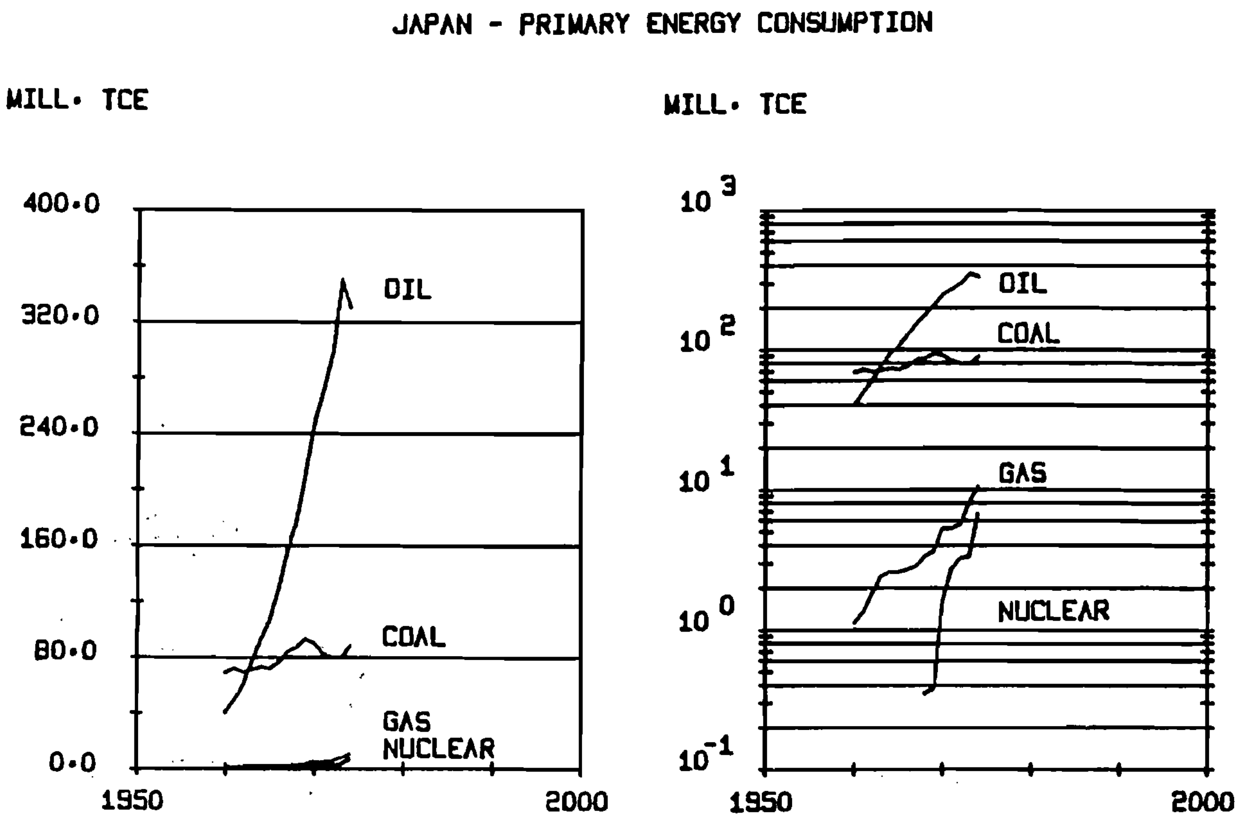
If we assume that gas growth was "forced" up to 10% and consequently fit the logistic with later data and set nuclear penetration (improbable) as fast as gas, we reach a more acceptable but not very different conclusion.



The primary energy consumption data for Canada do not show any particular pattern, except a very fast inroad of nuclear energy, although at a relatively low level. The logistic analysis reveals extremely smooth transitions, much similar to those of Austria, with time constants of the order of 70 to 80 years.

In spite of Canadian devotion to nuclear energy, we did draw a prudent scenario, taking about 16% nuclear in the year 2000.

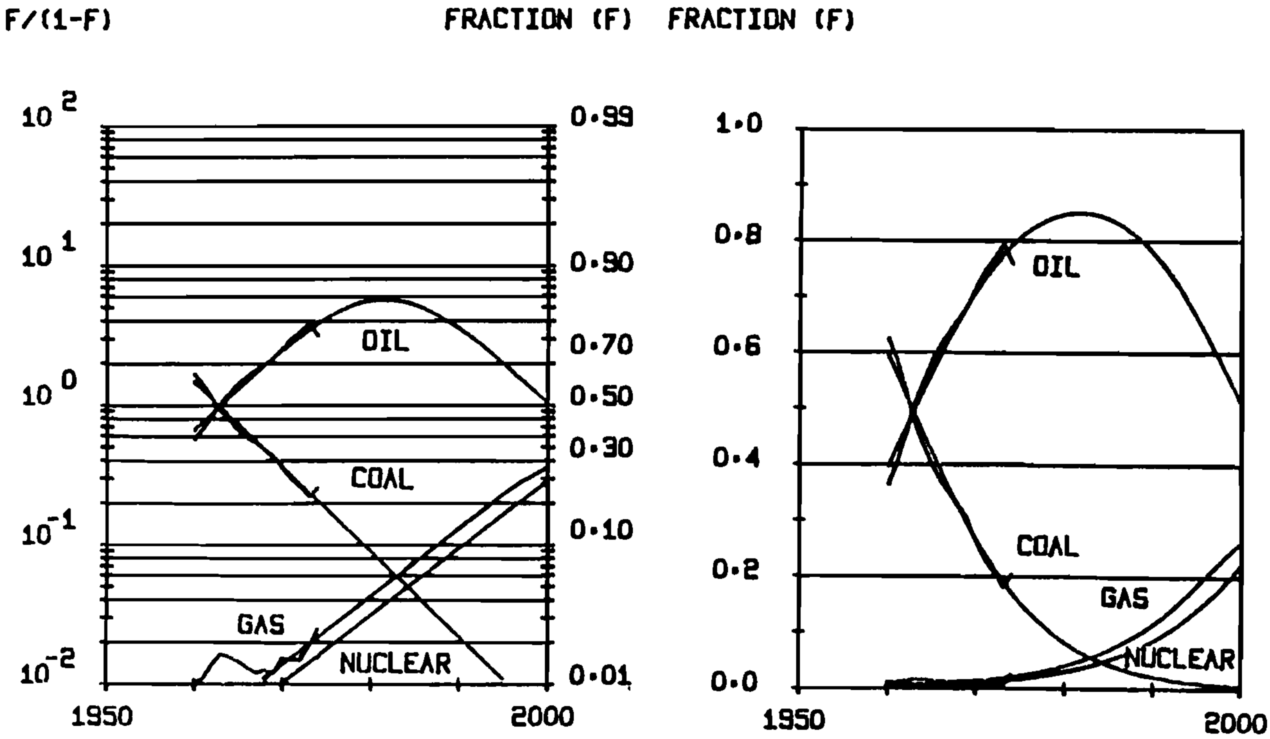
In agreement with most of the world, gas appears to peak and become dominant in the year 2000.



The primary energy consumption data for Japan are taken from OECD and cover the period 1960 to 1974 for coal, oil, natural gas, and nuclear, all expressed in million tce. Oil time series contain consumption of crude oil and petrochemical products.

Nuclear is just beginning. Today there are 20 GW(th) installed capacity, IAEA [1977], amounting to more than 2% of primary equivalent.

JAPAN - PRIMARY ENERGY SUBSTITUTION



O E C D   J a p a n : Primary energy substitution.

In spite of Japan's particular situation as a country with very large and fast expanded industry linked to an almost complete dependence on imports, the primary energy substitution shows nothing very unusual.

Coal is being substituted by oil, a trend initiated after World War II that appears to end in the nineties. The dependency on oil is fundamental, but only a little higher than that of France and similar to that of Italy. It starts saturating now, as the equations could have predicted (using data before the oil crisis!). According to the equations oil should be phased out around 2030 with a great time lag with respect to France or Italy.

Gas enters the scene somewhat late, at the end of the sixties; perhaps it has to be imported using the complex technology of LNG. Perhaps for the same reason it does not seem to play the same central role as in Europe or the US. According to the equations it should peak around the year 2010 in consonance with the world peak.

Nuclear is fairly hypothetical, although we have tried to use prudently the various forecasts. The isolated point near gas indicates the actual situation. With nuclear penetration reaching 10% in the nineties, the rate coincides with that of other fuels. It would then become dominant during the first half of the next century, even if a new source is introduced around the year 2000.

Today there are 20 GW(th) installed capacity, IAEA [1976], amounting in terms of primary equivalent to more than a 2% share. Additional 27.6 GW(th) are under construction and should be in commercial operation by 1982. Another 14.7 GW(th) are planned to be in service by 1984, IAEA [1977]. Assuming the long-term energy consumption growth to prevail during the next decade and a utilization factor of 75%, we have a nuclear share of about 7% by 1984. Our scenario of the long-term nuclear penetration rate assumes that licencing, political and construction problems will lead to delays. Thus, we predict a 7% share 4 years later in 1988.

At the turn of the century oil, gas, and nuclear appear to share equally the market which implies an extraordinary advance in the technologies of transporting natural gas (or some derived products?) overseas and a practical saturation of the electrical market by nuclear power stations.

With time constants of about 40 years, the system appears less dynamic than one could suspect.

Computer Software Package for the Substitution Model

N. Nakicenovic

1. INTRODUCTION

This program was designed to generate the dynamics of market substitution of products and technologies. It is an interactive program that gives prompts to the user, and the user responds to them with parameters affecting the course of the program execution. Input data are organized as time series, one series per record with a logical record number and its name. Model coefficients can be directly estimated by the program or read from the coefficients input file. An output file can be generated, and the results can be plotted on a linear or semi-log scale.

The program itself is designed in modules each having a distinct function, so that it is possible to supplement additional subroutines, or if necessary delete existing ones, for some special applications.

A simplified description of the model was given in previous sections. This manual does not go into the details of the model and should be used in conjunction with the model description.

2. INPUT FILES

Punch: The Punch file contains the time series, their names and logical numbers. The Punch file is compatible with the Bank program by Norman (1977). The Bank program can create and maintain the time series on a random file. Thus it can be used in conjunction with the Pene program to generate, modify, and store the Punch file. Table 3 reproduces the primary energy inputs for the world by different primary energy sources from

1860 to 1974 in the Punch file format with documentation. The original data are from Schilling and Hildebrandt (1977), and Putnam (1953).

The Punch file can be also generated directly by a simple FORTRAN program. An example of such a program is given in Table 1, and input cards and output in the Punch file format in Table 2.

Coef: The coefficients file can be generated by the program Pene if the parameters are estimated or directly read by the program from the Coef file. This file is compatible with the Auto program by Norman (1977), which offers wider options than the OLS estimates of the Pene program. Thus the coefficients can also be read by program Pene if they were generated either by Auto or by Pene in some previous run. An Incards file is generated by the program Pene when the option for the estimation of the coefficients is used. This file can be renamed and used as Cards file. Table 4 gives an example of a Coef file generated from the data given in Table 3.

Cards: This input file gives the possibility of avoiding the interactive mode of the program execution by storing the program execution instructions on this file. An Incards file is generated during each program execution, which can then be renamed and used as Cards input file if a repetition or batch-like execution of a given program run should be desired. An example of a Cards file is given in Table 5.

3. OUTPUT FILES

Output: The Output file is generated with the original data, the coefficients and their t-tests, and the estimated values. An example of the Output file is given in Table 6.

Incoef: When the coefficients are estimated in the program, the Incoef file is generated; it can be renamed Coef and used later as input file (see Table 4).

Incards: Each time the program is executed an Incards file is generated; it can be renamed Cards and used later to control the program execution (see Table 5).

Plotter: The Plotter output is written to devise 77; it can be sent either to the Plotter or to a file name (chosen by the user) which can be displayed or plotted later. Figures 1 and 2 give an example of Plotter output using the Punch file in Table 3 and the Cards file in Table 5.

4. PROGRAM PENE

The program was designed to be executed on the PDP 11/45 with the Unix operating system. The source code is written in FORTRAN.IV, so that the program could be modified for implementation in another system. With the exception of the plot subroutines, most other modifications could be easily mastered. The program Pene consists of a main program and nine subroutines. Table 7 shows the file structure of the program Pene.

Main.f: The Main program reads the input files, generates the output files, and controls the course of execution in accordance with the execution parameters provided by the user. This is illustrated by the flowchart in Table 8.

Tdatfrc.f: This subroutine converts the absolute values of the time series competing for a market into fractional shares, and puts them in a work matrix.

Fitlin.f: This subroutine generates OLS estimates of the coefficients for each fractional time series and the time series of the sum of all absolute values. The flowchart of this subroutine is given in Table 9.

Penetr.f: This subroutine uses the estimated coefficients and the algorithm Penetration to estimate the fractional market shares for the period specified by the user. The flowchart of algorithm Penetration is illustrated in Table 10.

Testtot.f: This subroutine uses the estimated fractional market shares and the estimated coefficients of the sum of all absolute values to estimate the absolute market shares, and puts them into the work matrix.

Tdattot.f: This subroutine copies the time series of the absolute market shares (original data) to the work matrix.

Marfunc.f: This subroutine calculates the coefficients from two given values of fractional market shares.

Plotf.f: Plots the content of the work matrix, i.e. either the original absolute and/or original fractional market shares or the estimated absolute and/or estimated fractional shares are plotted.

Plotlin.f: Establishes scale, axes, and labels for all linear plots.

Plotlog.f: Establishes scale, axes and labels for all semi-log plots.

5. INPUT LINES

In the interactive mode the program supplies the prompts with mnemonic names for program execution parameters. The user then assigns parameter values under the mnemonic names right adjusted (only names and titles are left adjusted) and CR when he is finished. If he wishes to use default values for parameters only CR is necessary (for names, $$$, left adjusted, must be given). This section explains the parameter values and their meaning. Error messages are supplied preceding the prompts of the next input line. If it is possible to correct an error the program will neglect or repeat the input line in question. Table 8 gives the flowchart of the program execution in response to the parameter lines (see above under Main.f).

A. Title

```
Market Penetration by N. Nakicenovic
      IIASA Version 20.03.78

*  give one-line title within this field    *absolute units*
```

Under this prompt a title (up to 50 characteristics long) characterizing the particular application of the model should be given within the specified field:

To the right under *absolute units* the units of the data under analysis should be given (centered). Appropriate conversion of the units should be given if the scaling option for the data is used (see parameter exp under B. Parameter Line).

B. Parameter Line

```
plt frc tot  iy  no dat est prt par sca exp
```

mnemonic	default	value	explanation
plt	0	0	To plot
		-1	Plot but do not draw or label the axis
		1	No plot
frg	0	0	semi-log plot for fractional market shares
		1	Linear plot for fractional market share
		2	Linear plot for summed fractional shares
tot	0	0	Semi-log plot for absolute market share
		1	Linear plot for absolute market share
		2	Linear plot for summed absolute shares
		4	Semi-log plot for summed absolute shares
iy	0	integer	Initial year expressed as positive or negative difference from 1900
no	100	integer	Number of points (cannot be greater than 300)

dat	0	0	Original time series as fractions and absolute values
		1	Only fractions
		2	Only absolute values
		3	No original data
est	0	0	Estimated market shares as fractions and absolute values
		1	Only fractions
		2	Only absolute values
		3	No estimated market shares
prt	0	0	No output file
		1	Output file is generated, zeros are suppressed
		2	Output file is generated, zeros are not suppressed
par	0	0	Do not sum absolute values
		1	Only sum of the absolute values
sca	0	0	Time-scale of standard length (4cm/50years)
		n	Where n is an integer: time-scale will be 1+n/2 times standard length
esp	0	0	Data will be unchanged
		n	Where n is an integer: data will be multiplied by 10** (n)

The parameters iy and no should be used with care: iy specifies the beginning of the time period to be investigated, i.e. the initial year, as the difference between this time point and 1900; e.g. 1860 would be specified as iy = -40, and 1940 as iy = 40. no determines the end of the time period under investigation. The parameter value is specified as the difference in years from the initial time point iy, excluding the year 1900; e.g. investigation of the period 1860 to 2000 is specified by iy = -40 and no = 140. Furthermore, no is rounded by the program by default to the nearest half of a century (50 years). For example, iy = -40 and no = 111 would imply the initial year 1860 and the final year 1971, however the program will by default change no to 140 making 2000 the final year. If this option is not desired 9000 should be added to the desired value of no; thus no = 9111 and iy = -40 determines the interval of 1860 to 1971.

C. Parameter Line

write series numbers on punch file:
nu1 nu2 nu3 nu4 nu5 nu6 nu7

Logical numbers of time series to be used in the model are to be given under nu1 to nu7 (maximum of seven separate time series can be entered). The program will respond by giving the number and the names of the time series extracted from the Punch file.

D. Parameter Line

```
enter $$$ for default, values otherwise:
default  iyd nod
```

iyd stands for the initial year of the time series to be used, expressed as positive or negative difference from 1900. If the default option is used the initial year will be the first year occurring in the time series.

The value entered for nod determines the number of observations of the time series to be used. If the default option is used all of the observations in the time series will be used.

E. Parameter Line

```
enter: 0 to read       coef
       1 to estimate
       2 to add/change
```

To read the model coefficients from the Coef file (see Coef and Incoef files above), zero should be entered which leads directly to G. Parameter Line. To estimate coefficients (provided option dat = 3 in Parameter line B is not used), one should be entered. The third option, entering two, also leads directly to Parameter line G, but in this case *all* coefficients are set to zero.

F. Parameter Lines

year year nu na

If option 1 is used in E. Parameter Line the user must give the time interval for which the coefficients are to be estimated by typing in the first and the last year of this interval. nu and na stand for the logical number and the name of the time series in question and are provided by the program. The time intervals for different series need not be the same.

G. Parameter Lines

```
if you do not change/add coef give $$$ under name
name     eqn year fraction year fraction
```

This option offers the possibility of adding scenarios about the behavior of new competitions that may not be available in the historical data base. It can also be used to change the estimated coefficients. The name of the competitor and its logical equation number (eqn) must be given together with the two desired fractional market shares (fraction) and the corresponding year. $$$ is typed left-adjusted under name to go to the next parameter line.

The exponential growth rate of the sum of all absolute values can be changed four times throughout the estimation period by entering total under name and 8 under eqn. year in this case denotes the beginning year for the new growth rate, and the growth rates should be entered under fraction (in fractional terms). The values entered will be displayed.

H. Parameter Line

```
write sequence numbers for 6 equations:
  1      2      3      4      5      6      7
 na1    na2    na3    na4    na5    na6    na7
```

Due to the possible changes of the coefficients in G. Parameter Line, the user must establish a chronological order of competitors. n stands for the number of competitors defined by the user in the previous steps, and na1 to na7 stand for the names of these competitors. Directly under these names and the numbers displayed above which denote the current chronological order, the new sequence numbers must be given by the user.

6. TUTORIAL EXAMPLE

The use of the program Pene is illustrated below by the example of primary energy consumption of the world given in the Punch file, Table 3. The Punch file containing the time series with consumption levels of different primary energy sources in million tons of coal equivalent between the years 1860 and 1974, is read by the program. The model coefficients are estimated over the whole historical period, and the file Incoef will be automatically generated (Table 4). An alternative nuclear energy penetration scenario is included specifying a 1% nuclear share in 1970 and a 6% share in 2000. In addition, total primary energy growth is changed twice from the long-term historical growth rate estimated over the period 1890 to 1950. The annual growth rate is changed to 6% in 1955 and to 3% in 1970. The model estimates are generated only for the historical period of 1860 to 1978. Two plots are generated in the plotter file (Figures 1 and 2). The first shows fractional market substitution on a linear axis plotted in the summed form, and the second shows the absolute consumption levels plotted on the logarithmic axis. Incards and Output files are also generated and reproduced in Tables 5 and 6.

In this example below, the lines marked "u" in the left column show user input lines, other lines are program prompts.

```
          Market Penetration by N. Nakicenovic
                 IIASA Version 20.03.78

  *       give one-line title within this field    *absolute units*
          world - primary energy substitution          bill. tce

   plt frc tot  iy  no dat est prt par sca exp
u        2     -509118           1       1  -3
    0    2   0 -50 118   0   0   1   0   1  -3
   write series numbers on punch file:
   nu1 nu2 nu3 nu4 nu5 nu6 nu7
u    1   4   5   7   8
     1   4   5   7   8   0   0
    5 series are read from punch file to locations:
     1       2       3       4       5       6       7
  wood pt oil     nat-gas coal-totnuclear
  enter $$$ for default, values otherwise:
  default  iyd nod
u $$$
          -40 115
  enter: 0 to read      coef
         1 to estimate
         2 to add/change
u 1
  year year 1 wood pt
u 1860 1974
  1860 1974
  year year 2 oil
u 1860 1974
  1860 1974
  year year 3 nat-gas
u 1860 1974
  1860 1974
  year year 4 coal-tot
u 1860 1974
  1860 1974
  year year 5 nuclear
u 1860 1974
  1860 1974
       ERROR *** 2 observations for this eqn
       therefore no statistics, both observations explained
  year year 6 total
u 1860 1950
  1860 1950
  if you do not change/add coef give $$$ under name
  name    eqn year fraction year fraction
u nuclear   5 1970 0.01     2000 0.06
  nuclear   5 1970 0.010000 2000 0.060000
  name    eqn year fraction year fraction
u total     8 1955 0.06     1970 0.03
  total     6 year growth   year  growth
  total     6 1955 0.060000 1970 0.030000
  name    eqn year fraction year fraction
u $$$
   write sequence numbers for 5 equations:
     1       2       3       4       5       6       7
  wood pt oil     nat-gas coal-totnuclear
u    1       3       4       2       5
     1       3       4       2       5       0       0
   new sequence of equations is:
     1       2       3       4       5       6       7
  wood pt coal-totoil     nat-gas nuclear
```

Figure 1.

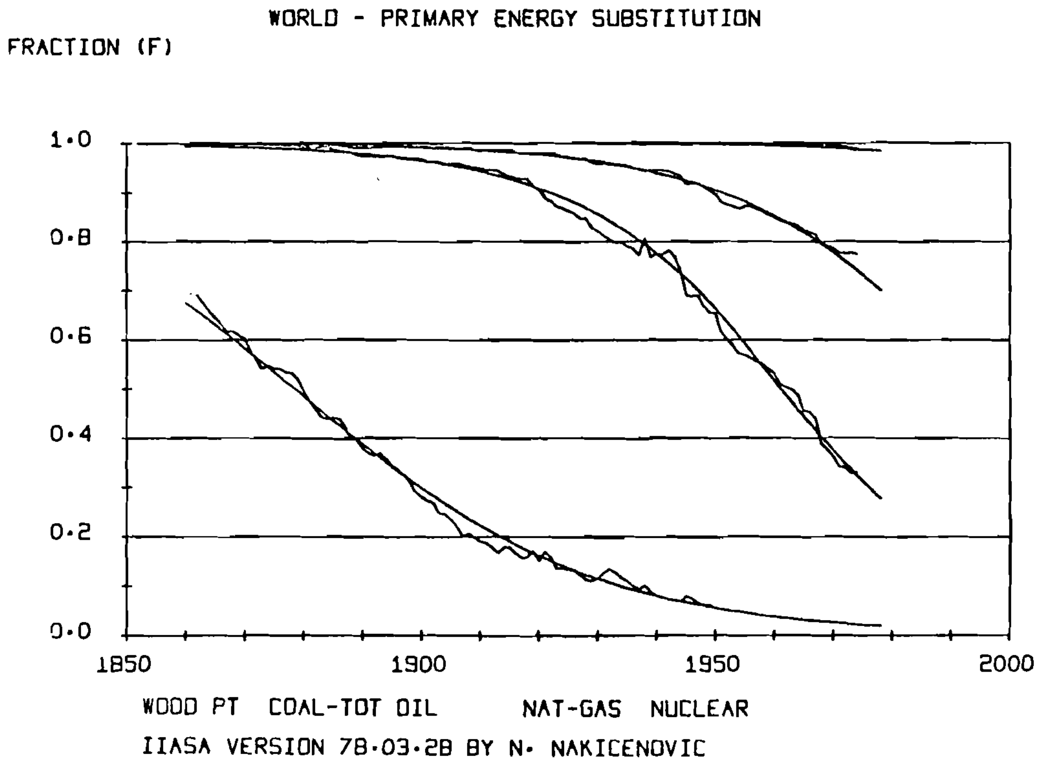


Figure 2.

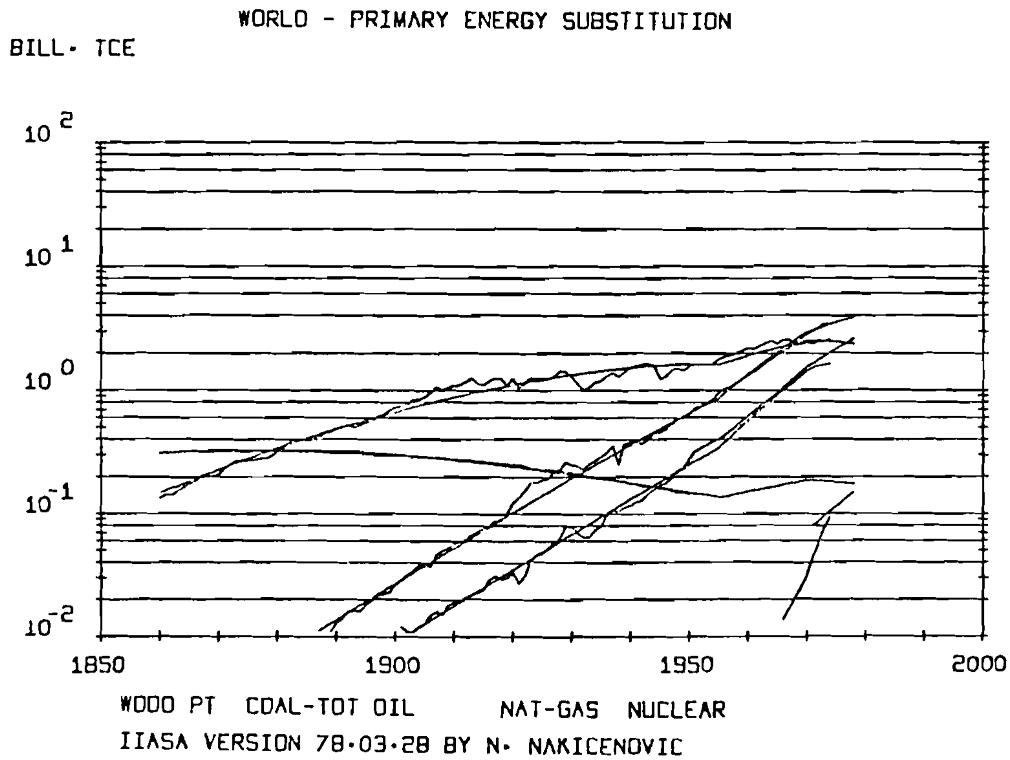


Table 1. Simple *Fortran* Program.

```
          real*8 t,for
          dimension f(300,7),t(7),for(9)
 105      format(i2)
 106      format(9a8)
 107      format(i4,x,a8,4i4/(8f10.3))
 108      format(5x,3h$$$//5x,3h$$$/)

          read (5,105) n
          read (5,106) (for(j),j=1,9)
          do 3 j=1,n
 3        read (5,106) t(j)
          do 1 i=1,300
          read (5,for,end=2) iyi,(f(i,j),j=1,n)
          no=i-1
          if (i.gt.1) go to 1
          iy=iyi
 1        continue
 2        ni=iy-1900
          ip1=1
          ib1=1
          do 9 j=1,n
          write (8,107) j,t(j),no,ni,ip1,ib1,(f(i,j),i=1,no)
 9        continue
          write (8,108)
          stop
          end
```

Table 2. Input and output files for the simple program.

<u>I N P U T</u>

```
 5
(i4,5(f10.2))
total
oil
nat-gas
coal
nuclear
1960    4126.00    1321.00     618.00    2187.00       0.00
1961    4225.76    1402.00     665.00    2157.00       1.76
1962    4527.60    1517.00     729.00    2279.00       2.60
1963    4874.24    1652.00     793.00    2425.00       4.24
1964    5168.00    1784.00     864.00    2514.00       6.00
1965    5229.68    1921.00     925.00    2374.00       9.68
1966    5650.84    2075.00    1010.00    2552.00      13.84
1967    5892.76    2218.00    1084.00    2574.00      16.76
1968    5897.88    2414.00    1182.00    2281.00      20.88
1969    6292.64    2611.00    1295.00    2362.00      24.64
1970    6728.92    2854.00    1417.00    2427.00      30.92
1971    6971.80    3029.00    1513.00    2387.00      42.80
1972    7287.58    3179.70    1583.70    2466.90      57.28
1973    7621.54    3426.60    1619.90    2498.80      76.24
1974    7691.34    3396.90    1646.10    2554.90      93.44
```

<u>O U T P U T</u>

```
   1 total       15   60     1    1
 4126.000  4225.760  4527.600  4874.240  5168.000  5229.680  5650.840  5892.760
 5897.880  6292.640  6728.920  6971.800  7287.580  7621.540  7691.340
   2 oil         15   60     1    1
 1321.000  1402.000  1517.000  1652.000  1784.000  1921.000  2075.000  2218.000
 2414.000  2611.000  2854.000  3029.000  3179.700  3426.600  3396.900
   3 nat-gas     15   60     1    1
  618.000   665.000   729.000   793.000   864.000   925.000  1010.000  1084.000
 1182.000  1295.000  1417.000  1513.000  1583.700  1619.900  1646.100
   4 coal        15   60     1    1
 2187.000  2157.000  2279.000  2425.000  2514.000  2374.000  2552.000  2574.000
 2281.000  2362.000  2427.000  2387.000  2466.900  2498.800  2554.900
   5 nuclear     15   60     1    1
    0.000     1.760     2.600     4.240     6.000     9.680    13.840    16.760
   20.880    24.640    30.920    42.800    57.280    76.240    93.440
```

Table 3. Punch File.

```
 1 wood pt    91 -40    1    1
 317.000   317.000   317.000   317.000   318.000   318.000   318.000   318.000
 318.000   318.000   318.000   318.000   319.000   319.000   320.000   320.000
 324.000   323.000   322.000   321.000   320.000   319.000   319.000   318.000
 317.000   317.000   316.000   314.000   313.000   311.000   310.000   308.000
 308.000   307.000   304.000   302.000   301.000   299.000   297.000   296.000
 296.000   293.000   292.000   288.000   288.000   287.000   284.000   282.000
 281.000   276.000   275.000   274.000   273.000   270.000   266.000   263.000
 261.000   259.000   257.000   252.000   249.000   247.000   242.000   231.000
 230.000   227.000   226.000   224.000   220.000   216.000   212.000   209.000
 203.000   202.000   198.000   194.000   191.000   191.000   184.000   181.000
 176.000   173.000   169.000   166.000   162.000   159.000   157.000   152.000
 149.000   147.000   144.000
 2 coal      115 -40    1    1
 132.000   140.000   139.000   149.000   162.000   172.000   181.000   194.000
 192.000   199.000   204.000   227.000   247.000   263.000   256.000   264.000
 267.000   273.000   273.000   287.000   314.000   338.000   363.000   388.000
 390.000   381.000   382.000   408.000   441.000   448.000   475.000   494.000
 499.000   487.000   509.000   536.000   552.000   577.000   608.000   667.000
 701.000   718.000   734.000   807.000   812.000   858.000   926.000  1023.000
 966.000  1010.000  1057.000  1077.000  1134.000  1216.000  1086.000  1070.000
1152.000  1215.000  1195.000  1040.000  1192.000   993.000  1056.000  1208.000
1186.000  1185.000  1177.000  1245.000  1357.000  1325.000  1217.000  1072.000
 952.000   997.000  1092.000  1125.000  1233.000  1291.000  1204.000  1297.000
1417.000  1483.000  1508.000  1534.000  1496.000  1167.000  1215.000  1369.000
1405.000  1319.000  1431.000  1504.000  1490.000  1489.000  1469.000  1590.000
1660.000  1733.000  1815.000  1891.000  1975.000  1938.000  2051.000  2187.000
2266.000  2128.000  2308.000  2334.000  2035.000  2110.000  2166.000  2127.000
2200.500  2226.600  2276.100
 3 lig-coal 115 -40    1    1
   2.000     2.000     2.000     3.000     3.000     3.000     3.000     3.000
   4.000     4.000     4.000     5.000     5.000     6.000     6.000     6.000
   7.000     7.000     7.000     7.000     8.000     8.000     9.000     9.000
   9.000    10.000    10.000    10.000    11.000    12.000    13.000    14.000
  14.000    15.000    15.000    16.000    17.000    19.000    20.000    21.000
  24.000    25.000    25.000    26.000    27.000    29.000    31.000    34.000
  35.000    36.000    36.000    37.000    41.000    43.000    40.000    41.000
  44.000    45.000    47.000    44.000    52.000    56.000    60.000    54.000
  57.000    62.000    62.000    67.000    72.000    77.000    65.000    60.000
  56.000    58.000    63.000    68.000    74.000    84.000    87.000    95.000
 102.000   104.000   103.000   106.000    93.000    58.000    80.000    88.000
  96.000   107.000   127.000   131.000   145.000   148.000   164.000   178.000
 186.000   198.000   204.000   206.000   212.000   219.000   228.000   238.000
 248.000   246.000   244.000   240.000   246.000   252.000   261.000   260.000
 266.400   272.200   278.800
 4 oil       113 -38    1    1
   1.000     1.000     0.000     1.000     1.000     1.000     1.000     1.000
   1.000     1.000     1.000     2.000     2.000     2.000     2.000     3.000
   3.000     4.000     5.000     6.000     6.000     5.000     6.000     6.000
   8.000     8.000     9.000    11.000    13.000    14.000    16.000    16.000
  16.000    16.000    20.000    21.000    22.000    23.000    26.000    29.000
  32.000    34.000    38.000    38.000    37.000    46.000    50.000    52.000
  57.000    60.000    62.000    68.000    71.000    75.000    80.000    88.000
  88.000    97.000   121.000   134.000   151.000   178.000   178.000   187.000
 192.000   221.000   232.000   260.000   247.000   241.000   230.000   253.000
 267.000   290.000   314.000   357.000   248.000   366.000   377.000   389.000
 367.000   396.000   454.000   455.000   481.000   530.000   602.000   597.000
 636.000   705.000   749.000   797.000   843.000   948.000  1026.000  1069.000
1137.000  1222.000  1321.000  1402.000  1517.000  1652.000  1784.000  1921.000
2075.000  2216.000  2414.000  2611.000  2854.000  3029.000  3179.700  3426.600
3396.900
```

Table 3 (continued).

```
  5 nat-gas    90 -15    1    1
   3.000      4.000      6.000      7.000      8.000      9.000      8.000      8.000
   7.000      6.000      5.000      6.000      7.000      8.000      9.000      9.000
  12.000     11.000     11.000     12.000     13.000     15.000     16.000     15.000
  18.000     19.000     20.000     21.000     22.000     23.000     24.000     29.000
  31.000     29.000     30.000     33.000     27.000     31.000     41.000     46.000
  48.000     53.000     58.000     63.000     78.000     79.000     69.000     64.000
  65.000     74.000     79.000     97.000    108.000    104.000    112.000    116.000
 124.000    130.000    145.000    157.000    169.000    176.000    196.000    220.000
 234.000    273.000    318.000    340.000    361.000    382.000    397.000    428.000
 464.000    505.000    566.000    618.000    665.000    729.000    793.000    864.000
 925.000   1010.000   1084.000   1182.000   1295.000   1417.000   1513.000   1583.700
1619.900   1646.100
  6 hydronuc   75    0    1    1
   6.000     10.000     11.000     13.000     15.000     18.000     21.000     25.000
  25.000     28.000     31.000     34.000     38.000     42.000     40.000     41.000
  47.000     52.000     53.000     49.000     58.000     52.000     58.000     68.000
  69.000     65.000     74.000     66.000     64.000     88.000     85.000     80.000
  61.000     84.000     87.000     96.000    105.000    119.000    120.000    127.000
 128.000    137.000    140.000    156.000    140.000    136.000    145.000    153.000
 161.000    156.000    180.000    199.000    204.000    204.000    207.000    222.000
 236.000    246.000    263.000    272.000    290.000    299.000    310.000    318.000
 333.000    358.000    389.000    390.000    410.000    440.000    452.000    481.000
 517.400    543.700    583.600
  7 coal-tot 115 -40     1    1
 134.000    142.000    141.000    152.000    165.000    175.000    184.000    197.000
 196.000    203.000    208.000    232.000    252.000    269.000    262.000    270.000
 274.000    280.000    280.000    294.000    322.000    346.000    372.000    397.000
 399.000    391.000    392.000    418.000    452.000    460.000    488.000    508.000
 513.000    502.000    524.000    552.000    569.000    596.000    628.000    688.000
 725.000    743.000    759.000    833.000    839.000    887.000    957.000   1057.000
1003.000   1046.000   1093.000   1114.000   1175.000   1259.000   1126.000   1111.000
1196.000   1260.000   1242.000   1084.000   1244.000   1049.000   1116.000   1262.000
1245.000   1247.000   1239.000   1312.000   1429.000   1402.000   1282.000   1132.000
1008.000   1055.000   1155.000   1193.000   1307.000   1375.000   1291.000   1392.000
1519.000   1587.000   1611.000   1640.000   1591.000   1225.000   1295.000   1457.000
1561.000   1426.000   1556.000   1635.000   1635.000   1637.000   1633.000   1768.000
1866.000   1931.000   2019.000   2097.000   2187.000   2157.000   2279.000   2425.000
2514.000   2374.000   2552.000   2574.000   2281.000   2362.000   2427.000   2387.000
2466.900   2498.800   2554.900
  8 nuclear    14   61    1    1
   1.760      2.600      4.240      6.000      9.680     13.840     16.760     20.880
  24.640     30.920     42.800     57.280     76.240     93.440
   $$$

  1 wood pt    8                                                   $
world fuel wood consumption in 10**6 tce extrapolated by Putnam
  2 coal       9                                                   $
world coal consumption in 10**6 tce from Hildebrandt, Schilling, Peters
  3 lig-coal   9                                                   $
world lig-coal consumption in 10**6 tce from Hildebrandt, Schi., Pet.
  4 oil        9                                                   $
world oil consumption in 10**6 tce from Hildebrandt, Schilling, Peters
  5 nat-gas    9                                                   $
world natural gas consumption in 10**6 tce from Hildebrandt, Schi., Pet.
  6 hydronuc   9                                                   $
world hydro & nuclear consumption in 10**6 tce from Hildebrandt, S., P.
  7 coal-tot   9                                                   $
world total coal consumption in 10**6 tce from Hildebrandt, Schi., Pet.
  8 nuclear    9                                                   $
world nuclear consumption in 10**6 tce from Hild., Schi., (1TWh=0.4tce)
   $$$
```

Table 4. Incoef and Coef files.

```
wood pt     1    2    -0.03968587    74.54809570
oil         2    2     0.04901962   -96.73044586
nat-gas     3    2     0.04833411   -96.53026581
coal-tot    4    2     0.00273743    -4.88342714
nuclear     5    2     0.19531250  -389.94577026
total       8    2     0.01958038   -37.19755936
$$$

$$$
```

Table 5. Incard and Cards Files.

```
          world - primary energy substitution             bill. tce
   0    2    0 -509118    0    0    1    0    1   -3
   1    4    5    7    8    0    0
$$$          0    0
1
1860  1974
1860  1974
1860  1974
1860  1974
1860  1974
1860  1950
nuclear    5 1970 0.010000 2000 0.060000
total      8 1955 0.060000 1970 0.030000
$$$        0    0 0.000000    0 0.000000
   1         3         4         2         5         0         0
```

Table 6. Output File.

MARKET PENETRATION BY N. NAKICENOVIC
IIASA VERSION 20.03.78

WORLD - PRIMARY ENERGY SUBSTITUTION BILL. TCE

OBSERVED VALUES

YEAR	TOTAL	WOOD PT	F	OIL	F	NAT-GAS	F	COAL-TOT	F	NUCLEAR	F
1860	0.45	0.32	0.703					0.13	0.297		
1861	0.46	0.32	0.691					0.14	0.309		
1862	0.46	0.32	0.691	0.00	0.002			0.14	0.307		
1863	0.47	0.32	0.674	0.00	0.002			0.15	0.323		
1864	0.48	0.32	0.658					0.17	0.342		
1865	0.49	0.32	0.644	0.00	0.002			0.18	0.354		
1866	0.52	0.32	0.632	0.00	0.002			0.18	0.366		
1867	0.52	0.32	0.616	0.00	0.002			0.20	0.382		
1868	0.52	0.32	0.617	0.00	0.002			0.20	0.381		
1869	0.52	0.32	0.609	0.00	0.002			0.20	0.389		
1870	0.53	0.32	0.603	0.00	0.002			0.21	0.395		
1871	0.55	0.32	0.577	0.00	0.002			0.23	0.421		
1872	0.57	0.32	0.558	0.00	0.002			0.25	0.441		
1873	0.59	0.32	0.541	0.00	0.003			0.27	0.456		
1874	0.58	0.32	0.548	0.00	0.003			0.26	0.449		
1875	0.59	0.32	0.541	0.00	0.003			0.27	0.456		
1876	0.60	0.32	0.540	0.00	0.003			0.27	0.457		
1877	0.61	0.32	0.533	0.00	0.005			0.28	0.462		
1878	0.61	0.32	0.532	0.00	0.005			0.28	0.463		
1879	0.62	0.32	0.519	0.00	0.006			0.29	0.475		
1880	0.65	0.32	0.495	0.01	0.008			0.32	0.498		
1881	0.67	0.32	0.475	0.01	0.009			0.35	0.516		
1882	0.70	0.32	0.458	0.01	0.009			0.37	0.534		
1883	0.72	0.32	0.442	0.01	0.007			0.40	0.551		
1884	0.72	0.32	0.439	0.01	0.008			0.40	0.553		
1885	0.72	0.32	0.442	0.01	0.008	0.00	0.004	0.39	0.545		
1886	0.72	0.32	0.439	0.01	0.011	0.00	0.006	0.39	0.544		
1887	0.75	0.31	0.421	0.01	0.011	0.01	0.008	0.42	0.560		
1888	0.78	0.31	0.401	0.01	0.012	0.01	0.009	0.45	0.579		
1889	0.79	0.31	0.394	0.01	0.014	0.01	0.010	0.46	0.582		
1890	0.82	0.31	0.378	0.01	0.016	0.01	0.011	0.49	0.595		
1891	0.84	0.31	0.368	0.01	0.017	0.01	0.010	0.51	0.606		
1892	0.85	0.31	0.364	0.02	0.019	0.01	0.009	0.51	0.607		
1893	0.83	0.31	0.369	0.02	0.019	0.01	0.008	0.50	0.603		
1894	0.85	0.30	0.358	0.02	0.019	0.01	0.007	0.52	0.616		
1895	0.88	0.30	0.344	0.02	0.021	0.01	0.006	0.55	0.629		
1896	0.90	0.30	0.336	0.02	0.022	0.01	0.007	0.57	0.635		
1897	0.92	0.30	0.324	0.02	0.023	0.01	0.008	0.60	0.646		
1898	0.96	0.30	0.311	0.02	0.023	0.01	0.008	0.63	0.658		
1899	1.02	0.30	0.291	0.02	0.023	0.01	0.009	0.69	0.677		
1900	1.06	0.30	0.280	0.03	0.025	0.01	0.009	0.73	0.687		
1901	1.08	0.29	0.272	0.03	0.027	0.01	0.011	0.74	0.690		
1902	1.09	0.29	0.267	0.03	0.029	0.01	0.010	0.76	0.694		
1903	1.17	0.29	0.247	0.03	0.029	0.01	0.009	0.83	0.714		
1904	1.18	0.29	0.245	0.04	0.032	0.01	0.010	0.84	0.713		
1905	1.23	0.29	0.234	0.04	0.031	0.01	0.011	0.89	0.724		
1906	1.29	0.28	0.220	0.04	0.029	0.02	0.012	0.96	0.740		
1907	1.40	0.28	0.201	0.05	0.033	0.02	0.011	1.06	0.754		
1908	1.35	0.28	0.208	0.05	0.037	0.02	0.011	1.00	0.744		
1909	1.39	0.28	0.198	0.05	0.037	0.02	0.013	1.05	0.751		
1910	1.44	0.26	0.190	0.06	0.039	0.02	0.013	1.09	0.757		
1911	1.47	0.27	0.187	0.06	0.041	0.02	0.014	1.11	0.759		

Table 6 (continued).

YEAR	TOTAL	WOOD PT	F	OIL	F	NAT-GAS	F	COAL-TOT	F	NUCLEAR	F
1912	1.53	0.27	0.178	0.06	0.040	0.02	0.014	1.18	0.767		
1913	1.62	0.27	0.167	0.07	0.042	0.02	0.014	1.26	0.776		
1914	1.49	0.27	0.179	0.07	0.048	0.02	0.015	1.13	0.758		
1915	1.47	0.26	0.178	0.08	0.052	0.02	0.016	1.11	0.754		
1916	1.57	0.26	0.167	0.08	0.051	0.03	0.019	1.20	0.764		
1917	1.64	0.26	0.158	0.09	0.054	0.03	0.019	1.26	0.769		
1918	1.62	0.26	0.159	0.09	0.054	0.03	0.018	1.24	0.769		
1919	1.46	0.25	0.172	0.10	0.066	0.03	0.021	1.08	0.741		
1920	1.65	0.25	0.151	0.12	0.073	0.03	0.020	1.24	0.755		
1921	1.46	0.25	0.170	0.13	0.092	0.03	0.019	1.05	0.720		
1922	1.54	0.24	0.157	0.15	0.098	0.03	0.020	1.12	0.725		
1923	1.71	0.23	0.135	0.18	0.104	0.04	0.024	1.26	0.737		
1924	1.70	0.23	0.135	0.18	0.105	0.05	0.027	1.25	0.733		
1925	1.71	0.23	0.133	0.19	0.109	0.05	0.028	1.25	0.730		
1926	1.71	0.23	0.132	0.19	0.112	0.05	0.031	1.24	0.725		
1927	1.82	0.22	0.123	0.22	0.122	0.06	0.032	1.31	0.723		
1928	1.94	0.22	0.113	0.23	0.119	0.06	0.032	1.43	0.735		
1929	1.96	0.22	0.110	0.26	0.133	0.08	0.040	1.40	0.717		
1930	1.82	0.21	0.116	0.25	0.136	0.08	0.043	1.28	0.704		
1931	1.65	0.21	0.127	0.24	0.146	0.07	0.042	1.13	0.686		
1932	1.51	0.20	0.135	0.23	0.153	0.06	0.043	1.01	0.670		
1933	1.58	0.20	0.128	0.25	0.161	0.07	0.041	1.06	0.670		
1934	1.69	0.20	0.117	0.27	0.158	0.07	0.044	1.16	0.682		
1935	1.76	0.19	0.110	0.29	0.165	0.08	0.045	1.19	0.679		
1936	1.91	0.19	0.100	0.31	0.164	0.10	0.051	1.31	0.685		
1937	2.03	0.19	0.094	0.36	0.176	0.11	0.053	1.38	0.677		
1938	1.83	0.18	0.101	0.25	0.136	0.10	0.057	1.29	0.707		
1939	2.05	0.18	0.088	0.37	0.178	0.11	0.055	1.39	0.679		
1940	2.19	0.18	0.080	0.38	0.172	0.12	0.053	1.52	0.694		
1941	2.27	0.17	0.076	0.39	0.171	0.12	0.055	1.59	0.698		
1942	2.28	0.17	0.074	0.37	0.161	0.13	0.057	1.61	0.708		
1943	2.35	0.17	0.071	0.40	0.169	0.15	0.062	1.64	0.699		
1944	2.36	0.16	0.069	0.45	0.192	0.16	0.066	1.59	0.673		
1945	2.01	0.16	0.079	0.46	0.227	0.17	0.084	1.23	0.610		
1946	2.11	0.16	0.074	0.48	0.228	0.18	0.083	1.30	0.614		
1947	2.34	0.15	0.065	0.53	0.227	0.20	0.084	1.46	0.624		
1948	2.47	0.15	0.060	0.60	0.244	0.22	0.089	1.50	0.607		
1949	2.40	0.15	0.061	0.60	0.248	0.23	0.097	1.43	0.593		
1950	2.61	0.14	0.055	0.64	0.244	0.27	0.105	1.56	0.597		
1951	2.66			0.71	0.265	0.32	0.120	1.64	0.615		
1952	2.73			0.75	0.275	0.34	0.125	1.64	0.600		
1953	2.80			0.80	0.285	0.36	0.129	1.64	0.586		
1954	2.86			0.84	0.295	0.38	0.134	1.63	0.571		
1955	3.11			0.95	0.305	0.40	0.128	1.77	0.568		
1956	3.32			1.03	0.309	0.43	0.129	1.87	0.562		
1957	3.46			1.07	0.309	0.46	0.134	1.93	0.557		
1958	3.66			1.14	0.311	0.50	0.138	2.02	0.551		
1959	3.89			1.22	0.315	0.57	0.146	2.10	0.540		
1960	4.13			1.32	0.320	0.62	0.150	2.19	0.530		
1961	4.23			1.40	0.332	0.67	0.157	2.16	0.510	0.00	0.000
1962	4.53			1.52	0.335	0.73	0.161	2.28	0.503	0.00	0.001
1963	4.87			1.65	0.339	0.79	0.163	2.43	0.498	0.00	0.001
1964	5.17			1.78	0.345	0.86	0.167	2.51	0.486	0.01	0.001
1965	5.23			1.92	0.367	0.93	0.177	2.37	0.454	0.01	0.002
1966	5.65			2.08	0.367	1.01	0.179	2.55	0.452	0.01	0.002
1967	5.89			2.22	0.376	1.08	0.184	2.57	0.437	0.02	0.003
1968	5.90			2.41	0.409	1.18	0.200	2.28	0.387	0.02	0.004
1969	6.29			2.61	0.415	1.30	0.206	2.36	0.375	0.02	0.004
1970	6.73			2.85	0.424	1.42	0.211	2.43	0.361	0.03	0.005
1971	6.97			3.03	0.434	1.51	0.217	2.39	0.342	0.04	0.006

Table 6 (continued).

YEAR	TOTAL	WOOD PT	F	OIL	F	NAT-GAS	F	COAL-TOT	F	NUCLEAR	F
1972	7.29			3.18	0.436	1.58	0.217	2.47	0.339	0.06	0.008
1973	7.62			3.43	0.450	1.62	0.213	2.50	0.328	0.08	0.010
1974	7.69			3.40	0.442	1.65	0.214	2.55	0.332	0.09	0.012

INTEGRALS FROM 1860 TO 1974 ARE:

TOTAL	WOOD PT	F	OIL	F	NAT-GAS	F	COAL-TOT	F	NUCLEAR	F
228.	24.	0.106	53.	0.233	24.	0.104	126.	0.556	0.	0.002

COEFFICIENTS ESTIMATED IN FITLIN.F

```
EQN 1  WOOD PT   IS: Y = -0.040*T+  74.548      R**2 = 0.990  VAR = 0.011
                        (-94.845) ( 93.514)

EQN 2  OIL       IS: Y =  0.049*T+ -96.730      R**2 = 0.984  VAR = 0.027
                        ( 72.373) (-73.976)

EQN 3  NAT-GAS   IS: Y =  0.048*T+ -96.530      R**2 = 0.979  VAR = 0.025
                        ( 58.850) (-60.698)

EQN 4  COAL-TOT  IS: Y =  0.003*T+  -4.883      R**2 = 0.024  VAR = 0.344
                        (  1.662) ( -1.547)

EQN 8  TOTAL     IS: Y =  0.020*T+ -37.198      R**2 = 0.972  VAR = 0.008
                        ( 55.570) (-55.412)

EQN 5  NUCLEAR   IS: Y =  0.061*T+-125.657    STARTING 1860

EQN 8  TOTAL     IS: Y =  0.060*T+-116.218    STARTING 1955

EQN 8  TOTAL     IS: Y =  0.030*T+ -57.118    STARTING 1970
```

ESTIMATED VALUES

YEAR	TOTAL	WOOD PT	F	COAL-TOT	F	OIL	F	NAT-GAS	F	NUCLEAR	F
1860	0.46	0.31	0.675	0.15	0.319						
1861	0.47	0.31	0.667	0.15	0.328						
1862	0.48	0.31	0.658	0.16	0.337						
1863	0.49	0.32	0.649	0.17	0.345						
1864	0.50	0.32	0.640	0.18	0.354						
1865	0.51	0.32	0.630	0.18	0.363						
1866	0.52	0.32	0.621	0.19	0.372						
1867	0.53	0.32	0.612	0.20	0.381						
1868	0.54	0.32	0.602	0.21	0.390						
1869	0.55	0.32	0.593	0.22	0.399						
1870	0.56	0.33	0.583	0.23	0.408						
1871	0.57	0.33	0.573	0.24	0.418						
1872	0.58	0.33	0.564	0.25	0.427						
1873	0.59	0.33	0.554	0.26	0.436						
1874	0.60	0.33	0.544	0.27	0.446						
1875	0.62	0.33	0.534	0.28	0.455						
1876	0.63	0.33	0.524	0.29	0.464						
1877	0.64	0.33	0.514	0.30	0.474						
1878	0.65	0.33	0.505	0.32	0.483						
1879	0.67	0.33	0.495	0.33	0.492						
1880	0.68	0.33	0.485	0.34	0.502	0.01	0.010				

Table 6 (continued).

YEAR	TOTAL	WOOD PT	F	OIL	F	NAT-GAS	F	COAL-TOT	F	NUCLEAR	F
1881	0.69	0.33	0.475	0.35	0.511	0.01	0.011				
1882	0.71	0.33	0.465	0.37	0.520	0.01	0.011				
1883	0.72	0.33	0.455	0.38	0.529	0.01	0.012				
1884	0.73	0.33	0.445	0.40	0.538	0.01	0.012				
1885	0.75	0.33	0.435	0.41	0.547	0.01	0.013				
1886	0.76	0.33	0.426	0.42	0.556	0.01	0.014				
1887	0.78	0.32	0.416	0.44	0.565	0.01	0.014				
1888	0.79	0.32	0.406	0.46	0.573	0.01	0.015				
1889	0.81	0.32	0.397	0.47	0.582	0.01	0.016				
1890	0.83	0.32	0.387	0.49	0.590	0.01	0.017				
1891	0.84	0.32	0.378	0.50	0.599	0.01	0.017				
1892	0.86	0.32	0.369	0.52	0.607	0.02	0.018				
1893	0.88	0.32	0.360	0.54	0.615	0.02	0.019				
1894	0.89	0.31	0.350	0.56	0.623	0.02	0.020				
1895	0.91	0.31	0.341	0.57	0.630	0.02	0.021				
1896	0.93	0.31	0.333	0.59	0.638	0.02	0.022				
1897	0.95	0.31	0.324	0.61	0.645	0.02	0.023				
1898	0.97	0.30	0.315	0.63	0.652	0.02	0.024				
1899	0.99	0.30	0.307	0.65	0.659	0.03	0.026				
1900	1.01	0.30	0.298	0.67	0.666	0.03	0.027				
1901	1.03	0.30	0.290	0.69	0.672	0.03	0.028				
1902	1.05	0.29	0.282	0.71	0.679	0.03	0.029				
1903	1.07	0.29	0.274	0.73	0.685	0.03	0.031	0.01	0.010		
1904	1.09	0.29	0.266	0.75	0.690	0.04	0.032	0.01	0.011		
1905	1.11	0.29	0.259	0.77	0.696	0.04	0.034	0.01	0.012		
1906	1.13	0.28	0.251	0.79	0.701	0.04	0.036	0.01	0.012		
1907	1.15	0.28	0.244	0.81	0.706	0.04	0.037	0.01	0.013		
1908	1.18	0.28	0.236	0.84	0.711	0.05	0.039	0.02	0.013		
1909	1.20	0.27	0.229	0.86	0.716	0.05	0.041	0.02	0.014		
1910	1.22	0.27	0.222	0.88	0.720	0.05	0.043	0.02	0.015		
1911	1.25	0.27	0.216	0.90	0.724	0.06	0.045	0.02	0.015		
1912	1.27	0.27	0.209	0.93	0.728	0.06	0.047	0.02	0.016		
1913	1.30	0.26	0.202	0.95	0.731	0.06	0.049	0.02	0.017		
1914	1.32	0.26	0.196	0.97	0.734	0.07	0.052	0.02	0.018		
1915	1.35	0.26	0.190	0.99	0.737	0.07	0.054	0.02	0.019		
1916	1.37	0.25	0.184	1.02	0.740	0.08	0.057	0.03	0.019		
1917	1.40	0.25	0.178	1.04	0.742	0.08	0.060	0.03	0.020		
1918	1.43	0.25	0.172	1.06	0.744	0.09	0.062	0.03	0.021		
1919	1.46	0.24	0.167	1.09	0.746	0.10	0.065	0.03	0.022		
1920	1.49	0.24	0.161	1.11	0.747	0.10	0.068	0.03	0.023		
1921	1.52	0.24	0.156	1.13	0.748	0.11	0.072	0.04	0.025		
1922	1.55	0.23	0.151	1.16	0.749	0.12	0.075	0.04	0.026		
1923	1.58	0.23	0.146	1.18	0.749	0.12	0.078	0.04	0.027		
1924	1.61	0.23	0.141	1.20	0.749	0.13	0.082	0.05	0.028		
1925	1.64	0.22	0.136	1.23	0.748	0.14	0.086	0.05	0.030		
1926	1.67	0.22	0.132	1.25	0.748	0.15	0.090	0.05	0.031		
1927	1.71	0.22	0.127	1.27	0.747	0.16	0.094	0.06	0.033		
1928	1.74	0.21	0.123	1.30	0.745	0.17	0.098	0.06	0.034		
1929	1.77	0.21	0.119	1.32	0.743	0.18	0.102	0.06	0.036		
1930	1.81	0.21	0.114	1.34	0.741	0.19	0.107	0.07	0.037		
1931	1.84	0.20	0.111	1.36	0.739	0.21	0.112	0.07	0.039		
1932	1.88	0.20	0.107	1.38	0.736	0.22	0.117	0.08	0.041		
1933	1.92	0.20	0.103	1.40	0.731	0.23	0.122	0.08	0.043		
1934	1.96	0.19	0.099	1.42	0.727	0.25	0.127	0.09	0.045		
1935	1.99	0.19	0.096	1.44	0.723	0.26	0.133	0.09	0.047		
1936	2.03	0.19	0.092	1.46	0.718	0.28	0.138	0.10	0.049		
1937	2.07	0.19	0.089	1.48	0.713	0.30	0.144	0.11	0.052		
1938	2.12	0.18	0.086	1.50	0.708	0.32	0.151	0.11	0.054		
1939	2.16	0.18	0.083	1.51	0.702	0.34	0.157	0.12	0.057		
1940	2.20	0.18	0.080	1.53	0.696	0.36	0.164	0.13	0.059		

Table 6 (continued).

YEAR	TOTAL	WOOD PT	F	OIL	F	NAT-GAS	F	COAL-TOT	F	NUCLEAR	F
1941	2.24	0.17	0.077	1.54	0.689	0.38	0.170	0.14	0.062		
1942	2.29	0.17	0.074	1.56	0.681	0.41	0.177	0.15	0.065		
1943	2.33	0.17	0.072	1.57	0.674	0.43	0.185	0.16	0.068		
1944	2.38	0.16	0.069	1.58	0.666	0.46	0.192	0.17	0.071		
1945	2.43	0.16	0.067	1.59	0.657	0.48	0.200	0.18	0.074		
1946	2.47	0.16	0.064	1.60	0.648	0.51	0.208	0.19	0.076		
1947	2.52	0.16	0.062	1.61	0.638	0.54	0.216	0.21	0.081		
1948	2.57	0.15	0.060	1.62	0.628	0.58	0.224	0.22	0.085		
1949	2.62	0.15	0.057	1.62	0.618	0.61	0.233	0.23	0.089		
1950	2.68	0.15	0.055	1.62	0.607	0.65	0.242	0.25	0.093		
1951	2.73	0.15	0.053	1.63	0.596	0.68	0.251	0.26	0.097		
1952	2.78	0.14	0.051	1.62	0.584	0.72	0.260	0.28	0.101		
1953	2.84	0.14	0.049	1.62	0.571	0.77	0.270	0.30	0.106		
1954	2.89	0.14	0.048	1.62	0.559	0.81	0.280	0.32	0.111		
1955	2.95	0.13	0.046	1.61	0.545	0.85	0.290	0.34	0.115		
1956	3.13	0.14	0.044	1.67	0.532	0.94	0.299	0.38	0.120		
1957	3.33	0.14	0.042	1.72	0.518	1.03	0.309	0.42	0.126		
1958	3.53	0.14	0.041	1.78	0.505	1.12	0.318	0.46	0.131		
1959	3.75	0.15	0.039	1.84	0.492	1.23	0.327	0.51	0.137		
1960	3.98	0.15	0.038	1.90	0.478	1.34	0.336	0.57	0.142		
1961	4.23	0.15	0.036	1.97	0.465	1.46	0.345	0.63	0.148		
1962	4.49	0.16	0.035	2.03	0.451	1.58	0.353	0.69	0.155		
1963	4.77	0.16	0.034	2.09	0.438	1.72	0.361	0.77	0.161		
1964	5.06	0.16	0.032	2.15	0.425	1.86	0.368	0.85	0.168		
1965	5.38	0.17	0.031	2.21	0.412	2.02	0.375	0.94	0.175		
1966	5.71	0.17	0.030	2.28	0.399	2.18	0.382	1.04	0.182		
1967	6.05	0.18	0.029	2.34	0.386	2.35	0.388	1.15	0.189		
1968	6.44	0.18	0.028	2.40	0.373	2.53	0.393	1.26	0.196		
1969	6.84	0.18	0.027	2.47	0.361	2.73	0.399	1.40	0.204		
1970	7.26	0.19	0.026	2.53	0.349	2.93	0.403	1.54	0.212		
1971	7.48	0.19	0.025	2.52	0.337	3.05	0.408	1.65	0.220	0.08	0.011
1972	7.71	0.18	0.024	2.50	0.325	3.17	0.412	1.76	0.229	0.09	0.011
1973	7.94	0.18	0.023	2.49	0.313	3.29	0.415	1.89	0.237	0.10	0.012
1974	8.18	0.18	0.022	2.47	0.302	3.42	0.417	2.02	0.246	0.10	0.013
1975	8.43	0.18	0.021	2.45	0.290	3.54	0.420	2.15	0.255	0.11	0.014
1976	8.69	0.18	0.020	2.43	0.279	3.66	0.421	2.30	0.265	0.13	0.014
1977	8.95	0.18	0.020	2.41	0.269	3.78	0.422	2.45	0.274	0.14	0.015
1978	9.23	0.17	0.019	2.38	0.258	3.90	0.423	2.62	0.284	0.15	0.016

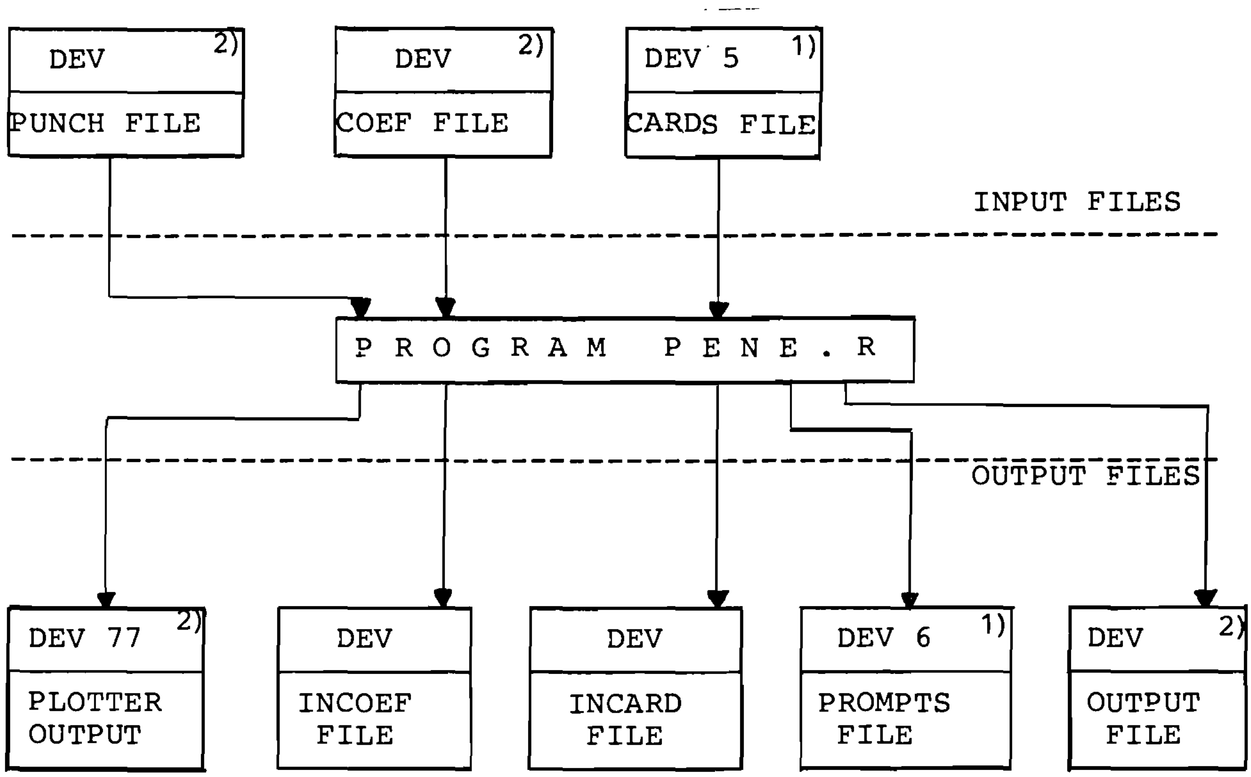
INTEGRALS FROM 1860 TO 1975 ARE:

229.	28.	0.122	124.	0.540	53.	0.231	24.	0.105	0.	0.001

INTEGRALS FROM 1975 TO 1978 ARE:

35.	1.	0.020	10.	0.279	15.	0.421	9.	0.265	1.	0.014

Table 7. File structure of the program *Pene*



1. Cards file contains control parameters. In interactive use, DEV 5 should be the terminal input, and prompts file should also be sent there: DEV 6 should be the output to the terminal. Incards file has the same information and structure as Cards file.

2. These files are optional and will be read or generated in accordance with the control parameters. Incoef file has the same structure as Coef file.

Table 8. Flowchart of the main program: *Pene*

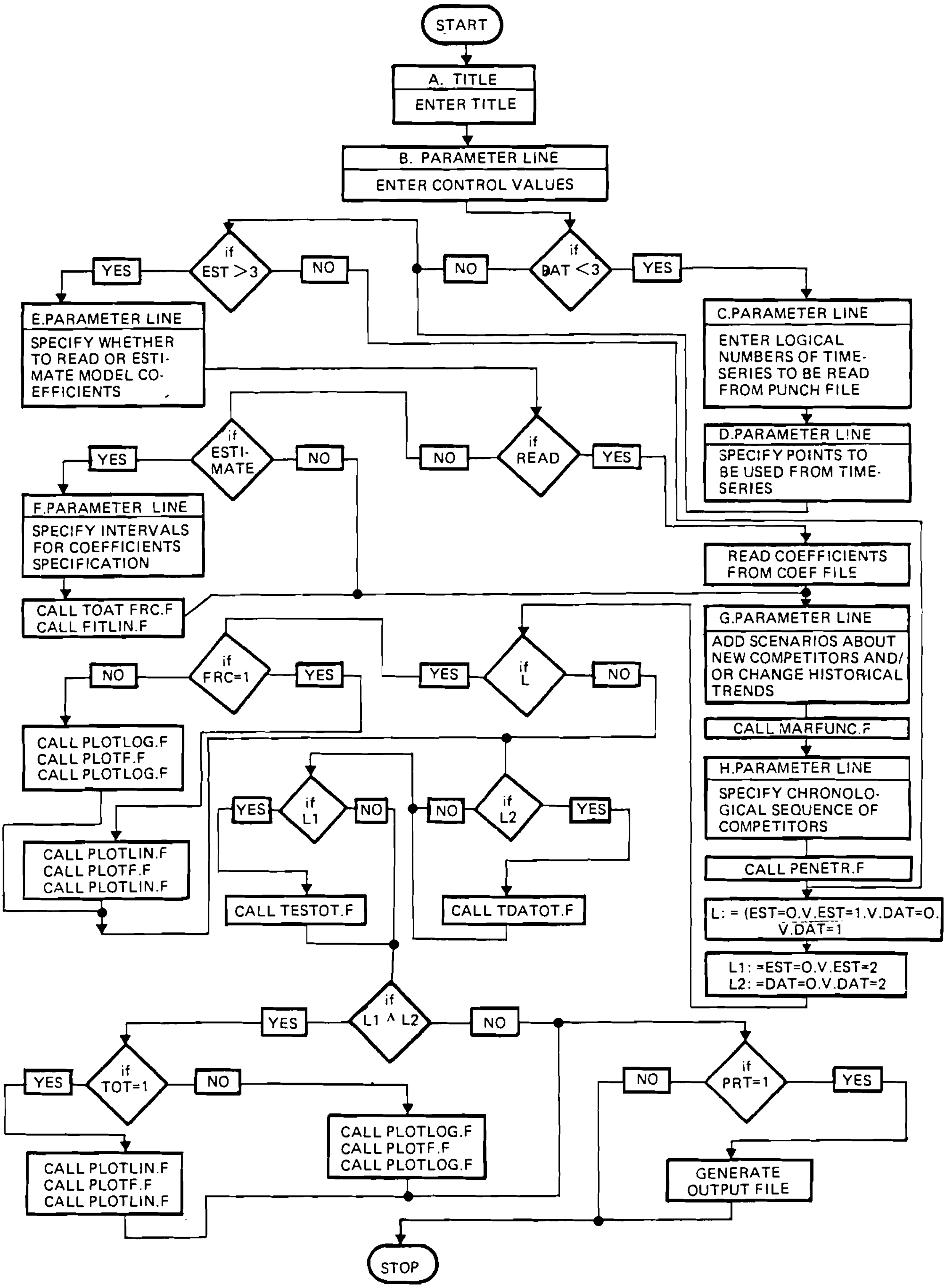


Table 9. Flowchart of the estimation subprogram: *fitlin.f*

Fitlin($F_i(t)$, iyd, nod, α_i, β_i)

↓

t_2:=iyd+1900+nod
t_1:=iyd+1900

↓

$y(t) := \log[F_i(t)/(1-F_i(t))]$

↓

$$\bar{y} := \frac{1}{t_2-t_1} * \sum_t y(t)$$

$$\bar{t} := \frac{1}{t_2-t_1} * \sum_t t$$

↓

$$\alpha_i := \{\sum_t [\log[F_i(t)/(1-F_i(t))]-\bar{y}] * (t-\bar{t})\} / \sum_t (t-\bar{t})^2$$

$$\beta_i := \bar{y}-\alpha_i * \bar{t}$$

↓

$$var := \frac{1}{t_2-t_1} * \sum_t (y(t)-\alpha_i * t-\beta_i)^2$$

$$t/\beta := \frac{\beta_i * \sqrt{(t_2-t_1) * \sum_t (t-\bar{t})^2}}{\sqrt{var * \Sigma t^2}}$$

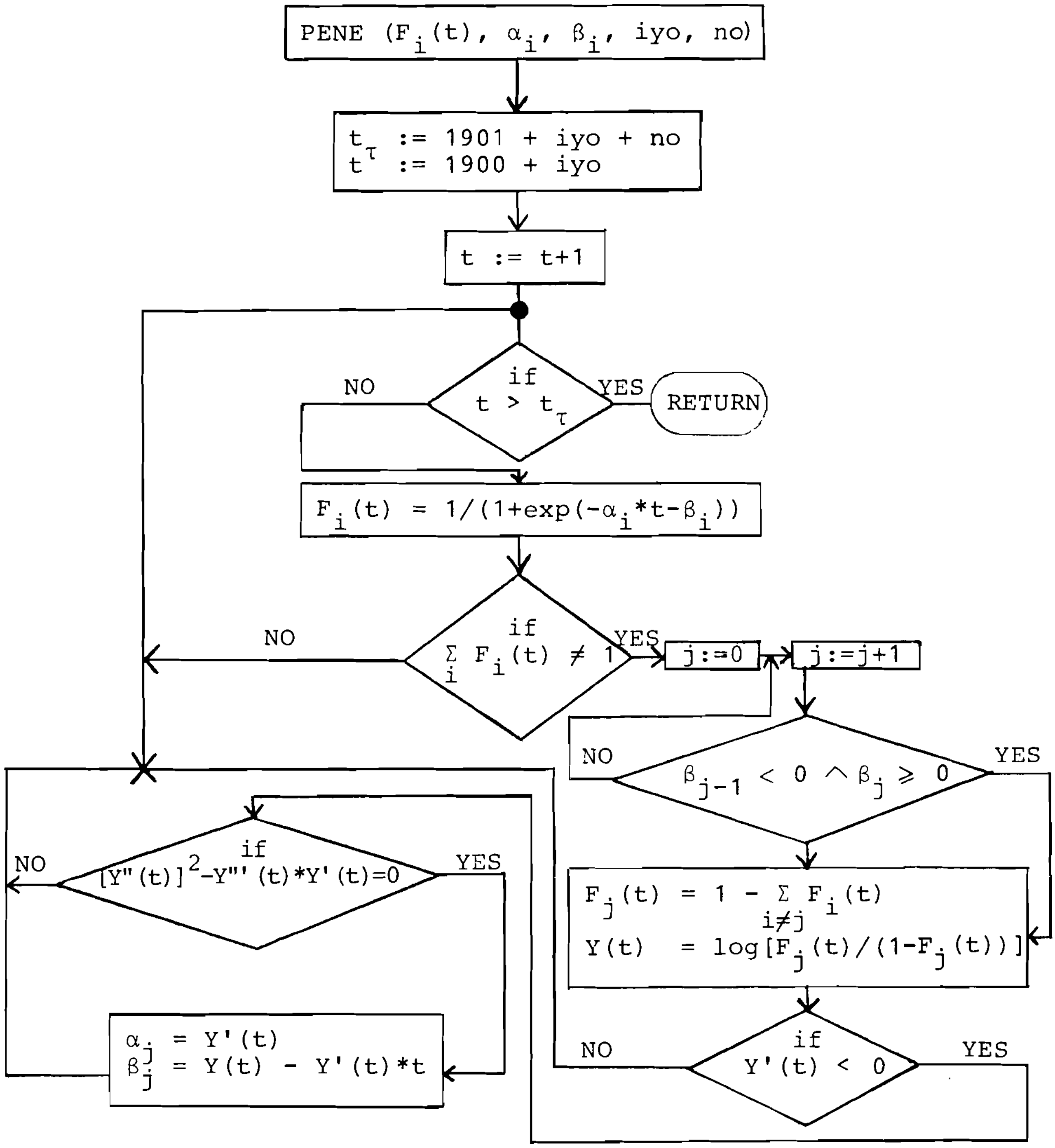
$$t/\alpha := \frac{\alpha_i * \sqrt{\sum_t (t-\bar{t})^2}}{\sqrt{var}}$$

↓

return

var is the variance of y(t); t/α and t/β are t-tests with t_2-t_1-2 degrees of freedom of the hypothesis $\alpha=0$ and $\beta=0$.

Table 10. Flowchart of the market substitution subprogram: *Penetr.f* (algorithm penetration).



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