WORKING PAPER

PATTERNS OF CHANGE:
Technological Substitution and Long Waves in the United States

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WP-85-50

IIASA
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ABSTRACT

Economic development and the advancement of technology is presented as a process of substituting old forms of satisfying human needs by new ones, or more precisely as a sequence of such substitutions. The examples, reconstructed from historical records, describe the quantitative, technological changes in energy consumption, steel production and merchant marine in the United States.

Logistic substitution analysis is used to capture the dynamics and regularity of these technological changes. It is shown that technological substitution analysis describes fundamental structural changes that lead to new economic patterns and forms. The emerging patterns of technological and economic changes during the last two to three centuries are shown to portray periodic recurrences at intervals of about half a century. In this sense, the technological substitution processes are related to the long swings in economic development because they identify and describe major and periodic fluctuations in the historical rate of technological change and accordingly also the secular changes in the rate of economic growth.

A phenomenological approach is adopted to indicate the evidence for the invariance and logical order in the sequence of technological changes and long wave fluctuations.

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1 INTRODUCTION

The analysis of historical replacement of old by new technologies has shown that most of these processes can be described by simple rules that are captured in the logistic substitution model (see Marchetti and Nakicenovic, 1979, and Nakicenovic, 1984), and that expressed in fractional terms the substitution follows characteristic S-shaped curves. In order to illustrate and describe the properties of the approach we will first give examples of how new energy forms replaced their predecessors, since technological changes in the energy system constitute one of the first and most complete applications of logistic substitution analysis. To further explore this method we then describe similar substitution processes in steel production and merchant marine.

The application of the logistic substitution model to the above examples indicates that improvements and growth are achieved through a regular but discontinuous process. Each new technology goes through three distinct substitution phases: growth, saturation and decline. This regular pattern points to a certain schedule and recurrence in structural change of competitive markets. The structural change in the above examples occurred at intervals of about 50 years.

The recurrence of changes every 50 years resembles the long wave fluctuations in economic development originally described by Kondratieff (1926). One of the most extensive explanations of the long wave was given by Schumpeter (1939). For Schumpeter, innovations come in clusters, and are not evenly distributed or continuously absorbed, due to the basic principles that govern the process of capitalist development. The clustering of technological and entrepreneurial innovations leads to the emergence of new industries and subsequent growth, but this growth necessarily leads to limits and eventual decline. Thus, wave-like forms of economic development are generated with phases of growth and senescense at intervals of about 50 years.

A hypothetical relation between the 50-year periods in the introduction of new technologies and saturation of the old ones and the 50-year period in the changing phases of growth and decline that is associated with the long wave must be verified empirically before the exact nature of the two phenomena connected with the process of technological change can be related to each other. The analysis will essentially consist of using a phenomenological approach to extract long fluctuations from the time-series in an attempt to filter out the long waves and to compare the so-derived fluctuation patterns with the dynamics of technological substitution. The changing phases of the long wave fluctuations will be illustrated with the same examples as the technological substitution: energy consumption, steel production and merchant marine.

All of the examples illustrate the American experience. Thus, while the results are equivalent to similar examples for some other industrialized countries and the whole world, it is inconclusive whether they may also be of a more general nature. Unfortunately, historical data cannot be reconstructed from available records for too many different cases, although the United Kingdom has been analyzed with equivalent examples. All of the reported examples and the historical data for the United States (and also the United Kingdom) are given in Nakicenovic (1984).

2 TECHNOLOGICAL SUBSTITUTION

Substitution of an old way of satisfying a given need by a new path has been the subject of a large number of studies. One general finding is that substitution of an old technology by a new one, expressed in fractional terms, follows characteristic S-shaped curves. Fisher and Pry (1970) formulated a very simple but powerful model of technological substitution. Their model uses a two-parameter logistic function to describe the substitution process. The basic assumption postulated by Fisher and Pry is that once a substitution of the old by the new has progressed as far as a few percent, it will proceed to completion along the logistic substitution curve:

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

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, while $1-f$ is that of the old one.

2.1 Primary Energy Consumption

The analysis of the competitive struggle between various sources of primary energy has been shown to obey a regular substitution process that can be described by relatively simple rules (Marchetti and Nakicenovic, 1979, and Nakicenovic, 1979). The dynamic changes in this process are captured by logistic equations that describe the rise of new energy sources and the senescense of the old ones. Figure 2.1 shows the primary energy consumption in the United States since the middle of the last century. Data are plotted on a logarithmic scale and show exponential growth phases in consumption of the most important sources of primary energy by piece-wise linear secular trends. Thus, it is evident that energy consumption grew at exponential rates during long time periods but no other regularities are directly discernable. However, the evolution of primary energy consumption emerges as a regular substitution process when it is assumed that energy sources are different technologies competing for a market. Unfortunately, the Fisher and Pry model cannot be used to describe the evolution of primary energy consumption, since evidently more than two energy sources compete for the market simultaneously.

In dealing with more than two competing technologies, we must generalize the Fisher and Pry model, since in such cases logistic substitution cannot be preserved in all phases of the substitution process. Every competitor undergoes three distinct substitution phases: growth, saturation, and decline. The growth phase is similar to the Fisher and Pry model of two competitors, 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 down of growth and the beginning of decline. After the saturation phase of a technology, its market share proceeds to decline logistically.

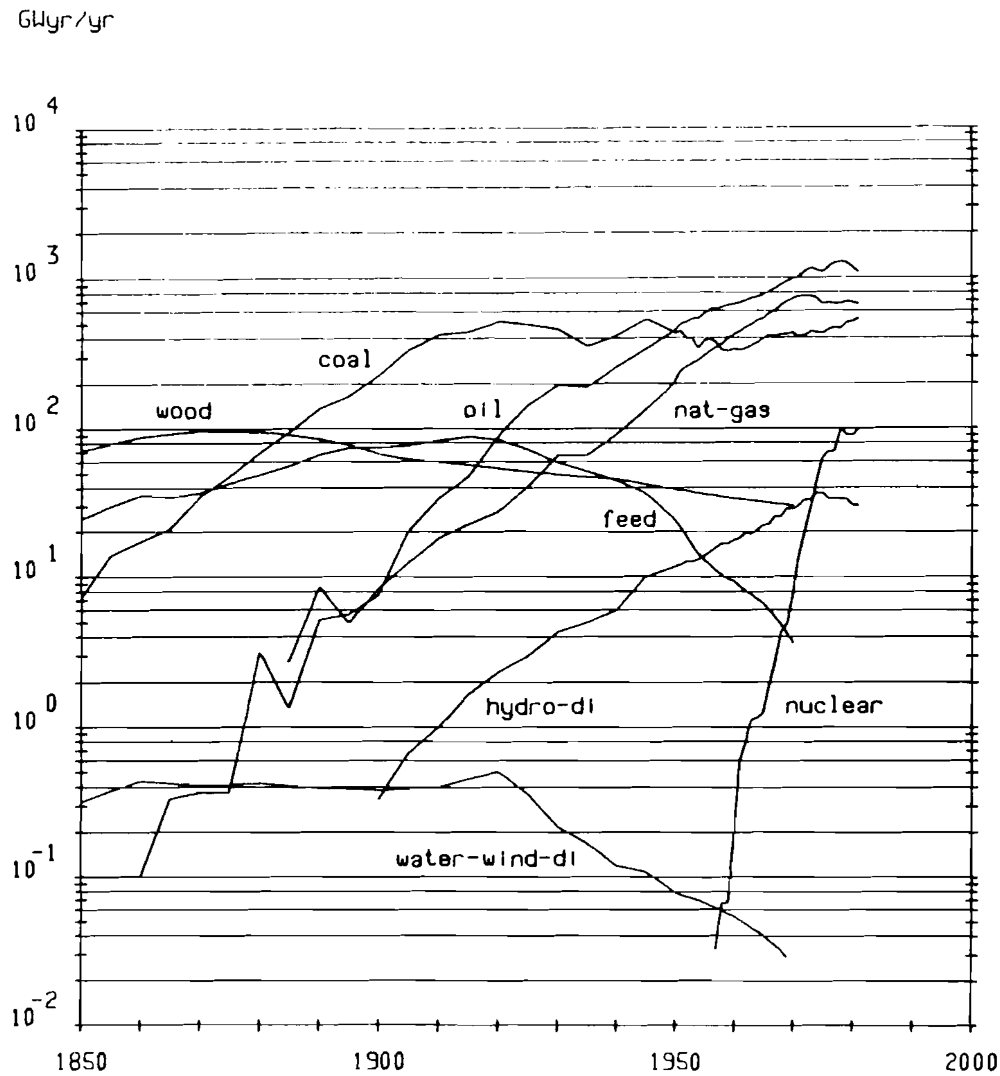

Figure 2.1 Primary Energy Consumption.

We assume that only one competitor is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates not influenced by competition from new competitors, and that new competitors enter the market and grow at logistic rates. The current saturating competitor is then left with the residual market share (i.e., the difference between 1 and the sum of fractional market shares of all other competitors) and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current saturating competitor has reached a logistic rate of decline, the next oldest competitor enters its saturation phase and the process is repeated until all but the most recent competitor are in decline. A more comprehensive description of the model and the assumptions is given in Nakicenovic (1979 and 1984).

In effect, our model assumes that competitors that have already entered their period of market phase-out are not influenced by the introduction of new ones. Deadly competition exists between the saturating competitor and all other more recent competitors. This generalized model offers a phenomenological description of the substitution process and has been successfully applied for about 300 cases from many countries ranging from primary to final energy and examples of technological substitution (see Marchetti and Nakicenovic, 1979, and Nakicenovic, 1984).

Figure 2.2 shows the primary energy substitution for the United States. Data and model estimates of the substitution process are plotted on a logarithmic scale using the quantity $f/(1-f)$ versus time (f representing fractional market shares). The piece-wise linear secular trends indicate logistic substitution phases. The departure of historical market shares from their long term paths, described by the logistic substitution model, sometimes last for over two decades only to return to the trend after the prolonged perturbation. This is the case with the market shares of coal and oil during the 1940s and 1950s, and fuel wood and animal feed during the 1860s and 1870s. This may also indicate a possible absorption of the departure of coal and natural gas market shares from their long term paths during the last ten years.

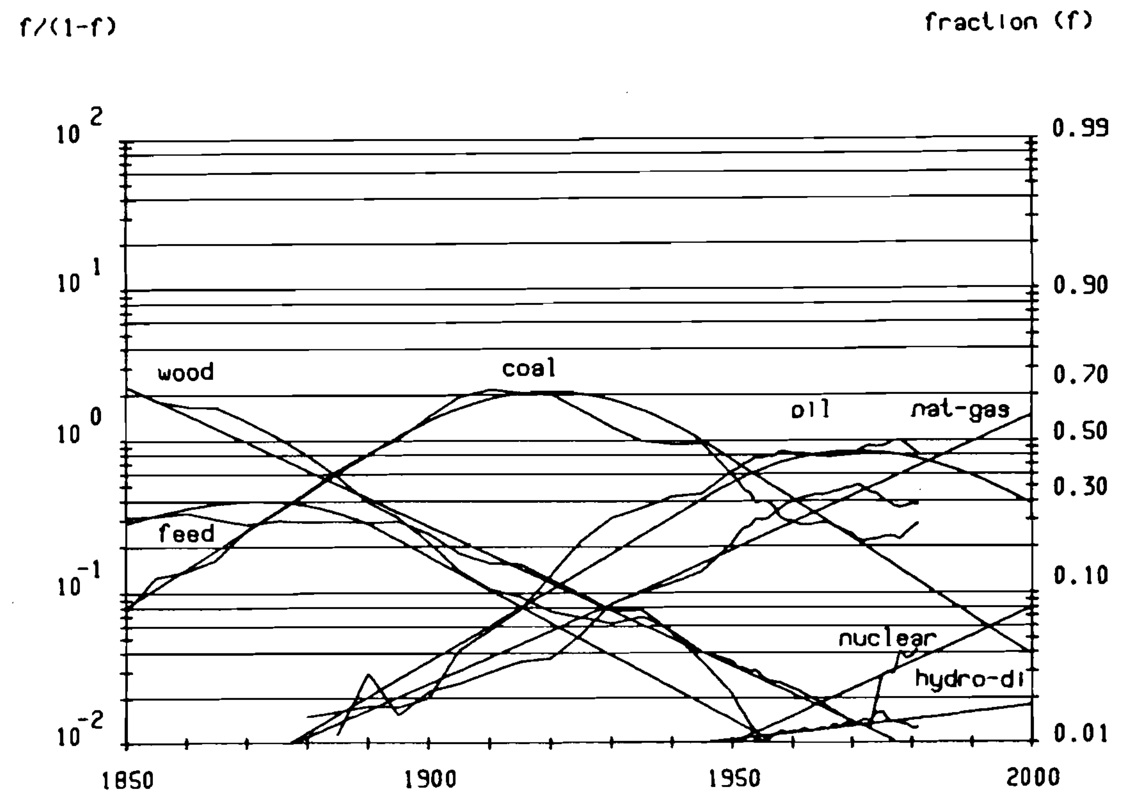

Figure 2.2 Primary Energy Substitution.

Animal feed reached its highest market share in the 1880s indicating that draft animals provided the major form of local transportation and motive power in agriculture despite of the dominance of railroads and steamships as long distance transport modes. Horse carriages and wagons were the only form of local transport in rural areas and basically the only freight transport mode in cities. It is curious that the feed and crude oil substitution curves cross in the 1920s as if to suggest the simultaneous substitution of the horse carriage and wagon by the motor vehicle.

The substitution process clearly indicates the dominance of coal as the major energy source between the 1870s and 1950s after a long period during which fuel wood and animal feed were in the lead. In the United States, wood remained to be the principal fuel for the railroads up to the 1870s, although railroads are considered the symbol of the coal age. The last phases of railroad expansion up to the 1920s, the growth of steel, steam ships and many other sectors are associated with and based on the technological opportunities offered by the mature coal economy. After the 1940s, oil assumed the dominant role simultaneously with the maturing of the automotive, petrochemical and many other modern industries.

Figure 2.2 shows natural gas as the dominanting energy source after the 1980s although crude oil still maintains about a 30 percent market share by the end of the century. For such an explorative "look" into the future, additional assumptions are required because potential new competitors such as nuclear or solar energy have not yet captured sufficient market shares in the past to allow estimation of their penetration rates. The starting point for market penetration of nuclear energy can be dated back to the 1960s when nuclear power acquired slightly less than one percent share in primary energy. In order to explore the behavior of the logistic substitution model when the competition between the energy sources is extended into the future, we assumed that nuclear energy could double its current market share of about four percent by the year 2000. This leaves natural gas with the lion's share in primary energy advancing its position to the major source of energy after this century.

Figure 2.2 indicates that it is possible to extract simple dynamic behavior from the complex evolution of primary energy use during the last 130 years. Nevertheless, the accuracy of the description is not perfect. We noted that some departures of historical data from the long term model trends last for more than two decades. This is to some extent due to the fact that the estimates of traditional energy use are only rough indicators of the actual consumption levels and that the data were available only at five-year intervals prior to 1950.

The evolution of commercial energy use in the United States has a longer recorded history than the use of traditional energy sources. Figure 2.3 gives the annual consumption of all commercial primary energy sources and fuel wood starting in 1800, while Figure 2.4 shows the substitution of these energy sources. In this example, the logistic substitution model describes with great precision the evolution of primary energy consumption. Due to the dominance of fuel wood as the major source of energy during most of the last century, the information loss associated with the lack of adequate annual estimates of energy use (feed requirements) of draft animals is not very large. Direct wind and water power are included in the data set, but due to their low contribution to total energy supply, when expressed in terms of their actual energy inputs, they are not observable at the one-percent level. Thus, before 1917 when coal entered the competition

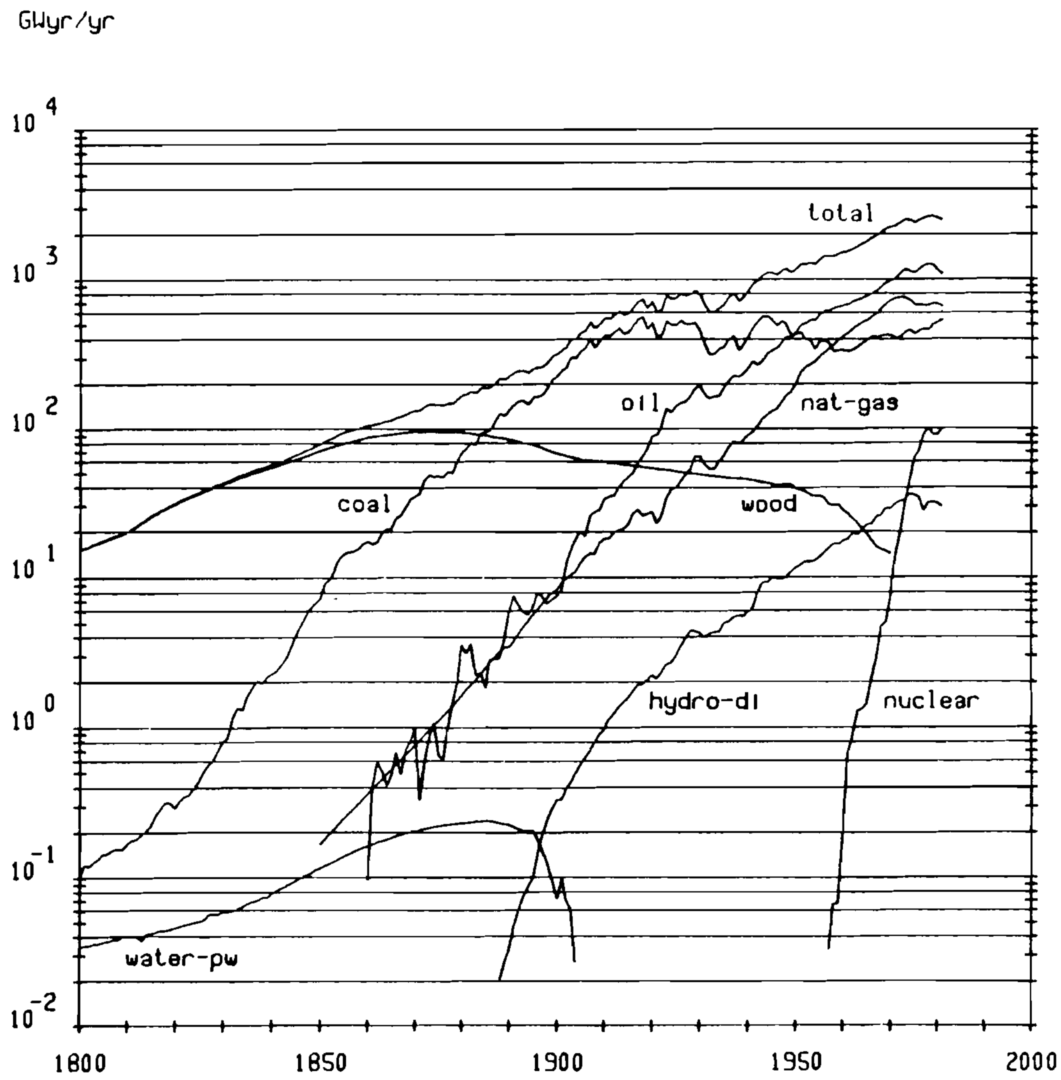

Figure 2.3 Consumption of Commercial Primary Energy Sources.

process, fuel wood provided virtually all the (commercial) energy needs. The senescense of fuel wood and the rise of coal can be seen very clearly. Up to the late 1880s, primary energy was essentially a zero-sum, two technology market - whatever gains coal made were translated into losses for fuel wood. The dominance of fuel wood, and later coal, shows an interesting symmetry, each period of dominance lasting slightly over 60 years. The initially slow introduction of crude oil and natural gas during this decade translated into market dominance 80 years later. It is also interesting that crude oil reached a one percent market share about two decades before the first automobiles were produced in the United States (actually four were manufactured in 1895, see Epstein, 1928). Further, the first use of oil and natural gas sources dates back to 1859, preceding the first automobiles by almost half a century.

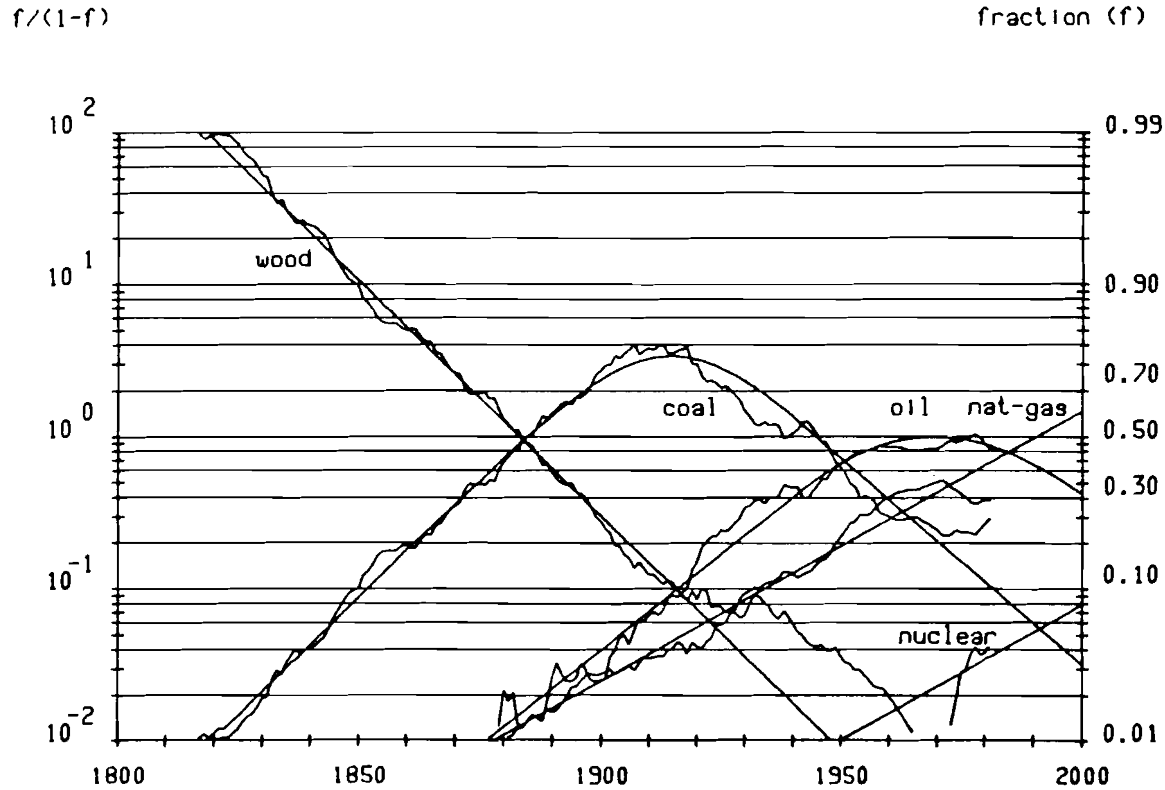

Figure 2.4 Substitution of Commercial Primary Energy Sources.

The regularity of this substitution process is due not only to the fact that the penetration rates of various energy sources remain constant over periods of about a century, but also due to the fact that the saturation levels of energy sources are much lower than the full market takeover. The introduction of new energy sources and the long time constant lead to maximum market penetrations of between 50 and 70 percent. New energy sources are introduced before the dominant ones have even reached a 50 percent share. In addition, the maxima are roughly spaced at intervals of about 50 years, which corresponds nicely to the time constant of about 50 years for market share increases from 10 to 50 percent. In order to further explore the regularity of this process we have used the logistic substitution model to describe similar substitution processes in steel production and merchant marine.

2.2 Steel Production and Merchant Marine

Figure 2.5 shows that steel production increased rapidly during the second half of the nineteenth century, after Henry Bessemer patented the first high-tonnage process for steel production in 1857. The next improvement in steelmaking was achieved by the introduction of the open-hearth furnace. The first open-hearth to be used widely was based on acid chemistry although later the basic open-hearth also found extensive use. The basic systems have a decided

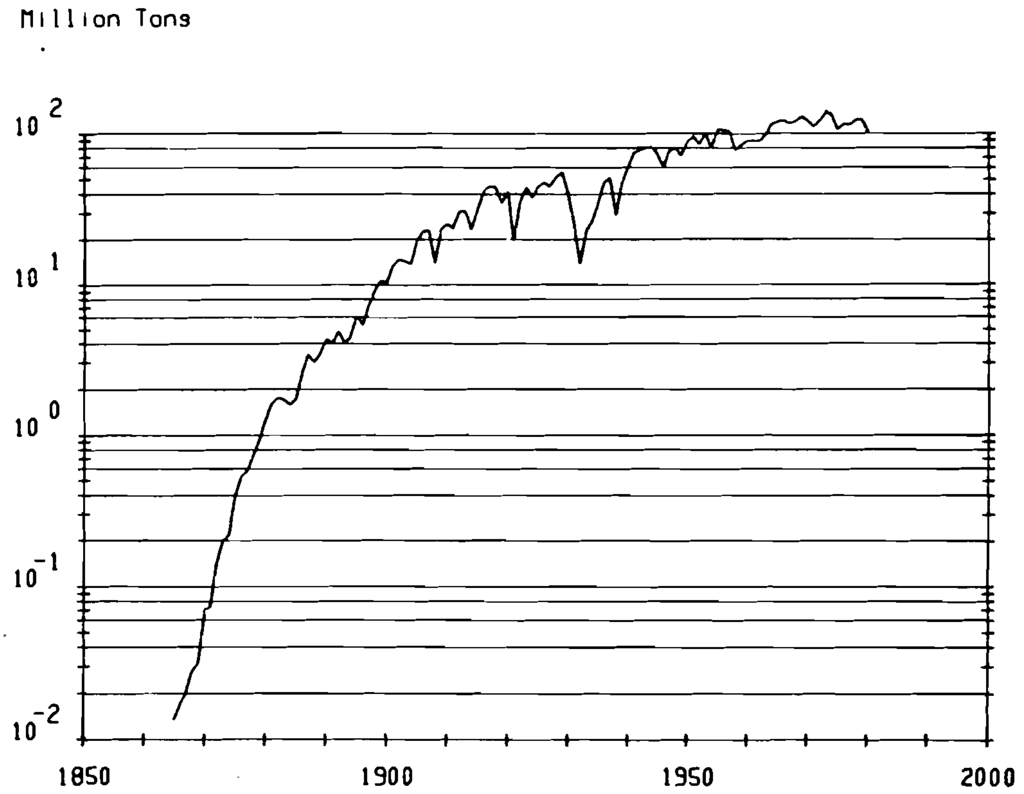

Figure 2.5 Steel Production.

advantage in flexibility with regard to raw materials consumed and grades of steel produced. The steelmaking processes were further improved by the use of oxygen for excess combustion instead of air. This offers many advantages such as faster melting and reduced checker chamber capacity. Consequently, the Bessemer process was also extended to basic chemistry and oxygen use, the most spectacular application originating in Austria as the Linnz and Donnewitz (L-D) process, now generally referred to as basic-oxygen steelmaking. The last improvement in steelmaking technology was the introduction of the electric arc furnace. The electric process has the advantage that it is suitable for making many grades of steel and can almost exclusively use recycled scrap iron and steel (Miller, 1984).

Figure 2.6 shows the actual technological substitution in steelmaking according to the process used. Prior to the introduction of the Bessemer process all steel was produced by the traditional crucible methods used since antiquity. Fortunately, data are available for the period before 1860, and Figure 2.6 shows that the Bessemer process replaced the traditional methods within two decades supplying almost 90 percent of all steel by 1880. From then on the Bessemer process was replaced by open-hearth steelmaking which supplied 50 percent of all steel by the end of the century. The use of the open-hearth process continued to increase during the first decades of this century and by the 1950s accounted for more than 90 percent of the steel produced. This process of technological substitution continued during the last 40 years with the introduction of the basic-oxygen and electric steel methods. The electric arc process was introduced

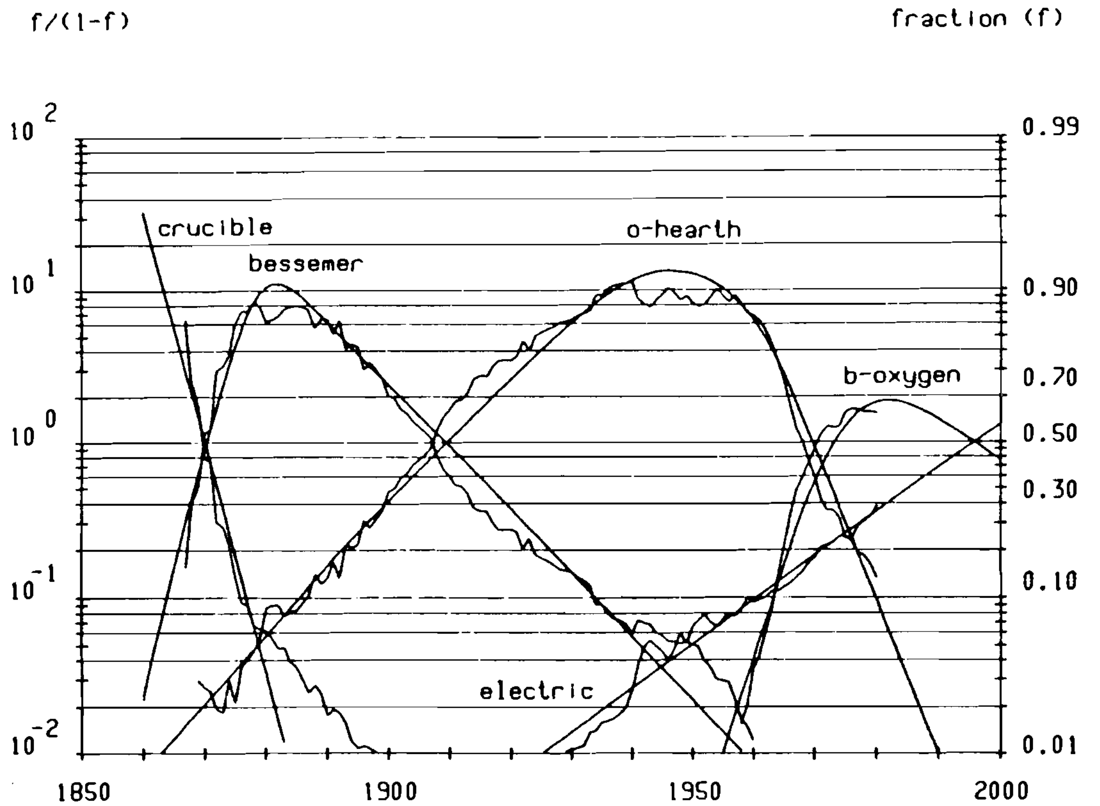

Figure 2.6 Technological Substitution in Steel Production.

as early as 1900, so that it gained importance before the basic-oxygen process. However, the basic-oxygen process expanded faster, probably because it is technologically similar to the open-hearth and Bessemer basic variants. During the 1960s, the basic-oxygen process portrayed very rapid share increases reaching more than 50 percent of the market in the 1970s. Accordingly, once the most important steelmaking process, open-hearth declined rapidly down to the ten-percent mark during the same period. The electric process is gaining importance and will probably overtake basic-oxygen within the next two decades due to the saturation of demand for domestic steel in the United States. The dwindling total production leads to higher and higher percentages of scrap iron and steel inputs instead of iron ore in addition to some imports of pig iron. This development favors the electric process since it is very energy efficient and with the stagnating demand for steel allows for almost exclusive use of recycled inputs (see Miller, 1984).

This example illustrates that the evolution of steelmaking technologies portrays a regular pattern that is similar to energy substitution. The description of the historical data by the logistic substitution model was consistently accurate, despite many turbulent and profound changes since the beginning of the so-called industrial revolution. Before returning to the analysis of recurring periods in technological change and long wave fluctuations in economic development, we will first consider the substitution process in the merchant fleet of the United States. This example illustrates the evolution of one of the oldest modes of transport. It covers a period of two hundred years and includes fundamental transformations of propulsion systems, increased speed and size of the vessels, and change of the construction methods and materials.

The traditional ship propulsion, in use ever since ancient times, was wind power and the traditional construction material was wood. With the development of the steam engine and the relatively high energy density of high-quality coals, it was possible to slowly replace sails with steam engines. The first designs were of a hybrid type employing both steam and wind power. With the increase in the size of vessels along with the expansion of overseas trade, and with the growth of the iron and steel industries, wood was increasingly substituted by iron and later steel as the basic construction material. In fact, the number of vessels remained practically constant since the end of the 18th century until the 1940s at about 25 thousand ships, doubling during the last three decades. During the same period of almost two centuries the total registered tonnage of the merchant fleet increased by almost two orders of magnitude implying that the average vessel is about 100 times larger today than in 1800. This enormous increase in the tonnage capacity of an average vessel can only be explained by continuous improvements in propulsion systems, construction materials and design.

Figure 2.7 shows the tonnage growth of the merchant fleet in the United States since 1789 and Figure 2.8 shows the substitution of sailing by steam ships, both coal and oil fired, and later the market penetration of motor, diesel and semi-diesel ships in terms of their respective tonnage. Sailing ships dominanted the merchant fleet until the 1880s although steamers acquired a one percent share of the total tonnage in 1819, more than half a century earlier (two years after coal reached a one percent share in primary energy). By the 1920s steam vessels constituted more than 90 percent of merchant tonnage, thus the replacement of the traditional sailing ship lasted one hundred years. During the same decade motor ships were introduced and their share of total tonnage has increased ever since, although even today they have not acquired much more than one tenth of the fleet tonnage. Consequently, steam ships remain an important type of merchant vessel and are projected in Figure 2.8 to stay in that position through to the end of the century, although today they are fueled by oil and in some cases use steam turbines instead of coal fired atmospheric engines. During the Second World War, the share of motor ships sharply increased, but this perturbation was reabsorbed during the 1960s to return to the long term trend indicated by the logistic substitution model.

The application of the logistic substitution model to the historical replacement of older by newer forms of energy, steel production and propulsion of merchant vessels indicate that improvements and growth are achieved through a regular but discontinuous process. From the time of its first commercial use, each new technology grows logistically until it reaches a saturation phase and then proceeds to decline logistically while being replaced by a newer and more promising technology. During each phase of the substitution process the dominant technology appears to be strong and unassailable, but with time it decays as emerging competitors "attack" the newly exposed position of the mature technology. In general, the saturation point is not determined by mere physical or resource limitations but rather through the dynamics of the introduction of new technologies. Thus, the market shares increase until limits are reached that appear to be endogenous to the market (or system) itself. The limits are encountered usually before the complete market takeover. They are imposed by the structure of a given market that is in turn related to overall economic and social development and not necessarily to mere resource

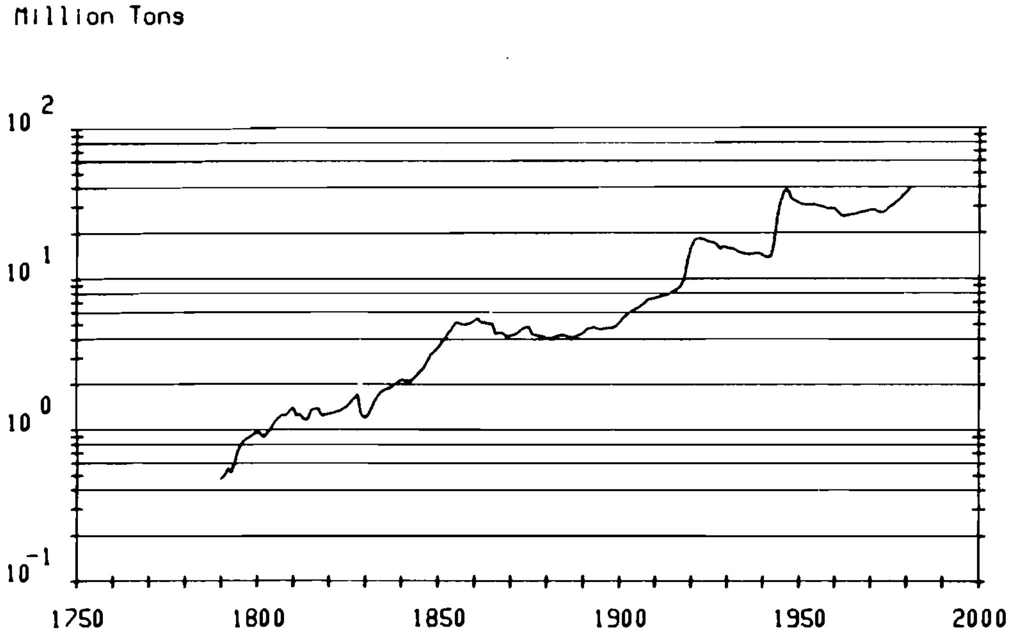

Figure 2.7 Tonnage of Merchant Vessels.

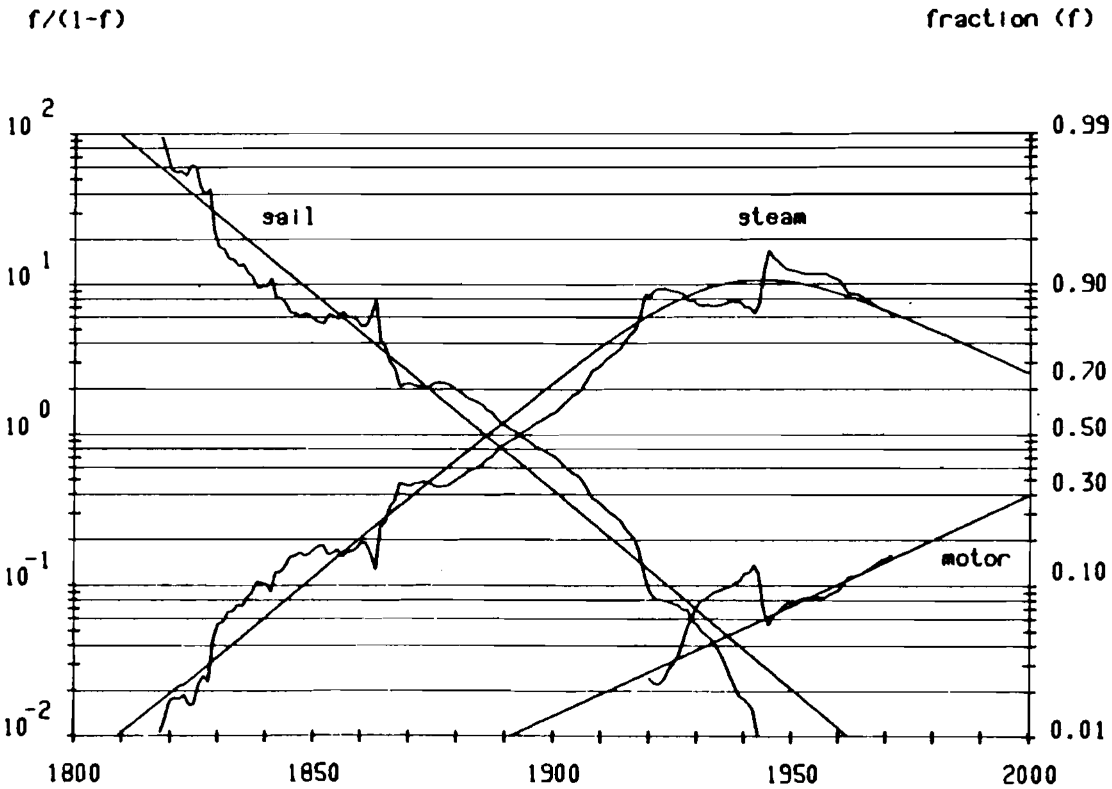

Figure 2.8 Substitution in Merchant Vessels by Propulsion System.

depletion. Once these limits are reached further growth becomes economically and socially unviable. Thus, technological and economic changes have a regular pattern and rules that point to a certain rhythm and schedule in the structural change of other human activities. Horse riding, wood fire, and sailing ships have become aesthetic and recreational activities in the developed economies after they have been replaced by new technologies while they still constitute a daily necessity in many developing parts of the world as means of transportation and source of energy.

3 LONG WAVES AND CHANGE OF TECHNOLOGY

We have seen that technological advancement is an evolutionary but not continuous process. Technological change and diffusion follow regular substitution patterns characterized by successive alternation of growth and senescence with a duration in the order of 50 years for large systems and infrastructures. It is therefore only natural to ask whether the whole process of economic growth and development can also be considered as a series of leaps with periods of rapid growth and periods of relative stagnation that are related to rise and fall of dominant technologies and economic sectors. From history we know that this is at least an approximate description since a number of serious depressions and crises as well as periods of unusual prosperity and great achievements have been recorded since the beginning of the industrial age.

This hypothetical connection between technological substitution and the long wave must be verified empirically before the exact nature of the two phenomena connected with the process of technological development can be related to each other. Here, we will examine and document the evidence for the presence of long waves in the economic development of the United States. Examples for other countries were reported elsewhere (see Nakicenovic, 1984; Marchetti, 1981; Bianchi, Bruckmann and Vasko, eds., 1983). The analysis will essentially consist of using a phenomenological approach to extract long fluctuations from historical records in an attempt to filter out the long waves and to compare the so-derived fluctuation patterns with the dynamics of technological substitution.

Kondratieff (1926) and Schumpeter (1935) have already used a similar approach in the search of invariants in the dynamics of long waves. They assumed that every sequence of annual economic (or other) quantities and indicators can in principle be decomposed into two components - a secular trend and the fluctuations around this trend. In practical terms, the method consists of first eliminating the secular trend from non-stationary time series and then determining the residual fluctuations of the time series. The second stage consists of eliminating all other fluctuations shorter than the long wave. Usually, it is sufficient to form a moving average longer than the duration of the business cycle (i.e., longer than a decade). This operation is not always necessary since the long wave movements are sometimes observable in the residual even without the elimination of shorter fluctuations.

In general, trend elimination from time series that are not stationary is usually more difficult than the decomposition of the stationary series into various fluctuations. Specifically, it is not always obvious which method of trend elimination should be used. We have used three different methods: the moving average over sufficiently long time periods in order not to remove the long wave fluctuations, the exponential and the logistic growth curves. In many cases we have applied more than one method for trend elimination in order to test the sensitivity of the obtained results with respect to such changes.

3.1 Wholesale Prices of Commodities

The regularity of fluctuations in price data was the phenomenon that first stimulated Kondratieff and his predecessors to postulate the existence of long waves in economic development. These waves are most pronounced in the wholesale price indices for all commodities in the United States, but they can be observed in the price indices of other industrialized countries, examples include the United Kingdom, France and Germany. Figure 3.1 shows the wholesale commodities price index in the United States from 1800 to 1982. Wholesale prices appear to be stationary with long fluctuations almost over the whole historical period. Only after the 1940s can a pronounced inflationary trend be observed that had a magnitude greater than any other fluctuation before.

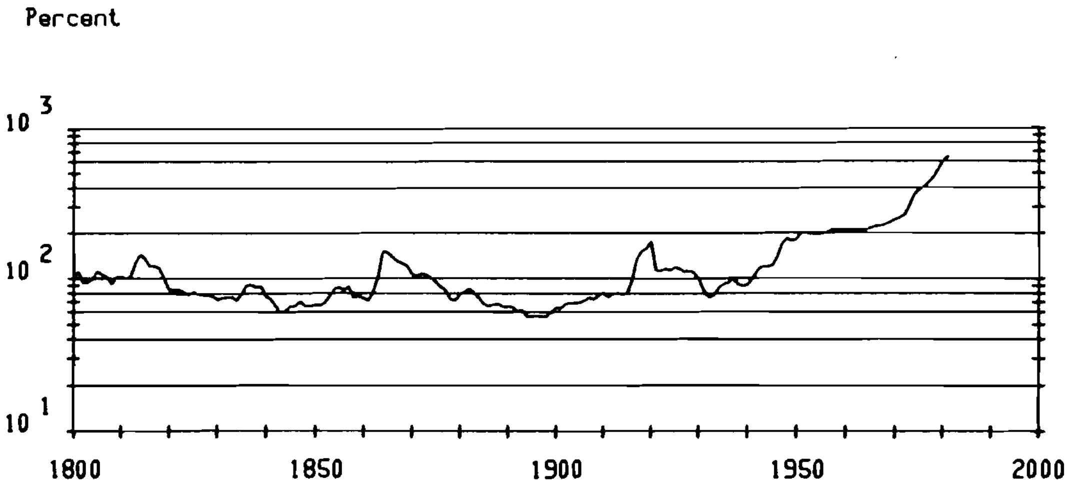

Figure 3.1 Wholesale Price Index.

The pronounced price peaks of the 1780s, 1820s, 1870s, 1920s and sharp increases during the last decade are spaced at intervals of four to five decades. These recurring long swings in prices are in our opinion not the primary causes of the long wave phenomenon but rather a good indicator of the succession of alternating phases of the long wave. We consider the long swings in price movements to indicate the phases of growth and saturation with increasing level of prices, and phases of recession and regenerative destruction with decreasing price levels.

In order to obtain a clearer picture of the succession of the long waves in the price indices, we have decomposed the time series into fluctuations and a secular trend. Since the secular trend does not indicate a simple functional form we have used a 50 year moving average method for its elimination from the time series. We have smoothed the resulting residuals (i.e., the relative difference between the actual price level and its secular trend expressed as a percentage) with a 15 year moving average. The resulting series of smoothed and unsmoothed residuals is shown in Figure 3.2 for the United States. The average duration of the two fluctuations between the 1840s and 1940s is about 50 years with small variance in the duration and amplitude. The occurrence of peaks and troughs varies by not more than a few years.

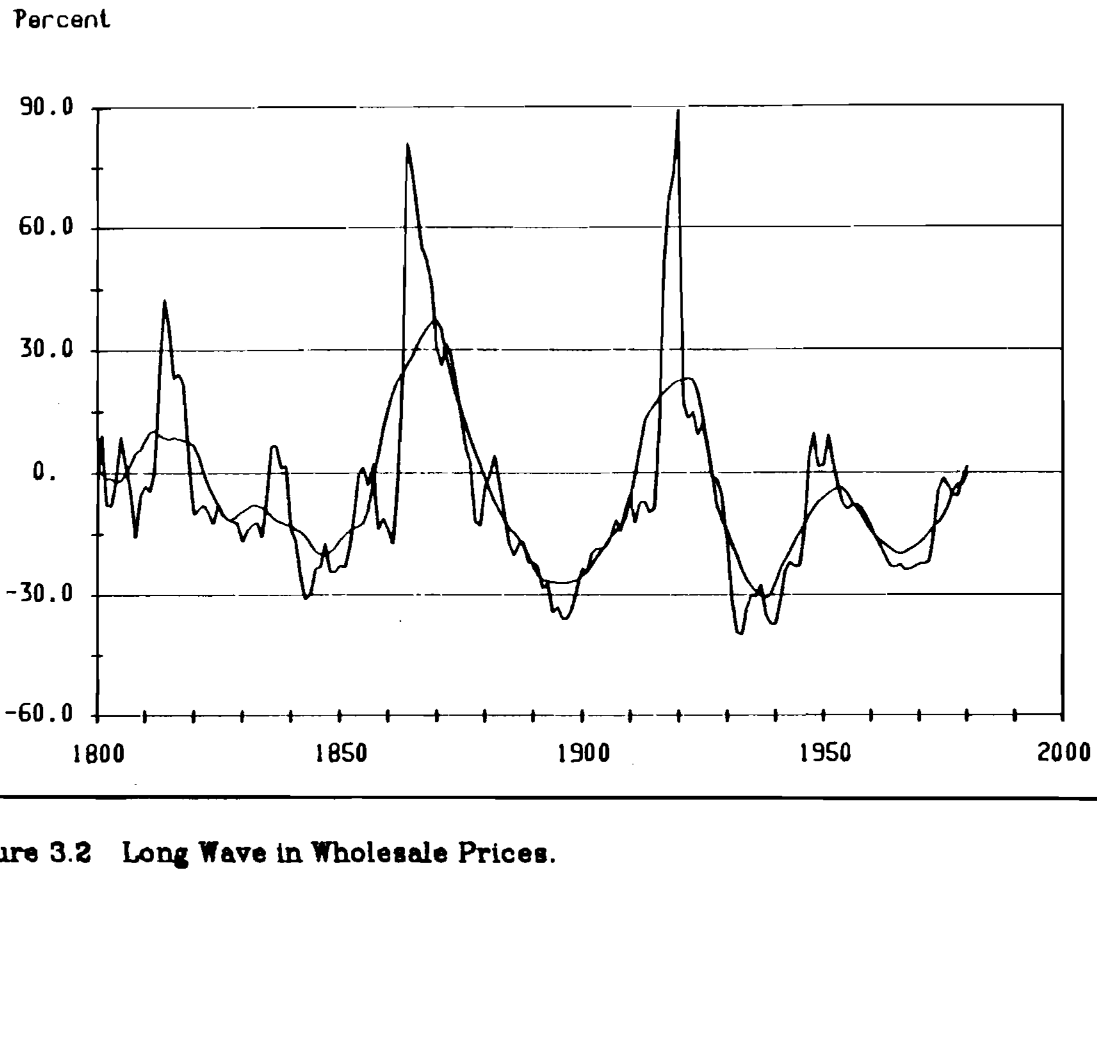

Figure 3.2 Long Wave in Wholesale Prices.

3.2 Primary Energy Consumption

Energy use is one of the rare quantitative indicators that can, at least in principle, be compared over long periods of time in spite of many technological changes and substitutions of old by new sources of energy. This is possible because the use of different energy sources can be expressed in common energy units. The major difficulty associated with such comparisons is that most of the energy used during the early periods of the industrial revolution constituted non-commercial sources. We have already discussed the problems involved in estimating the levels of non-commercial use in the past. In the context of long waves we are interested in relative changes in the levels of energy use and not in the growth and relative shares of various energy sources. These fluctuations around the secular trends, however, may be to an extent obscured by the fact that especially fuel wood, the most important of all non-commercial energy sources, was estimated primarily on the basis of per-capita use. Thus, since the fuel wood time series do not represent actual use, but rather serve as an indicator of the relative importance of its use, some of the fluctuations may not be contained in the data. Nevertheless, at least three distinct phases can be observed in the growth of primary energy consumption in the United States (see Figure 2.3). After rather stable long-term growth rates, a phase of more rapid growth starts in 1900 and continues until 1930. After a short interruption the rapid growth resumes a few years later and continues until the last decade.

The secular trend of primary energy use in the United States can be captured by a number of functional forms. Stewart (1981) used the logistic growth curve to eliminate the secular trend basing his estimate on five-year averages of primary energy consumption. The resulting fluctuations around this trend showed pronounced long waves. The drawback of this approach is that he used shorter time series starting in 1860, so that only the last and the current wave were displayed. Our data base goes back to 1800 and extends over one more wave.

We will use our extended data base and will employ three different estimation methods of the secular trend: the geometric 50-year moving average, and the logistic and exponential growth curves. Figure 3.3 shows the historical primary energy consumption in the United States (from Figure 2.3) with two alternative secular trends: the logistic fit with a saturation level of about eight TWyr/yr to be reached after the year 2050 and an exponential fit that leads to astronomical consumption levels in the far future. Being the simplest of the three secular trends, the moving average is not shown in the figure in order not to obscure the other two trends.

Figure 3.4 shows the residuals, smoothed with a 15-year moving average, resulting from the three alternative estimation methods of the secular trend (the logistic and exponential estimates and the 50-year geometric moving average). The fluctuations show the same regular and parallel movements as the long waves in prices (see Figure 3.2). The second upper turning point in energy consumption is not as pronounced as in price movements and it also occurred approximately a decade earlier. This could in part be explained by the fact that about 90 percent of total energy consumption was supplied by fuel wood during this period (see Figures 2.2, 2.3 and 2.4). As was mentioned earlier, the fuel wood time series represent estimates that were based primarily on the population growth so that they do not portray many fluctuations observed in other energy sources.

It should be noted that the turning points of the fluctuations are relatively invariant to the estimation method. The amplitudes of the fluctuations, however, depend on the estimation method. Especially the amplitude of the last upper turning point in 1975 is very sensitive. It is lowest in the case of the exponential fit since the low rates of energy growth during the last ten years are below the trend of the exponential growth curve. It is also interesting to note that the lower turning point of the first wave in Figure 3.4 is dated in 1897 by the moving average method and in 1883 in the case of the exponential and logistic methods. This confirms the fact that the moving average method is not well suited for timing the turning points of the long wave. In spite of such relatively small changes in the dating of this turning point and a larger variance in the amplitude of the last wave, the parallel fluctuations of all three long wave curves indicate that the broad features of the fluctuations in primary energy consumption are not a function of the method used to eliminate the secular trend from the data.

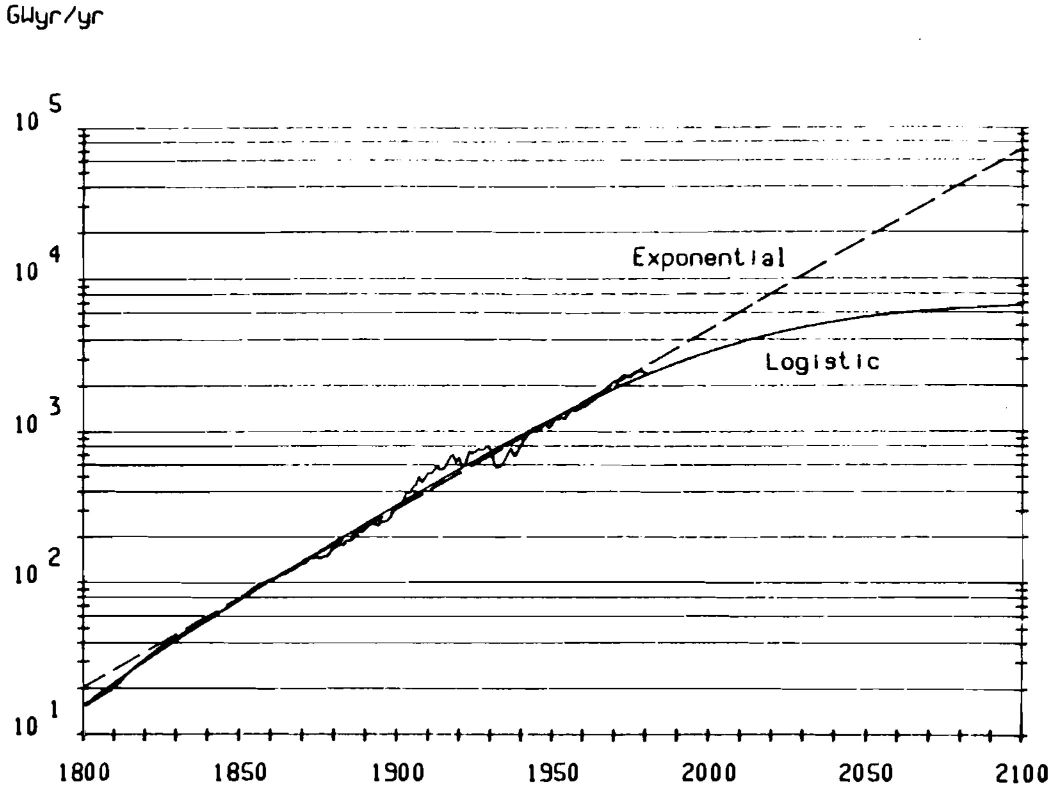

Figure 3.3 Primary Energy Consumption (with Two Secular Trends).

Apparently, all three methods are suited for trend elimination in this particular context, and since the moving average is the easiest to compute, this sensitivity analysis offers an *a posteriori* justification for using the simplest method of trend elimination in the examples.

The consumption levels of fossil energy sources are known with greater certainty than the estimates of older, non-commercial energy sources. This is especially critical in the United States where fuel wood constituted the major source of energy during the last century. Figure 3.5 shows the fluctuations in fossil energy use (i.e., fuel wood was eliminated from the data set). The pronounced fluctuations indicate the long wave more clearly than the total primary energy consumption from Figure 3.4. Fuel wood consumption (see Figure 2.3) is very smooth, probably because population growth was one of the most important secular trends used to estimate the data. Thus, during the last century when fuel wood was the most important source of energy, it obscured some of the fluctuations present in fossil energy sources. Without fuel wood, primary energy consumption as such portrays pronounced long wave movements.

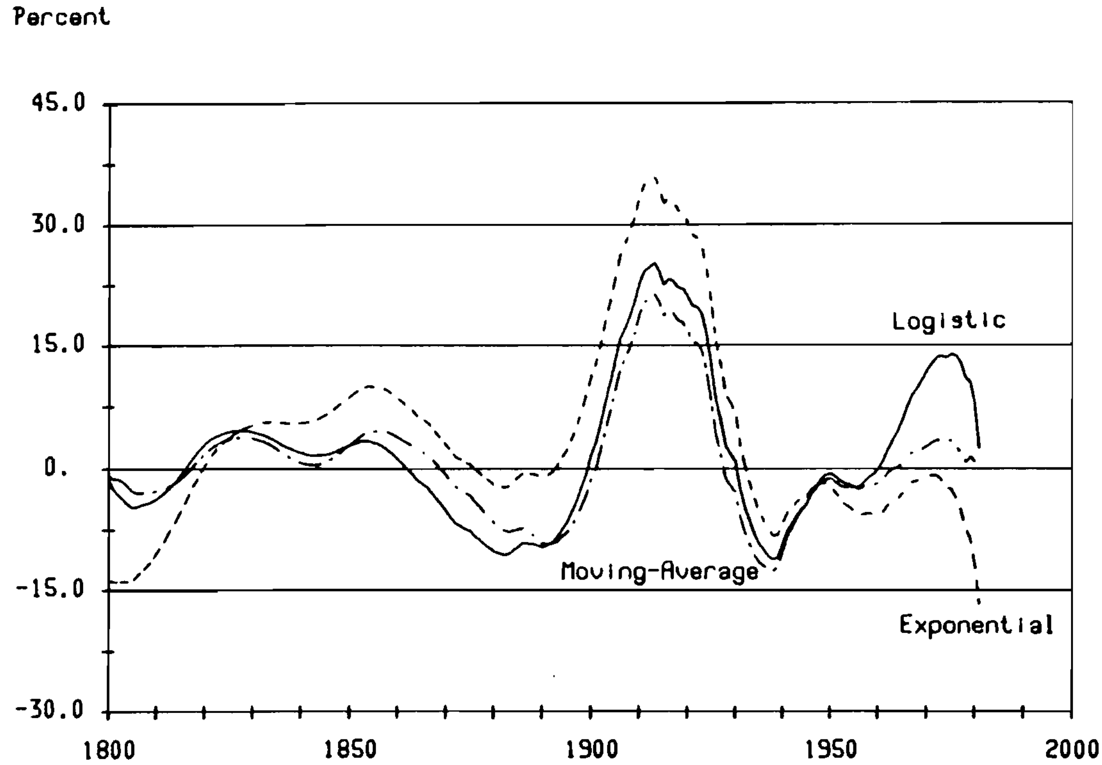

Figure 3.4 Long Wave in Primary Energy Consumption (Three Estimates).

3.3 Efficiency of Energy Use

There are many ways of determining the efficiency of energy use. The most obvious indicators are the efficiencies of primary energy conversion to secondary and final energy forms. Another possibility is to estimate the efficiency of energy end-use. Examples include the amount of fuel needed for travel, or for space conditioning. All of these efficiences have improved radically since the beginning of the industrial revolution along with the introduction of more efficient technologies. In some cases the improvements span almost an order of magnitude. For example, in 1920 the average efficiency of natural gas power plants in the United States was nine percent, whereas today the best gas turbine power plants can operate with efficiences of almost 60 percent. Over longer periods the improvements are even more impressive. For example, the second law efficiency of prime movers increased by two orders of magnitude since 1700, that of lamps by almost three orders of magnitude during the last century and so on (see Marchetti, 1979). All of these efficiency improvements of individual technologies are translated into more effective use of energy and other materials at the level of the overall economic activity. Some efficiency increases result from improved technologies and others from substitution of the old by new technologies.

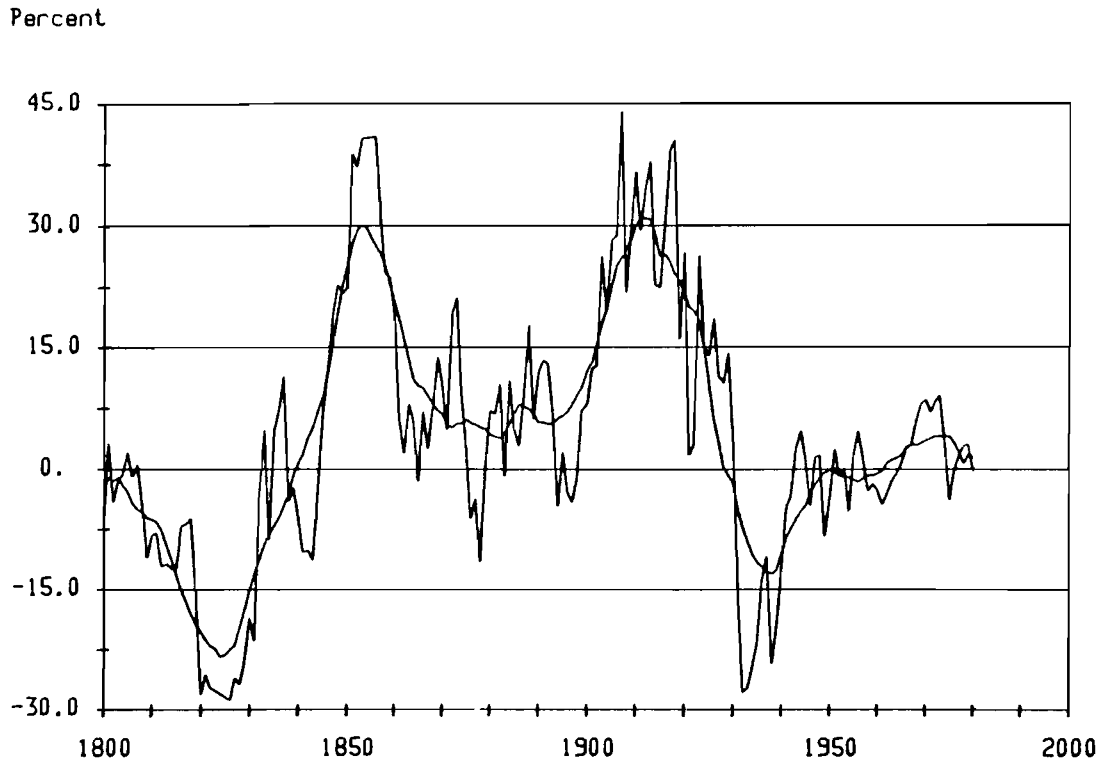

Figure 3.5 Long Wave in Fossil Energy Consumption.

The extent of these changes and improvements can be expressed at an aggregate level by the amount of primary energy consumed per unit of gross national product in a given year. Figure 3.6 shows the ratio of energy consumption over gross national product (energy intensity) for the United States. The average reduction in energy consumed to generate one dollar of gross national product was about 0.9 percent per year during the last 180 years. The ratio decreased from more than ten kilowatt-years per (constant 1958) dollar in 1800 to slightly more than two kilowatt-years per dollar in 1982. Thus, a regular decline in energy intensity of the whole economy prevailed over a long historical period indicating that energy conservation is a historical process that was discovered as a concept only during the last decade.

Figure 3.7 shows the fluctuations in energy intensity in the United States after the elimination of the secular trend by a 50-year geometric moving average. The fluctuations show pronounced long wave movements and a high degree of synchronization with the price swings. During the downswings in prices the energy intensity of the economy decreased more rapidly and during the upswings less rapidly. This means that during the downswing in economic activity general rationalization measures of individual enterprises cause larger energy savings compared with the average historical reductions. As the competition intensifies during the recession and depression, energy savings become an important factor in cost reduction. With recovery, new demands and prospects of continued

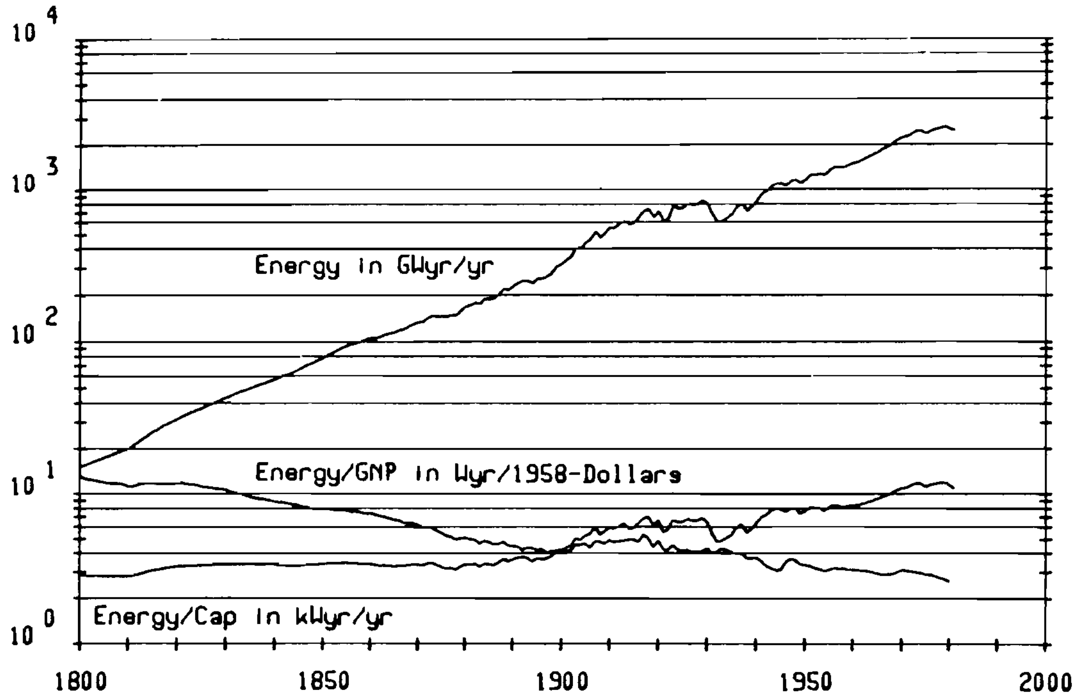

Figure 3.6 Primary Energy, Gross National Product and Energy Intensity.

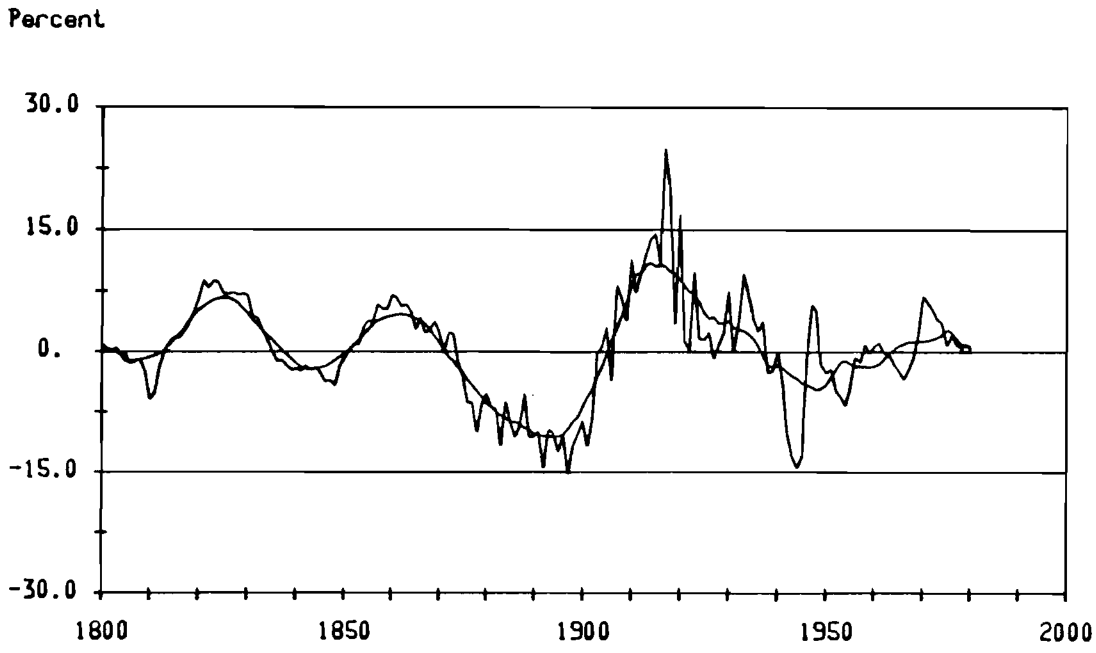

Figure 3.7 Long Wave in Energy Intensity.

economic growth release many pressures associated with saturating markets. Most of the entrepreneurs in the new growth sectors must intensify their activities in order to meet new demands, and low energy intensity ceases to be an important competitive criterion. New technologies and energy forms offer possibilities for continued expansion in new markets so that relative energy use intensifies. Toward the end of the prosperity period the growth process encounters limits once more. These are reflected in saturating demand and general price inflation illustrated by the long wave of wholesale price movements (see Figure 3.2). Thus, during the downswing energy use reductions become important. These reductions are not only due to efforts to cut costs as a reaction to saturating demand, but also due to a host of social constraints. Many energy technologies, along with other economic activities, become socially and environmentally unacceptable toward the end of prosperity. This means that some diseconomies that were socially acceptable during the growth phase become internalized as additional economic costs or as explicit limits to further expansion. These causes of additional costs appear to off-set the benefits of the economies of scale achieved during the expansion phase. In fact, with the demand reductions during the downswing the large capacities that offered economies of scale become sources of additional costs as excess capacity.

The relationship between primary energy consumption patterns and the long wave appears to extend beyond the parallel changes in the relative level of energy consumption and energy intensity with the fluctuations of other long wave indicators such as the wholesale prices. Figure 3.8 shows the fluctuations in energy intensity (energy over gross national product from Figure 3.6) together with primary energy substitution (from Figure 2.2) for the United States. The upper turning points of energy intensity fluctuations correspond to the saturation points of primary energy sources. The upper turning point that occurred in 1860 is related to the saturation in animal feed substitution, the 1915 turning point with the saturation in coal substitution, and the turning point of the 1970s with the saturation of crude oil. In addition, new energy sources reached one-percent market shares during the times of low energy intensity (during the 1880s and the 1950s). Thus, the dynamics of energy substitution in the United States indicate a close relation to the succession of the long wave fluctuations but it is still an open question whether a similar relationship can be confirmed for other countries.

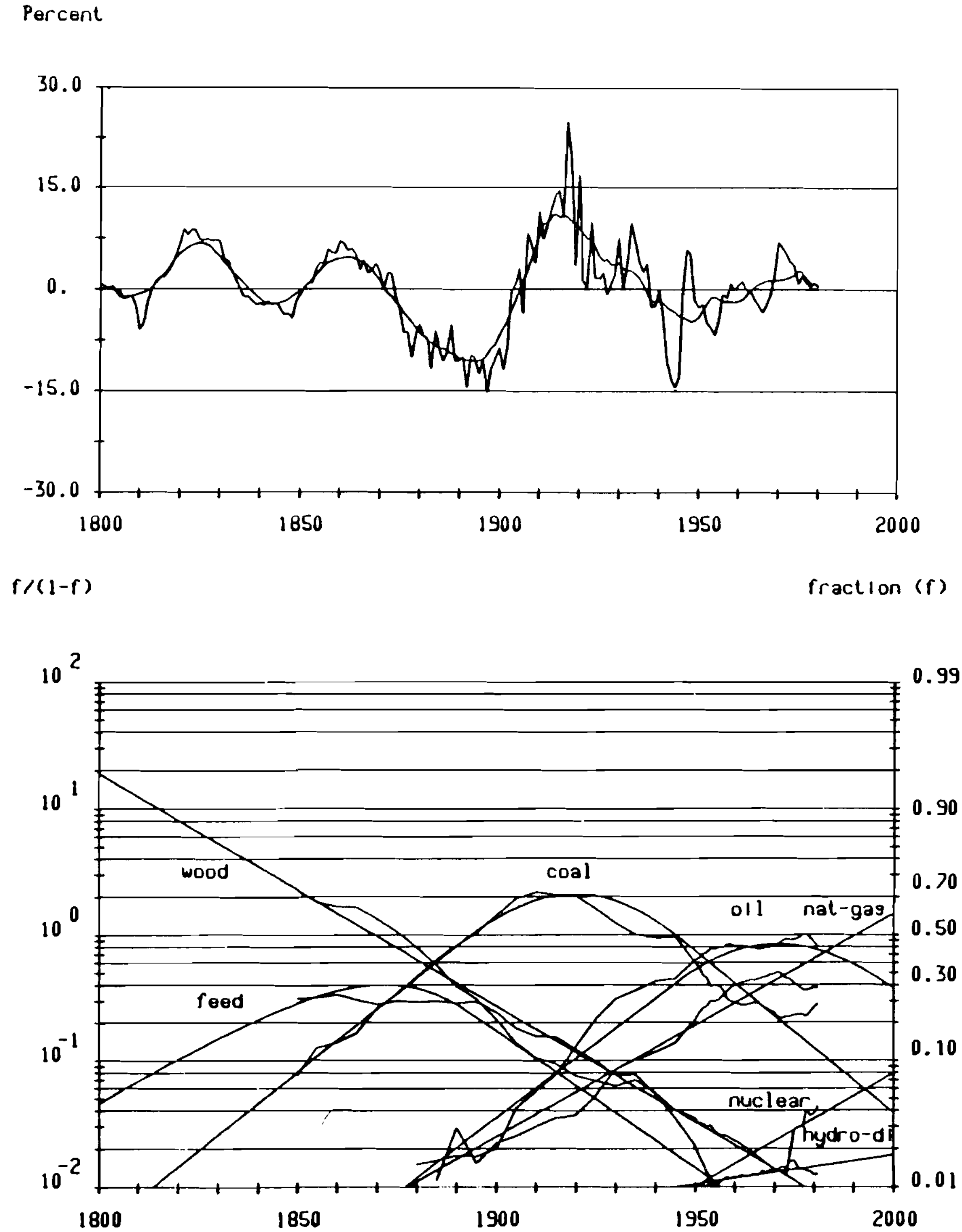

Figure 3.8 Primary Energy Substitution and Long Wave in Energy Intensity.

3.4 Physical Indicators: Steel and Ships

In addition to primary energy substitution, we have shown the examples of technological substitution in steel production and merchant ships. Now we will consider these two examples again in the context of the long wave. Figure 3.9 shows the long wave fluctuations in steel production, derived from total steel production since 1860 (given in Figure 2.5) by using a 50-year, geometric moving average to eliminate the secular trend and an 15-year moving average to smooth the fluctuations of annual residuals. It should be observed that the long wave movements in steel production are out of phase with respect to the price swings. The lower and upper turning points precede by about one to two decades the corresponding turning points in prices. This probably means that the markets for steel are more sensitive to the first signs of economic changes and thus respond before other sectors to the emergence of favorable or unfavorable conditions. The reasons for this advanced response of the steel industry may be relatively simple. It is possible that steel, as one of the most important industrial materials, is by and large used in capital intensive goods that have a relatively long life-time and consist of large units. Typical examples from the last century are the railroads and ships, today they are power plants, refineries, large buildings, factories, etc. Even a small decrease in demand for these goods, if it would occur simultaneously, would have an important effect on the reduction of steel production. Thus, it is possible that the first signs of economic change are visible in the fluctuations of steel production because the effect of smaller reductions in many other sectors is amplified when translated into steel demand. If this actually is the case, than one could use the fluctuations of steel production as an early warning for the upcoming turning points of the long wave.

Figure 3.10 shows the long wave fluctuations in the tonnage of merchant vessels. The same data were used as in Figure 2.7 where we considered the technological substitution by type of vessel employed by merchant fleets. The fluctuations correspond to the long waves in prices although a major irregularity occurred after the last wave. A second peak follows immediately after the upswing and downswing between the 1890s and the 1930s. This second peak rises during the 1940s, reaches a maximum in 1950 and than declines during the 1950s and 1960s. It is interesting to note that this second peak can also be detected in other indicators, but it is not so pronounced as in this case. For example, the fluctuations in primary energy consumption also portrayed such a peak during the same period, but it appeared to be only an acceleration and deceleration during the upswing phase of the long wave that was initiated in 1944 with a global peak in the 1980s. Even the wholesale price index shows a subdued fluctuation during the same period with a local peak in 1955, a decline and a renewed rise after 1971. Although, this fluctuation is also present in some other indicators of the long wave, it is by far not so pronounced as in the case of merchant fleet tonnage. Thus, it is not clear from the empirical evidence alone whether the current long wave should be divided into two waves of shorter duration, or whether this intermediate fluctuation is an integral part of a single long wave initiated in 1944. If the first alternative hypothesis would be accepted, then the long waves would be subject to an acceleration in frequency because the last fluctuation, as a separate long wave, extends only over three decades.

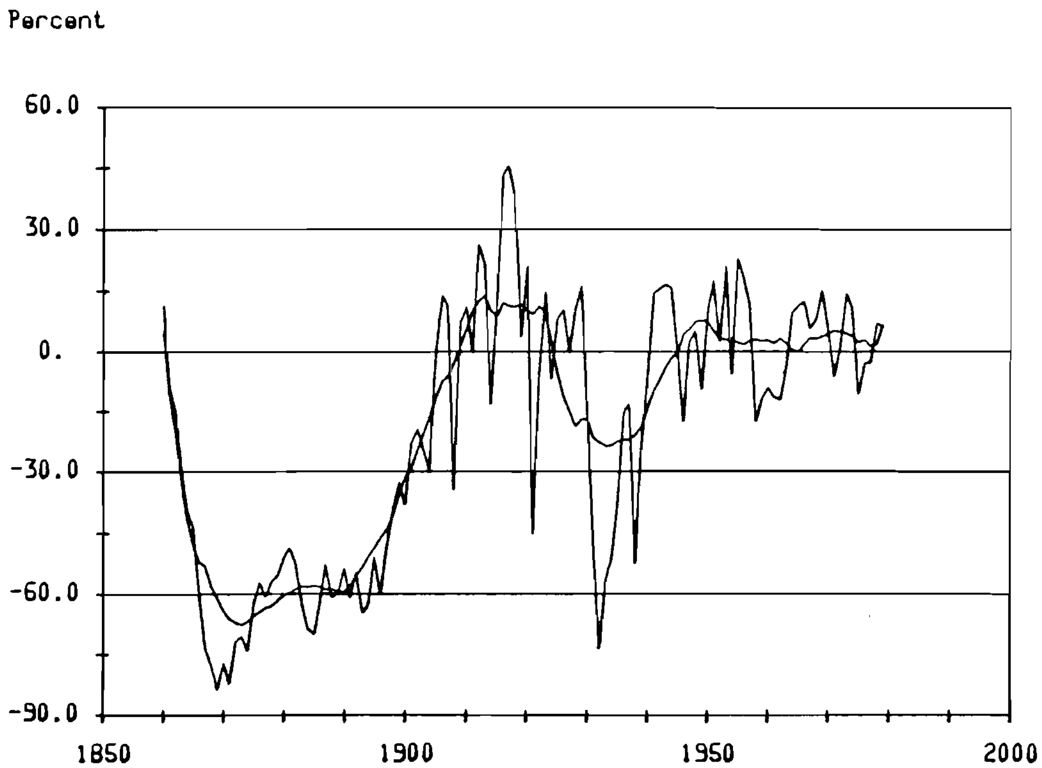

Figure 3.9 Long Wave in Steel Production.

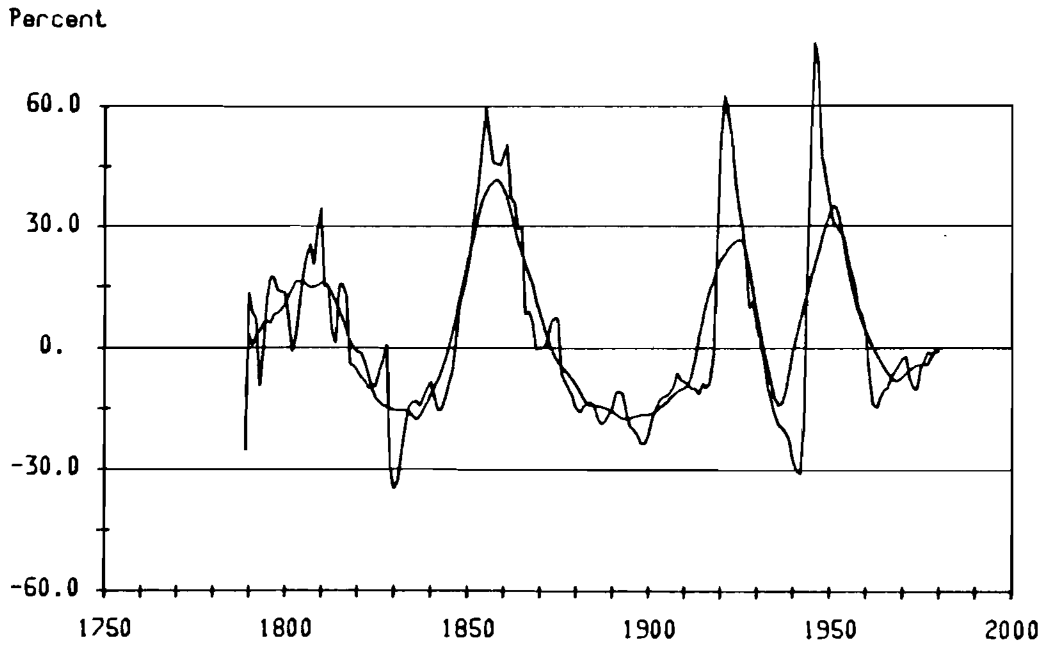

Figure 3.10 Long Wave in the Tonnage of Merchant Vessels.

4 DYNAMICS OF CHANGE

At the risk of overgeneralizing, we can state that there is strong evidence that symmetric or at least similar changes in patterns of energy consumption and price *niveau* occur from one long wave to another although the historical content and individual manifestations change profoundly so as to make the symmetry apparent only at the higher level of abstraction. In order to understand the actual mechanisms behind the long wave phenomenon and change in technology, we must acquire better statistical and analytical descriptions of various mechanisms and causal relationships of what we generally call historical experience. This would also imply that we need to understand the course of specific events and their individual manifestations that lead, for example, from a period of rapid growth after the Second World War to the oil shocks of the 1970s, saturating world markets, increasing national debt in many quarters of the world and the economic slow-down of the last decade. For the time-being we can only observe that the particular circumstances change from one long wave to another, but that the sequence of fluctuations and changes at a higher level of abstraction indicate a striking regularity. The annals of business cycles (see for example Thorp and Mitchell, 1926) show that the severe crises or so-called Great Depressions occur regularly during the downswing of the long waves. It suffices here to mention the Great Depressions and financial panics of 1819, 1874 and 1929 in the United States that with small variance occurred throughout the rest of the world. This immediately suggests an obvious historical manifestation of the prolonged periods of stagnation, but this does not answer the question whether these Great Depressions are a necessary characteristic of the downswing. A possible answer to such questions depends on whether we expect also in the future the continuation and recurrence of the approximate patterns of change experienced during the last three long waves.

4.1 Synchronization and Recurrence

The analysis of technological substitution in steel production, merchant vessels and energy showed that the same basic mechanism can be applied to describe the observed structural changes. In all three cases older technologies were replaced by new ones with regular recurring patterns. Figure 4.1 shows these three substitution cases. Besides the now obvious similarity in the substitution patterns, it should be observed that the timing of the saturation phases is also strikingly synchronized in the three examples. In order to facilitate the comparison we have shifted the curves in time so as to align the saturation phases. In comparison to the saturation of coal in the example of primary energy substitution, the saturation of open-hearth steel technology and steam ships is lagged by about 20 years. Once the curves are shifted in time by two decades, as shown in Figure 4.1, other saturation phases correspond to each other as well. For example, the saturation of hay as the energy source for animal feed was reached in the 1870s and the saturation of Bessemer steel about 20 years later. A similar correspondence can be observed for the last saturating technologies - crude oil and basic-oxygen steel. The substitution of other merchant vessels by motor ships corresponds nicely to market penetration of electric steel and to natural gas with a lag of about 20 years. This may be

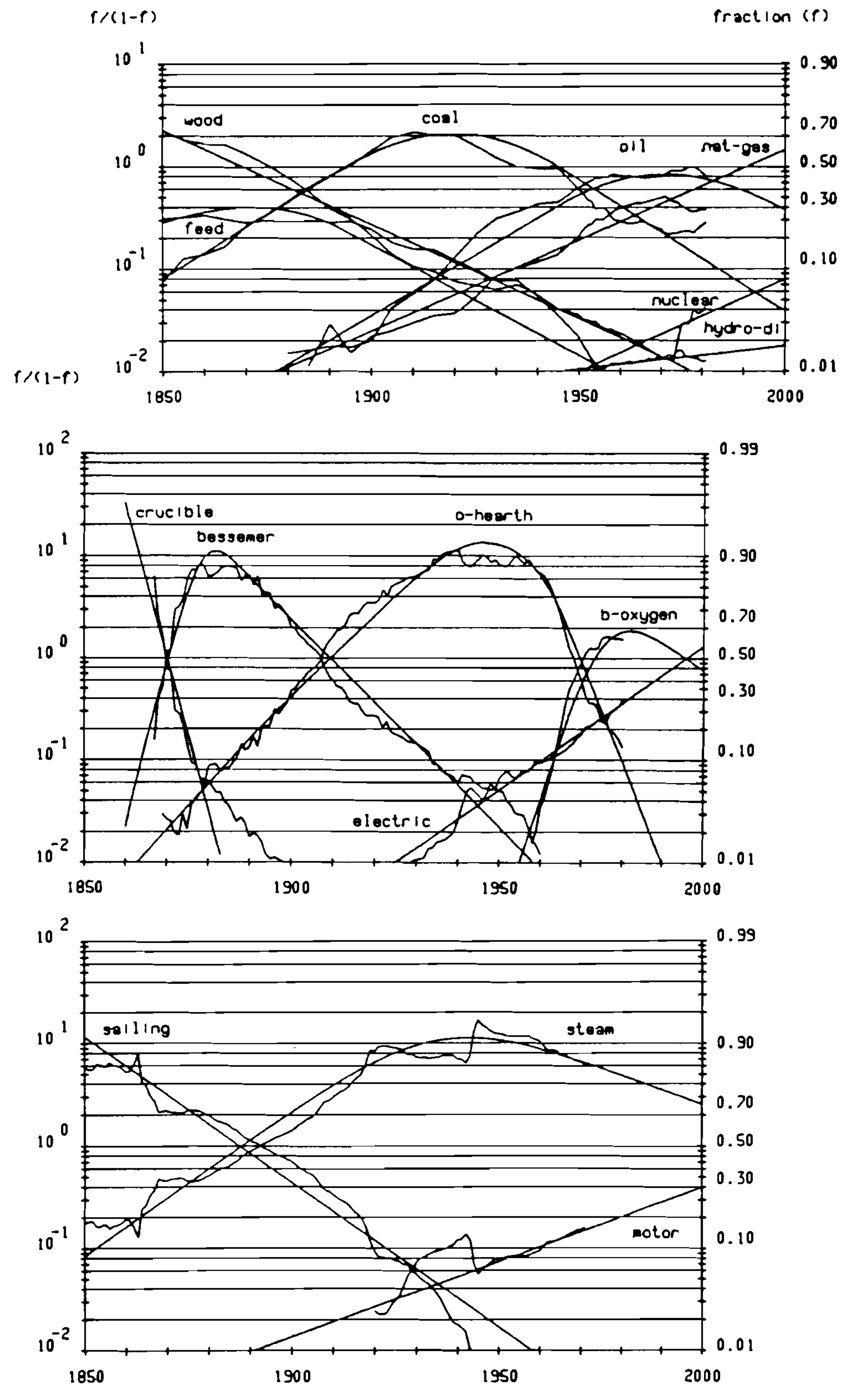

Figure 4.1 Energy, Steel and Merchant Vessels.

indicative of the continuing synchronization of the dynamic substitution processes in the future, after allowing for the relatively short time lag. It should be observed that the lag of 20 years spans a shorter period of time than the duration of the upswing or downswing phases of the long wave. Although the timing of the introduction of new technologies at the one-percent level differs in the three examples, the change in leadership from the old to the new dominating technology is strikingly similar. The open-hearth steel making process emerged as the dominating technology (in 1907) about 21 years after coal replaced fuel wood as the major source of energy (in 1886). The lag was even shorter in the case of steam ships which overtook sailing ships in 1892. Thus all three takeovers took place within two decades. Half a century later, a similar correspondence can be observed again. Crude oil surpassed coal in 1950 and basic-oxygen steel overtook the open-hearth process in 1969. Again a lag of two decades. Just as in the case of the long wave fluctuations, we find that the substitution dynamics can be characterized by coordinated 50-year phases of change in market domination from old to new leading technologies and energy sources.

A possible explanation of this similarity in the substitution patterns is that the specific changes that led to the replacement of old by new technologies and energy sources were interrelated. For example, the new steel processes and marine propulsion systems were dependent on new energy technologies. On the other hand, the new energy sources could only be developed with increased intensity of energy use, such as in the new industrial and urban complexes that emerged as the availability of transport possibilities and basic materials increased (symbolized here by steel and merchant vessels). This kind of interdependent lacing of technological development and growth of demand indicates that a certain degree of synchronization in the substitution processes could be expected. This of course still leaves the question of the precise nature of the 50-year time constant unanswered. Since we have already shown that the three substitution processes appear to be synchronized after allowing for a two-decade lag in the timing of crucial market saturation and takeover events, we will now consider the timing of long wave fluctuations and energy substitution (taking it to be indicative of other technological substitution processes).

Figure 4.2 shows energy substitution (from Figure 2.2) on the lower plot and long wave in energy consumption, energy intensity and wholesale prices (from Figures 3.4, 3.7 and 3.2) on the upper plot. *In toto*, Figure 4.2 summerizes the results of the phenomenological analysis of the dynamics of technology and the long wave in economic development. A careful examination of the timing and patterns of changes shows that they are all in tune. The saturation periods of energy technologies coincide with the peaks in prices and energy intensity (see also Figure 3.8). The period of decline from saturation to loss of dominance (i.e. loss of the highest market shares) lasts in the order of 25 years, or about as long as the downswing phase of the long wave which is characterized in Figure 4.2 by the fluctuations of energy consumption, intensity and the price index. By symmetry, the upswing of the long wave is paralleled by the growth of the new energy source from newly acquired dominance to saturation.

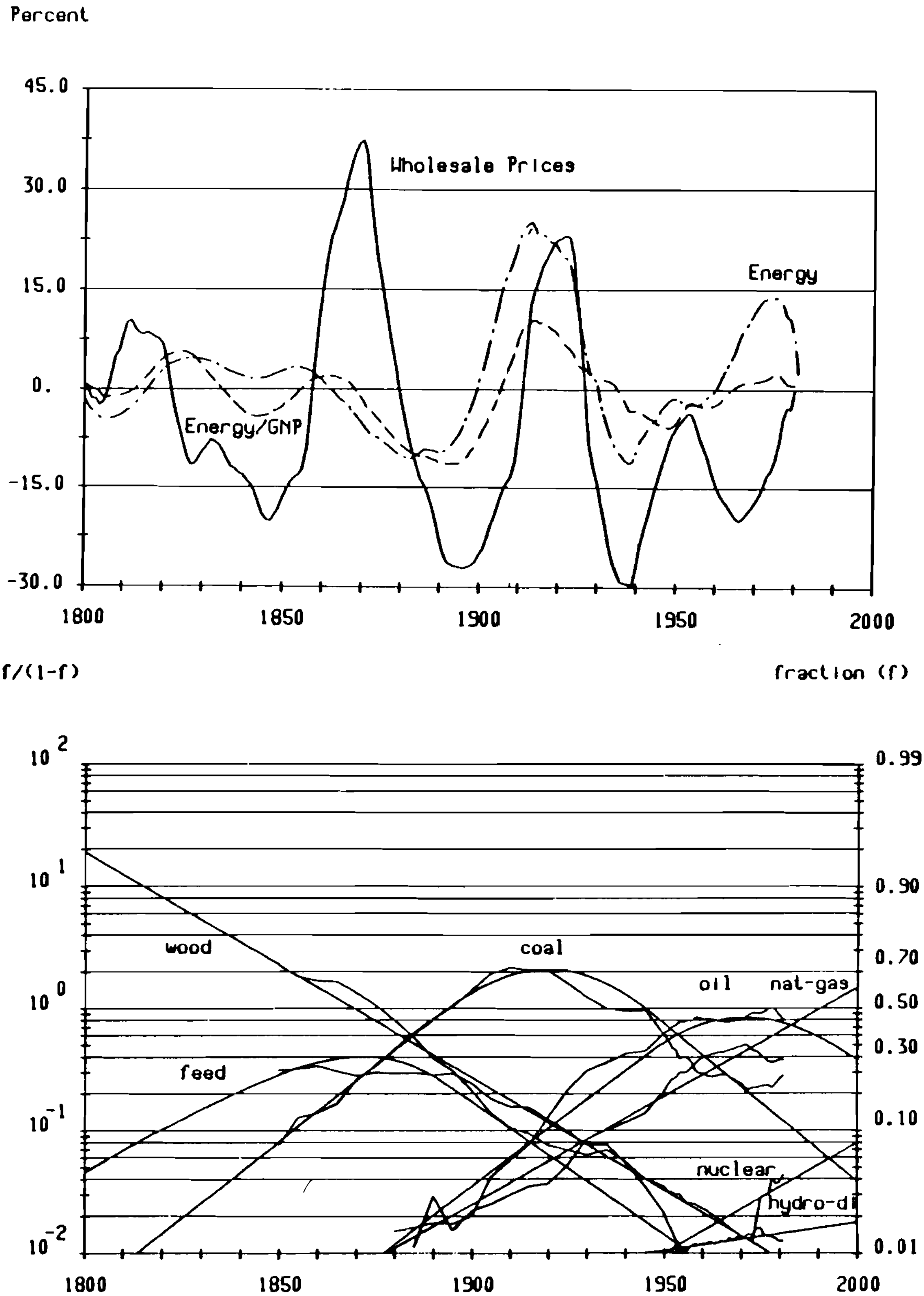

Figure 4.2 Long Waves and Substitution Dynamics.

4.2 Conclusions

The fact that all of the events that characterize profound changes in technology and economic structure occur in tune is striking, but it leaves many questions open. For instance, we have observed that technological substitution in steam propulsion and merchant vessels is lagged by about two decades behind the equivalent events in energy substitution. This would imply that these other dominating technologies do not saturate during the end of the prosperity phase, but rather during the onset of the downswing. Perhaps this is an artifact of the choice of technological substitution processes in that they are very closely related to the changes in the structure of the energy system. Yet, given the sparse statistical records, it is difficult to find other examples that span equivalent historical periods.

Nevertheless, the importance of the energy system and related infrastructural developments appears to be crucial with respect to the observed pulses in economic activity. For example, the construction of great canals throughout Europe and the United States during the eighteenth and beginning of the nineteenth century was initiated by the ever increasing need to transport timber and other goods in larger quantities over longer distances. Later, railroads caused a similar boom period basically due to the same reasons - the concentration of production in urban areas required a more efficient transport system that also helped in the acquisition of new and larger markets. Thus, canals and railroads expanded existing markets and "created" new ones for new products. In terms of the energy system, the large canals are associated with the transport of fuel wood that was at that time the primary source of energy in many industrial activities such as iron smelting. The railroad era is very closely related to the widespread diffusion of steam and coal related industries.

In terms of the long wave fluctuation, we will call the upswing phase from 1773 to 1810 the "age of canals" and the upswing from 1840 to 1869 the "age of railroads". Accordingly, we call the upswing from 1895 to 1920 the "age of electricity" because of its significant contribution to the rapid development of new industries and communication technologies. The last upswing, from 1945 to the 1970s, we symbolically identify with the motor vehicles, aircraft and petrochemical industries. Unfortunately, it is not possible to time this last turning point with any precision, but in view of the empirical evidence in the synchronization of technological substitution processes, energy efficiency and other indicators, it probably occurred during the "oil crises" of the early 1970s that mark the saturation of crude oil and its eventual replacement as the dominant source of primary energy. Let us assume for the sake of naming a particular reference year that it in fact occurred in 1973. If this were actually the case and assuming the continuation of the long wave fluctuations, the next turning point could be expected sometime around the turn of the century. Going further into the future the following upswing phase could be expected to last until the 2030s.

The overall picture that emerges suggests that each upswing phase is associated with large infrastructural development. This development first opens many new product and factor markets and toward the end of the prosperity phase leads to eventual saturation of these markets and full adoption of the technologies that were introduced during the recovery period. This was the process that occurred between the end of the Second World War and the initiation of a downswing ten to fifteen years ago. Some of the developments of the current downswing period we can already anticipate. For example, the energy intensity curve in Figure 3.7 indicates that during the next three decades we can anticipate further relative improvements in the energy efficiency of the economy (i.e., reductions in the amount of primary energy consumed per monetary unit of gross national product in real terms). Thus, we can expect further dissemination of energy efficient technologies and institutional measures during the downswing phase until the end of the century. As far as energy technologies are concerned, the market penetration analysis suggests natural gas as the best candidate for eventual dominance as the major energy source during the upswing period after the 1990s. Natural gas is the cleanest fossil fuel and from that perspective alone it is attractive. It also promises well as a very efficient source of electricity and clean fuels. Widespread use of natural gas would require new infrastructures for the long-distance transport, conversion to fuels and electricity, and distribution to the final consumer. Thus, construction of large grids and new industries based on natural gas would be required. Candidates for future growth sectors related to the wider use of natural gas range from technologies for control and management of large, distributed grids for transport and distribution of energy and other goods, to bio-engineering technologies that would allow for greater efficiency and low-temperature chemical and industrial conversion and production processes based on methane and electricity. Thus, enzymes and microchips may be the hardware that could allow the transition to a methane-based energy system. These are just some of the possible candidates, but they are consistent with the apparent requirements that emerge from the overall pattern of economic pulses and technological substitution dynamics since the beginning of the industrial revolution. Before these and other new technologies could expand during the next upswing, the next decades would bring a period of renewal and "creative destruction". A period of rapid (relative) deflation can be expected together with prolonged unemployment and an economic slowdown. These are the selection mechanisms that in the past distilled the successful from a wide range of promising technologies and entrepreneurial innovations. The existing patterns will have to be destroyed before new ones can emerge and their destruction will mark the beginning of renewal and a promise of prosperity.

Most of these speculations about the nature and timing of future events is based on the dynamics of equivalent changes in the past. Some of the patterns of these dynamic changes can be projected into the future. Our analysis of the market substitution mechanisms indicated that the invariance of the timing of market saturation and takeover times also allows *ex post* projections over periods that span the duration of the long wave (see Nakicenovic, 1984). Similarly, our analysis of the long swings in many indicators, ranging from energy efficiency to price fluctuations and Marchetti's invention and innovation pulses (see Marchetti, 1981), provide strong historical evidence that these events are precisely timed and invariant.

Perhaps the most important question is why the clock that tunes such events as the dynamic changes in technology and long waves in economic activity operates on a 50-year scale. Since we have shown that the events that mark structural changes are synchronized and follow a logical order, the question of the time-scale invariance is crucial. If it were answered all the other events, since they occur in logical order apparently as required, would fit the grand pattern like pieces of a puzzle.

There are many reasons to assume that inertia and slow absorption do not allow profound changes to occur more often than once per human generation or about every 50 years. It is difficult to imagine that people and societies that have invested large resources in creating and adopting to a given environment would accept profound changes and abandon technologies, markets and social institutions as long as they function or are not shown to be inferior to innovations after sufficiently extensive comparisons. Thus, new technologies and innovative entrepreneurial activities cannot diffuse immediately even if they are superior to the traditional practice. They have to withstand selection processes over long periods before their viability and resilience as a replacement for old methods is accepted. Since we have seen that technologies and markets are interlaced, once we accept a natural rhythm for profound changes to be one generation or about 50 years the synchronization of the pulses and technological changes follows as a direct consequence of interdependencies.

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