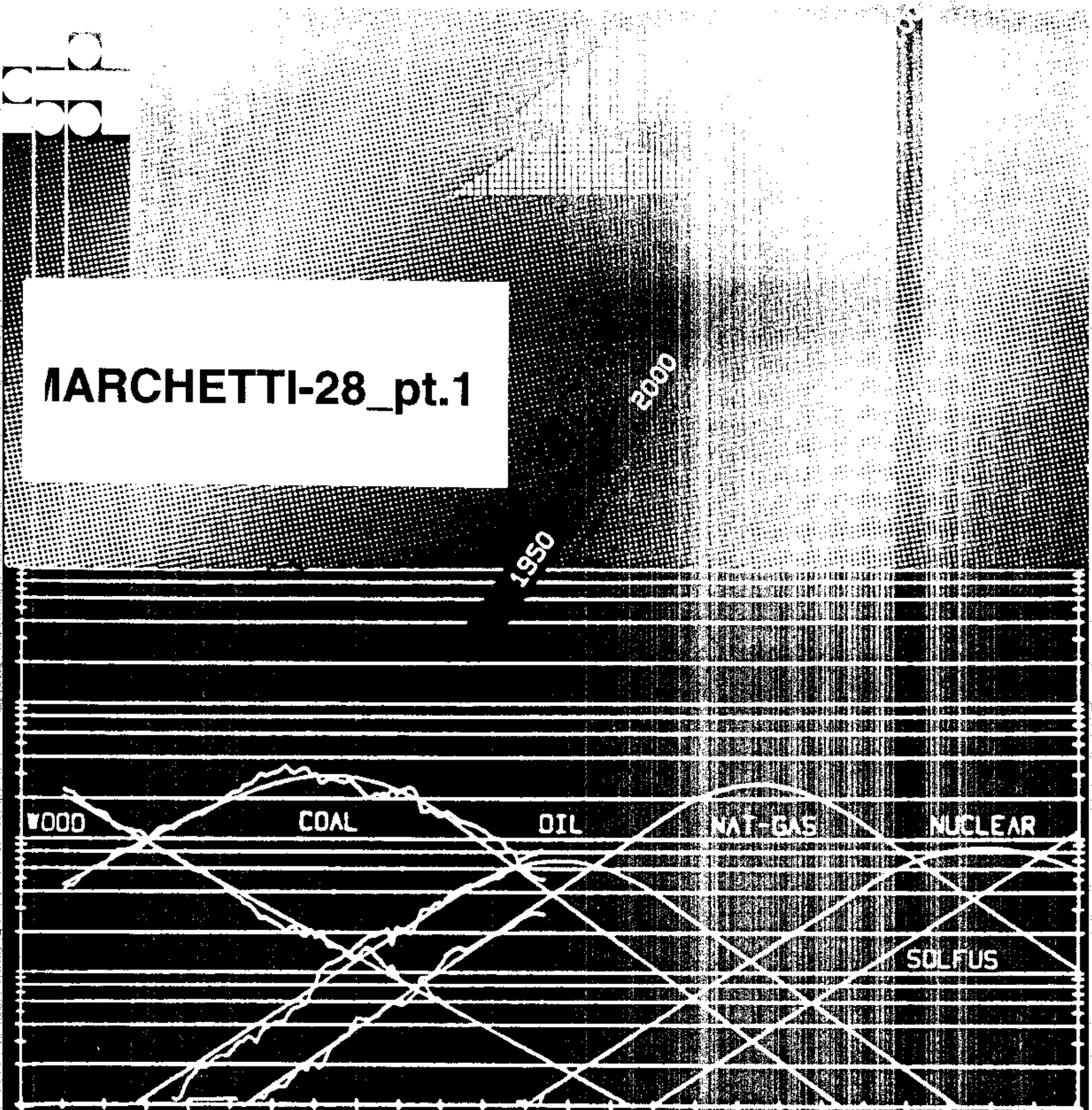
MARCHETTI-28_pt.1



The Dynamics of Energy Systems and the Logistic Substitution Model

C. Marchetti
N. Nakicenovic

RR-79-13
DECEMBER 1979

ClibPDF - www.fastio.com

THE DYNAMICS OF ENERGY SYSTEMS AND THE LOGISTIC SUBSTITUTION MODEL

C. Marchetti and N. Nakicenovic

RR-79-13
December 1979

Work carried out under a grant from the Volkswagenwerk Foundation

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

ClibPDF - www.fastio.com

PREFACE

One of the objectives of IIASA's Energy Systems Program is to improve the methodology of medium- and long-range forecasting in the areas of the energy market and energy use, demands, supply opportunities and constraints. This is commonly accomplished with models that capture and put into equations the numerous relationships and feedbacks characterizing the operation of an economic system or parts of it. Such an approach encounters many difficulties, which are linked to the extreme complexity of the system and the fairly short-term variation of the parameters and even of the equations used. Consequently, these models lend themselves to short- and perhaps medium-range predictions, but normally fail to be useful for predictions over a period of about 50 years, the time horizon that the Energy Systems Program has chosen for study.

Following the current scheme of attacking similar problems in the physical sciences, we have left aside all details and interactions, and have attempted a macroscopic description of the system via the discovery of long-term invariants. Heuristically, this approach is certainly not new. In a broad sense, the sciences can be seen as a systematic search for invariants.

This work is dedicated to the empirical testing and theoretical formulation of an invariant, the logistic learning curve, as it applies to the structural evolution of energy systems and systems related to energy, such as coal mining. The great success of the model in organizing past data, and the insensitivity to major political and economic perturbations of the structures obtained seem to lend great predictive power to this invariant.

This Research Report represents only part of the work done at the International Institute for Applied Systems Analysis, under a grant from the Volkswagenwerk Foundation, FRG, on the potential of logistic

ClibPDF - www.fastio.com

analysis in describing energy systems. It is completely documented in the Administrative Report to the foundation entitled "The Dynamics of Energy Systems and the Logistic Substitution Model" (Marchetti *et al.* 1978).

The present paper reproduces the descriptive part in Section B of the Administrative Report. The software is described by Nakicenovic (1979). As for the theoretical treatment in Section C by Peterka, a new issue of "Macrodynamics of Technological Change: Market Penetration by New Technologies" is available (Peterka 1977). Fleck's contribution to Section C on the regularity of market penetration is part of his forthcoming doctoral dissertation at the University of Karlsruhe. Section A of the Administrative Report is the executive summary.

ClibPDF - www.fastio.com

SUMMARY

Information, material, and energy are the basic constituents of civilization, and it is most natural that we should try to assess their respective roles and internal mechanisms. The question of energy has been enjoying much attention lately, 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, inimical to an objective appreciation of the facts. In this study in IIASA's Energy Systems Program, we have attempted to leave aside emotions and *ad hoc* interpretations. Sticking only to the facts, we have tried to find out if they have an internal order of their own, or, in the terminology of physics, if they can be described phenomenologically. We find that this is possible.

Our initial working hypothesis was that primary energies, such as wood, coal, oil, gas, and nuclear energy, are just technologies competing for a market. Consequently, market penetration analysis, as it has been developed by Mansfield (1961) and many others, should be applicable. In order to test the power and the limits of this analysis, we worked on as many examples as could be used, on three different levels of aggregation:

Primary energy inputs for the world as a whole
Primary energy inputs for individual nations or clusters of nations
Energy subsystems, such as electric utilities

A total of about 300 cases were examined. Since the goodness of fit was consistently high, the examples in this report have been chosen for mainly didactic reasons. The United States is particularly well represented, largely because of the quality and detail of U.S. statistics. A good repre-

ClibPDF - www.fastio.com

sentation of FRG data was also attempted. Since supertankers have made the energy system a world system, the case of the world as a whole was given special attention for its political and resource implications. Although the main thrust of our analysis has been to provide a simple, objective, and internally consistent description of the past, we made a projection of the future, as it is described by the equations, and commented on it. But given that our projections are often different from what one has come to expect according to current wisdom, our attempt has to be considered exploratory. After all, it is perfectly legitimate in scientific research to test the limits of a newly discovered tool by extending its range of application beyond its "natural" bounds.

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

On the whole, we believe that the basic objective of this work has been fulfilled: we explored the field experimentally, showing the great efficiency of our model in organizing data. In doing so, we have presumably generated more problems than we have solved, which is a good indication that we have been plowing a fertile field.

ClibPDF - www.fastio.com

CONTENTS

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

1 INTRODUCTION

Four years ago, the International Institute for Applied Systems Analysis began 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 for only two competitors. But it is a 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 us to deal with more complicated cases. These constraints were defined empirically from a few cases, but proved very successful in dealing with virtually all the cases that we analyzed. A mathematical formulation of the substitution process is given below and the manual for the software package is given in Nakicenovic (1979).

2 THE LOGISTIC FUNCTION AND SUBSTITUTION DYNAMICS

Substitution of a new way 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 by the new competitor.

ClibPDF - www.fastio.com

Most of the studies of technological substitution are based on the use of the logistic function. The logistic function, however, is not the only S-shaped function, but it is perhaps the most suitable one for empirical analysis of growth and substitution processes because of both the ease in interpreting the meaning of its parameters and the simplicity in estimating the parameters from the observed phenomena. Another S-shaped function, the Compertz curve, has also been frequently used, especially to describe population, plant, and animal growth (see, e.g., Richards 1959).

The widespread empirical applications of the logistic function as a means of describing growth phenomena also originated in the studies of human population, biology, and chemistry. The first reference to the logistic function can be found in Verhulst (1838, 1845, 1847). Pearl (1924, 1925) rediscovered the function and used it extensively to describe the growth of populations, including human population. From then on, numerous studies have been conducted only to confirm the logistic property of most growth processes. Robertson (1923) was the first to use the function to describe the growth process in a single organism or individual. Later, the function found application in work concerning bioassays (see e.g., Emmens 1941, Wilson and Worcester 1942, and Bergson 1944), and in work on the growth of bacterial cultures in a feeding solution, autocatalyzed chemical reactions, and so on.

One of the first studies that showed that technological substitution can be described by an S-shaped curve was the pioneering work of Griliches (1957) on the diffusion of the hybrid corn seed in the United States. He showed that hybrid corn replaced traditional corn seed in different states in a very similar way; the S-shaped substitution was only displaced in time by a few years and lasted differing lengths of time from one state to another.

Following the work of Griliches, Mansfield (1961) developed a model to explain the rate at which firms follow an innovator. He hypothesized that the adoption of an innovation is positively related to the profitability of employing the innovation and negatively related to the expected investments associated with this introduction. Mansfield substantiated the theoretical implications of his model by the empirical analysis of the diffusion of 12 industrial innovations in four major industries.

One of the most notable models of binary technological substitution, which extended Mansfield's findings, 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:

ClibPDF - www.fastio.com

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

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 observed; they can, however, be estimated from the historical data.

Two sets of examples are shown here (Figures 1 and 2) from the original papers of Fisher and Pry (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.

In dealing with more than two competing technologies, we have had to generalize the Fisher–Pry model since in such cases logistic substitution

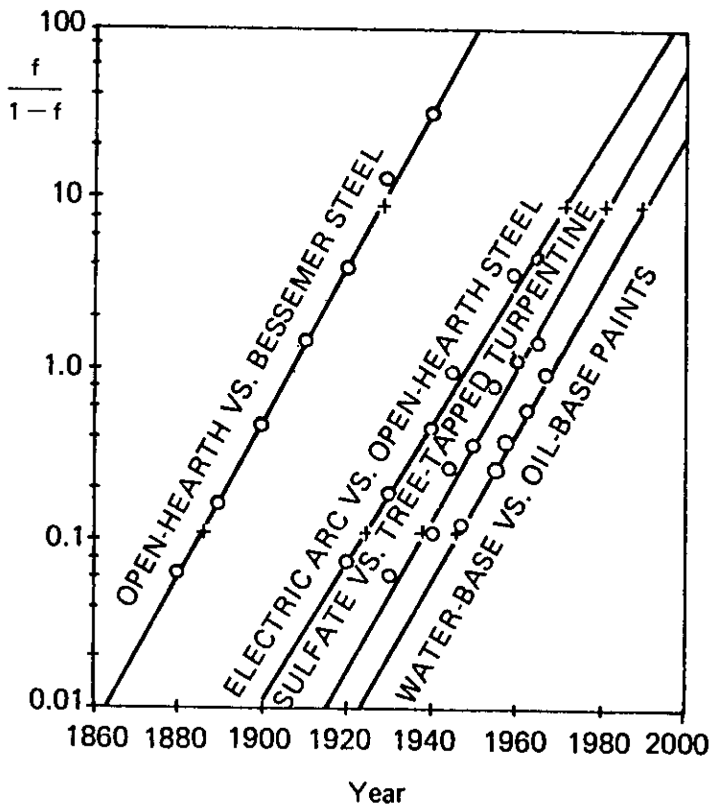


FIGURE 1 Technological substitution in the production of steel, turpentine, and paints. Source: Fisher and Pry (1970).

ClibPDF - www.fastio.com

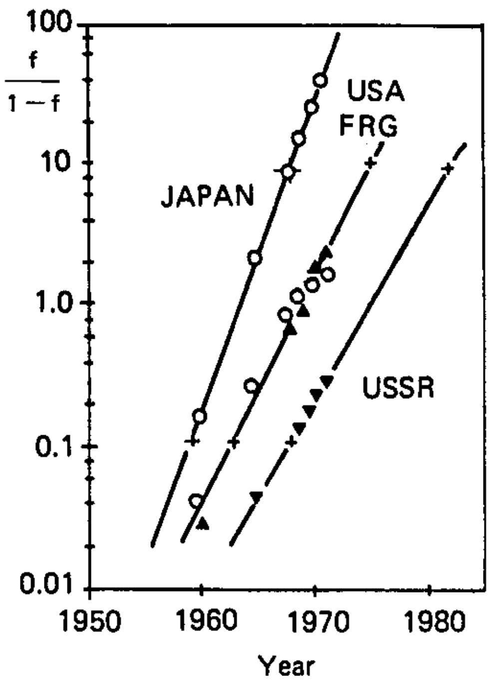


FIGURE 2 Substitution of the basic oxygen furnace for open-hearth and Bessemer steel production. On the line in the middle, the triangles represent the FRG and the circles represent the USA. Source: Pry (1973).

cannot be preserved in all phases of the substitution process. Every given technology undergoes three distinct substitution phases: growth, saturation, and decline. The growth phase is similar to the Fisher–Pry binary logistic substitution, but it usually terminates before full substitution is reached. It is followed by the saturation phase which is not logistic, but which encompasses the slowing of growth and the beginning of decline. After the saturation phase of a technology, its market share proceeds to decline logistically.

We assume that only one technology is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates uninfluenced by competition from new technologies, and that new technologies enter the market and grow at logistic rates. The current saturating technology is then left with the residual market share and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current saturating technology has reached a logistic rate of decline, the next oldest technology enters its saturation

ClibPDF - www.fastio.com

phase and the process is repeated until all but the most recent technology are in decline. In effect, our model assumes that technologies that have already entered their period of market phaseout are not influenced by the introduction of new ones. Deadly competition exists between the saturating technology and all other technologies.

3 A SIMPLIFIED ANALYTICAL TREATMENT

Let us assume that there are n competing technologies ordered chronologically in the sequence of their appearance in the market, technology 1 being the oldest and technology n the youngest. 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 with the historical period. Let us call the beginning of this interval t_B and the end t_E.

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

$$f_i(t) = 1/[1 + \exp(-\alpha_i t - \beta_i)]$$

where $i = 1, \ldots, n$ and where α_i and β_i are the estimated coefficients. Now we identify the saturating technology, j, as the oldest technology still increasing its market share. The market shares are then defined by:

$$f_i(t) = 1/[1 + \exp(-\alpha_i t - \beta_i)] \qquad \text{for } i \neq j$$

For j they are defined by

$$f_j(t) = 1 - \sum_{i \neq j} f_i(t)$$

At this time, technology j is in its saturation phase and all other technologies are either growing or declining logistically.

Now we need a criterion to identify the end of the saturation phase and the beginning of the decline of technology j, at which time the function $f_j(t)$ will become logistic again on its way down and the burdens of saturation will fall on technology $j + 1$. To establish this criterion, we use the properties of the function

$$y_j(t) = \log \frac{f_j(t)}{1 - f_j(t)}$$

ClibPDF - www.fastio.com

If $f_j(t)$ were logistic, $y_j(t)$ would be linear in t. However, for $f_j(t)$ in its saturation stage, the function $y_i(t)$ has negative curvature, passes through a maximum where technology j has its greatest market penetration, and then decreases. The curvature diminishes for a time, indicating that $f_j(t)$ is approaching the logistic form, but then, unless technology j is shifted into its period of decline, the curvature can begin to increase as newer technologies enter the market place. Phenomenological evidence from a number of substitutions suggests that the end of the saturation phase should be identified with the time when the ratio of the curvature of $y_j(t)$ to its slope reaches its minimum value. We take this criterion as the final constraint in our generalization of the substitution model, and from it we determine the parameters for technology j in its logistic decline.

In mathematical form, the criterion for termination of the saturation phase for technology j is

$$y_j''(t)/y_j'(t) = \text{minimum}$$

(note that y'' and y' are both negative in the region of the minimum). When the minimum condition is satisfied, we call this time point t_{j+1}, the time of the beginning of saturation for technology $j + 1$, and determine coefficients α and β for the declining phase of technology j from the relationships

$$\alpha_j = y_j'(t_{j+1})$$

$$\beta_j = y_j(t_{j+1}) - \alpha_j t_{j+1}$$

Then the next-oldest technology $j + 1$ enters its saturation phase, and the process is repeated until the last technology n enters its saturation 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 to organize 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 kept in mind when using the results.

ClibPDF - www.fastio.com

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" usually shows up with 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 own legs, its speed of penetration is always lower. This transition point, or kink in the curve, usually occurs by the time penetration has reached 2 or 3 percent 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 indicator 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 percent 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 percent of the market share) for the introduction of a new energy source in the world is about 100 years. Consequently, from the point of view of the competitors, not very much is going to happen during the first 50 years of the introduction of a new technology. This offers much breathing space when we discuss the world. But prudence is advisable when we deal with a time constant of only 20 or 30 years, as we find for the FRG.

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

ClibPDF - www.fastio.com

fact that oil successfully penetrated the energy market when coal still had an enormous potential, just as coal had previously penetrated the market when wood still had an enormous potential. The causal importance of the political argument is weakened by the smooth substitution observed over a period of more than a 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 price changes 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 re-adjustments between various energy sources. While this is only a hypothesis, which merits a deeper study, the very rapid price adjustments after recent oil price increases are well in tune with it.

The most important predictions of our model that differ from those in the current literature are that there will be

A relatively rapid phaseout of coal as a primary energy source
A quite important role for natural gas in the next 50 years
A negligible role in the next 50 years for new sources such as geothermal energy, solar energy, and fusion because 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 for energy R&D. This appears to be very wise, if not internally consistent, because the lead times of the systems are so long that nothing could be started rationally if higher 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; our work is centered in the past, where we try to find order and which we try to understand rationally.

5 THE EXAMPLES

The aim of the experimental part is to show the scope 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

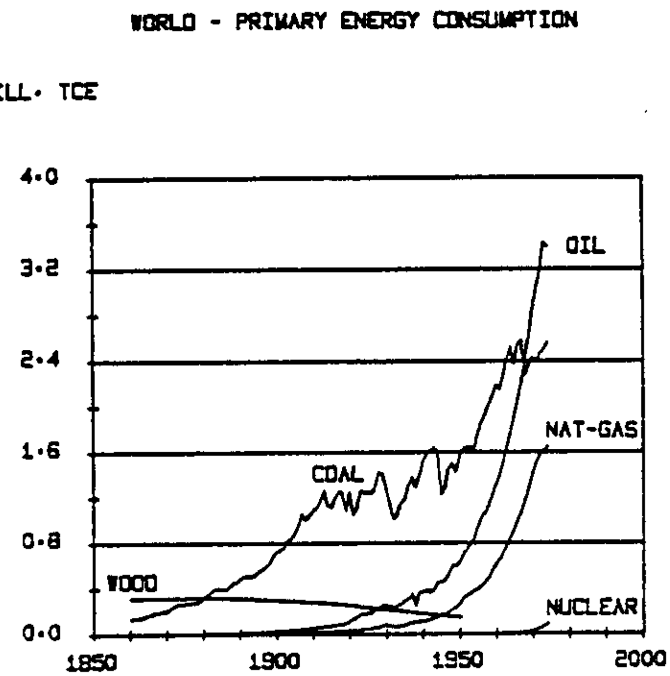
ClibPDF - www.fastio.com

In total, we used 60 data bases to generate 300 examples for 30 different spatial and structural subsets of the world energy system. The goodness of fit was consistently high in all examples, so the cases reported here have *been chosen mainly for didactic reasons*.

The United States is particularly well represented, largely because of the quality and detail of its statistics. We also made an effort to have a good representation for the Federal Republic of Germany. If this research should be continued, collaboration with an institute for statistics would have a multiplicative effect on the results.

To make the curves easy to interpret, the substitution graphs are drawn using the transformation $\log[f/(1-f)]$ 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 only from an examination of the graphs. The graphs showing total energy consumption are drawn on either logarithmic or linear axes, or on both, depending on the dispersion of the data.

ClibPDF - www.fastio.com



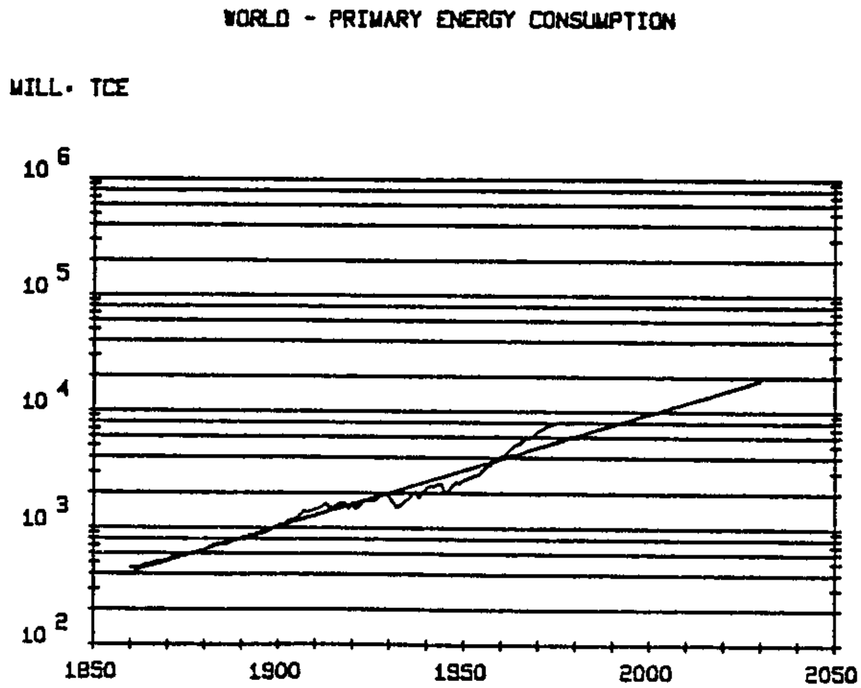
World energy consumption is reported first in various forms to illustrate and clarify our methods of logistic analysis. Our world statistical data base includes wood, coal, oil, natural gas, and nuclear energy as the major energy sources of history.

Historical data on the consumption of coal, oil, natural gas, and nuclear energy from 1860 to 1974 were taken from Schilling and Hildebrandt (1977), and data on fuel wood consumption were taken from Putnam (1953). Although fuel wood consumption levels for the years 1950 to 1974 were not available, during this period the use of fuel wood was not very large so that any error thus introduced is not significant. All energy sources have been expressed in terms of their energy content in tons of coal equivalent (tce); 1 tce equals 7 million kcal.

Nuclear energy was not available directly as primary equivalent but in gigawatt hours of electricity (GWh(e)). We have converted nuclear electric energy into tce of nuclear energy on the basis of an overall thermal-to-electric conversion rate of 33 percent.

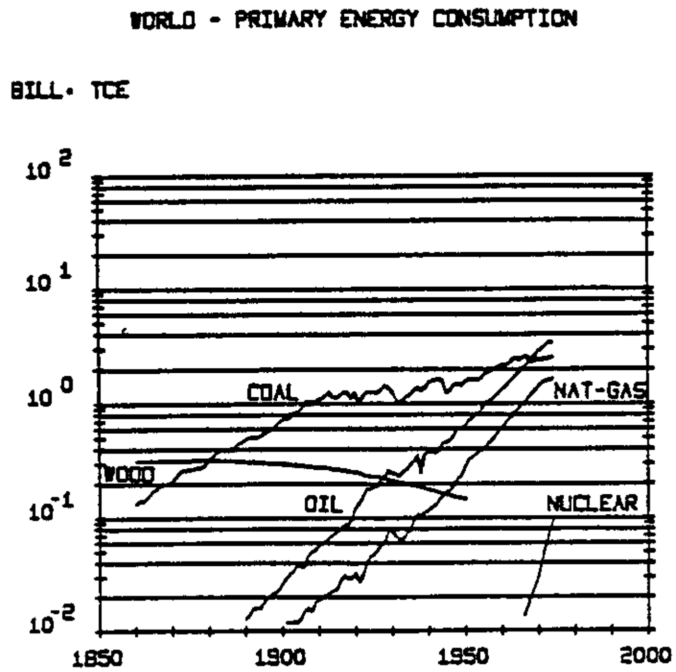
The energy inputs for the world are plotted here in billions of tce according to primary energy form. Many features related to economic or political events appear in the figure, but no consistent patterns are visible. Initial growth of new sources appears to be exponential. The smoothness of the line for wood raises suspicion and points to artificial estimation methods used to generate the original wood consumption time series.

ClibPDF - www.fastio.com



When wood is included with the commercial energy sources, the development of world energy consumption appears fairly regular until World War II, with a growth of 2.2 percent per year. After 1950, not only were the losses reabsorbed that occurred as a consequence of the great recession, but some overshooting occurred 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.

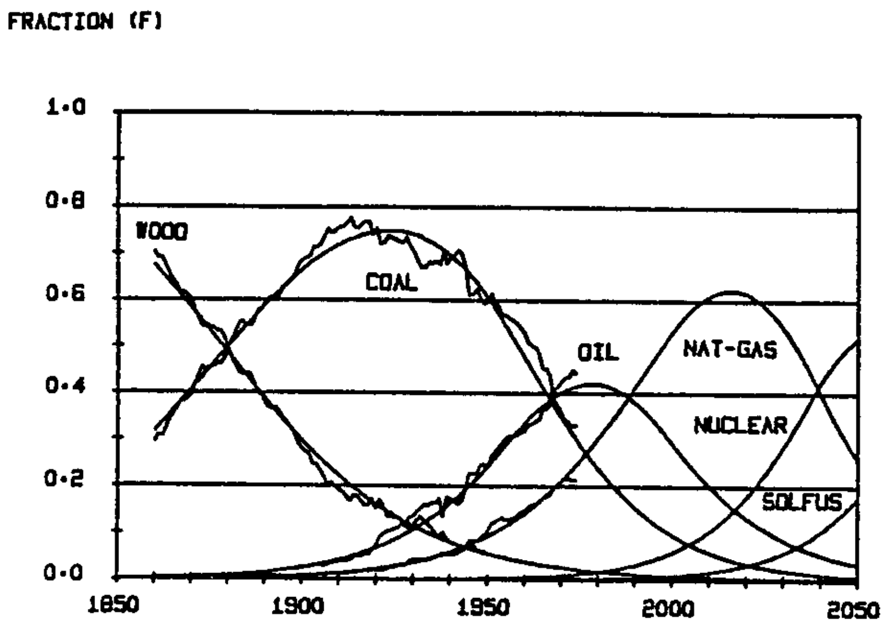
ClibPDF - www.fastio.com



New sources appear to grow with exponential trends. Therefore, we plotted them in semilogarithmic form. The presence of some straight 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 of the use of the various primary energy sources.

ClibPDF - www.fastio.com

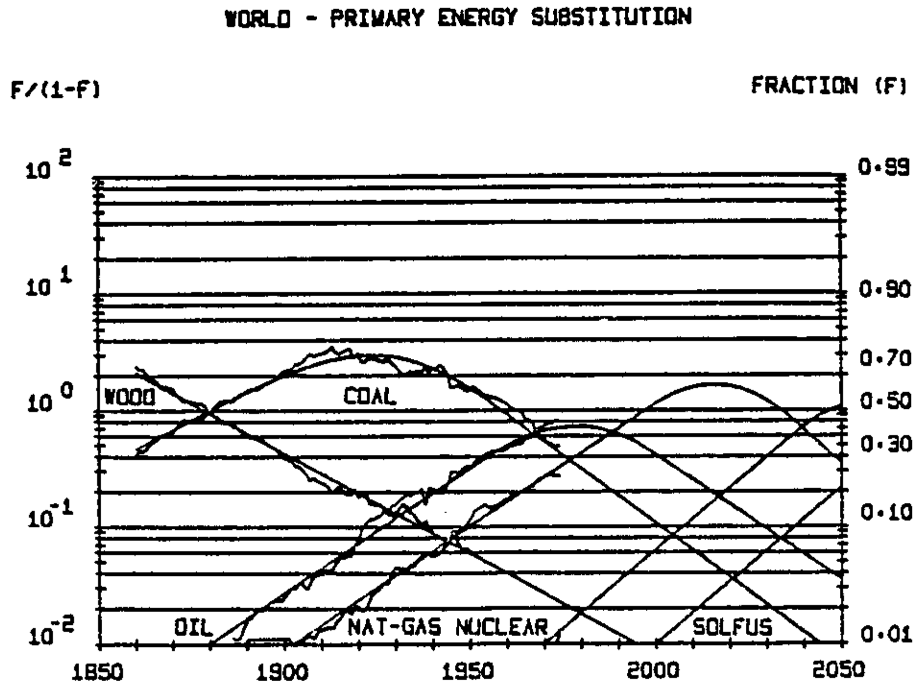
WORLD - PRIMARY ENERGY SUBSTITUTION



Here the contributions of the various primary sources are shown 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.*

When we look to the future, the figure contains two primary energy sources for which a complete fitting of the parameters was not possible. For nuclear energy the present penetration is still too low to determine the slope of the penetration. We have estimated the rate from progress to date and from official plans. For SOLar or FUSion, the scenario is completely hypothetical. Because rates of penetration were almost the same for coal, oil, and gas, we assumed an equal rate for nuclear and SOLFUS, in the spirit of "business as usual." The unexpected dominance of natural gas over the next 50 years will be discussed later in the report.

ClibPDF - www.fastio.com



ClibPDF - www.fastio.com

The curves of the preceding figure are now plotted as $\log[f/(1-f)]$; the logistic curves 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 percent to 50 percent of the market. We call this length of time the *time constant* of the system.

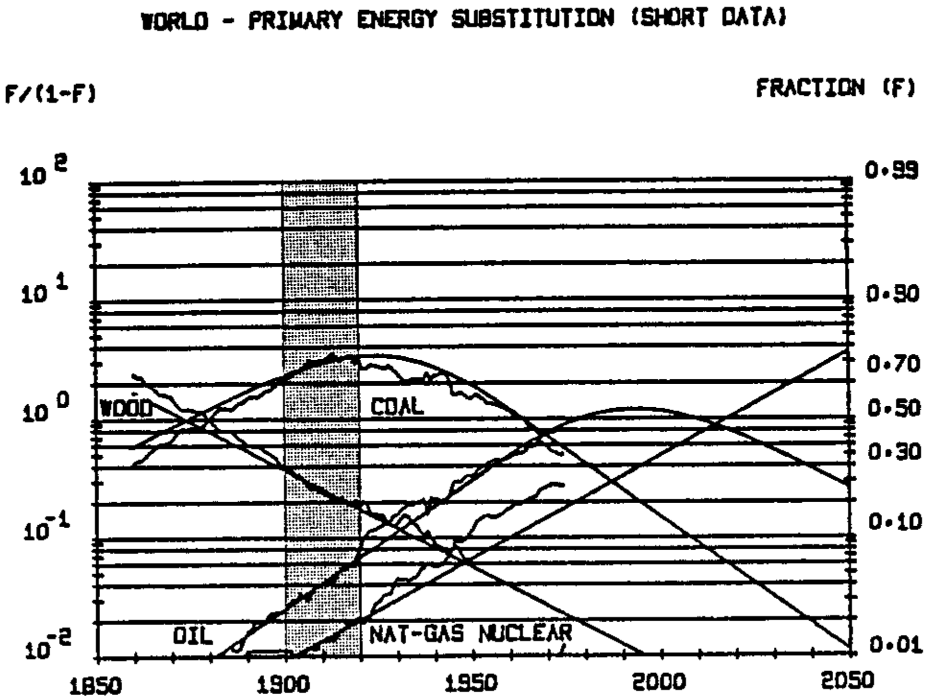
The regularity refers not only to the fact that the rate of penetration (defined as constant α in the equation and corresponding to the slope of the curves) remains constant over such very long periods when so many perturbing processes seem to take place, but also to the fact that all perturbations are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

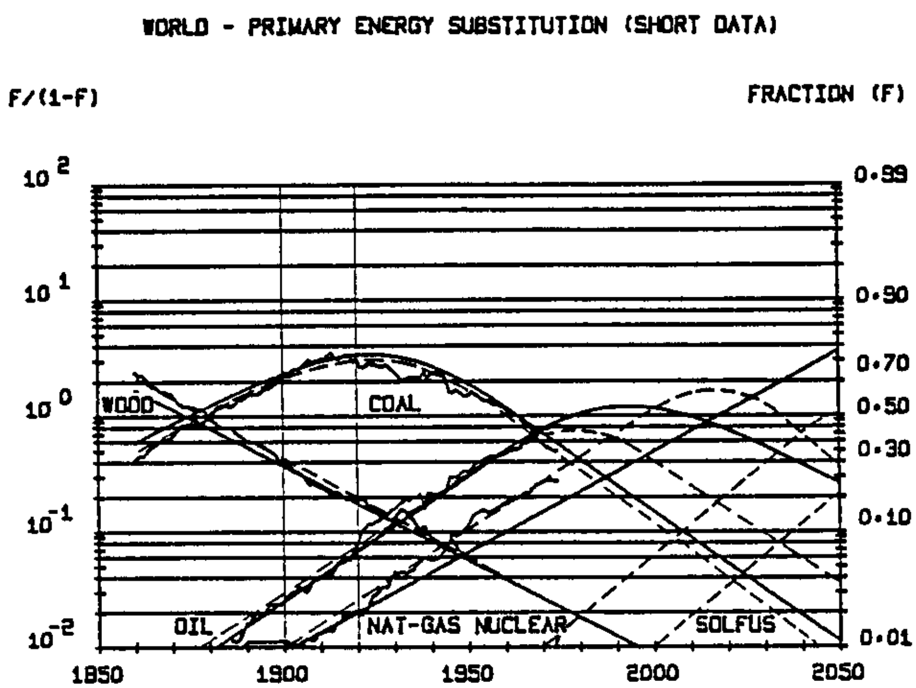
It is also interesting to note that no source finally saturates the market, although nuclear may do so if it is not followed by something else. The dynamics of the introduction of new sources and the high time constant lead to maximum penetrations of 60 to 70 percent. This is also true for most smaller systems, as will be shown later.

Nuclear achieved only a 1-percent share of primary energy in the early 1970s; thus its future penetration rate cannot be distilled from the historical data. In 1977, installed nuclear capacity reached 88 GW(e) (IAEA 1977). Taking an overall utilization factor of 75 percent, the nuclear share in primary energy consumption is about 2 percent.

By 1990, according to the IAEA (1977), power plants currently under construction and planned should be in service; thus, the total installed capacity should be at least 430 GW(e). With a rough utilization factor of 75 percent, this corresponds to a 5- to 10-percent share in 1990, depending on whether we use a 2-percent or a 3-percent 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-percent nuclear share in the year 2000. Note that the introduction of SOLFUS in the year 2000 would not influence nuclear until around 2050.

ClibPDF - www.fastio.com





ClibPDF - www.fastio.com

As available statistics are sometimes unreliable, have gaps lasting for long periods of time, or refer to certain energy sources and not to others, we have tried to check the stability of the fitted functions and of the forecasts with 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, since only two points are needed to define a straight line. Consequently, the large number of statistical data 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-percent share and consequently its long-term substitution rate may not yet be established.

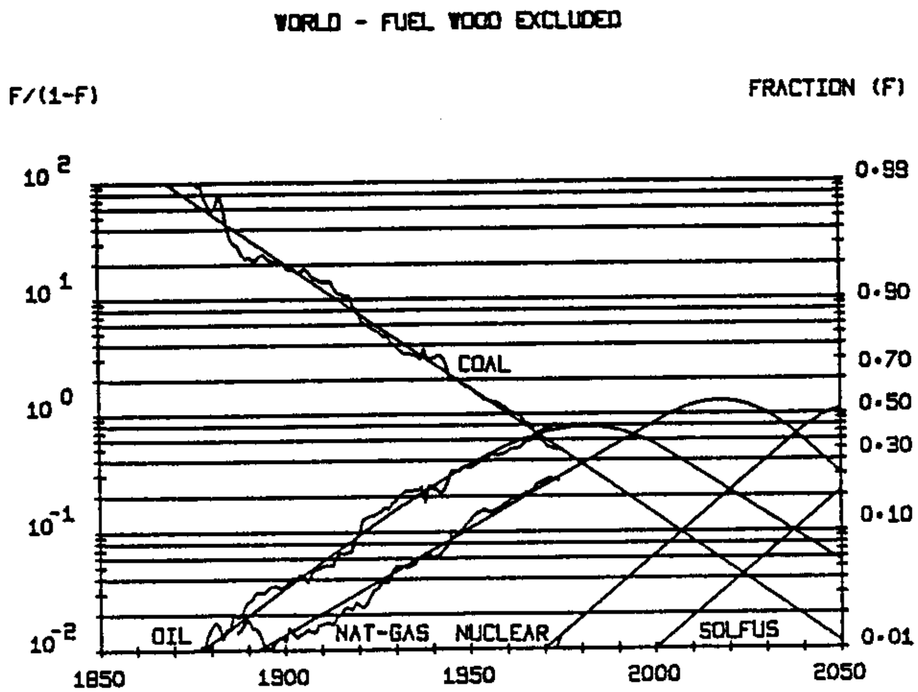
The smooth curves fitted to the 1900–1920 data still show an extraordinary agreement with the data outside the historical period. Natural gas deviates somewhat and there is an error in the "prediction" of about 7 percentage points at the end of the period. This may seem relatively large, but it is a prediction made 50 years ahead from a small market share, and with a depression and a war in between!

Because the model does not predict the introduction of new primary energy sources, nuclear does not appear at all in these projections. Yet the absence of nuclear was of no consequence for the 50 years from 1920 to 1970, and, as shown in the previous figure, nuclear will be of little consequence for the other energy sources until it penetrates 5–10 percent of the market in about 2000.

These observations are of the greatest importance since they give logical support to the use of our system of equations for projections into the future. In the lower figure, superposing the curves fitted on a short data base with those fitted on the complete data base shows the relatively small differences. Additionally, whenever the timing and penetration rates of future technologies must be estimated, as for nuclear and SOLFUS, the system of equations serves to establish internal consistency for each scenario.

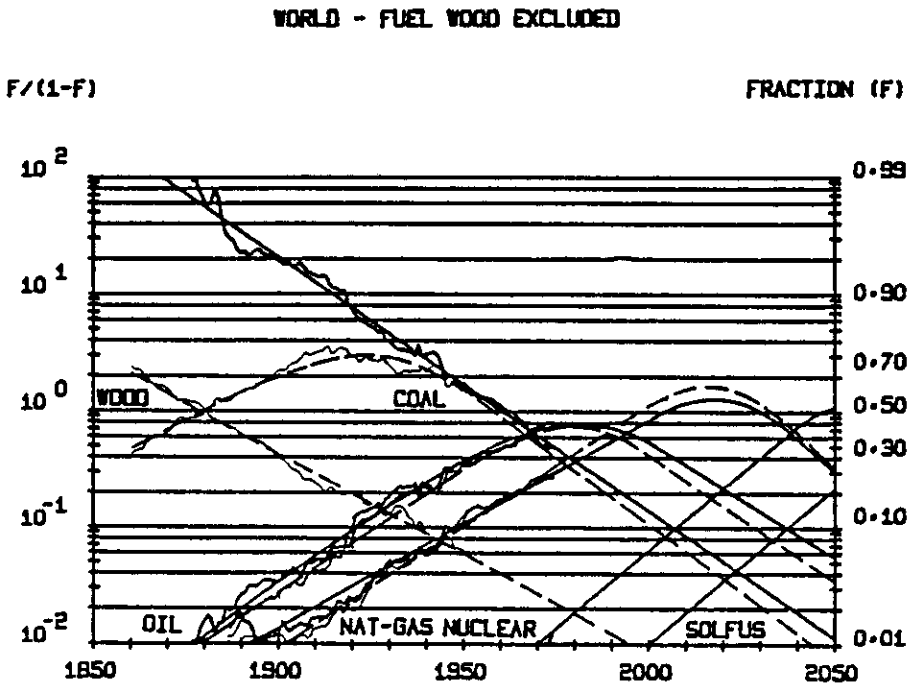
Superposition of the curves calculated with the short data base (solid lines) and the extended data base (dashed lines) shows the remarkable predictive ability of the short data base over a period of half a century, and illustrates the gradual accumulation of errors.

ClibPDF - www.fastio.com



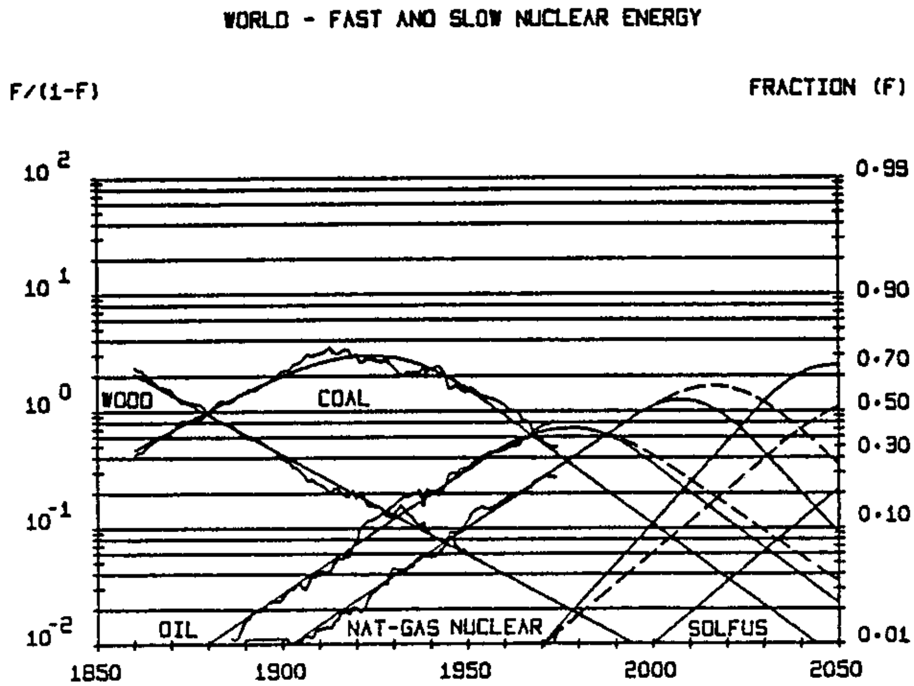
This experiment shows that much information about the total system can be extracted from a structural subset. From the complete data base, we had the impression that wood statistics were too smooth to be accurate, and in a certain measure represent educated guesses of the statistical offices. Consequently, we omitted wood and analyzed the competitive behavior of the other primary sources left in the market. As the figure shows, the logistic description fits the subset perfectly. In the following figure, the curves with and without wood are superposed, to show that little information is lost when wood statistics are eliminated.

ClibPDF - www.fastio.com



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 percent of the market, showing that key information about the dynamics of the market is contained in and can be extracted from restricted subsets of the original data base.

ClibPDF - www.fastio.com

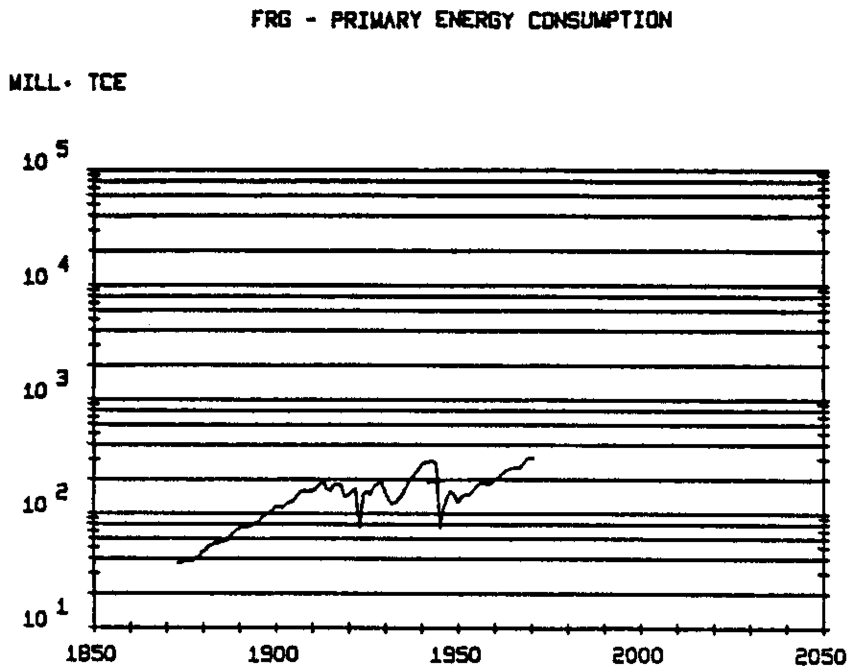

WORLD - FAST AND SLOW NUCLEAR ENERGY
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
WOOD
COAL
OIL
NAT-GAS NUCLEAR
SOLFUS
1850
1900
1950
2000
2050

The history of nuclear energy is too short and the market penetration of nuclear energy is too small to provide a reliable indication of the long-term market penetration rate. We made a sensitivity analysis to explore the consequences of this uncertainty. A plot with a nuclear energy share of 6 percent in the year 2000 and one with a 10-percent share in the year 2000, almost doubling the rate, are superposed.

This figure reveals very interesting properties of the logistic competition. Primary fuels on their way down are insensitive to a change in the rate of newcomers. After the great fuss about nuclear energy tramping into the garden of coal, and coal being reshaped as 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 marginally with oil, which may disappoint those who install nuclear power stations to reduce their need for oil imports. The problem of resource availability that 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.

ClibPDF - www.fastio.com



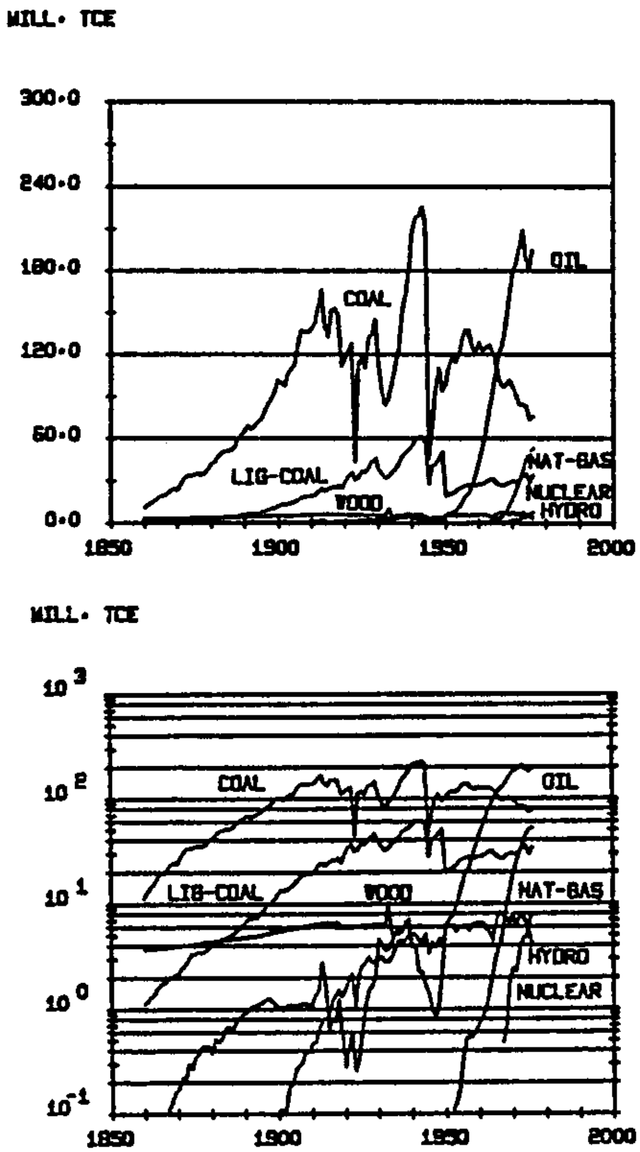
This figure shows the total energy consumption for Germany from 1870 until 1949 and for the FRG from 1950 until 1970. The fluctuations between the two world wars cover a perfect stagnation. It is interesting, if perhaps accidental, that the curve after 1950 matches exactly that before 1910 with the same values and the same growth rate of 4.3 percent. The data after 1950, however, refer to the FRG only.

The original data for the period 1870–1974 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 Kernforschungsanlage Jülich (1977) for 1975 and by Rheinisch-Westfälisches Elektrizitätswerke (1978).

Data on fuel wood consumption from 1870 to 1950 were taken from Putnam (1953) and were converted from British thermal units (Btu) to tons of coal equivalent (tce). No data on wood were available for the last three decades, but during this time wood has had only a marginal share of the market. Nuclear energy inputs, given in gigawatts of electricity (GW(e)) in IAEA (1977), were converted into tce, with a thermal-to-electric conversion efficiency of 33 percent and a utilization factor of 75 percent.

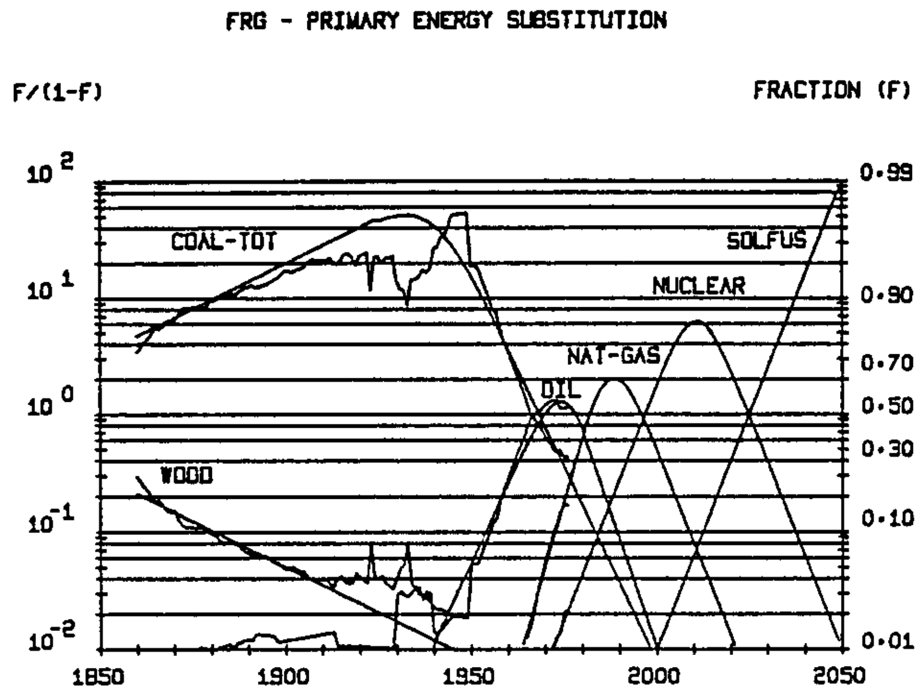
ClibPDF - www.fastio.com

FRG - PRIMARY ENERGY CONSUMPTION



The evolution of energy consumption for Germany and the FRG is shown here for the various primary energy sources, in linear form (top) and in semilogarithmic form (bottom), to emphasize the startup periods. Although a war, a depression, another war, and a partition have had major impacts on total energy consumption, they have had relatively little effect on market shares of the various energy sources, as shown in the following figures.

ClibPDF - www.fastio.com



ClibPDF - www.fastio.com

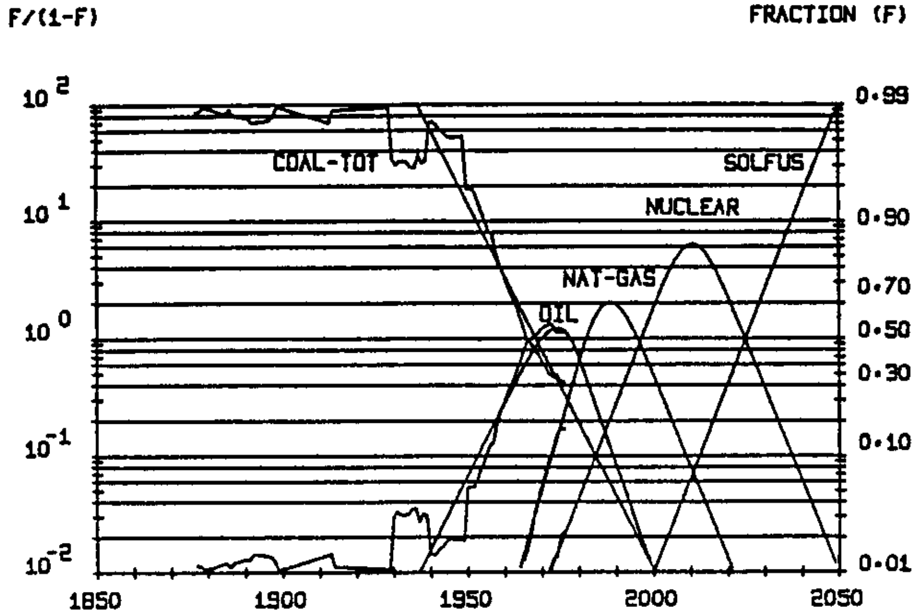
The logistic analysis is reported here first with wood and then without wood. Since wood statistics tend to be unreliable, they are eliminated to avoid a possible source of perturbation. In both cases, the scene appears fully dominated by coal before World War II. The sudden jump of oil to 3 percent in the thirties from a stationary 1 percent is unexplained and could merit further analysis. It may have something to do with preparation for the war. Between 1945 and 1972, substitution proceeded very smoothly and logistically, with oil becoming dominant with a fairly short time constant 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 must result from forces internal to the economy of the FRG. 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 percent before it slows down to its steady penetration rate. No such kink for gas appears in the curve for the FRG. It is possible that the kink may appear later, in which case we will have overestimated its long-term penetration rate.

Second, the nuclear penetration rate was estimated on the basis of historical data. However, due to its relatively low share of primary energy (2.2 percent in 1976) we have checked this penetration rate to see that it corresponds to the number of power plants currently under construction and those planned for the future. The IAEA (1977) gives a total installed capacity of 21 GW(th) in 1977 for the FRG; an 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 percent over this period, these plans would indicate 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 percent per year gives a nuclear primary share of 30 million tce in 1982 and 50 million tce in 1985. Thus, our nuclear penetration rate can be characterized as being somewhat pessimistic on the basis of current plans, and presumably realistic as a lower limit on the future role of nuclear energy in the FRG. The true fate of nuclear should be revealed in the next 10 years.

A SOLar or FUSion (SOLFUS) 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 ultimate effect of the next source on nuclear. Altogether, the FRG appears to behave normally but more dynamically than systems of similar size and structure, such as France or the UK.

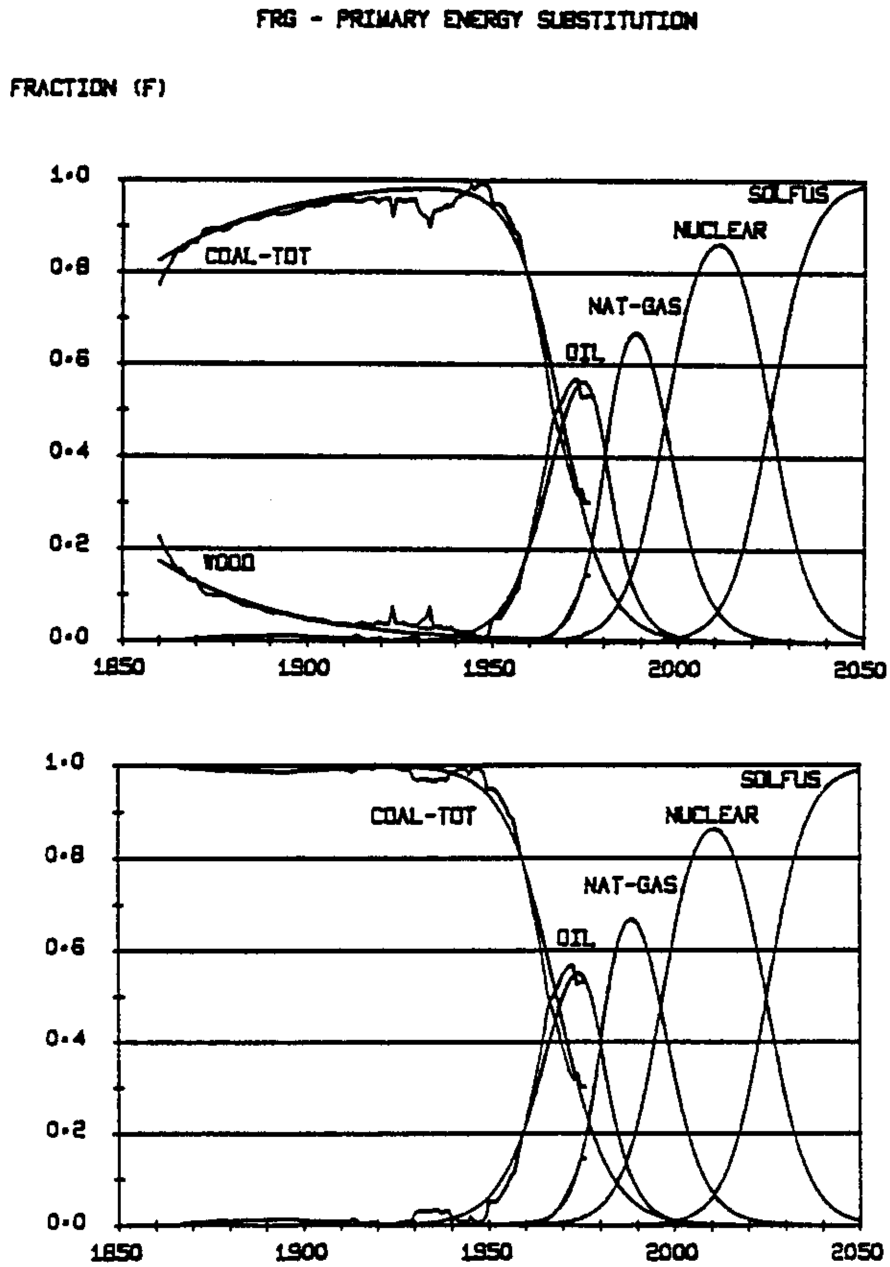
ClibPDF - www.fastio.com

FRG - PRIMARY ENERGY SUBSTITUTION



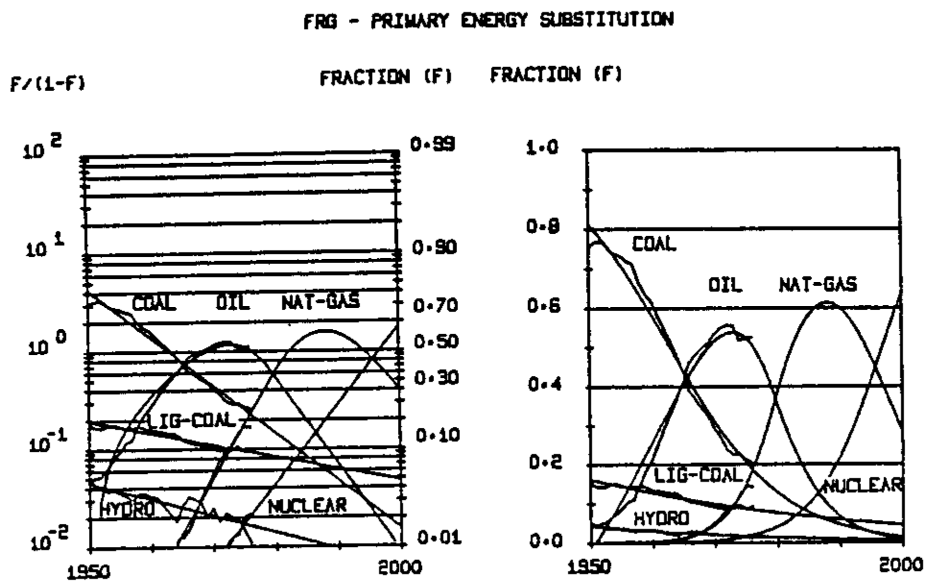
As the statistics on fuel wood are often unreliable, we have eliminated wood and analyzed how the other fuels share the market for commercial energy sources. Oil remains at a level of 1 percent for half a century and shows again that actual logistic market penetration does not start until the market 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 virtually disappear in the year 2000, a feature common to the UK, the Netherlands, and Belgium. *If this happens to be true, what will automobiles run on?* Perhaps on LNG, H_2, or *methanol.*

ClibPDF - www.fastio.com



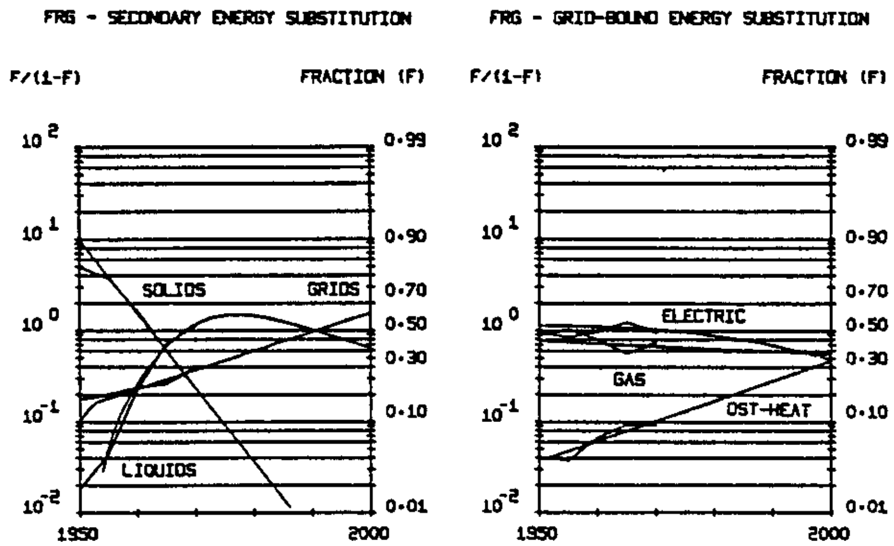
The overwhelming predominance of coal in the German economy prior to 1950 is illustrated again in these linear–logistic plots of the same substitution processes shown in the previous two figures. The upper plot includes wood and the lower plot does not.

ClibPDF - www.fastio.com



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. For the FRG, data are available to treat them independently, which we do in these figures. We also include hydropower, converted to its fuel equivalent by assuming the appropriate thermal power plant efficiency. This separation of the data appears fruitful. Hydropower shrinks in importance, while lignite has its own precise trend and appears to overtake coal in the late eighties. *Can it be a source of fuel for cars, perhaps via methanol?*

ClibPDF - www.fastio.com

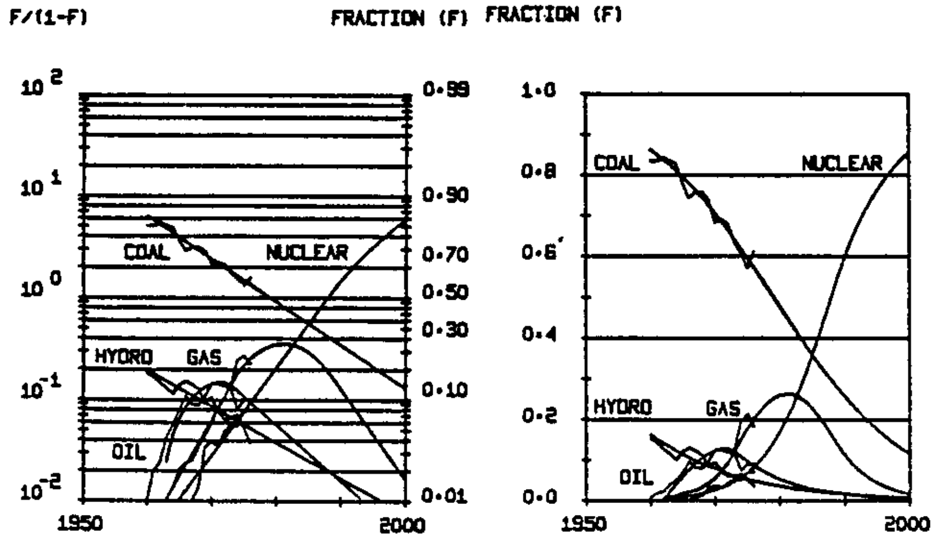


In the same way as we supposed that primary energies are technologies competing for a market, we also assumed that secondary energies behave in the same fashion. The analysis is based on historical data from Sassin (1977).

The left-hand figure shows the market shares of solids (coke, coal, and lignite), liquids (mostly heating oils), and distribution grids (electricity, gas, and hot water) to ultimate consumers in homes, offices, and factories (i.e., excluding the transportation segment of the economy). The right-hand figure shows how the three grid technologies compete among themselves for the overall grid market, revealing a great future for district heating, unless a new system is available in the next 20 years.

ClibPDF - www.fastio.com

FRG - ELECTRICITY GENERATION BY PRIMARY INPUTS



ClibPDF - www.fastio.com

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 FRG electricity industry is undergoing a very fast transformation, with nuclear finally replacing 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 simply as a result of market expansion.

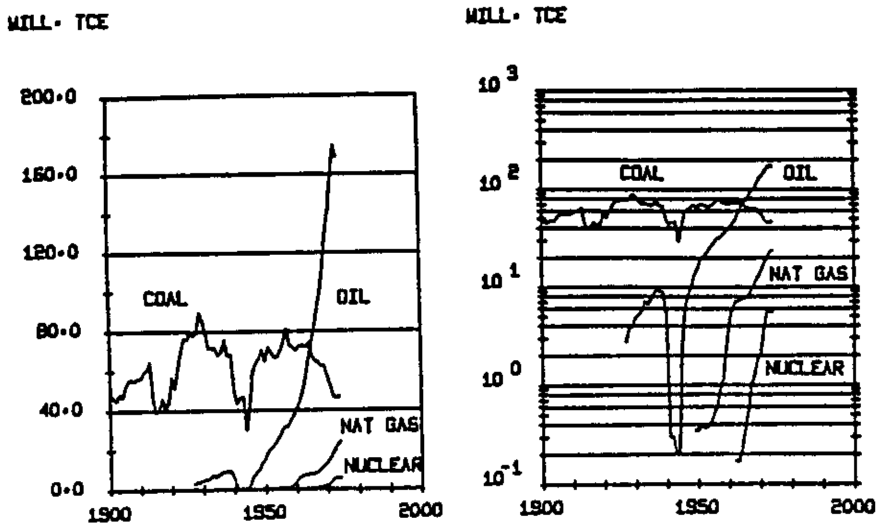
As nuclear is most suited to baseload generation, having very low marginal costs, a question arises about the utilization of part-time capacity available when this baseload is saturated, which seems to occur in the mid-eighties. It is not improbable that this may spur the production of synthetic fuels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

In order to cross-check the consistency of the relatively fast phaseout of coal and lignite in the primary inputs, and the relatively more sluggish disappearance in the electricity 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 percent. This is not illustrated here, but the projections are consistent.

Data for electricity generation by primary energy source from 1950 to 1974 were taken from Atomwirtschaft-Atomtechnik (1976). Data from 1950 to 1958 were only estimates; thus, we did not use them. The original data are given in gigawatt hours of electricity output. For the purpose of comparison with primary energy consumption, we have converted the data into millions of tons of coal equivalent. However, this conversion is not very exact since we did not account for the different efficiencies of various fuels. Instead, we have taken an overall average efficiency for all inputs. The errors resulting from the approximate conversion to million tce are small. Data for 1975 and 1976 were taken directly from Rheinisch-Westfälisches Elektrizitätswerke (1978) and Kernforschungsanlage Jülich (1977) in millions of tons of coal equivalent.

ClibPDF - www.fastio.com

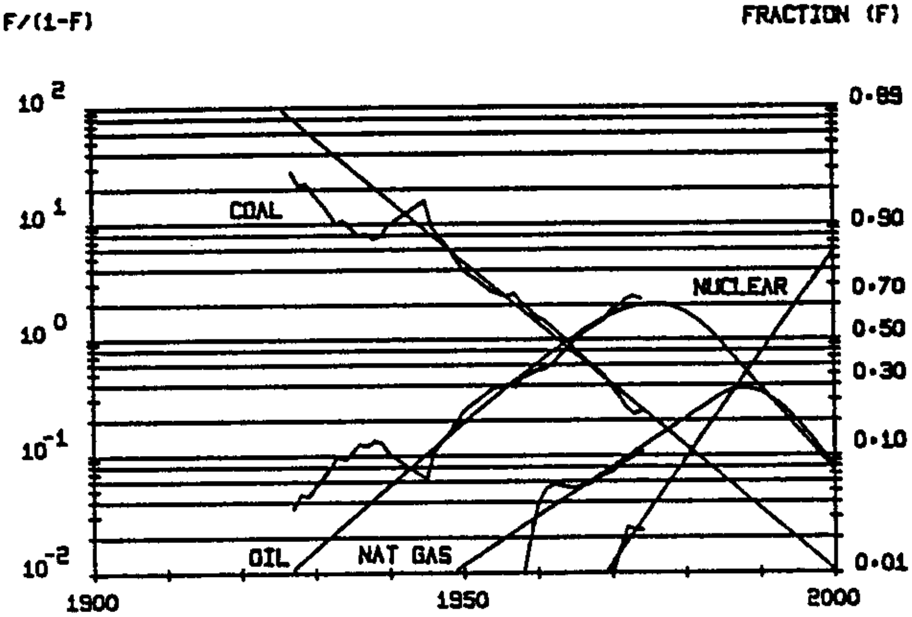
FRANCE - PRIMARY ENERGY CONSUMPTION



Two sets of data were used for analysis of the substitution dynamics of primary energy for France. The first set is from Weitsch (1976) and was available for the period 1900 to 1974. The second set comes from the OECD (1976). Time series for coal, oil, natural gas, and nuclear are reported in millions of tons of coal equivalent for the period of 1960 to 1974. Oil data contain crude oil and petrochemical products. The agreement of the data sets for the overlapping period of 1960 to 1974 is very good. The first data set is illustrated here in linear and semilog form to amplify the starting period. The second data set is considered later in the report.

ClibPDF - www.fastio.com

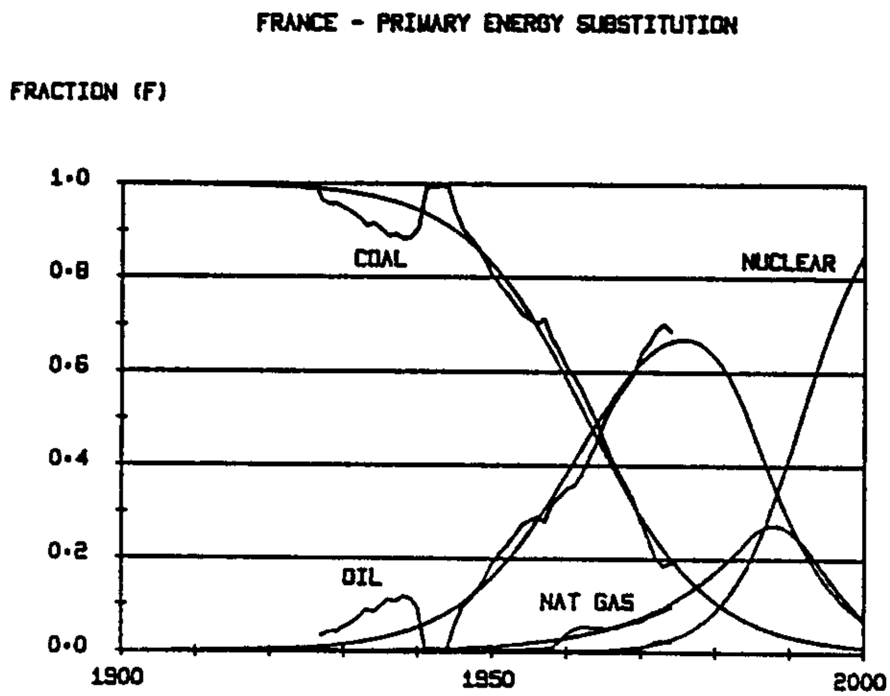
FRANCE - PRIMARY ENERGY SUBSTITUTION



This example of 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 later, leaving more breathing space for a decision on automobile fuels. 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; nuclear 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 1990. The very fast growth of natural gas up to about 7 percent of the market might be interpreted as the manifestation of an intensive external support (by the state?), a hypothesis that is yet 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 the military occupation, and if we "cancel" the 5 years that it lasted. From the linear–logistic plot, France seems to be a much less dynamic system than the FRG. Time constants are in fact about 50 years.

ClibPDF - www.fastio.com

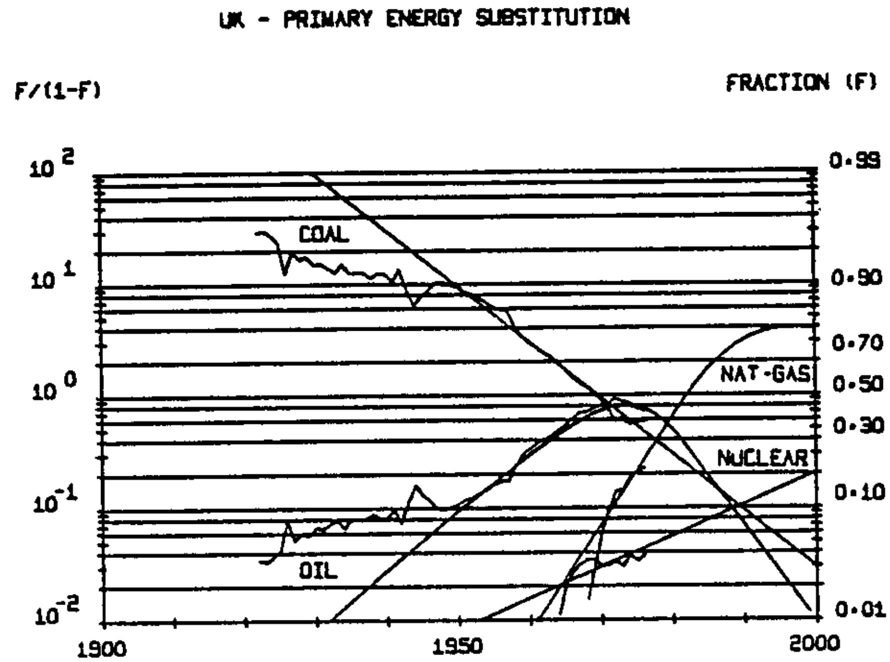


ClibPDF - www.fastio.com

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, the penetration of gas is strongly related to that of nuclear, but even oil is strongly influenced. It can be deduced that nuclear is really a hot point in the energy policies of France.

Nuclear energy controlled more than a 2-percent share of primary energy in 1972 after 2 years of very steep growth from a 1-percent share in 1970. This corresponded to 9.7 GW(th) installed capacity reported by the IAEA (1977) for 1972. According to the same source, additional plants with a total of 58.2 GW(th) installed capacity are under construction, with commercial operation 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 of 5.6 percent per year (1960 to 1974) and a power plant utilization factor of 75 percent, the nuclear share will be about 14 percent of primary energy in 1981. 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. If historical rates for other substitutions also apply for nuclear, its penetration would be much slower: 8 percent in 1980. We used that rate in our scenario, which therefore should be considered a very prudent one.

ClibPDF - www.fastio.com



Historical data on consumption levels of coal, oil, natural gas, and nuclear energy for the United Kingdom come from three sources. The period of 1860 to 1950 has been taken from Putnam (1953), from 1950 to 1974 from Ormerod (1976), and 1975 and 1976 from the UK Department of Energy (1976, 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 in the energy market during the last century. Even in 1950, it still contributed 90 percent of primary energy consumption. From 1950 on, the substitution proceeded at high rates. By 1970, oil already controlled a 50-percent share, and natural gas had 10 percent, starting at 1 percent in 1968. However, the natural gas penetration curve 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 network being fed by city gas, i.e., mainly from coal, which natural gas simply took over and saturated by 1970, so it did not face the usual growth limitations of a new technology. Therefore, we use only points after 1969 to estimate the natural gas penetration trend.

ClibPDF - www.fastio.com