The Dynamics of Energy Systems and the Logistic Substitution Model

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EXECUTIVE SUMMARY

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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 casts 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.

Information, materials and energy are the basic constituents of our civilization and it is most natural that we should try to assess their relative roles and internal mechanisms.

Energy has lately received great attention, partly because of the very successful move by the oil cartel in 1973. The political consequences and the promotional infrastructure of that move have generated a highly emotional atmosphere, very contrary to an objective appreciation of the facts.

In this study we try to get rid of all emotions and ad hoc interpretations. We stick to facts only, i.e. to statistical data, and try to find if they possess an internal order, or, using a terminology borrowed from physics, if a phenomenological description is possible. We found it is.

Our initial working hypothesis was that primary energies, like wood, coal, oil, gas, nuclear, are just technologies competing for a market. Consequently market penetration analysis as developed, e.g., by Mansfield (1961) and many others should be applicable.

We actually took the formulation by Fisher and Pry (1970) which is the most phenomenological of all, as it just tries to fit statistical data with two parameter logistic functions. In their original work, these authors treated competitions between two technologies only. For the case of energy in the last 50 years usually more than two competitors were present. Consequently we extended their methodology to the case of multiple competition. In their original treatment the basic assumption postulated 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:

$$\frac{F}{1-F} = \exp\ (\alpha t+\beta) \qquad (1)$$

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 of the old one. The coefficients α and β are sufficient for the description of the whole substitution process. They are unfortunately not known, but they can be estimated from a swath of historical data.

In the case of multiple competition, the obvious condition that the sum of all the market fractions equals 1,

$$\sum_{i=1}^{n} F_i = 1 \tag{2}$$

where n is the number of competitors, cannot be met with n functions of the form (1). We assumed then that one of the fractions is defined as the complement to 1 of the sum of the others. The technology behaving as "residual" is the oldest of the growing ones.

The details of the treatment are given in the main report; however, broadly speaking, technologies that already entered their market phase-out are not influenced by the introduction of new ones. The deadly fight is only between growing technologies of different age.

In order to test the power and the limits of this analysis we worked as many examples as possible from three different levels of aggregation.

1. Primary energy inputs for the world as a whole;
2. Primary energy inputs for single nations or cluster of nations; and
3. Energy subsystems, like electric utilities.

On the whole we examined about 300 cases. The quality of fitting being consistently high, the criteria of choice for the examples given in the report are mainly didactical ones. The US are particularly well represented, mainly because of the quality, detail and readability of their statistics. We also made an effort to have a good representation for the FRG. As the supertanker made energy a world system, also the world case has been given special attention for its political and resource implications.

Two examples drawn from the main report are given here with the annexed comments: the case of the world, and that of the FRG. For the world Figure 2 is meant to show the perfect fitting obtainable with our system of logistic equations. Figure 3, much more impressive, shows that the coefficients of the equations can be determined using a quite short data base. This strongly supports the use of such an analytical method for forecasting.

Although the main scope of our analysis has been to provide a simple, objective and selfconsistent description of the past; we actually drew the future as described by the equations and commented on it. As the situation appears often different from what we should expect from current wisdom, our attempt has to be considered as exploratory. It is perfectly legitimate, in research, to test the limits of a newly discovered tool, by using it in, a posteriori, improper areas.

The great success of our preliminary analysis, fully confirmed by the 300 cases examined for this work, has spurred the curiosity about the mechanisms behind the rigorous behavior of such complex systems. In fact the application of a certain rule, even if always successful in practice, confronts very strong psychological barriers if it lacks a certain logical frame linking it causally to the body of accepted knowledge.

Phenomena rooted in social behavior are always very difficult to "explain" in such a way, because if we rely too much on the basic, irrational, and stochastic roots of our decisions, then the explanation is rejected as "too mechanistic". If on the other hand we rely on the perception people have of themselves, as rational and wise decision makers, then we fall into a maze of ad hoc explanations that strongly resembles local politics.

Economists, who have faced a much similar problem, have made a great, partially successful, effort in describing and organizing the monetary measurables of human activity. Although they too miss primary causes they can introduce concepts of minimization and optimization which permit choices and structuring of the systems.

Our attempt to "hook" the market penetration rules to the accepted scientific system have followed both routes.

Fleck takes the stochastic "irrational" view. Social processes, and introduction of a new technology is a social process, are seen as the envelope of a maze of tiny decisions, causally unrelated, and, like nails in the path of a falling ball, slowing down its chute and "diffusing" its landing point. A good social example of this process is given by the diffusion of an infection e.g. the common flu. Although in a case-by-case analysis the biologist can give a fair causal description of the process, the contacts that lead to the diffusion are within another realm of causality and are better described stochastically.

Learning processes are well described in such a way, and they yield logistic curves. Fleck then visualizes the diffusion of a technology as a social learning process under constraints. The stability of the curves is a mark of the stability of man and society as learning structures.

The weak point of the theory is that the critical parameters have to be measured post hoc, and they are not reducible to other measurements that could be made before the penetration is initiated.

Peterka on the other hand follows a more classical route, taking economics as a driving force. He assumes that an industry to expand has to generate profits. External capital can produce some time shifts, providing actual money for expected gains, but the picture is not much blurred by that. Consequently, as substitution is driven by differential growth rates, these rates must be driven by differential profits.

His approach is based on the long-term balance of capital flows governing production using one of several competing technologies. With the main assumption that a viable technology, when established, has to live and grow on its own account, the mean value of the external capital flow has to be equal to zero. In this way a set of differential equations is obtained by which the multivariate competition is governed. Using market shares instead of the absolute production of particular technologies makes it possible to eliminate the market price and decomposes the description and forecasting of the substitution process into the evolution of market shares and the growth of the total production of the given commodity. This is, perhaps, the main trick in the development of the model. Only the dynamics of market shares is followed in detail, which depends on differences in production costs, on specific investments, and on the total growth rate factor. The analysis shows that in the case of n competitors the number of model parameters can be reduced to 2(n-1) and in most cases even to n-1. It is also shown that the fluctuations of model parameters over time are smoothed so that only their mean values are significant. This explains the high regularity in the behavior of market shares observed in the past.

Both deterministic and stochastic models for the substitution process are developed. The stochastic version is exploited in derivation of optimal procedures for extraction of information about the model parameters from known historical data and in quantitative description of the uncertainty of forecasting.

To facilitate practical application, the main theoretical results are condensed into algorithms and computer subroutines and their use is demonstrated on practical examples. The forecast of market penetration by nuclear energy is an example of how a new technology can be incorporated into the model using its economic assessment.

The elaborated algorithms and computer subroutines make the theory directly applicable and also make it possible to incorporate the model of market penetration into more complex models.

The model cannot forecast the birth of a new technology. A newcomer has to be introduced into the model exogenously using its economic assessment, as demonstrated by the example of nuclear energy. This limitation being kept in mind, the problem of the validity of the forecasts is treated extensively and another example is given for the stability of the underlying forces.

It is a common belief that an economic and industrial breakthrough did occur after World War II, and this view is supported by many indicators, e.g. the rate of growth of energy consumption. Using statistical data between 1945 and 1971 the parameters in the model have been estimated, and the model used to "backcast" the past history of primary energy substitution for the world. The result is given in Figure 4.

The penetration of a market by new technologies is a very complex interplay between producers and consumers. Peterka's study emphasizes the macroeconomic view on the producer side. The consumer side is reflected in the correction by which the total production costs have to be reduced in order to respect the difference in market price the average consumer is ready to pay for the higher quality of satisfaction of his need. In some cases this correcting term cannot be considered as stationary and can be influenced by advertisement and/or by official propaganda. In these cases the consumer side and the spread of information should be considered in more detail.

In societies with planned economies the mechanism of an open market is replaced by economic balances and decisions made by planning institutions and committees. However, not even a planned economy can afford to support a loser without special reasons. The planners also have to respect the social demand in order to ensure a fluent and regular distribution of products but they can control the substitution process, by setting taxes and different prices (both can be reflected in the model in total production costs), in order to achieve some goals. It is believed that the model developed in this study could serve as a planning tool for these purposes.

Speaking about possible control of the substitution process another important point has to be mentioned. No technology can start from zero without external financial help. The magnitude of the initial external investment actually determines the initial conditions for the model and may considerably accelerate (or delay if it is too small) the substitution process, especially when the new technology is profitable but requires high investments. The example of nuclear energy is treated in some detail.

Altogether we hope that the basic objective of the grant has been fulfilled: we explored the field experimentally showing the great efficiency of our model in organizing data, and we tried two ways to bring its working under logical scrutiny.

The fact that during this operation we have presumably generated more problems than we solved is a good indication that we are plowing a fertile field.

LIST OF EXAMPLES PRESENTED
IN THE PHENOMENOLOGICAL PART OF THE REPORT

The World

The Federal Republic of Germany

France

The United Kingdom

The United States of America

OECD (Organization for Economic Co-operation and Development):

- Europe
- Austria
- Belgium
- The Netherlands
- France
- The United Kingdom
- Italy
- Canada
- Japan

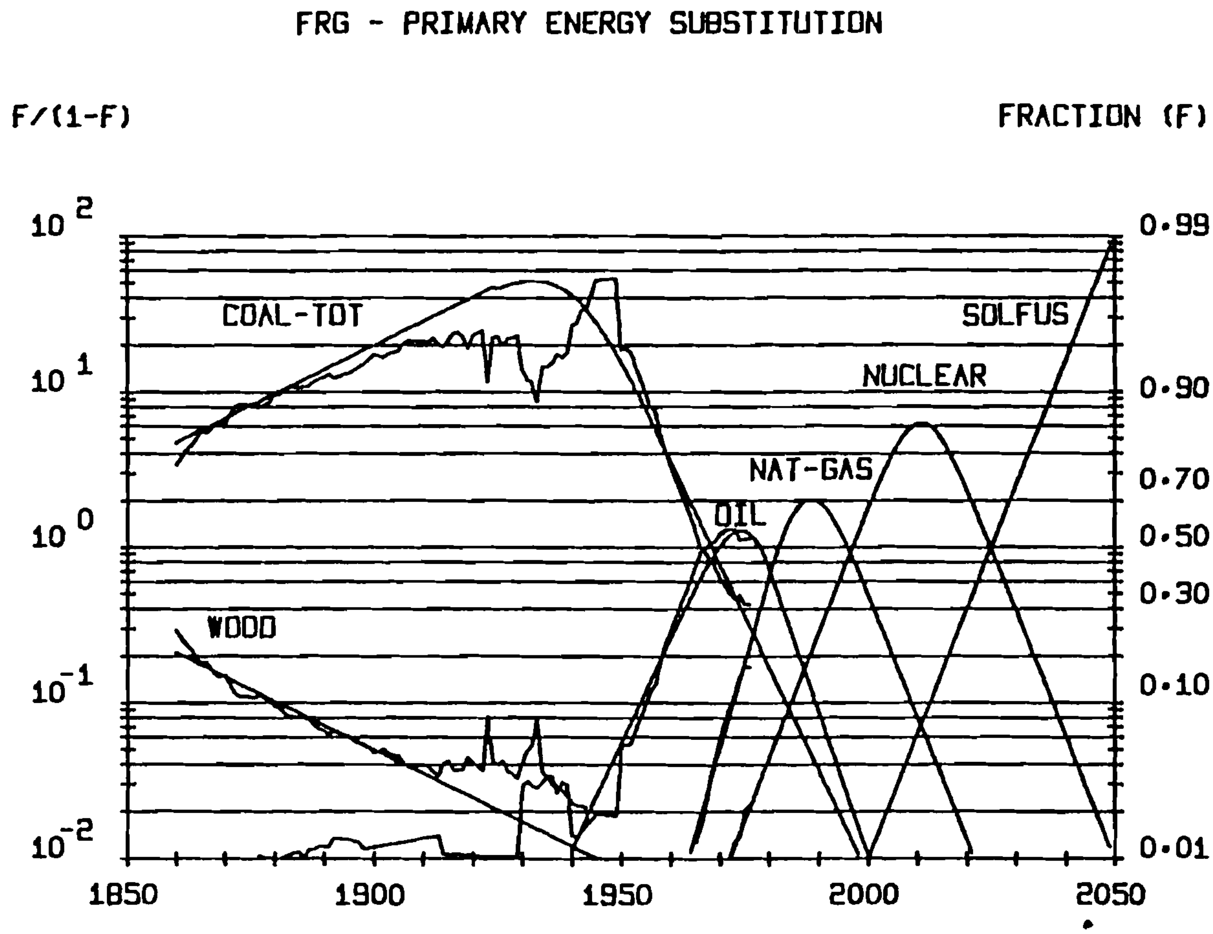
FRG - PRIMARY ENERGY SUBSTITUTION
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
COAL-TOT
WOOD
SOLFUS
NUCLEAR
NAT-GAS
OIL
1850
1900
1950
2000
2050

Figure 1.

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

The primary energy substitution for the FRG is reported here on a logistic plot. The shares of different energy sources are plotted as F/(1-F) on the logarithmic scale, where F is the fractional market share.

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. 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.

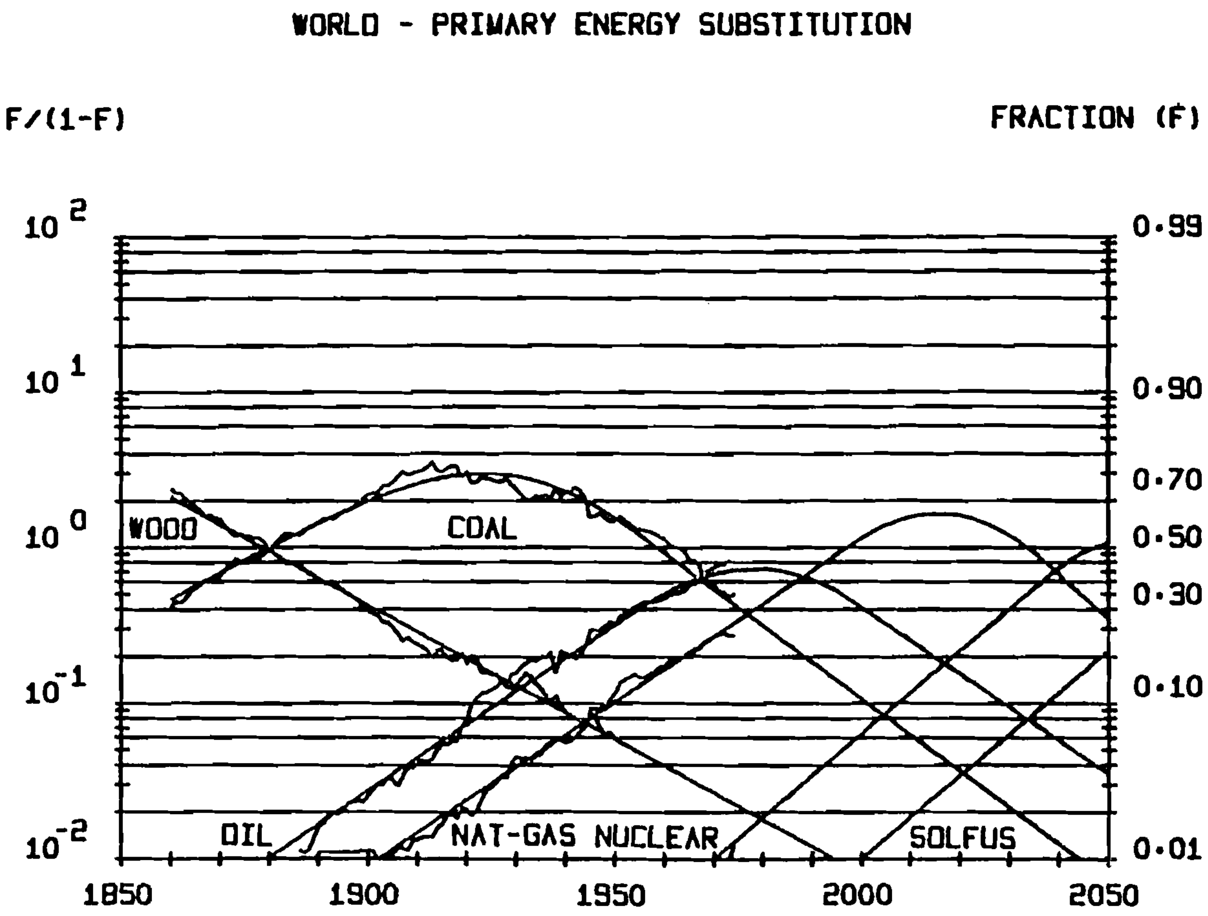
WORLD - PRIMARY ENERGY SUBSTITUTION
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
WOOD
COAL
OIL
NAT-GAS
NUCLEAR
SOLFUS
1850
1900
1950
2000
2050

Figure 2.

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

The first fact to be observed about the primary energy substitution of the world 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 is shown in the phenomenological part of the report.

Nuclear achieved only a 1% share of primary energy in the 1970s; thus its future penetration rate cannot be distilled from the historical data. Today the nuclear share in primary energy consumption is about 2%. Our nuclear scenario, based on power plants presently under construction and those planned to come into commercial operation by 1990's, prescribes a 6% nuclear share in year 2000.

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".

This graph reveals very interesting properties of the logistic competition. Primary fuels in their way down are 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 preemptying 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 substitution 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.

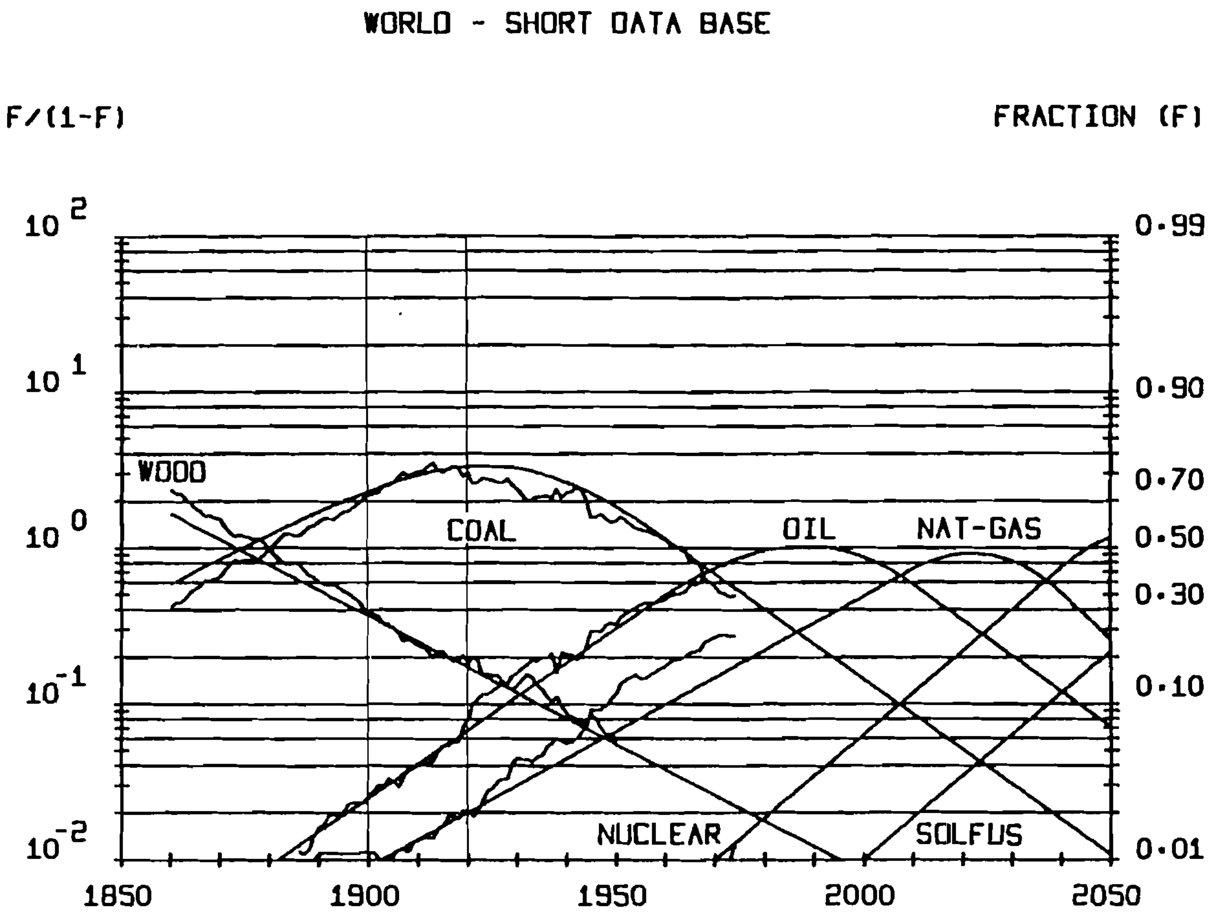
WORLD - SHORT DATA BASE
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
WOOD
COAL
OIL
NAT-GAS
NUCLEAR
SOLFUS
1850
1900
1950
2000
2050

Figure 3.

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.

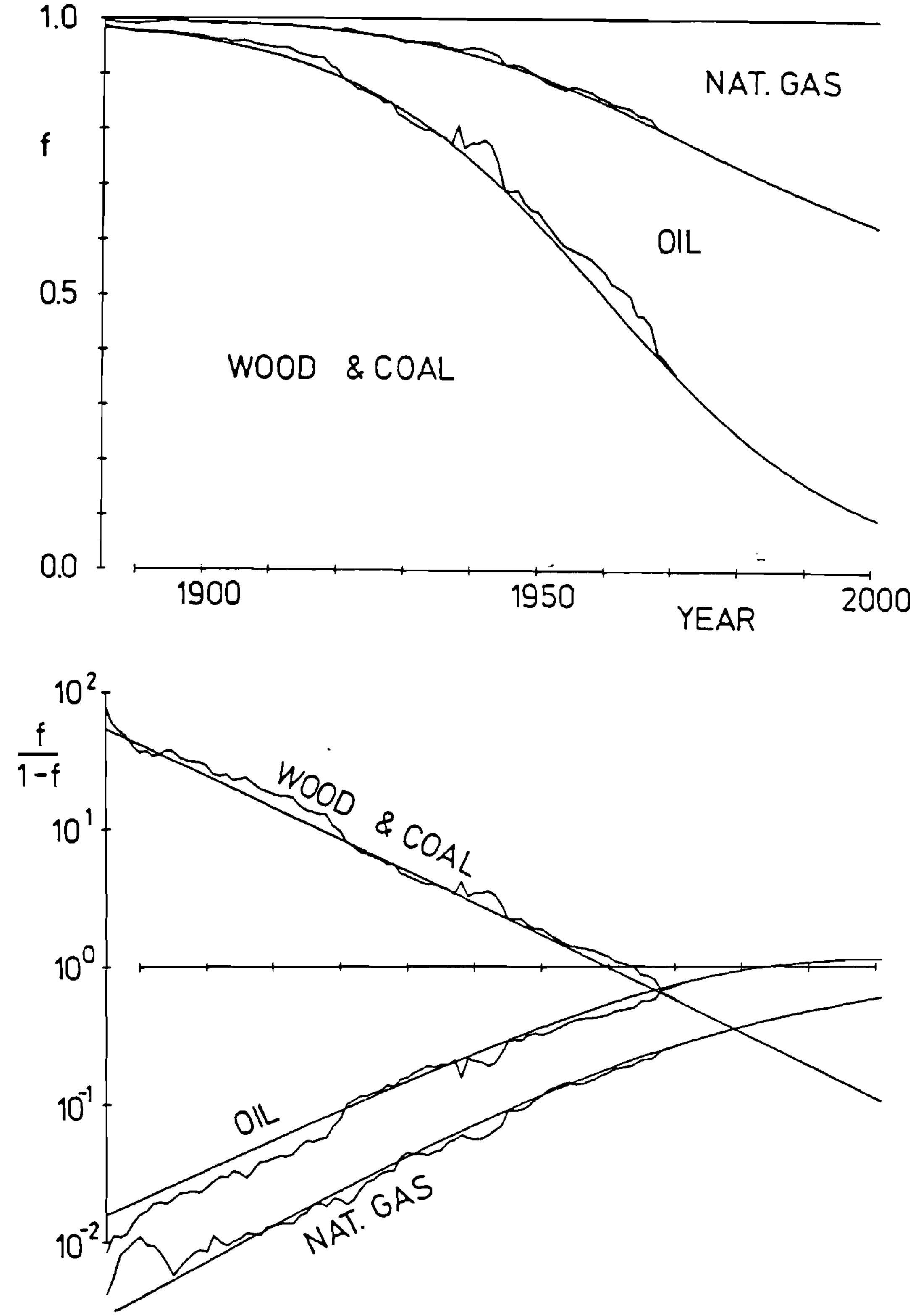

Figure 4.

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

Example of backcasting. Only 1945-1971 data have been used to estimate the coefficients in Peterka's equations.

References

Mansfield, E. (1961), Technical Change and the Rate of Imitation, Econometrica, Vol. 29, 4, 741-766.

Fisher, J.C., and R.H. Pry (1970), A Simple Substitution Model of Technological Change, Report 70-C-215, General Electric Company, Research and Development Center, Schenectady, NY; see also Technological Forecasting and Social Change, 3, (1971), 75-88.