CHAPTER 9

Dynamics of Change and Long Waves

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> *"Evolution is the result of a sequence of replacements."* Elliott W. Montroll, 1978

9.1. Introduction

Much of the long-wave debate centers around the existence of empirical evidence and possible explanations of the phenomenon, but even those who claim that such long-term fluctuations in economic life are real argue whether the waves and their timing are regular and to what extent various events are synchronized. We will argue that the long-wave phenomenon is one particular way of describing technological, economic, and social change and development. We show that this evolutionary development process is the result of a sequence of replacements of one technique (technology, artifact, product, practice, organization, tradition, or idea) by another.

Long waves emerge because a number of important replacements take place simultaneously, leading to a prolonged phase of economic growth. Likewise, these replacements and growth processes tend to saturate during relatively short periods resulting in prolonged recession, economic restructuring, and technological and social change. It is during these periods that innovations cluster and eventually lead to a new "wave" of replacements and growth. This hypothesis does not require a high degree of synchronization or "focusing" for either the innovation clusters or the saturation clusters. Instead, it is sufficient that a number of important replacements take place simultaneously resulting in the periods of prolonged growth.

Denoting the time interval that it takes to replace from 10% to 90% of old practice or technique by ΔT, all that is required is that the ΔTs overlap for a number of important substitutions. This requirement implies a certain degree of clustering of saturations and innovations, but the clusters need not be sharply focused during the troughs of the long wave. In fact, they are initiated during the end of the growth phase, which is followed by a period of turbulence when the first important replacements start saturating, and last well into the beginning of the upswing phase marked by a new pulse of replacements. This view of the long wave is also consistent with Kleinknecht's observation that innovation clusters can be observed around the troughs. However, they do not appear to be as strongly focused as originally maintained by Mensch (see Mensch, 1979; Kleinknecht, 1987; Chapter 4). We will show that important technologies saturate around the troughs and, more importantly, that the time intervals covered by their ΔTs encompass prolonged periods of growth and expansion. Long-wave pulsations (flares) in prices will be used as an indicator of the various phases, especially the sequence of growth and recession phases.

On the basis of our assumptions, the dynamics of change and economic growth can be decomposed into a sequence of replacements that generate periods of growth followed by recession. These are marked by turbulence caused by the lagged saturation of the replacement processes. Innovations eventually lead to a new phase of replacements and thus growth. The innovations should not be viewed in the narrow technical sense, because they also include new social and organizational forms and ideas and creation of new practices. At the aggregate level, e.g., physical output or gross national product (GNP), the indicators portray long-term increases interrupted by phases of turbulence. In other words, the aggregate indicators look like step functions where each step is a plateau with large fluctuations, and the periods of growth between the plateaux are S-shaped curves. Due to the inaccuracy of the data and the inherent difficulty of identifying exact resolutions of different phases in the long waves, we will use a number of different indicators simultaneously to describe technological and economic changes.

We will use both physical indicators, such as energy consumption or length of transport infrastructures, and monetary indicators, such as prices or output at given prices. A large number of indicators give a higher precision in identifying growth pulses, replacements of old by new, and various phases in the long wave. This higher precision is reached in the statistical sense and same way as a large number of synchronized clocks will give a better time measurement than a single one does (official time is in fact measured by an average). Thus, the multidimensional approach increases the accuracy of the results in spite of often insufficient data quality, especially for the records from last century or before.

Another reason for analyzing a number of different indicators for the same time periods and same processes of change (e.g., energy, transport, prices) is that not all can be described by the same secular patterns. For example, prices often portray fluctuations, some of them with relatively long periods, but rarely increasing or decreasing secular trends of more than a few decades. Growth and senescence of technologies or consumption levels, on the other hand, often have consistent secular trends with very long duration (compared with the long wave). Usually, the secular trend of growth and senescence processes can be described by S-shaped (often logistic) curves. However, not all can be described by simple (or single) S-shaped functions. Sometimes more complex patterns are observed, which are often described by envelopes that can be decomposed into a number of S-shaped growth or senescence phases.

Two typical cases are successive growth pulses with intervening saturation and a period of change, and simultaneous substitution of competing technologies. We argue that (1) the population, production, or performance of inanimate (man-made) objects or systems can be described by successive growth pulses that often have an S-shape, the same shape encountered in the growth of populations, "organisms," etc., as originally described by Verhulst (1844) and Pearl (1924); and (2) these growth pulses can be decomposed into a sequence of replacements, originally exploited by Fisher and Pry (1971), as the appropriate model for the dynamics of industrial replacements, and later extended to simultaneous replacement of more than two competing technologies (Marchetti and Nakicenovic, 1979). In the first case, successive S-shaped pulses usually represent, for example, the growth of energy consumption or successive improvements in performance, such as aircraft speed records. Here the first pulse is associated with an old technology, the piston engine, and the second with the new technology, the jet engine (see Nakicenovic, 1987a). In the second case, simultaneous substitution of competing technologies is usually described by increasing market shares of new technologies and decreasing market shares of old technologies, such as the replacement of sails by steam and later by motors.

Thus, we will describe the dynamics of change and the long waves with a number of different indicators (that is, by vector rather than by scalar measurements). Usually an asymmetrical view is offered, using either price or physical (technological) indicators as explanatory variables. Our description is not frozen into one or the other view, but rather we offer a symmetrical description by considering many dimensions of these dynamic processes.

First, we will illustrate the waves (flares) in prices. Second, we will show that the expansion of the most important means of transportation, starting with canals and ending with aircraft, can be seen as a replacement process where the substitution of older for newer technologies overlaps the growth phases in the long wave. This analysis starts, somewhat unconventionally, with the youngest technologies (aircraft and airways) and ends with the oldest (canals and waterways). Finally, we will show that the evolution of the energy systems and steel production also follows a similar pattern where important replacement processes take place during the growth phases of the long wave. In addition, we will show that total global production of energy and steel evolved through two growth pulses that are related to the last two long waves. Throughout the text we will use the price flares as a clock for the long waves.

9.2. Price Waves

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 life. 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 including the United Kingdom. *Figure*

9.1 shows the wholesale price index in the United Kingdom from 1560 to 1982 and *Figure 9.2* in the United States from 1800 to 1982. In both countries prices appear to be stationary with long fluctuations almost over the whole period. Only after the 1940s can a pronounced inflationary trend be observed that had a magnitude greater than any other previous fluctuation. In the United States prices reached pronounced peaks around the years 1780, 1815, 1865, and 1920,

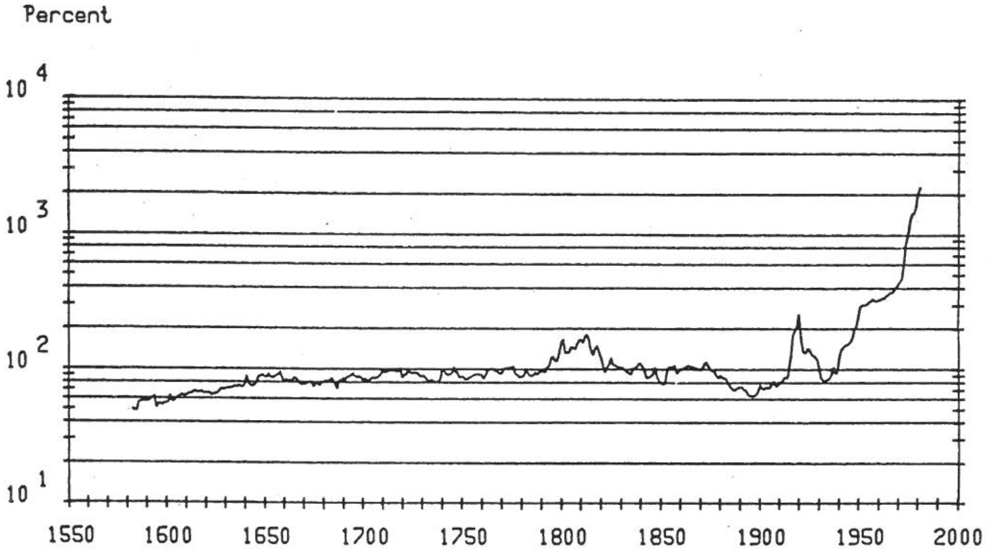

Figure 9.1. Wholesale price index, UK.

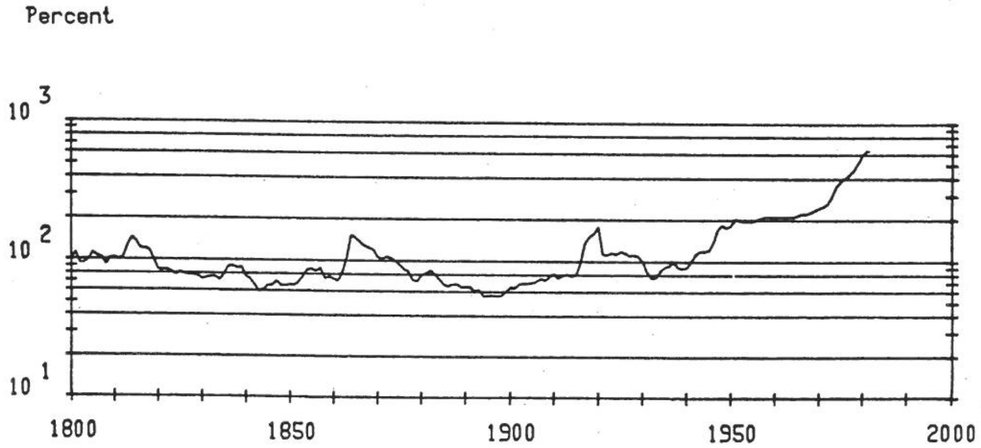

Figure 9.2. Wholesale price index, USA.

and there were also sharp increases during the last decade. In the United Kingdom, the fluctuations were subdued until the end of the eighteenth century. The first pronounced peak occurred around the year 1810, a weaker but prolonged peak around the year 1872, another pronounced peak in 1920, and a prolonged inflationary period during the last decade. Because all pronounced inflationary periods in both countries are associated with major wars, Hartman and Wheeler (1979) observed that the absence of strong inflation during the mid-nineteenth century in the United Kingdom could be partly due to the absence of such military conflict.

Clearly, price fluctuations in the United Kingdom and the United States display a broadly similar pattern, although the behavior in the United States prior to the mid-eighteenth century is not well documented and is uncertain. Prices in the United Kingdom portray a long decline from 1660 to about 1740 with two pronounced peaks in 1699 and 1710, and a long rise from about 1740 to about 1810, followed by another decline. The turning point between these two periods of rising and falling prices corresponds to the first pronounced peak. Especially large price rises occurred between 1785 and 1792 as the Industrial Revolution gained momentum. In the United States, a pronounced price peak occurred during the Revolution and the recovery period between 1775 and 1785. Although the two countries differed substantially in many respects, such as the level of industrialization, institutional development, energy use, and internal conflicts, the parallel in the pattern of price fluctuations through the nineteenth and twentieth centuries is striking. In the face of quickened industrialization, the Napoleonic Wars (UK), and the War of 1812 (USA), prices rose until the 1820s. A period of declining trend continued through 1850 (UK) and 1843 (USA), followed by a rising trend that was more pronounced in the United States, undoubtedly associated with the Civil War. The period from 1873 to 1896 is characterized by a declining trend in both countries, and the succession of rising and falling periods has remained almost exactly parallel until the present. Since World War II, prices in the United Kingdom and the United States have risen almost uninterruptedly and to unprecedented levels.

The price fluctuations in both countries indicate a regular and parallel pattern as will be elaborated shortly. Price peaks of the 1780s, 1820s, 1870s, and 1920s 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 rapid growth and saturation with the increasing level of prices and phases of recession, and regenerative destruction with decreasing price level (see Schumpeter, 1939).

To obtain a clearer picture of the timing of the long waves that are observable in the price indices of the two countries, 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 51-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

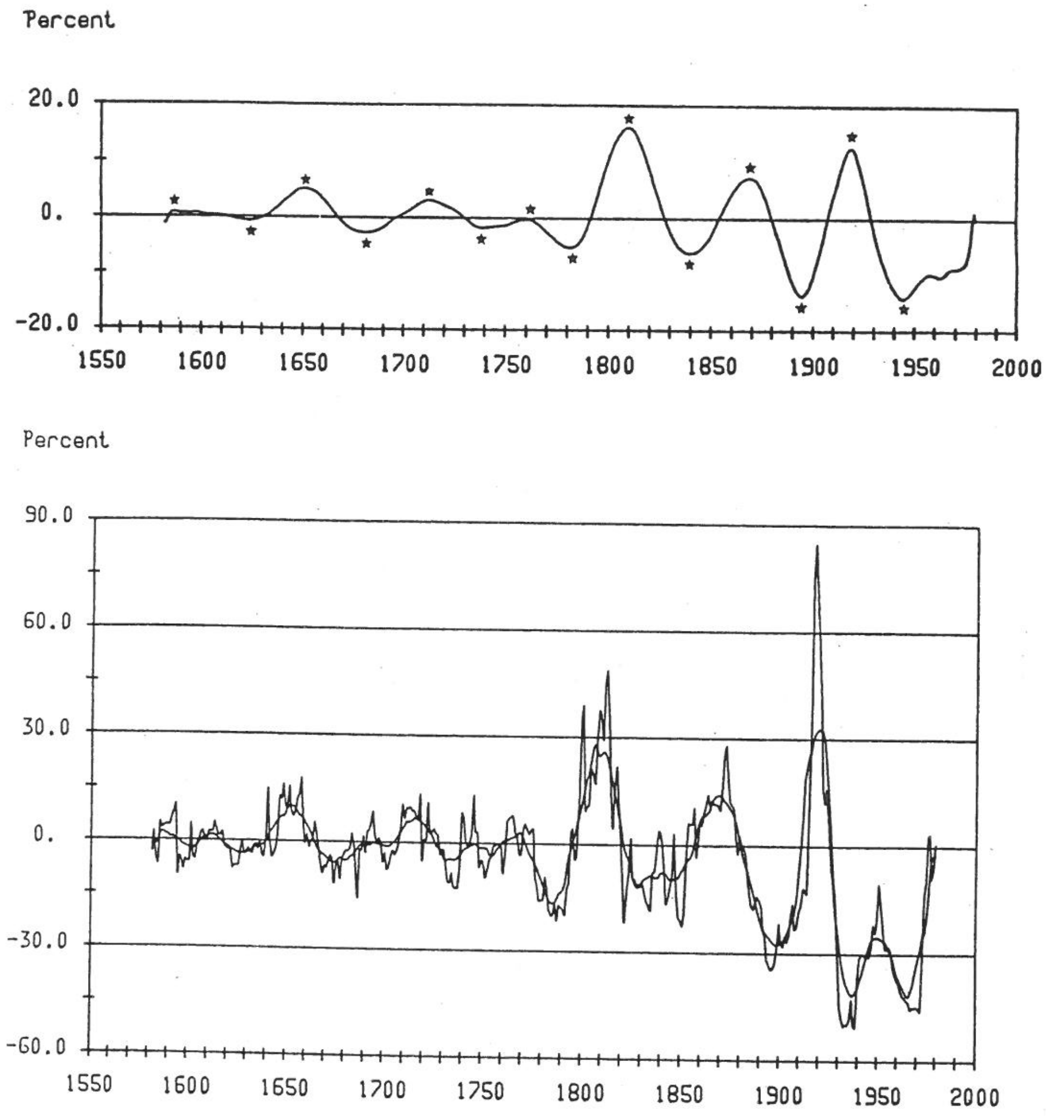

Figure 9.3. Long wave in wholesale prices, UK.

resulting stationary series (smoothed and unsmoothed residuals) are shown on the lower plots in *Figure 9.3* for the United Kingdom and in *Figure 9.4* for the United States. The upper plots in *Figures 9.3* and *9.4* show ***stylized indicators*** of the long swings in prices. The curves have been derived by smoothing the residuals by a 25- (instead of a 15) year moving average. We have chosen such a long moving average to eliminate some of the more pronounced fluctuations from the residuals that overlap the five-decade long swings. The stars approximately indicate the turning points of the long waves. We are aware that this kind of simple smoothing can introduce spurious fluctuations into the time series.

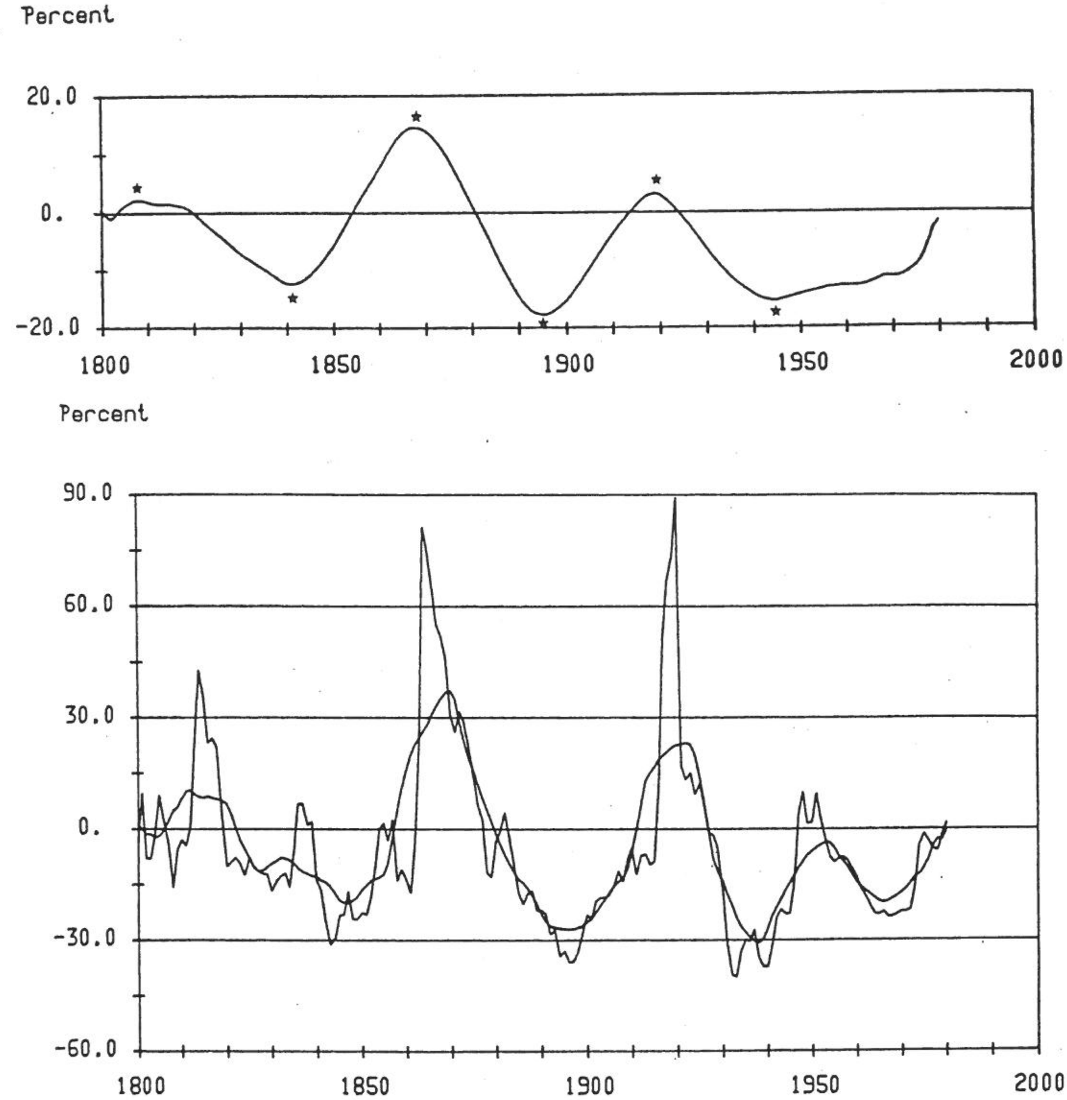

Figure 9.4. Long wave in wholesale prices, USA.

This empirical determination indicates not only a parallel development of the price movements in the two countries, but also a high degree of synchronization. For the period before 1800 in the United Kingdom, we dated turning points in the years 1623, 1651, 1681, 1712, 1739, 1753, and 1773. The intervals between the four succeeding troughs are 58, 58, and 44 years and between the three peaks 61 and 41 years. As the Industrial Revolution gained momentum, first in the United Kingdom and later in the United States, the long swings became more regular and the magnitude of the fluctuations increased. The average amplitude of the fluctuations rose from less than 10% in preindustrial United Kingdom to about 20% in both countries. *Table 9.1* shows the dates of the turning points and the duration of the long swings in prices for the two countries.

The average duration of the fluctuations is about 50 years and the occurrence of peaks and troughs varies by not more than one or two years. We consider *Table 9.1* a rough, empirical indicator of the timing of long waves in the two leading countries. This timing is similar to the stylized schemes derived by van Duijn (1983) and Bieshaar and Kleinknecht (1984). In subsequent examples we will use this empirical indicator of the long-wave turning points to determine the correspondence between the fluctuations that we will establish in other monetary and quantitative indicators of economic development.

Table 9.1. Chronology of the long wave, UK and USA.

	Price swings			
	United Kingdom		*United States*	
Phase	*Period*	*Duration*	*Period*	*Duration*
Downswing	1585–1623	48		
Upswing	1623–1651	28		
Downswing	1651–1681	30		
Upswing	1681–1712	31		
Downswing	1712–1739	27		
Upswing	1739–1753	24		
Downswing	1753–1773	20		
Upswing	1773–1810	37		
Downswing	1810–1840	30	1809–1841	32
Upswing	1840–1869	29	1841–1869	28
Downswing	1869–1895	26	1869–1895	26
Upswing	1895–1920	25	1895–1920	25
Downswing	1920–1945	25	1920–1945	25
Upswing	1945–		1945–	

9.3. Transport Systems

9.3.1. Aircraft

We will now show that the evolution of transport systems and infrastructures can be analyzed as a sequence of replacements of old modes of transportation by new ones. Furthermore, the substitutions of old for new technologies overlap the growth phases in the long-wave fluctuations as indicated by price flares. The analysis starts, somewhat unconventionally, with the youngest transport system (air travel) and ends with the oldest (canals and waterways).

The rapid expansion of air travel during the recent decades has its roots in developments achieved in aerodynamics and other sciences many decades ago, and especially in the engineering achievements made between the two wars. The DC-3 airliner is often given as the example of the first "modern" passenger transport because in many ways it denotes the beginning of the "aircraft age." The use of aircraft for transportation has increased ever since and its performance has improved by about two orders of magnitude. *Figure 9.5* shows the increase in air transport worldwide measured in billions of passenger kilometers per year

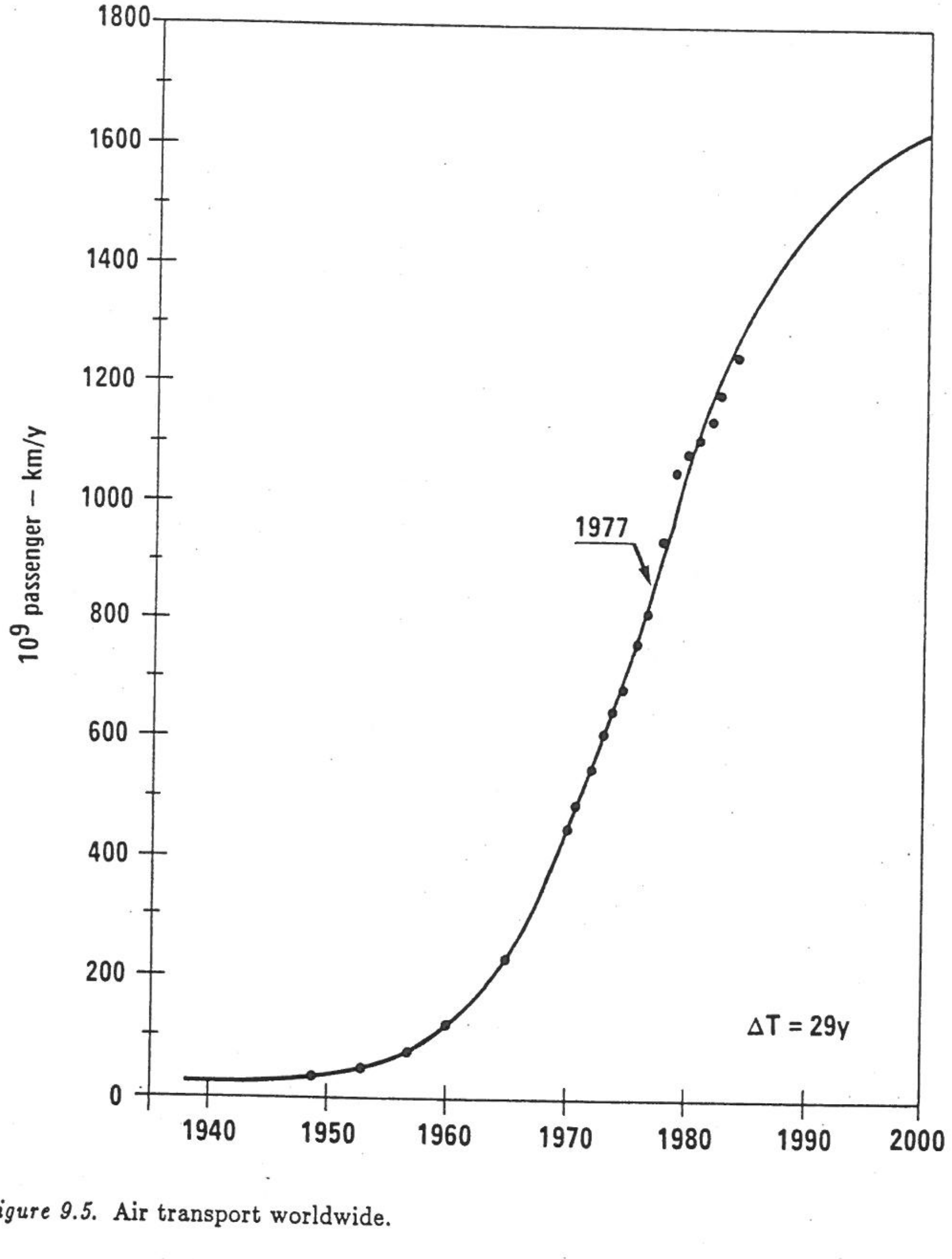

Figure 9.5. Air transport worldwide.

(passenger-km/yr). It gives all carrier operations including those of planned economies. The logistic function has been fitted to the actual data, and it indicates that the inflection point in the growth of air travel occurred about 10 years ago (1977).[1] Thus, after a period of rapid exponential growth, less than one doubling is left until the estimated saturation level is achieved after the year 2000. The figure shows that the most rapid expansion of air travel in the world lasted from the 1930s until the 1970s and that the growth rate has been declining for about the past 10 years. Therefore, air travel expanded in much the same way growth processes do in biology, as S-shaped growth patterns. The most rapid expansion of air travel took place during the growth phase of the long wave.

Figure 9.6 shows the same data and fitted logistic curve transformed as $x/(\kappa - x)$, where x denotes the actual volume of all operations in a given year and κ is the estimated saturation level. The data and the estimated logistic trend line are plotted in *Figure 9.6* as fractional shares of the saturation level, $F = x/\kappa$, which simplifies the transformation to $F/(1-F)$. Transformed in this way, the data appear to be on a straight line, which is the estimated logistic function.

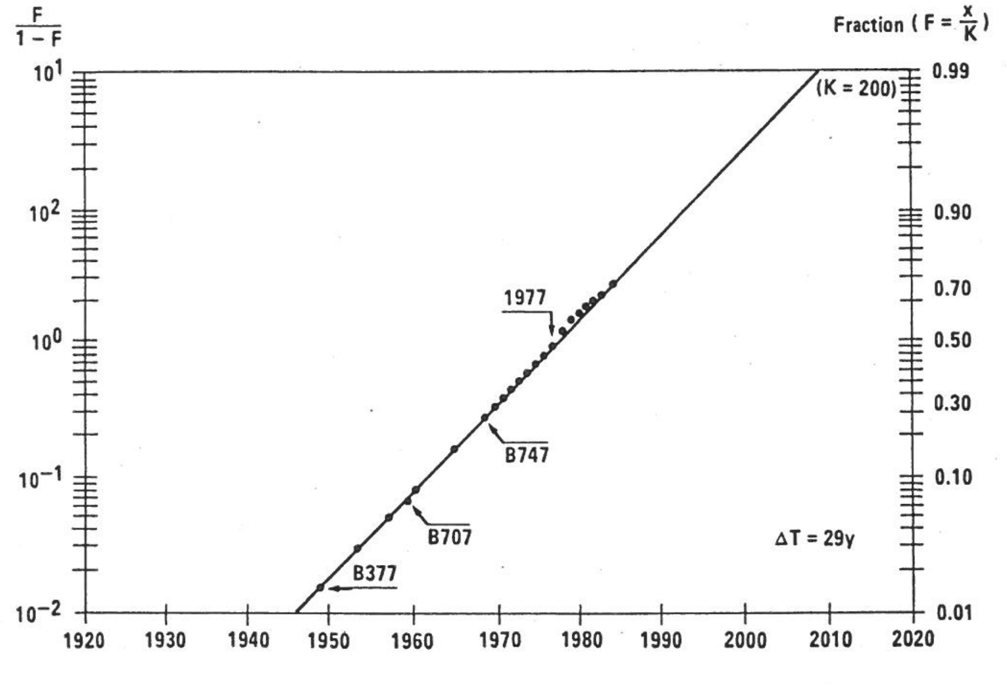

Figure 9.6. Air transport worldwide, logistic plot.

Perhaps the more interesting results are that it took about 30 years for world air transport to reach the inflection point (half the estimated saturation level) and that after two decades the saturation level will be reached. This raises a crucial question. What will happen after saturation? Can we expect another growth pulse, a decline, or the instability of changing periods of growth and decline? Most likely a new period of growth associated with new technologies will follow the projected saturation (see also Lee and Nakicenovic, Chapter 1).

During the same period, while air travel worldwide increased by two orders of magnitude, the productivity of the individual aircraft also increased by two orders of magnitude from the DC-3 to the Boeing 747 (see Nakicenovic, 1987a). Another growth phase of air travel, or some other new transport system, in the next century would require an analogous increase in the productivity of the vehicles. In the case of aircraft this would imply supersonic or hypersonic (extremely large subsonic transports) or both.

How probable is the development of a large cruise supersonic or hypersonic transport? S-pulses do not usually occur alone but in pairs. Usually structural change occurs at the saturation level, leading to a new growth pulse and in turn to new productivity and performance requirements for succeeding technologies. This logic would suggest the need for a more productive means of long-distance transportation for the next century than the current wide-bodied families of subsonic aircraft. It is questionable whether history repeats itself, but we will show that in the past each growth phase of the long wave is associated with the evolution of a number of important technologies that tend to saturate during the end of the prosperity phase and during the recession phase of the long cycle. Below we illustrate that the growth of the older technology, road transport systems, in the United States can be described by a pair of successive growth pulses with an intervening saturation during the 1930s marked by a period of change. Using the data available, we illustrate the evolution of road vehicles and other transport systems in the United States, but will return to analyzing long waves and technological change at the global level thereafter.

9.3.2. Automobiles

At the beginning of this century, few proponents of the automobile envisaged that its use would spread so rapidly throughout the world. As a commercial and recreational vehicle, the motor car offered many advantages over other modes of transportation, especially animal-drawn vehicles. Perhaps the most important advantage was the possibility of increasing the radius of business and leisure transport.

The most rapid expansion of the automobile was witnessed in the United States. It had a relatively late start in relation to European countries, such as France, Germany, and the United Kingdom. According to the records, four motor vehicles were used in the United States in 1894. This was followed, however, with an impressive expansion of the automobile fleet: 90 in 1897; 8,000 in 1900; almost half a million 10 years later; and more than one million after another two years. Thus the United States quickly surpassed European countries both in production and in the number of vehicles in use.

Figure 9.7 shows the rapid increase in the number of cars used in the United States. It also shows that the expansion of the automobile fleet is characterized by two distinct secular trends, with an inflection in the 1930s followed by less rapid growth rates. Since the two secular trends on the curve appear to be roughly linear on the logarithmic scale, the automobile fleet evolved through two exponential pulses. Thus, in this example, the growth of the automobile fleet did not follow a simple, single S-shaped growth pulse.

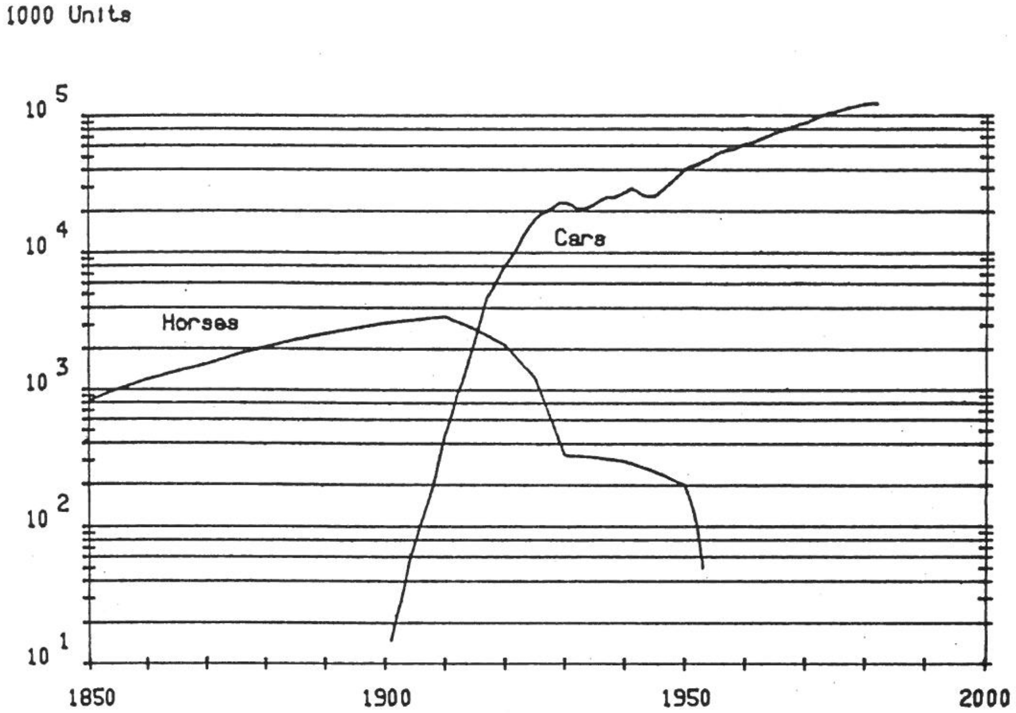

Figure 9.7. Number of automobiles and road horses (and mules), USA.

The working hypothesis here is that the two trends indicate two different phases of the dissemination of motor vehicles in the United States. The first characterizes the substitution of motor vehicles for horse-drawn vehicles and the second the actual growth of road transport after animal-drawn vehicles essentially disappeared from American roads. Thus the first expansion phase was more rapid since it represents "market takeover" or substitution for older means of transport, whereas the second represents the actual growth of road vehicle fleets and their associated infrastructure, such as highway systems. The inflection point that connects the two growth pulses coincides with the prolonged recession in the long-wave cycle. Thus our hypothesis implies that the motor vehicle fleets evolved differently in the two adjacent Kondratieff cycles.

The lack of historical records of the exact number of horse-drawn vehicles in the United States soon after the introduction of the automobile in 1895 makes it difficult to describe accurately the assumed substitution of the motor car for the horse during the first, more rapid expansion phase of the motor vehicle fleets. The number of draft animals (road horses and mules) and the automobiles given in *Figure 9.7* are therefore a rough approximation of this substitution process. *Figure 9.8* gives fractional market shares of horses and cars in all road vehicles (sum of horses and cars). Market shares, F, are plotted on a semilogarithmic plot transformed as $F/1 - F$, as a ratio of the market shares of one technology over the other since fractional market shares always sum to one.[2]

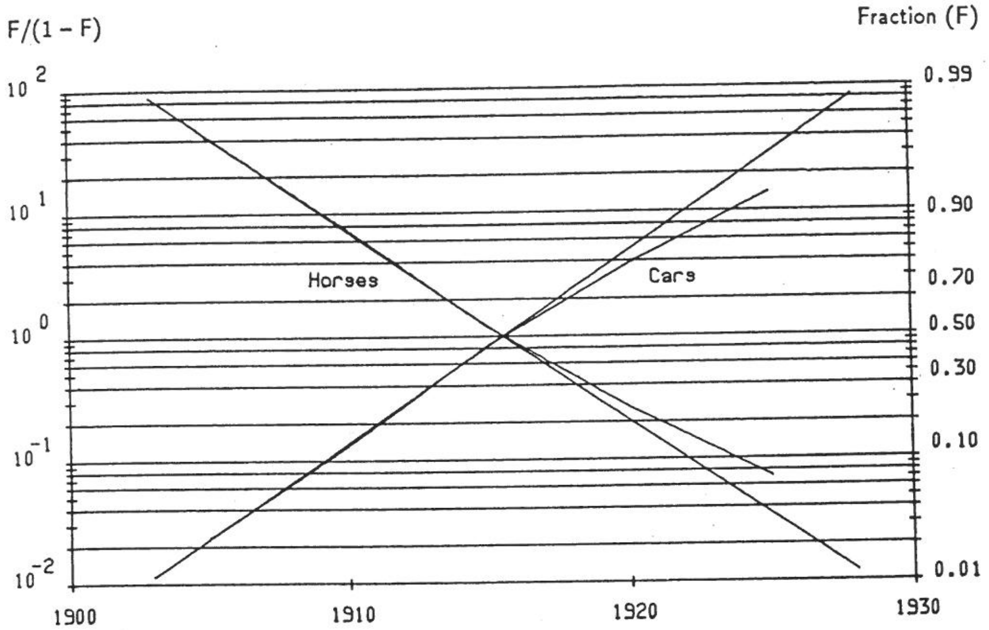

Figure 9.8. Substitution of horses for automobiles, USA.

Figure 9.8 indicates that the automobile replaced animal-drawn road vehicles during a relatively short process and proceeded along a logistic path. Motor vehicles achieved a 1% share of road vehicles shortly after 1900 and a 50% share in 1916. A complete takeover occurred in 1930 when there were 0.3 million road horses and mules and 23 million cars, an increase from less than 2 million cars 10 years earlier. Thus the inflection point in the growth of the automobile fleet from *Figure 9.7* actually coincides with the end of the replacement of animal-drawn road vehicles by motor cars and explains the apparent saturation in the growth of motor vehicles observed by many analysts during the late 1920s and early 1930s. This perceived saturation marks the beginning of a new phase in the motorization of America, with growth rates comparable with those of the expansion of horse-drawn vehicles before the automobile age. Seen from this perspective, the number of all road vehicles increased from 1870 to 1930 but from 1900 to 1930 the automobiles replaced the horses, whereas after the total replacement, only the number of cars was expanding during the last long wave. In most European countries, the rapid expansion of the automobile also started during the last Kondratieff wave. In this example we see two aspects in the dynamics of technological change: the growth of technological populations, in this case road vehicles, and the replacement of older by newer technological species. *Figure 9.9* shows the growth in the number of all road vehicles as a continuous growth process with an apparent saturation level of about 350 million vehicles after the year 2000 and a ΔT equal to about 100 years.[3] Because the growth of road transport in general and the substitution of automobiles for horse-drawn carriages and wagons overlap in time, together they produce two growth trends in the growth of the automobile fleet with an inflection point in the 1930s making the structural change in the composition of the road vehicle fleets. Therefore, this example illustrates that during the last two growth phases of a long wave, road vehicle fleets developed differently. One tentative conclusion from this example could be that the further development of road vehicles could take another new path after the 1990s.

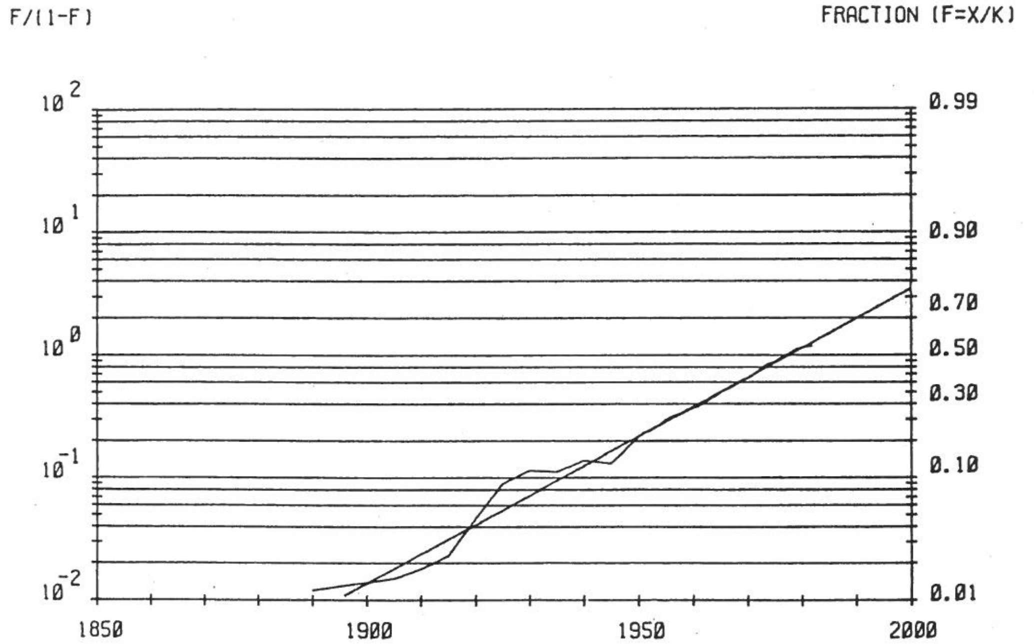

Figure 9.9. All road vehicles in use, USA.

The expansion of the road vehicle fleets in the United States and the growth of the global air travel illustrate two important aspects of technological and economic change. The expansion of air travel was shown as a S-shaped *growth pulse*. This example parallels growth processes in biology, for example, growth of a leaf or bacteria population. The replacement of horses by cars shows *substitution* of an old for a new technology as an S-shaped increase in market shares of the new competitor.

We have argued that during each expansion phase of the long wave a number of important technologies are developing simultaneously, growing, replacing old ones, and usually enhancing each other. Road transport systems require, in fact, elaborate and sophisticated infrastructure. The development of road transport vehicles (and infrastructure) illustrates the succession of replacements of old by new as one of the basic features of the development process. Furthermore, it shows that the different replacement processes are associated with the two long waves. Thus we have seen that the expansion of automobiles in the United States and global air travel took place during the growth phase of the last long wave, whereas the replacement of horses by cars was a feature of the previous long wave when railroads were the dominant form of transport in most of the developed world. Railroads are now in the post-saturation phase; their position as a means of passenger travel is being eroded in most industrialized countries and has become insignificant in the United States. A symbol of this decay is the discontinuance of the transcontinental railway service in the United States.

9.3.3. Transport infrastructures

Both air and railroad transport systems require elaborate infrastructures. In fact, airports and railroads were obviously constructed for the sole purpose of providing infrastructure for aircraft and trains. However, this distinction is not clear for roads, although we have shown that the construction of surfaced roads preceded the expansion of the automobile fleet. This similarity in the evolution of the transport systems is perhaps indicative of an invariance in the development process of transport systems and their underlying infrastructure. A serious problem arises, however, when comparing railroads and roads with other transport systems that do not depend exclusively on the rigid, man-made links between them. Airways and waterways, for example, rely less on man-made links between the nodes because they use the natural environment (air, rivers, coastal waters). Nevertheless, they require an elaborate infrastructure, such as airports, harbors, and canals. Thus it is difficult to compare the total length of the implicit airway and waterway routes with the total length of the main railroad tracks and surfaced roads. As an approximation in the analysis of the evolution of transport infrastructures, we will use the sparse accounts and probably inaccurate estimates about the construction of canals as an indicator for the total network of the waterway transport systems.

Figure 9.10 shows the length of the three successive transport infrastructures: canals, railroads, and surfaced roads. In the United States the first canals were built during the 1780s but in fact, canal construction really accelerated during the first decades of the nineteenth century, making that period the "canal era." It expanded very rapidly to about 2,000 miles until 1831, when 13 miles of the Baltimore and Ohio Railroad went into operation. Thus the canal era lasted until the railways became the main mode of long-distance transport a decade later. From this point of view, the 1830s were turbulent years: many turnpikes were abandoned; canal construction was reaching its peak; and important early railway projects were already completed. *Figure 9.10* shows that the railroads remained the longest transport network until 1920, when they were surpassed by the rapidly expanding road system and the automobile. The construction of railroads saturated during the following decade and has been decreasing ever since. This is analogous to the saturation of canals during the 1840s and their decline thereafter. *Figure 9.10* shows that the evolution of the transport infrastructure can be seen as a succession and replacement of older with newer transport systems, although at any given time more than two systems were actually in operation.

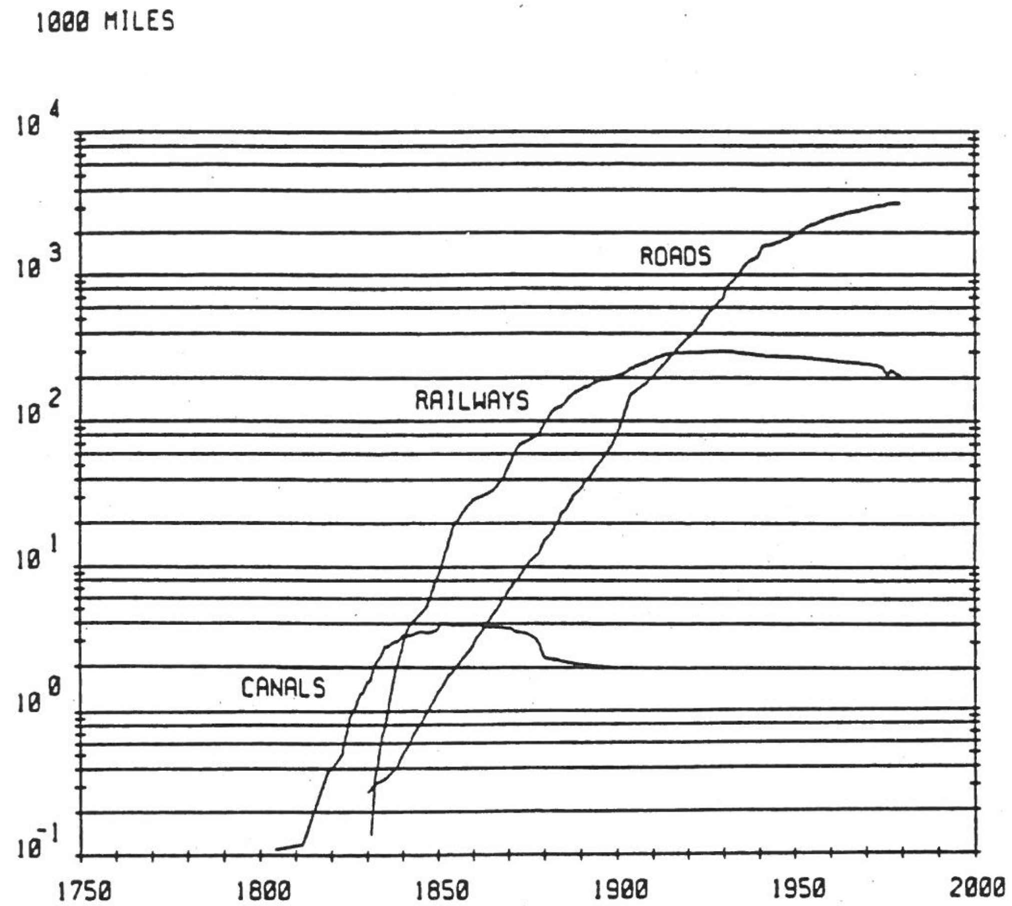

Figure 9.10. Length of transport infrastructures, USA.

This succession of the three transport infrastructures can be described in terms of three S-shaped growth pulses that are given together with the estimated logistic curves in *Figure 9.11*. Seen as successive growth pulses, the expansion of canals saturated during the 1860s at a level of about 4,000 miles and the expansion of railroads saturated during the 1930s at a level of about 300,000 miles, whereas roads will saturate during the coming years. Thus, the three transport systems saturated successively at intervals of about six decades. *Figure 9.12* shows the same growth pulses transformed so that the data and the S-curve appear as a straight line. This indicates that the development of canals was much quicker (with a ΔT of about 30 years) than the expansion of railroads and roads (with a ΔT of 54 and 56 years, respectively). Thus, canals have a time constant comparable with that of airways.

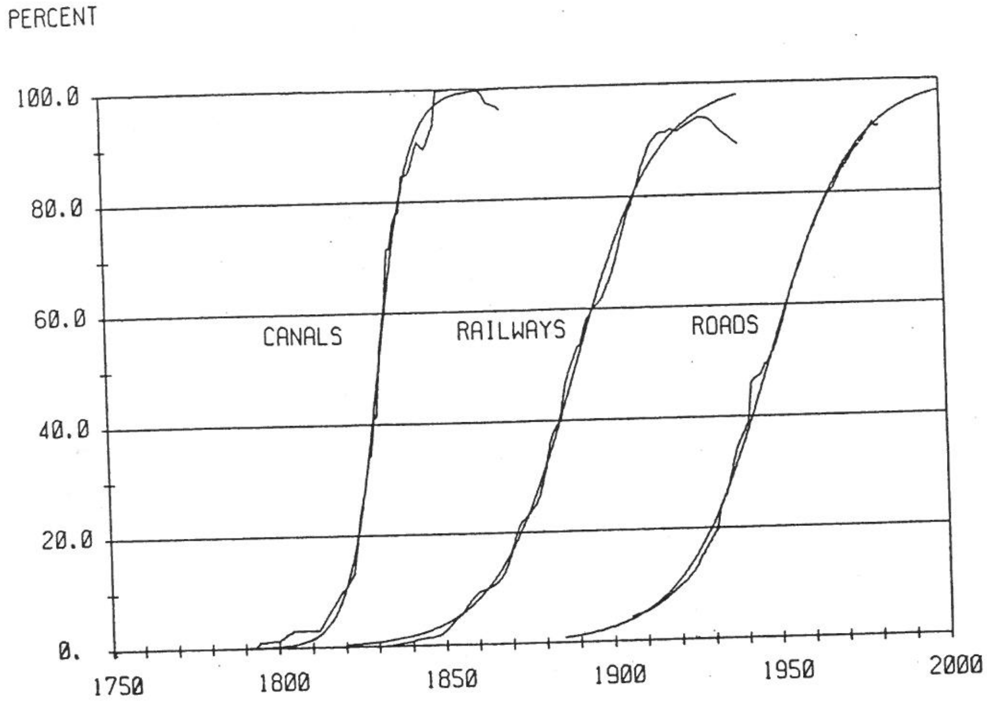

Figure 9.11. Growth of infrastructures as fraction of saturation, USA.

The difference in the time constant between air and inland water transport systems, on the one hand, and rail and road transport, on the other, indicates that at least at this level of comparison transport systems having more extensive infrastructures may take longer to expand, and possibly to complete the whole life cycle from growth to saturation and later senescence. Thus, it is remarkable that in spite of these differences, the saturation in the growth of these three infrastructures coincides with the beginning of the prolonged recessions in the last three long waves.

To assess whether the time constants are really different, *Figure 9.13* shows the successive substitutions of the three transport infrastructures and the federal airway route miles. The substitution process is shown as relative market shares (*F*) of a given transport infrastructure to the total length of all of the infrastructures together.[4] From this perspective the replacement of the four systems over time appears as a regular process.

This result may appear to contradict the earlier observation that the total length of railway tracks and surfaced roads took longer to construct than water and airway routes. In fact, the timetable associated with the substitution dynamics of infrastructural length is surprisingly consistent in relation to the duration of growth pulses of the four transport modes during the past 180 years. The apparent inconsistency results from the different ways of measuring the

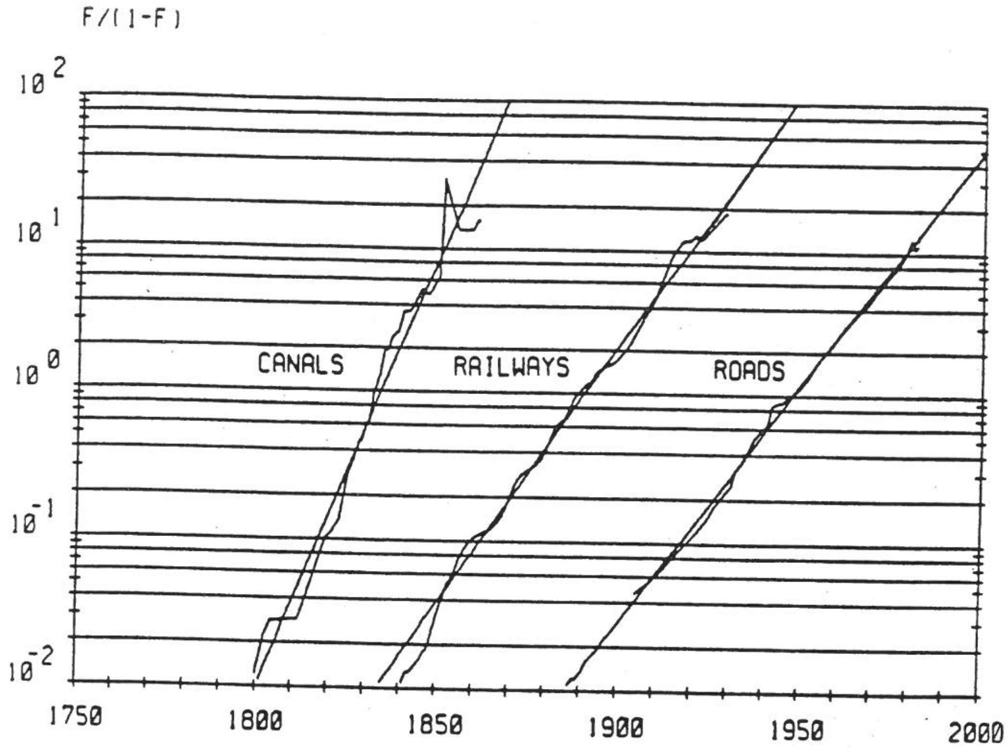

Figure 9.12. Growth of infrastructures as fraction of saturation, transformed.

growth rates and life cycles of the respective infrastructures. In the case of market shares the increase in a particular transport infrastructure is analyzed in terms of the length of all networks. Thus, even the rapid growth rate of airway route mileage is translated into a comparatively long time constant because at the same time the total length of all transport networks is also growing rapidly. As a result of these rapid growth rates, the share of surfaced roads has been declining since the 1970s, whereas the total length of surfaced roads is still growing toward the ultimate saturation level.

Thus, the total length of a transport infrastructure (in this case, canals, railroads, and surfaced roads) can still be growing even decades after ultimate saturation and final senescence, while the share of its length in all transport infrastructures is declining. The saturation and decline of market shares therefore precede saturation in absolute growth in a growing market, meaning that in those cases the eventual saturation of any competing technology can be anticipated in the substitution dynamics.

This description of the evolution of transport systems and infrastructures shows that during each growth phase of the last three long waves one of the important transport systems developed in the United States. Thus, Schumpeter's association of the last three long waves with canals, railroads, and automobiles can be confirmed from the empirical point of view.

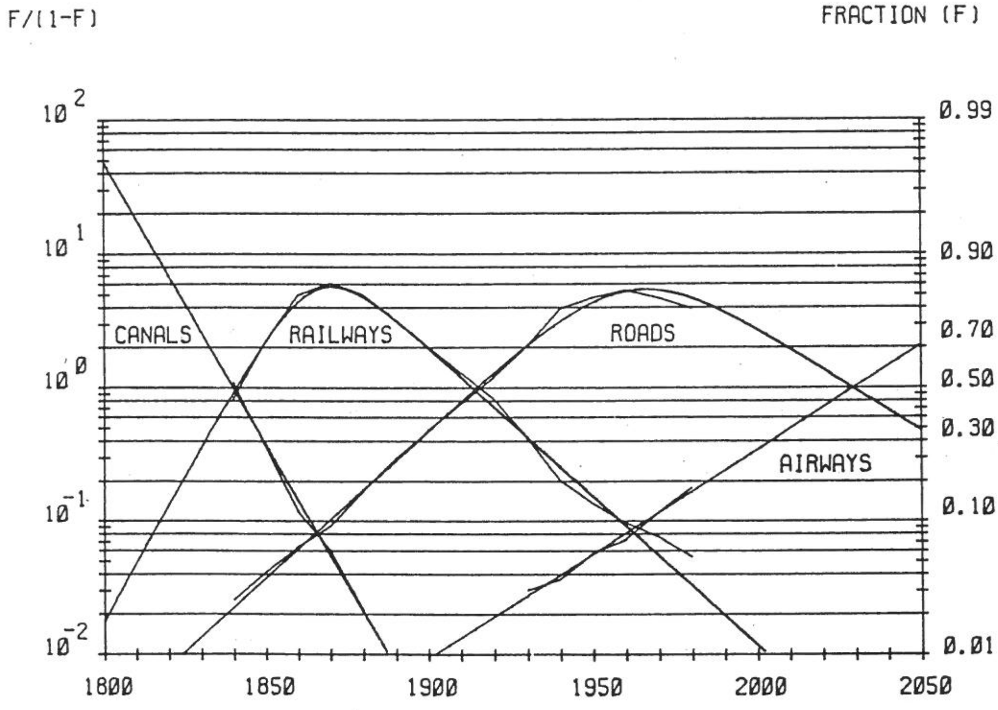

Figure 9.13. Substitution of transport infrastructures, USA.

9.4. Steel and Energy

9.4.1. Steel production

A widely accepted view is that the iron and steel industry constitutes a more mature sector of developed economies and an important sector in developing countries. In other words, iron and steel production is approaching or already has reached saturation and is declining in the industrialized countries, but it is still growing in most of the developing world. Subsequently, the iron and steel industry worldwide is in different phases of development, ranging from the early development and expansion phase to that of maturity and decline. We will attempt to give empirical evidence for this broad and long-term development of global steel production. In Chapter 8 Grübler analyzes specific changes of individual countries and technologies in greater detail.

Metallurgy dates back to the dawn of human civilization, but, because metals were precious, wood, stone, and sometimes bones were the dominant materials to help accomplish a difficult task. In spite of a wider and more sophisticated use of metals (initially mostly copper and bronze, and later also iron and some steel), the use of traditional materials prevailed through antiquity and the Middle Ages. The voracious use of iron and steel evolved parallel with the so-called Industrial Revolution. *Figure 9.14* illustrates the enormous increase in steel production worldwide since 1860. Production and growth has been especially rapid since the end of World War II, increasing from about 160 million tons to more than 850 million tons in less than four decades. *Figure 9.14* also shows wide fluctuations in steel production during the 1920s and 1930s and again during the last decade.

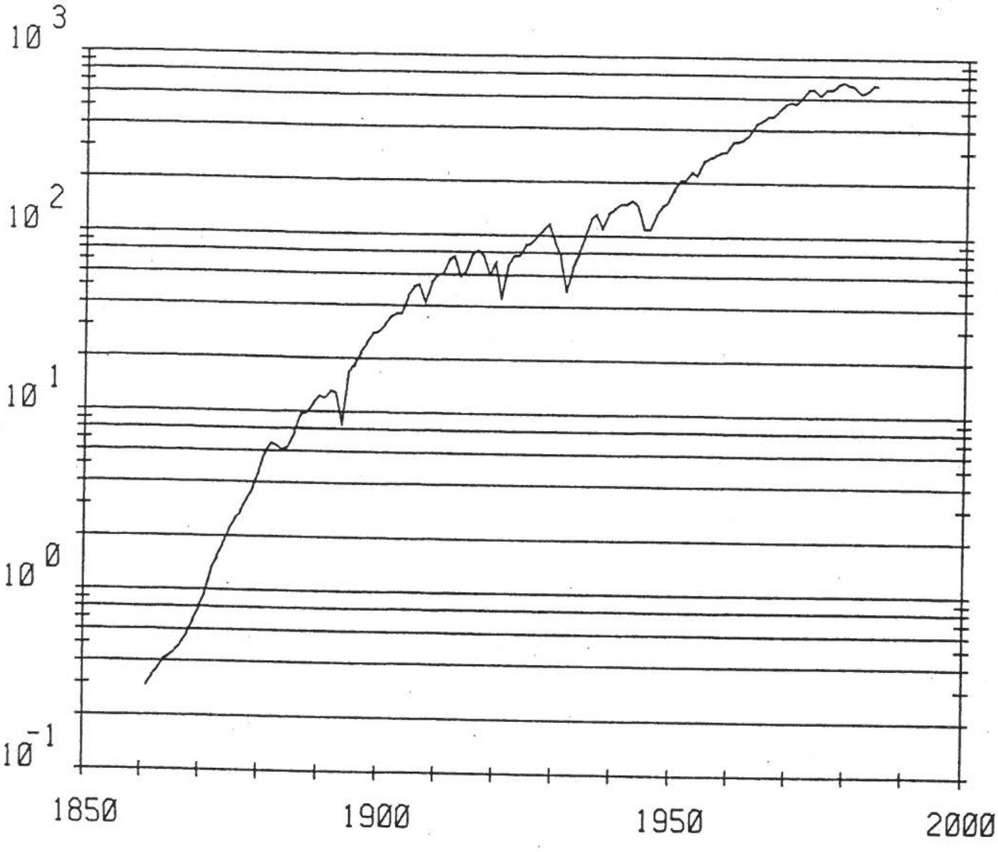

Figure 9.14. Global steel production. (Source: Grübler, 1987.)

This enormous increase in steel production is due to the crucial role that materials have in the development of industrial societies. The precise details of this strong coupling between economic development in general and materials in particular is truly complex, but the basic reason is actually obvious and transparent – the effectiveness and design of machines, equipment, and infrastructure depend to a substantial degree on the materials of which they are made. The discussion about the development of transport infrastructures illustrated this point very vividly: successive replacements of turnpikes, canals, railways, roads, and airways paralleled major improvements in construction materials from wood and stone to iron, steel, and concrete, and during recent decades to more advanced alloys and materials.

The introduction of better materials was instrumental for the development of new manufacturing techniques, energy sources, and transport systems. Metallurgy, manufacturing, energy, and transport all developed owing to numerous cross-links as one improvement or breakthrough made another possible and sometimes necessary. It so happens that during the last two centuries iron and steel were perhaps the most critical of all widely used materials. While stone and wood continued to be important materials, the advent of steam, railroads, and the coal "age" would not have been possible with wood and stone. In fact, a more efficient technology for producing high-quality steel was required, and, after a series of major innovations ranging from the substitution of charcoal for coke to new casting methods, it culminated in the invention of the Bessemer steel process in 1857. *Figure 9.15* shows the simplified representation of the technological changes in steel production since 1860, starting with puddle steel as the oldest production method and ending with electric arc steel. *Figure 9.15* shows the fractional market shares (F) of the five competing steel technologies transformed as $F/(1-F)$ on a semilogarithmic plot.[5]

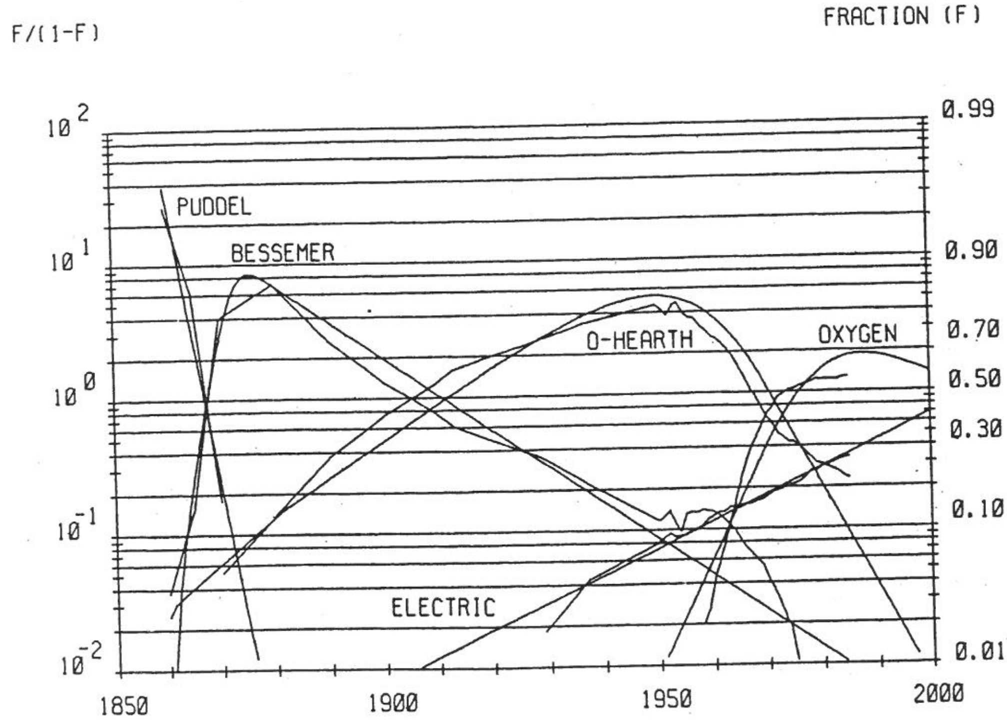

Figure 9.15. Steel substitution, world. (Source: Grübler, 1987.)

In spite of the very different nature of the five steel production technologies, their chemistry, energy sources, share of scrap iron, etc., they all appear to be in competition with each other, the newer technology eventually displacing the older. The linear trends indicate where the replacement of old with new technologies followed logistic curves. Grübler (Chapter 8) shows that the same historical trend can be observed in most industrialized countries. The replacement of crucible and puddle steel was a very fast process, whereas the open hearth method developed into the dominant steel technology over many decades. Bessemer became the dominant steel technology during the 1870s and thereafter its importance declined, while the open hearth process expanded. From 1870 to 1950 most of the increase in global steel production was achieved by the improvements and expansion of the open hearth method. The electric arc steel process was introduced during the 1920s, and its market share is still expanding with increasing amounts of recycled steel in the total production. After 1950 basic oxygen steel expanded vigorously, but now its relative contribution to steel production is saturating.

Thus, we have identified three distinct phases in the evolution of steel technologies. The first ended with the swift introduction of Bessemer steel, the first industrial process that could achieve high-quality and large-scale production of steel. The second is congruent with the development of the open hearth steel process, and the third marks the expansion of electric and basic oxygen methods. Another way of describing this succession of replacements in the evolution of the steel industry is to decompose the aggregate steel production (from *Figure 9.14*) into appropriate development phases. *Figure 9.16* shows total steel production (from all five technologies) in per capita terms as two distinct S-shaped growth pulses. The first starts with the dominance of the Bessemer method and mirrors the expansion of the open hearth process, while the second starts with the introduction of the electric arc process and accelerates with the expansion of basic oxygen steel.

Figure 9.17 shows the same growth pulses transformed so that the two S-shaped curves appear as straight lines.[6] Transformed in this way, the two pulses appear as parallel lines indicating equal duration of the two pulses with a ΔT of about 45 years. The two pulses overlap during the period of highest turbulence indicating that another period with large fluctuations in per capita (and therefore total) steel production may have started. These two pulses coincide with the growth phases of the last two long waves (see the rough timing for the long waves in the United Kingdom and the United States given in *Table 9.1*). *Figure 9.18* shows that in addition to broad fluctuations in the wholesale prices, the prices of iron and steel also show pronounced flares during the depression years in these countries. Thus, the iron and steel prices reflect important structural changes in the global steel industry.

This example confirms our original hypothesis that each growth phase of the long-wave cycle is associated with the expansion of a number of important new technologies through successive replacements of the old ones. Furthermore, the evolution of transport infrastructures and steel technologies is a very regular replacement process, but the saturation of dominant technologies does not correspond exactly to the timing of the depression phases in the long wave.

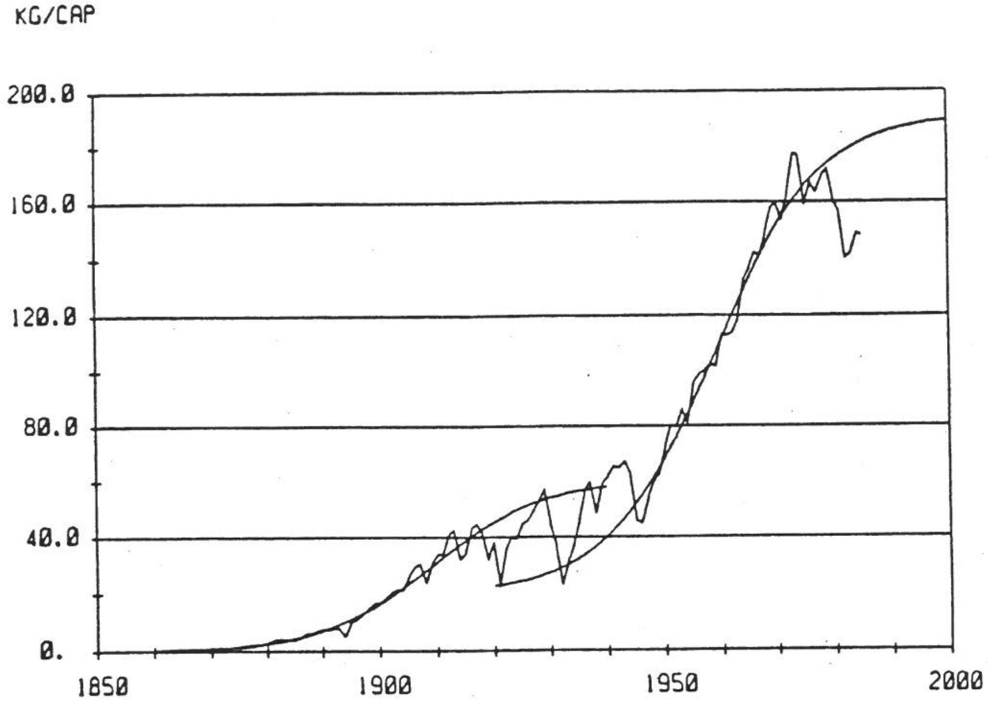

Figure 9.16. Global per capita steel production. (Source: Grübler, 1987.)

Instead, the saturation periods are more dispersed in time so that some occur before the depression years (e.g., canals in the United States) and some at the beginning of the upswing (e.g., saturation of open hearth steel in North America and West Europe).

9.4.2. Energy consumption

At the beginning of the nineteenth century, fuelwood, agricultural wastes, and mechanical wind and water power supplied most of the inanimate energy in addition to animal and human muscle power. We have seen that a considerable infrastructure of roads (turnpikes) and canals was in place for timber and later coal transport, although the widespread use of coal became possible with the emergence of railroads. Thus, like today, the use of energy in the early industrial development phase also depended on the transport system, and energy was an important component of goods transported on turnpikes, canals, waterways, and railroads. The development of energy and materials, and in particular steel technologies, is related in the same way as energy and transport systems. Better fuels made better steel processes possible, while higher-quality metals were crucial in further improving the whole energy system.

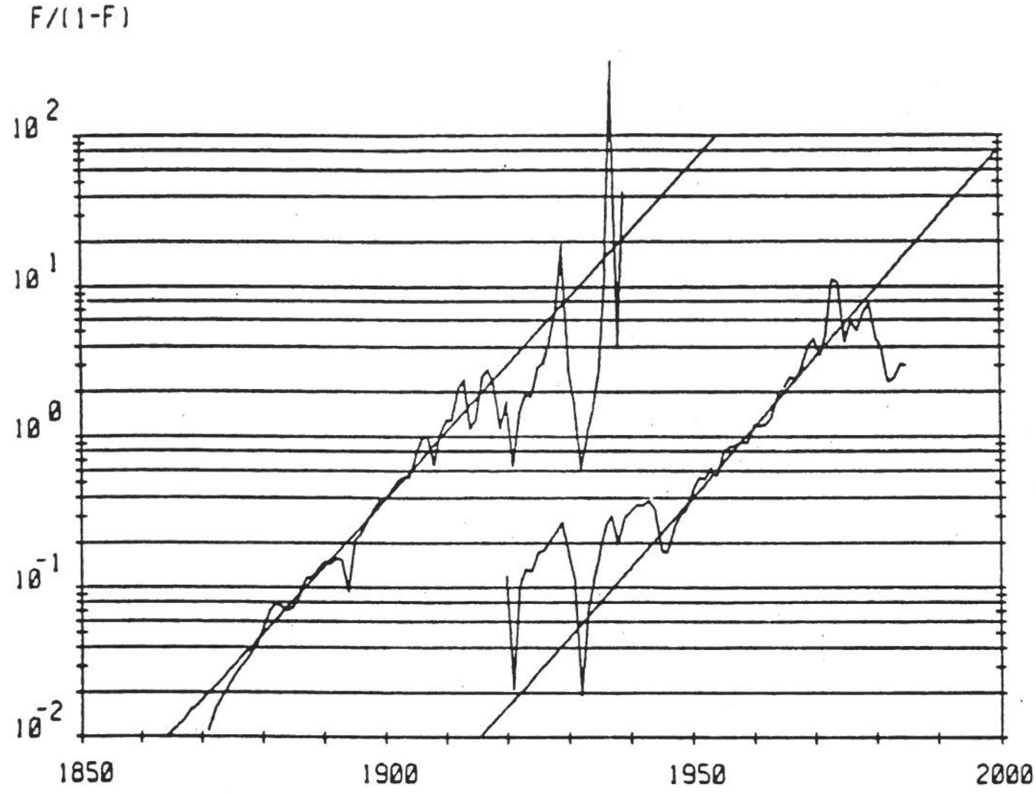

Figure 9.17. Global per capita steel production, transformed. (Source: Grübler, 1987.)

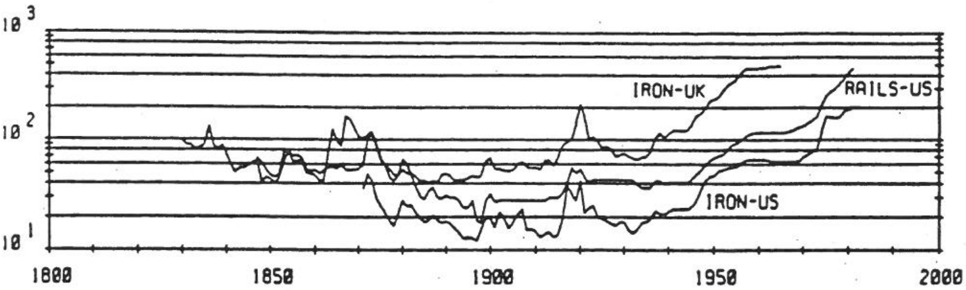

Figure 9.18. Irons and steel price indices, UK and USA. (Source: Grübler, 1987.)

Fuelwood represented most of the commercial primary energy inputs during the last century. *Figure 9.19* shows the annual consumption of fuelwood, fossil, and nuclear energy sources in the world since 1860. Data are plotted on a semilogarithmic scale and show the exponential growth phases in consumption by piecewise linear trends.

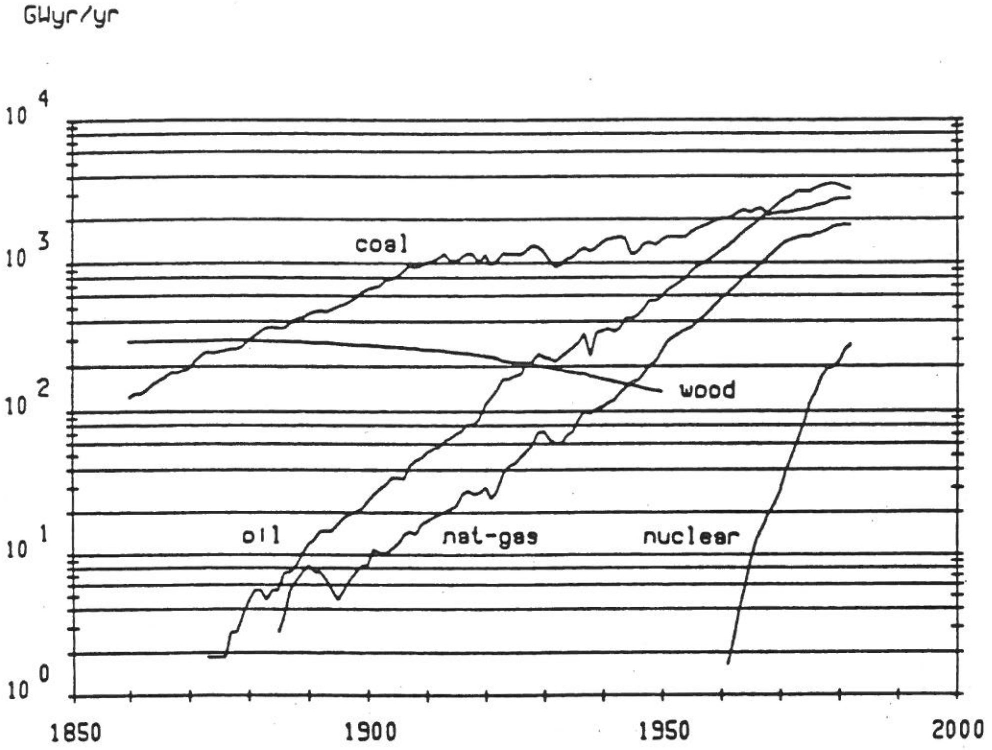

Figure 9.19. Global primary energy consumption.

Since the beginning of the century the consumption of fuelwood at the global level has declined as a commercial energy source, although it is still used widely, especially in the developing world. With the expansion of railroads and the steel industry, as well as the application of steam in general, the use of coal increased exponentially until the 1910s when a new, less rapid growth phase started. Since their introduction in the 1970s, oil and natural gas have been consumed at even more rapid rates. In fact, oil and natural gas curves have the same slope and thus almost identical growth rates; they are shifted in time by about 15 years. The increased use of oil and natural gas paralleled the growth of the petrochemical and electrical industries, and the expanded use of internal combustion and electric prime movers. Because nuclear energy is still in its early phase of development, the steep growth of the last two decades may not indicate the possibility of rapid expansion in the future. During the last few years, the growth of nuclear energy has declined worldwide to more moderate rates.

Primary energy consumption (including fuelwood) increased exponentially at an average growth rate of about 2% per year. The decline of older energy sources was more than compensated for by the rapid growth of the new ones. Thus, energy systems, like transport infrastructures and steel processes, evolved through a sequence of replacements of old by new technologies, practices, and

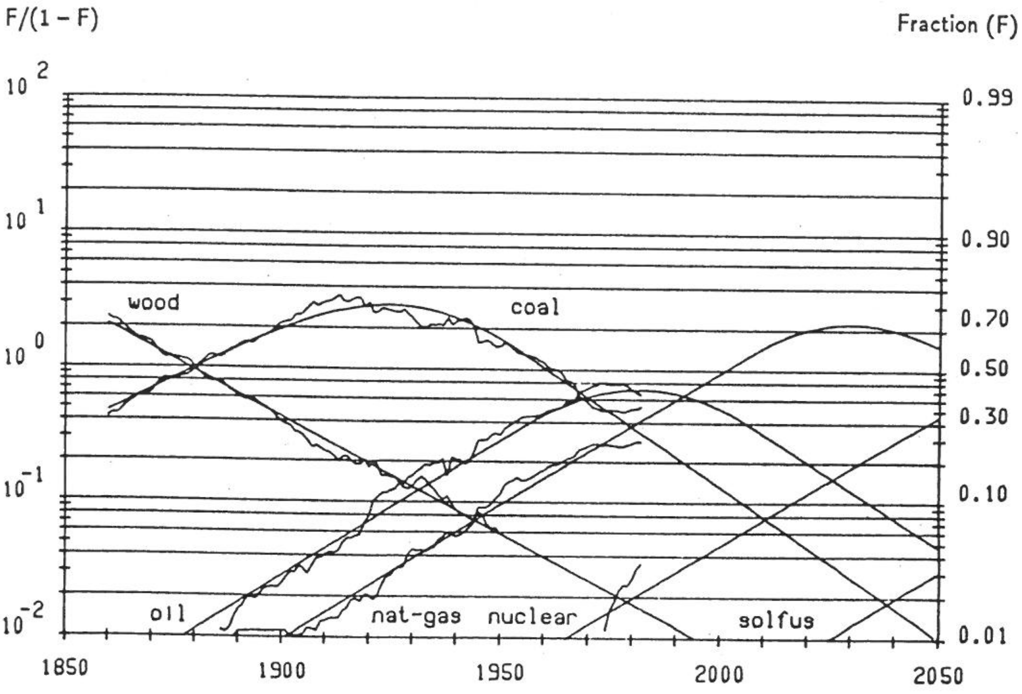

Figure 9.20. Global primary energy substitution.

methods. *Figure 9.20* shows the primary energy substitution process in terms of the fractional shares (F) held by each of the five energy sources in total consumption and plotted as $F/(1-F)$ on a semilogarithmic scale.

Compared to the substitution of transport infrastructures and steel technologies, the replacement of energy sources is a remarkably regular process. The slopes of the linear segments in the substitution process (logistic curves) are nearly the same, indicating that all four older energy sources have almost the same ΔT of about 100 years. Furthermore, the market shares do not reflect important historical events such as the world wars – the long-term trends are remarkably stable.

Based on these historical trends, we have used a scenario to project nuclear energy shares into the future. We have assumed the same slope as the expansion of oil and natural gas, implying a 5% market share by the year 2000. This indicates the possibility of a larger growth of nuclear energy in the next century, but also means *very few* additions to the current generating capacity during the next decades.

Coal saturated during the 1920s and oil during the 1980s. This again corresponds well to the timing of the last Kondratieff cycle. The growth phase until the 1920s is characterized by the expansion of the coal, railroad, and iron and steel industries, while the next growth pulse corresponds to the expansion of the oil, petrochemical, electricity, and road transport industries. These two growth pulses can be seen more explicitly at the aggregate level in total energy consumption. *Figure 9.21* shows the per capita global primary energy consumption divided into two growth pulses that reflect the substitution of primary energy sources. The first one was initiated with the rapid expansion in coal consumption after the 1860s and ends during World War II, by which time coal's share curved into a phase of decline. The second pulse is initiated with the onset of coal saturation and the beginning of the oil expansion phase (oil surpassed fuelwood in 1925) and accelerated after both fuelwood and coal were in decline. This second growth pulse is apparently nearing completion as the oil market shares in primary energy saturate.

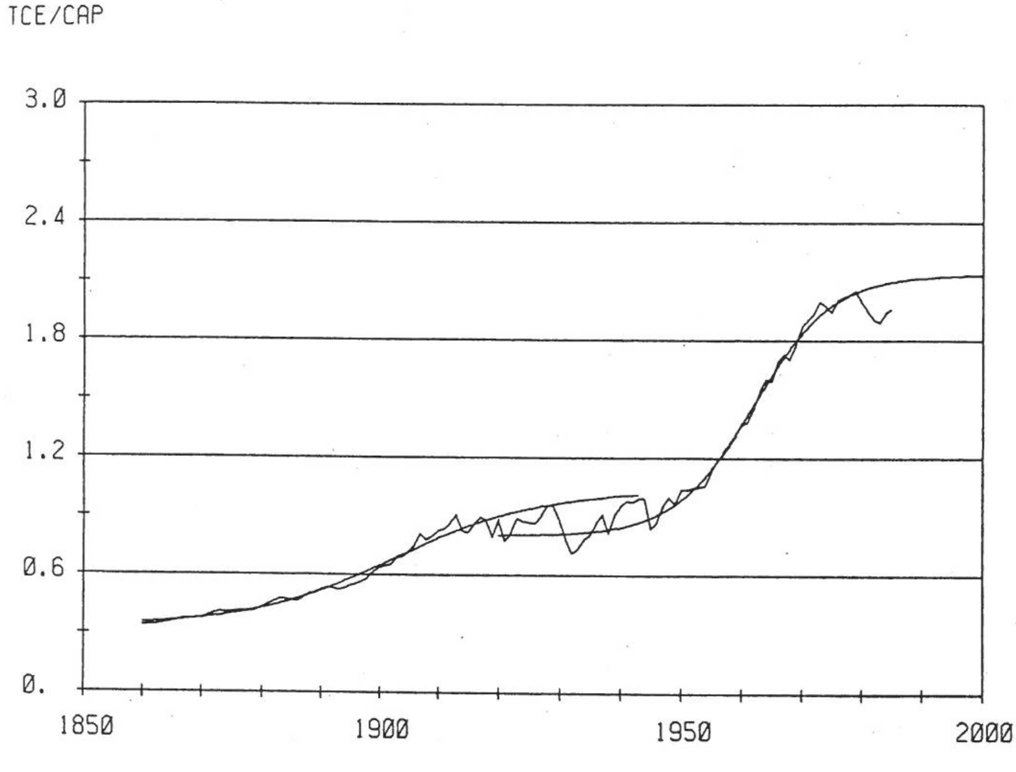

Figure 9.21. Global per capita energy consumption. (Source: Grübler, 1987.)

Figure 9.22 shows the same growth pulses transformed so that the two S-shaped curves appear as straight lines.[7] In this way the differences between the two growth pulses are more clear. The ΔT of the first pulse is longer than 60 years whereas it is shorter than 40 years for the second one. In contrast to this asymmetry the two growth pulses in per capita steel production had almost identical slopes and a ΔT of about 45 years (see *Figure 9.17*). In spite of these obvious differences between the energy and steel pulses, the analogy of the two processes is very strong and their timing almost identical. In fact, the deviations of the actual growth pulses from the estimated logistic curves show almost identical patterns. Fluctuations are strong at the beginning of the pulses until more than 10% of the saturation level is reached and they increase again above the 50% level. This result indicates that in addition to the regular pattern in the substitution of old for new technologies during the last two long waves, energy and steel use evolved through equivalent growth pulses that are concurrent with the upswing phases of the two last waves.

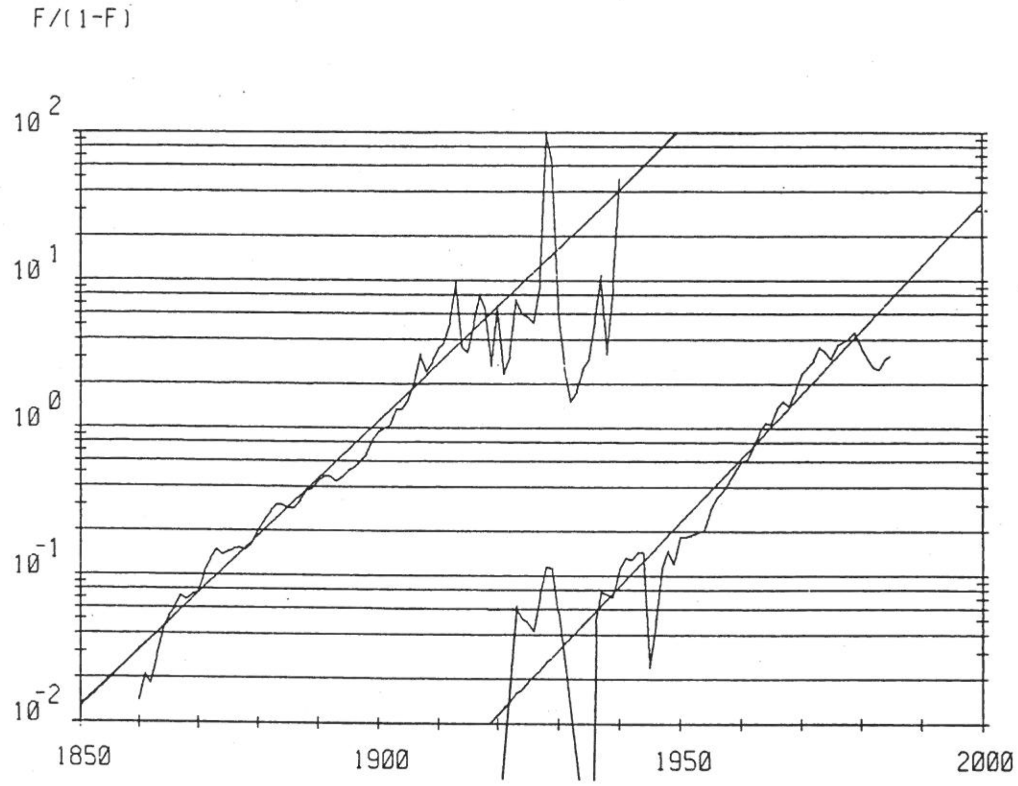

Figure 9.22. Global per capita energy consumption, transformed. (Source: Grübler, 1987.)

9.5. Energy and Prices

The above description of the complex process of technological and economic change is obviously incomplete. Certainly, there are many other, perhaps better, ways of describing the dynamics of transport infrastructures, steel production, and energy consumption. The intriguing aspect of the replacement dynamics and price fluctuations is that they appear to be interwoven with regular features and related to both the invariant pattern of substitution dynamics and the long waves in economic life. To show that this is not a feature unique to the last two long waves, we will show similar congruence in replacement dynamics of primary energy in the United States and price fluctuations over a period of about two centuries.

9.5.1. Primary energy

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 for new sources of energy. This is possible because different energy sources can be expressed in common energy units. Fortunately, it is possible to reconstruct the history of the more important sources of energy for the United States since 1800, because a more complete record of energy consumption exists for this country than for the world. *Figure 9.23* shows the annual consumption of fuelwood, fossil energy, mechanical water power, and hydroelectric power in the United States since 1800. As in *Figure 9.19*, data are plotted on a semilogarithmic scale and show the exponential growth phases in consumption by piecewise linear trends. The growth of total energy consumption was on average about 3% per year in the United States. The general pattern in the evolution of the energy in the United States, however, is not different from that in the world as a whole. In a way this is not surprising since the United States is the largest energy consumer during this century.

Figure 9.24 shows primary energy substitution in the United States. Mechanical water power (mostly water and some windmills) and hydroelectric power are not plotted in the figure because of their small contribution to total energy supply: they barely exceeded the 1% level during short periods and were otherwise under that critical level. This shows that the omission of these energy sources due to the lack of data in the example of energy substitution at the global level is probably not too crucial, although the share of these noncommercial energy sources must be higher worldwide than in the United States.

Before the 1820s fuelwood fulfilled virtually all energy needs in the United States. Coal entered the competition in 1817 at the 1% level and until the 1880s it was essentially a two technology market – whatever gains coal made were translated into losses for fuelwood. Crude oil and natural gas were first used in the United States at the beginning of the nineteenth century, and both held a 1% market share during the 1880s. From then on the use of crude oil expanded, and by 1950 the consumption of crude oil surpassed that of coal. (Even as late as the 1920s, however, the consumption of crude oil was not much larger than that of fuelwood.) The use of natural gas surpassed the use of coal nine years later. In comparing this period with earlier periods, it is remarkable that the structure of energy consumption changed more during the period of oil dominance than ever before.

Natural gas exploration, production, and transport significantly indicate different trends from oil technologies, although natural gas was associated with the oil industry ever since its first commercial use. Nevertheless, most energy accounts bind natural gas to oil because of the large production of associated natural gas from oil wells. Except at the point of production, associated natural gas, or oil-technology gas, is indistinguishable from gas produced from natural

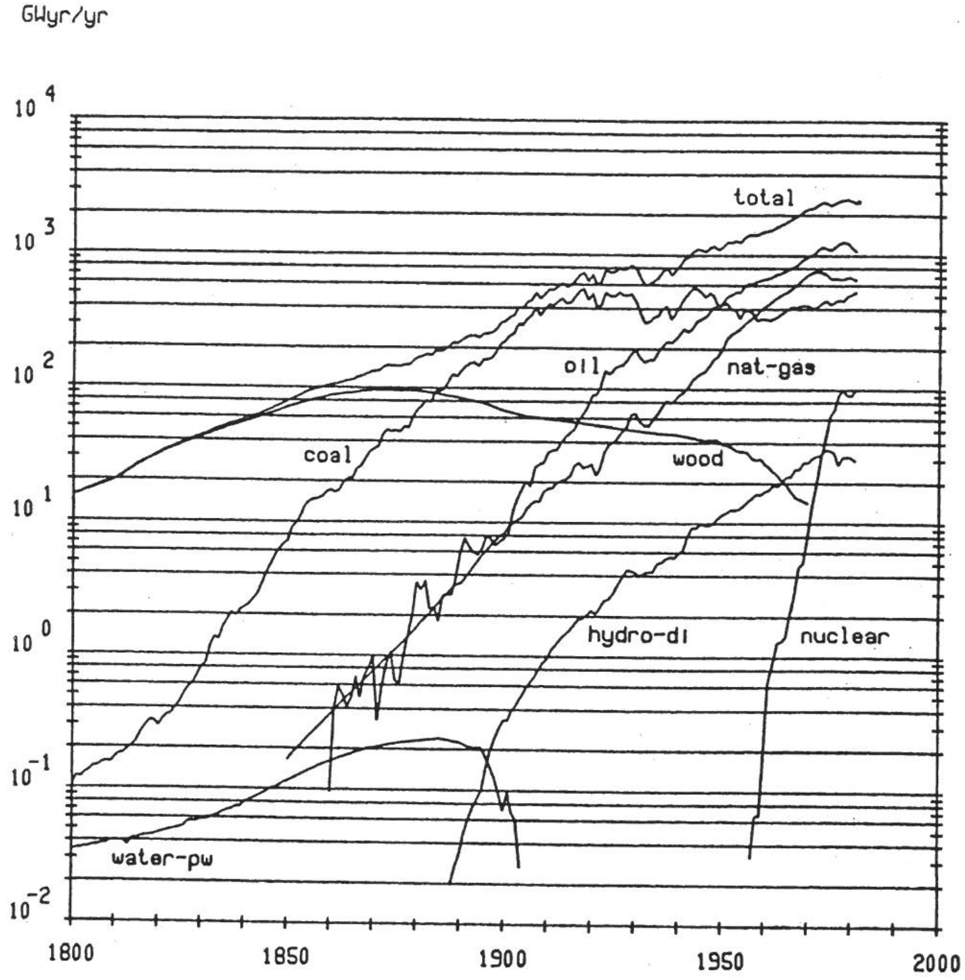

Figure 9.23. Primary energy consumption, USA.

gas wells. The fact that this distinction is difficult to make, and is consequently ignored in historical data, is to an extent misleading since oil and gas technology have portrayed distinctly different trends during the last century. This is however not reflected in oil and natural gas consumption data given in *Figure 9.23.* The distinction between associated gas and crude oil, in terms of primary energy accounting, is desirable and is consistent with the tradition of adding city gas produced from oil or coal to these primary energy sources rather than to natural gas.

To illustrate that natural gas is becoming increasingly uncoupled from oil technologies, we have attempted to reconstruct the primary energy balances by adding associated gas to crude oil and subtracting the same amount from natural gas consumption (but leaving net imports with natural gas balances). The revised market shares are given in *Figure 9.24*. The resulting replacements can

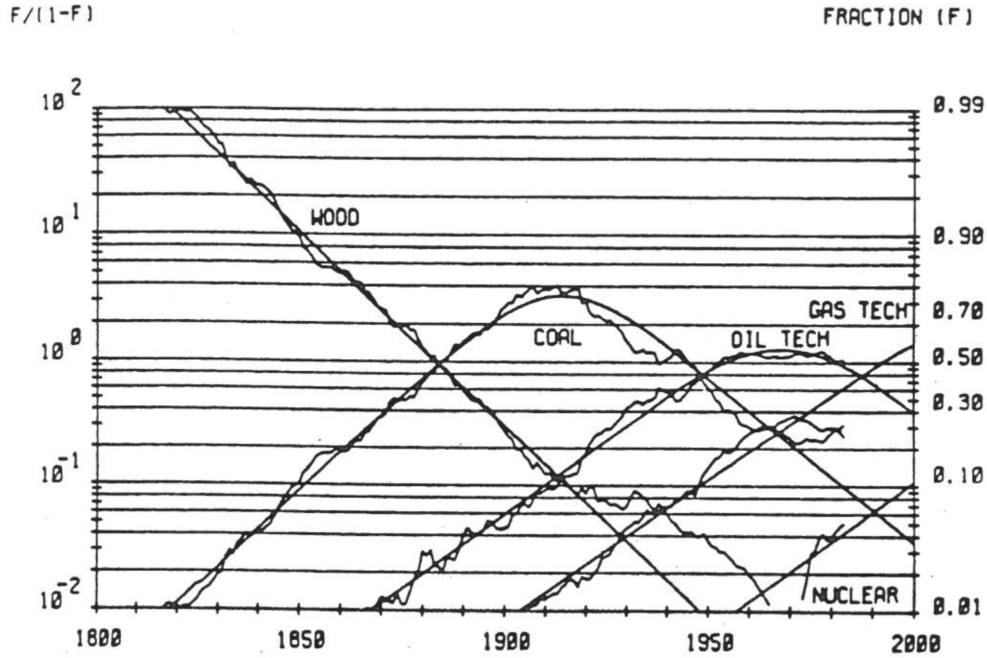

Figure 9.24. Primary energy substitution, USA.

be characterized by very regular time constants because the historical data are apparently accurate enough to provide the information required for this further analytical resolution. This is possible in the case of primary energy consumption in the United States because associated (oil technology) and nonassociated (gas technology) natural gas production is accounted for in the historical records.

This result shows that although associated gas has long been available as a by-product of oil, its use does not represent the actual evolution of gas technologies. *Figure 9.24* shows that the resulting substitution process improves the regularity to the extent that the time constants (ΔTs) now cluster at about 70 years for all energy sources and that the saturation intervals between coal, oil, and gas technologies are all separated by about 50 years. During the saturation periods of the dominant energy sources, new ones are introduced. Gas technologies are introduced during the saturation of coal, and nuclear energy during the saturation of oil. Thus, the evolution of the energy system reflects with perfect symmetry the long waves in prices and the associated periods of growth and structural change.

The slope of the nuclear energy penetration is determined by a scenario to have a ΔT of about 70 years by specifying a 10% market share by the year 2000. After the 1990s gas technologies clearly emerge as the most important energy source in the projection given in *Figure 9.24*. However, the natural gas (gas technology) shares have been below the trend line during the last few years while the coal shares have exceeded the projected market shares. It remains to be seen whether this disparity between our projections and actual development will be reabsorbed in the coming years like the "under- and overconsumption" of coal and oil, compared with trend lines during the 1920s and 1930s, which were eventually absorbed. It is conceivable that the uncoupling of oil and gas industries may provide a vehicle for wider use of natural gas in the future.

Although the saturation periods of coal and oil technologies are separated by about 50 years and during these periods of saturation new energy sources are introduced (gas technologies and nuclear energy, respectively), we still have yet to probe further into the past to test whether an even older energy source saturated during the previous long wave, i.e., during the 1870s.

Figure 9.25 shows that it is possible to include a partial reconstruction since 1850 of an even older energy source in the United States – animal feed. It represents an energy source equivalent to the amount of food consumed by the working animals (mostly horses and mules used in transportation and agriculture).

Animal feed reached its highest market share in the 1880s indicating that draft animals provided the major form of local transport and motive power in agriculture in spite of the dominance of railroads and steamships as long-

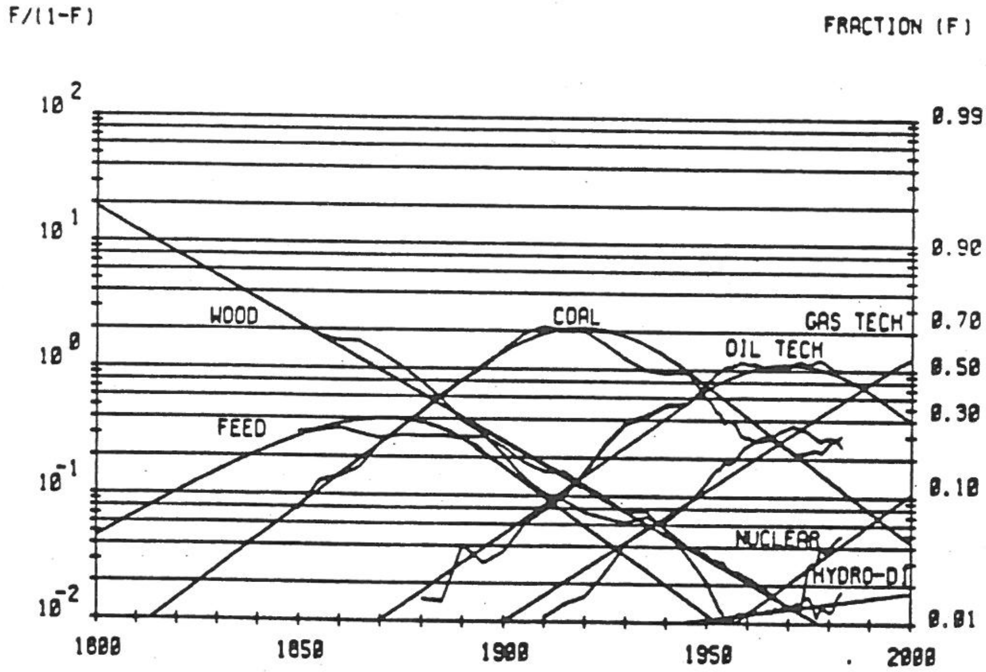

Figure 9.25. Primary energy substitution (with feed), USA.

distance transport modes (see the discussion on evolution of transport systems above). It is curious that the feed and oil technologies cross in the 1920s as if to suggest the simultaneous substitution of the horse carriage and wagon by the motor vehicles (see *Figure 9.8* and Nakicenovic, 1987b).

Figure 9.25 indicates that the replacement dynamics can result in a perfect symmetry of the successive substitutions of older for newer energy forms, providing a rather complete reconstruction of past patterns in energy use. Three emerging saturation periods are separated by about 50 years starting with animal feed in the 1880s, coal in the 1920s, and oil technologies during the 1980s. Each economic growth phase that connects the periods of energy saturation and prolonged recession throughout the economy is characterized by the expansion of two energy sources, one with large market shares "attacking" the saturating energy source and the other just emerging during the periods of saturation and structural change in the energy system. Next we will investigate another feature of the evolution of energy use in the United States that reflects the long waves in terms of the energy intensity of the whole economy.

9.5.2. 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 9%, whereas today the best gas turbine power plants can operate with efficiences of almost 50%. 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 uses 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 for new technologies. In general, replacement follows when the saturation in additional improvements of an established technology is reached.

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 9.26* shows the total primary energy consumption (from *Figure 9.23*), per capita consumption, and the ratio of energy consumption over gross national product (energy intensity) for the United

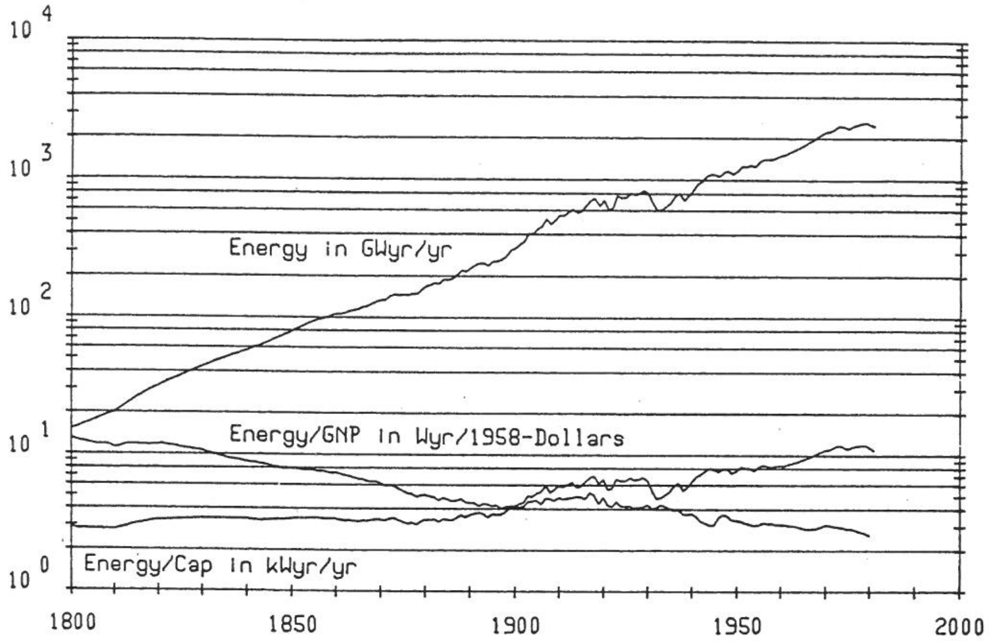

Figure 9.26. Primary energy, gross national product, and energy intensity, USA.

States. The average reduction in energy consumed to generate one dollar of gross national product was about 0.9% per year during the last 180 years. The ratio decreased from 10 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 replacement process that was discovered as a concept only during the last decade.

Figure 9.27 shows the fluctuations in energy intensity in the United States after the elimination of the secular trend by a 51-year geometric moving average. The fluctuations show pronounced long-wave movements and a high degree of synchronization with the price swings (see *Table 9.1*). *Figure 9.28* shows the evolution of energy prices in comparison with the wholesale price index from *Figure 9.4* and the heat and lighting price index (the last two indices are almost indistinguishable from each other), and in *Figure 9.29* the oil prices are also shown as an index to indicate the concurrent changes in energy and wholesale prices.

During the downswings in prices the energy intensity of the economy decreased more rapidly and during the upswings less rapidly. This illustrates relatively high energy price elasticity since energy prices changed in unison with general price movements as shown in *Figure 9.29.* 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.

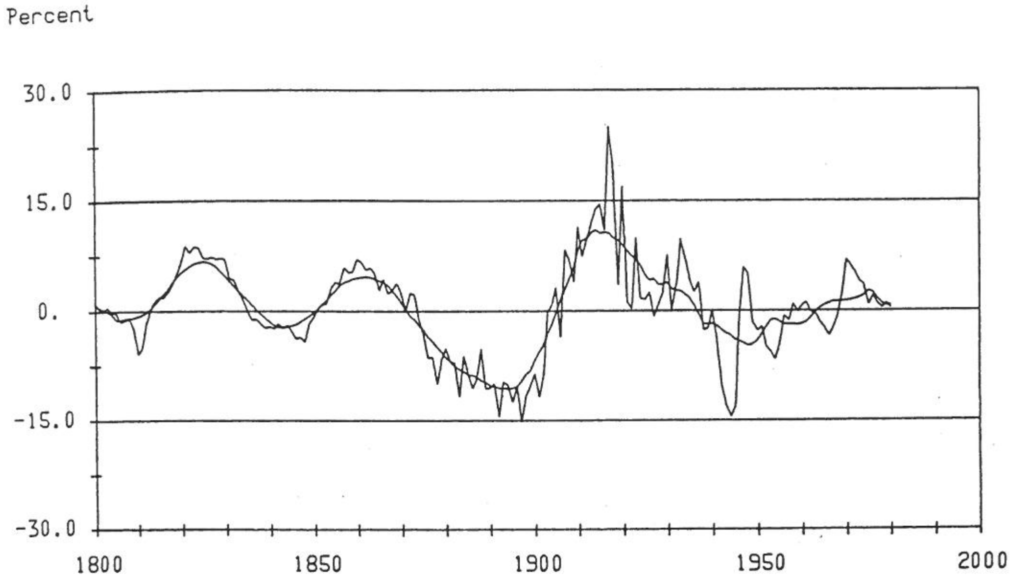

Figure 9.27. Long waves in energy intensity, USA.

As the competition intensifies during the recession and depression, energy savings become an important factor in cost reduction, also because of generally higher energy prices in addition to the overall price inflation. With recovery, new demands and prospects of continued economic growth release many pressures associated with saturating markets. Price levels are also much lower at the beginning of the new growth phase. Most entrepreneurs in the new growth sectors must intensify their activities 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 9.4*). 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 offset 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.

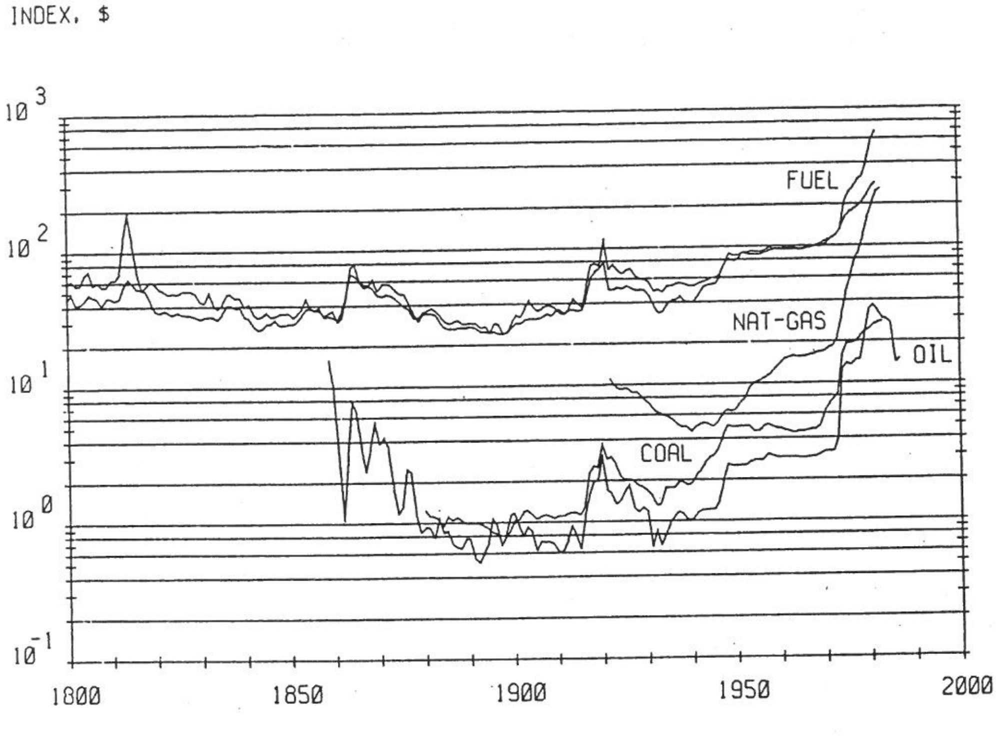

Figure 9.28. Energy and wholesale prices, USA.

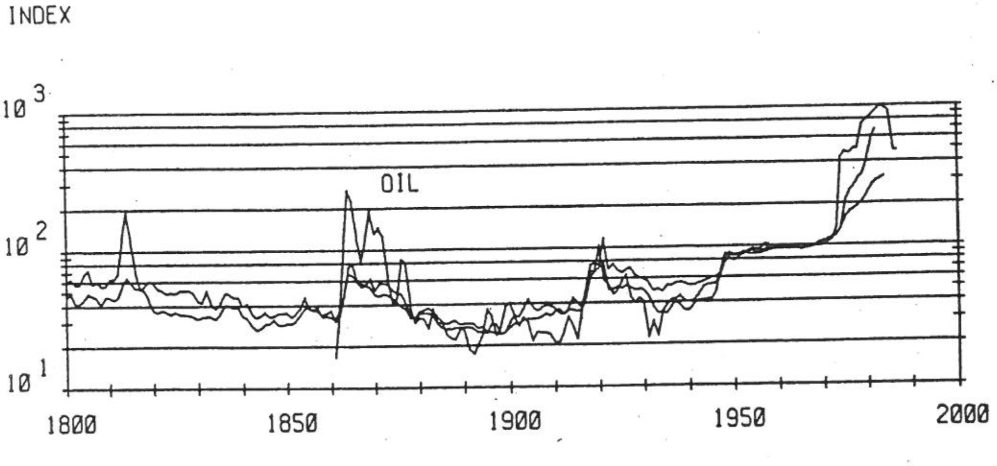

Figure 9.29. Oil – heat and lighting – and wholesale price indices, USA.

The relationship between primary energy consumption patterns and the long wave appears to extend beyond the parallel changes in the per capita level of energy consumption and energy intensity with the fluctuations of other long-wave indicators such as wholesale prices. Comparing ***Figure 9.25*** with ***Figure 9.27*** indicates that the upper turning points of energy intensity fluctuations correspond to the saturation points of primary energy sources. The upper turning point that occurred in the 1870s 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 1% market shares during the times of *high* energy intensity (during the 1870s, 1910, and 1973). Thus, the succession of the long waves indicates a similar timing as the dynamics of energy substitution and the changes in steel production and transport infrastructures.

9.6. Dynamics of Change

At the risk of generalizing, we can state that there is strong evidence that symmetric or at least similar changes in the patterns of energy consumption, steel production, transport infrastructures, 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. Thus, only patterns of change are similar while the symmetry breaks with an attempt to relate individual events that are always unique to a particular historical situation and thus different from one long wave to another. This is the essence of the analysis presented here – recurring patterns emerge as we consider sequences of replacements of old by new technologies, growth pulses, and deviations from smoothed secular trends. In all three cases the individual distinctions are removed from the data. It is the individual distinctions that "condense" the time series to actual (original) indicators removing the symmetry in patterns among periods of growth and periods of saturation and change.

To understand the actual mechanisms behind the long-wave phenomenon and changes in technology, economy, and society, we must acquire better analytical and statistical descriptions of the causal relationships we generally call experience. This would also imply that we need to understand the course of specific events and their individual manifestations that led, for example, from a period of rapid growth after World War II to the oil shocks of the 1970s, saturating world markets, changing industrial structure, increasing national debt in many quarters of the world, and developing the economic slowdown 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 structural changes at a higher level of abstraction indicate a striking regularity. Thus, the symmetry is destroyed in the transition from a sequence of replacements and fluctuations to particular circumstances and individual events. In other words, the individual event, such as an innovation, is unique, but the pattern of change appears to be regular for the emergence of innovations taken together as a dynamic process.

The annals of business cycles (see, for example, Thorp and Mitchell, 1926; Mitchell, 1927) show that the severe crises or so-called Great Depressions occur regularly during the downswing of the long waves. It suffices here to mention that the Great Depressions and financial panics of 1819, 1874, and 1929 in the United States 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.

The analysis of technological substitution in steel production, energy consumption, and transport infrastructures showed that the same basic approach can be applied to describe the structural changes. In all three cases older technologies were replaced by new ones with regular recurring patterns. Besides the now obvious similarity in the substitution patterns, it should be observed that the timing of the saturation phases is to some degree synchronized in the three examples.

In all three cases technologies that have saturated before 1850 (canals, crucible and puddle steel, and fuelwood) are declining, although at different rates. The next "wave" of technologies to reach saturation in terms of market shares between 1870 and 1875 are railways, Bessemer steel, and animal feed as a source of energy. During the 1920s coal saturated, in 1950 open hearth steel, in 1970 length of roads and oil technologies, and in 1980 oxygen steel. This indicates that the saturation periods measured in terms of relative market shares are not perfectly aligned, but that they are grouped around the upper turning points in the long wave as indicated by price fluctuations (see *Figure 9.4*). What is more important however is that during period of saturation of some technologies and prolonged economic recession, the next generation of growing technologies surpasses the declining ones, e.g., crucible and puddle steel by open hearth process, canals by roads, fuelwood by oil and gas, railroads by airways, and Bessemer by electric and oxygen steel. This illustrates that the periods of prolonged recession are indeed periods of structural change when dominating technologies are either close to saturation or already declining and when older declining technologies are surpassed by the emerging ones. Another way of stating this symmetry is that the dominating technology in each example bridges the period between the end of growth in one wave and the beginning of growth in the next as its market shares curve from increase through saturation to decline.

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 transport infrastructures 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 transport infrastructures and steel production). 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 portray similar features and relatively close the timing of crucial market saturation and takeover events, we will now consider the timing of long-wave fluctuations and energy substitution.

Figure 9.30 shows energy substitution (from *Figure 9.25*) on the lower plot and long wave in energy consumption, energy intensity, and wholesale prices (from *Figures 9.4* and *9.27*) on the upper plot. Here we have implicitly assumed that energy substitution is indicative of other replacement processes because the timing of saturation periods, introduction of new energy sources, and ΔTs are perfectly symmetrical in this example. Thus, *Figure 9.30* summarizes the results of the phenomenological analysis of the dynamics of technology and long waves. 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. The period of decline from saturation to loss of dominance (i.e., loss of the highest market shares) lasts on the order of 25 years, or about as long as the downswing phase of the long wave, which is characterized in *Figure 9.30* 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.

9.7. Conclusions

A number of important technologies and growth sectors emerge within relatively short periods of time: they expand because they are interrelated, and they enhance each other because they are interlaced and interdependent. Long waves emerge because the replacement of old technologies and methods and the growth of new ones take place simultaneously, leading to a prolonged phase of economic growth. Likewise, these replacements and growth processes tend to saturate during relatively short periods of time resulting in prolonged recession and turbulence, restructuring of the economy, and technological and social change.

The prolonged recession period reduces economic opportunities, and also leads to excess production capacities, unemployment, and lower intensity of other factor inputs. This change in the economic environment from relatively continuous growth to stagnation, recession, and turbulence makes the application of financial innovations attractive as other opportunities for return on capital decline. The prolonged stagnation and recession period is characterized by volatility and expansion of speculative instruments and decline in productive investments. As volatility increases so do the risks, and it is conceivable that this diverts some capital and human resources into innovative activities.

Some evidence exists that innovations cluster around the recession periods and eventually lead to a new "wave" of replacements and growth. This basic pattern can recur and be repeated in completely different circumstances provided that the growth of a number of important technologies is to an extent synchronized. All that is necessary is a distinction between periods of growth and periods

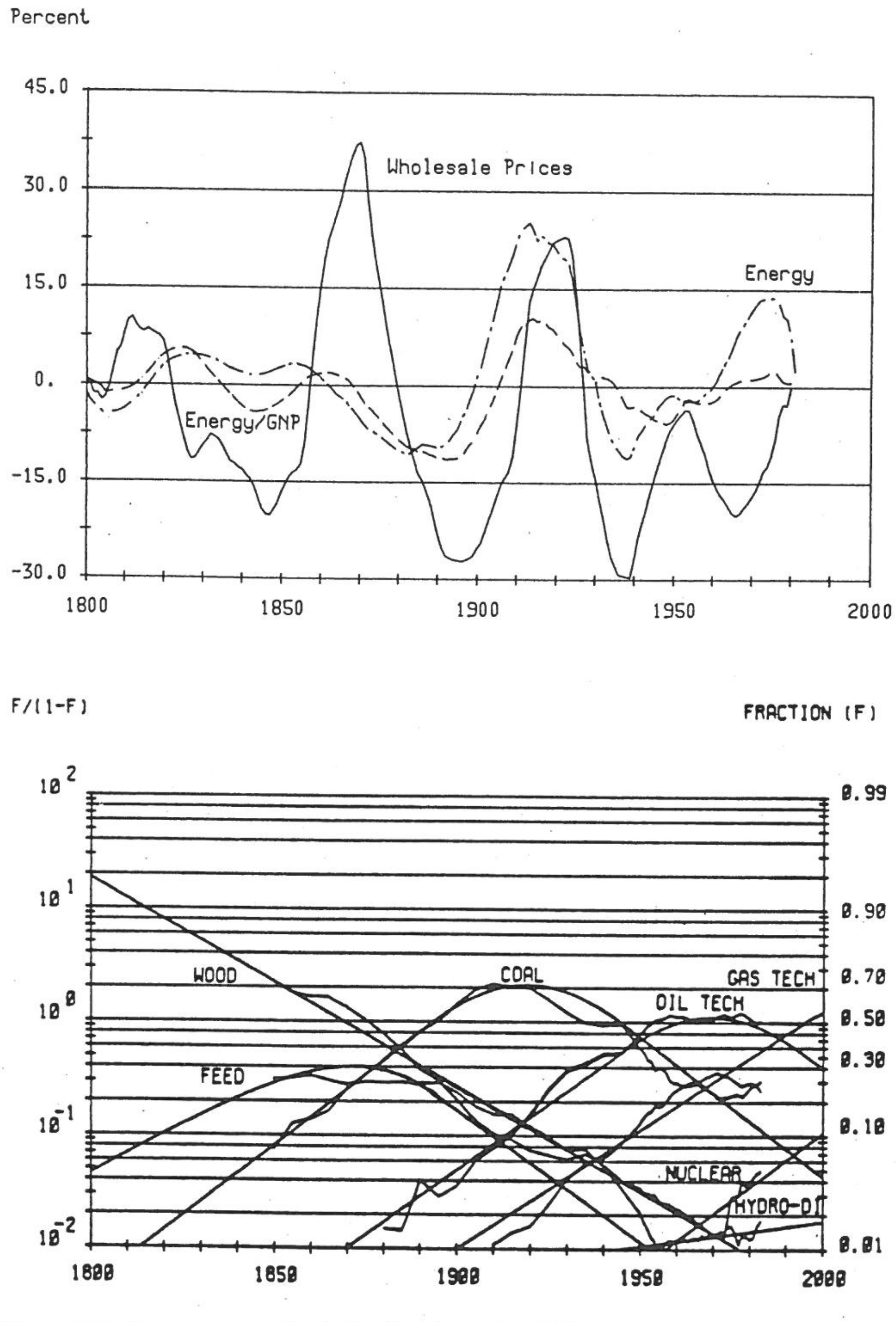

Figure 9.30. Long waves and substitution dynamics, USA.

of change. This hypothesis does not require a high degree of synchronization or "focusing" for either the innovation clusters or the saturation clusters. It is sufficient that a number of important replacements take place and cause a period of prolonged growth. Certainly this is a very simplistic and stylized scheme of technological change and economic and social development, but it is supported by the empirical evidence of technological substitution in energy, steel, and transport and in the overall price movements. This evidence supports the existence of weak clusters in the growth phases of different technologies, and perhaps weaker evidence for saturation clusters. A larger "sample" of case studies would be required to confirm this result in the statistical sense. For the time being it is not clear whether the phenomenological evidence is representative enough to allow generalization of the results or not. The example of primary energy substitution in the United States (see *Figure 9.25*) is remarkable in that is portrays a perfect symmetry of introduction, growth, and saturation of technologies and price movements over a period of almost two centuries.

The fact that some 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 replacements in steel production and transport infrastructures do not portray perfectly symmetrical patterns as primary energy substitution. This means that technologies saturate in broad waves that start at the end of the prosperity phase and extend to the beginning of the next Kondratieff wave. Perhaps this is an artifact of the choice of technological substitution processes in that they are very closely related to each other and represent the most important growth sectors. 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 centuries was initiated by the ever increasing need to transport timber and other goods in larger quantities over longer distances. Later, railroads were associated with 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, large canals were associated with the transport of fuelwood, which at that time was the primary source of energy for many industrial activities such as iron smelting. The railroad era was very closely related to the widespread diffusion of steel, steam, and coal-related industries.

In terms of the long-wave fluctuations, we will name the upswing phase from 1773 to 1810 the "age of canals" and the upswing from 1840 to 1869 the "age of railroads." Accordingly, we name 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 motor vehicles, roads, aircrafts, 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 after the "oil crises" of the early 1970s, which marked 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 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 on the basis of this scheme, the next 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 World War II and the initiation of a downswing five to ten years ago. We can already anticipate some developments of the current downswing period. For example, the energy intensity curve in ***Figure 9.27*** indicates that during this and the next 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 could also become a very efficient source of electricity and clean fuels. Widespread use of natural gas would require new infrastructures for production, long-distance transport (e.g., by pipelines or by superconductive cables via electricity), 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.

Another growth sector discussed in terms of technological change are transport systems and infrastructures. One possible development could be an advanced aircraft with substantively higher productivity than the Boeing 747. It could be a super large subsonic transport, a cruise supersonic, or a hypersonic spacecraft. In any case, such advanced means of transport would require new infrastructures, such as airports and "feeder" aircraft, and other transport modes to and from airports. Cruise supersonic and hypersonic transports would also require new sources of energy and new materials. Methane and hydrogen are obvious candidates to replace kerosine, so that the coupling to natural gas is obvious. It is analogous to the simultaneous development of the petrochemical and automobile industries. New materials are related to a possible replacement for the saturating steel industry, which in the long run will have to expand to other materials as recycled steel and the electric process exhaust their market potentials.

These are just some 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 "gales of creative destruction" (Schumpeter, 1935). A period of rapid (relative) deflation can be expected together with prolonged unemployment and further economic slowdown. These are the selection mechanisms that in the past distilled the successful from a wide range of promising new 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 speculations about the nature and timing of future events are based on the dynamics of equivalent changes in the past. The perfect symmetry between changes in the primary energy and price fluctuations shows that certainly price mechanism alone cannot explain all of the dynamic changes. The secular trends in prices are however consistent with the structural changes in energy. There is an intertemporal price elasticity of energy use. As prices increase energy is saved (intensity decreases) and new energy sources are introduced. In some way prices appear to have short range as a "force" in a dynamic economy. Savings are introduced in the face of a recession, but they only create unemployment and excess capacities. It is the innovations that can "tunnel" through the Kondratieff "barrier" and create a new period of growth. From a large number of innovative activities only a few are successful, most cannot escape from the recession and decline. In the past the few successful innovations were important enough to create a new period of growth. Thus, from the dynamic perspective prices appear to have a shorter range while innovations have little importance in the short run, but are of fundamental importance over periods longer than the business and the inventory cycles.

This illustrates why the Kondratieff wave is a long cycle, but perhaps the most important question is why the clock that times 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 and 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.

Notes

[1] One general finding of a large number of studies is that many growth processes follow characteristic S-shaped curves. Logistic function is one of the most widely applied S-shaped growth curves and is given by:

$$x/(\kappa-x)=\exp(\alpha t+\beta),$$

where t is the independent variable usually representing some unit of time, α,β, and κ are constants, x is the actual level of growth achieved, while $\kappa-x$ is the amount of growth still to be achieved before the (usually unknown) saturation level κ is reached. Taking logarithms of both sides gives the left side of the equation to be expressed as a linear function of time so that the secular trend of a logistic growth process appears as a straight line when plotted in this way. Substituting $F=x/\kappa$ in the equation expresses the growth process in terms of fractional share F of the asymptotic level κ reached, i.e., the equation becomes:

$$F/(1-F)=\exp(\alpha t+\beta).$$

[2] One general finding of a large number of studies is that substitution of an old technology for a new one, expressed in fractional terms, follows characteristic S-shaped curves. Fisher and Pry (1971) formulated a simple but powerful model of technological substitution by postulating that the replacement of an old by a new technology proceeds along the logistic growth curve:

$$F/(1-F)=\exp(\alpha t+\beta),$$

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

[3] We define ΔT as the time elapsed between the achievement of one and 50% of the saturation level κ, i.e., in this example $\Delta\mathrm{T} = 95.5$ years. Because of the symmetry of the logistic function, the same time is required for the increase from 50 to 99% of the saturation level. An alternative definition of ΔT is the time elapsed between the achievement of 10 and 90% level. In this case ΔT would be slightly different from the other definition, but for all practical applications both definitions can be used interchangeably.

[4] The fractional shares (F) are not plotted directly but as the linear transportation of the logistic curve, i.e., $F/(1-F)$ – in this more general case, as the ratio of the market share taken by a given transport infrastructure over the sum of the market shares of all other competing infrastructures. This form of presentation reveals the logistic substitution path as an almost linear secular trend with small annual perturbations. Thus, the presence of some linear trends in ***Figure 9.13*** indicates where the fractional substitution of transport infrastructures follows a logistic curve. 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. This is illustrated by the substitution path of rail tracks, which curves through a maximum from increasing to declining market shares (see ***Figure 9.13***). In the model of the substitution process, we assume that only one competitor is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates, and that new competitors enter the market and grow at logistic rates. As a result, the saturating technology is left with the residual market shares (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 assumptions is given in Nakicenovic (1979).

[5] As in *Figure 9.13*, the fractional shares (F) are not plotted directly but as the linear transformation of the logistic curve, i.e., $F/(1-F)$ – as the ratio of the market share taken by a given steel technology over the sum of the market shares of all other competing technologies. Also in this figure, this form of presentation reveals the logistic substitution path as an almost linear secular trend with annual perturbations. The presence of some linear trends in *Figure 9.15* indicates where the fractional substitution of steel technologies follows a logistic curve.

[6] Transformation $F/(1-F)$ is used where $F = x/\kappa$, κ is the estimated saturation level and x the steel production in a particular year, so that F represents the fraction of the saturation.

[7] Transformation $F/(1-F)$ is used where $F = x/\kappa$, κ is the estimated saturation level and x the energy consumption in a particular year, so that F represents the fraction of the saturation.

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