# Technological Change as a Learning Process

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## Introduction

Technological change can be seen as a social learning process. Early development of each single new technology involves experimentation and testing before the design and its possible applications are sufficiently refined to attempt commercialization and entry into the competitive market place. At the beginning, new technologies are often inferior compared to their mature alternatives in their economic and often also technical performance, but they hold the advantage of giving a new service or performing new tasks not possible with traditional methods. Before economic attractiveness is achieved, costly investments are made to improve the economic performance of a new technology. This is the learning aspect. The process really never stops. Technologies are improved continuously form the laboratory to senescence.

As new technologies evolve they replace the more traditional alternatives. This is the case for single technological innovations such as the replacement of horses by cars or records by compact discs. But more often than not technologies are related to each other and form whole clusters of innovations that interact with each other. They are best characterized by phrases such as the age of coal, steam, steel and railways.

Together, the technological learning and diffusion clusters form the process of change that increases productivity, performance, efficiency and environmental compatibility of human activities and thus fundamentally transform our societies and way of life.

This paper presents the historical analysis of technological change. It reviews the empirical evidence for both aspects of this process – technological learning and clustering. It also shows that the overall direction of technological change, especially in the energy area, leads to higher performance, efficiency, quality of service as well as lower environmental impacts. These improvements in the energy system are reflected in the overall trend toward decarbonization.

## Decarbonization and Mobility

There is a wide divergence in expectations about future global energy needs and consequently also emissions of greenhouse gases (GHG). Recent scenario comparisons show

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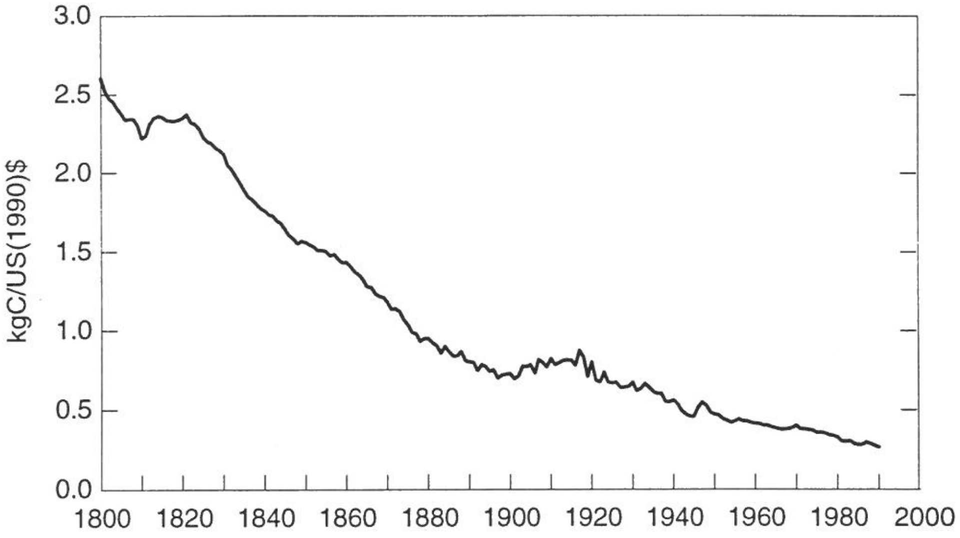


Figure 1: Decarbonization of economic activities in the USA expressed in kilograms of elementary carbon per unit of GDP at constant 1990 prices [kgC/US(1990)$].

that, if anything, the range of alternative scenarios for future emissions is increasing despite the large research effort in this area and numerous studies of future GHG emissions. Uncertainties about future energy needs and emissions have not significantly declined. Typical ranges of carbon dioxide emissions by 2100 vary between about two to more than 30 GtC (billion tons of elementary carbon) e.g., see Pepper *et al.*, 1992. To a large extent assumptions about the future technological change explain the difference in these different views of the future.

Technological change is no doubt one of the prime driving forces of future energy needs and GHG emissions. For example, Figure 1 shows that the specific carbon dioxide emissions per unit value added have declined by almost an order of magnitude during the last two centuries in the USA, from about 2.5 kgC per $1 GDP (at 1990 prices) in 1800 to about 0.3 kgC per $1 GDP in 1990. This formidable reduction in specific emissions of GHG is to a large extent due to technological change as expressed in the improvements of performance of energy extraction, conversion, transport, distribution and end-use technologies, and as expressed in the substitution of old by new technologies. There are other important factors that have also influenced this impressive reduction, namely structural change in the economy, changes in the consumption patterns and so on. Some of them are technological in nature others are not. The end result is that the "productivity" of carbon, if measured as factor input, increased by more than one percent per year during the last two centuries.

The ratio of carbon dioxide emissions over energy consumption is even more directly the result of technological change in the energy system. Figure 2 shows the carbon intensity of energy expressed as carbon dioxide emissions per unit primary energy consumption in the USA. Although only data for the USA are shown here, a similar tendency toward lower carbon intensities is evident throughout the world despite many differences in individual countries. The rate of decline in the USA - about 0.3 percent per year - is quite typical; the many other countries analyzed to date have, on average, a similar decline in carbon intensity.

The reduction of carbon intensity is the result of technological change - the substitution of

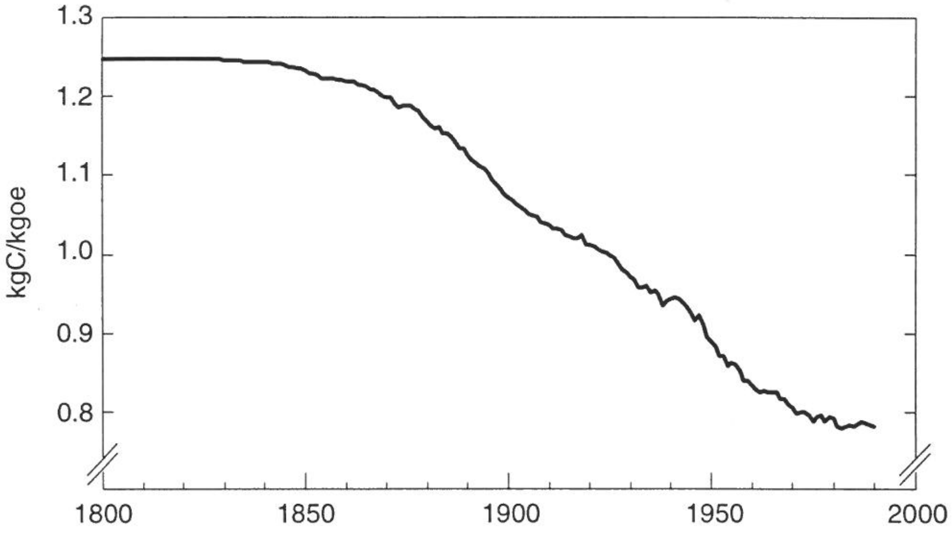


Figure 2: Carbon intensity of energy in the USA expressed in kilograms of elementary carbon per unit primary energy consumption [kgC/kgoe].

carbon intensive fuels, such as coal, by less carbon intensive ones, such as oil and natural gas. The gradual emergence of zero-carbon energy sources, starting with hydropower and nuclear energy and now including a range of renewable sources, further reduce the ratio of carbon to energy. Since we are measuring carbon intensity at the level of primary energy, conversion efficiency and other factors do not directly influence the ratio. Indirectly they of course do. For example, natural gas is considered to be the fuel of choice in many applications because of high conversion efficiencies and low environmental impacts including lowest carbon dioxide emissions of all fossil fuels. Decarbonization is thus an important indicator of technological change in the energy system.

Figure 3 demonstrates the dynamics of this evolution in the USA and the global energy system in the form of a triangle. At the beginning of the industrial revolution, in the 1800s, most of the energy consumption constituted traditional (non-commercial, non-fossil) sources such as fuel wood, feed for working animals, mechanical water power, agricultural waste, and so on. During the next hundred years, these traditional energy sources were largely replaced by coal. By the 1900s, coal's share of total primary energy rose to more than 70 percent while the role of the traditional energy declined. During this century, oil and natural gas subsequently replaced coal, and during the last two decades some humble substitution of oil and gas by nuclear and renewables can be observed. Thus, the tendency to lower carbon intensity of primary energy appears as a historical development process characterized by the successive substitution of primary energy sources. In the long run, a transition to a non-fossil era may be possible.

Figure 4 disaggregates the dynamics of primary energy evolution in the USA by source. While the large-scale succession of fuel types is less evident, the figure clearly highlights the evolution and competition of particular energy technologies and infrastructures. Rapid expansion phases of energy sources can be seen over periods of few decades, followed by the more lengthy process of diffusion and adoption in many different market segments. For example, the direct mechanical waterpower is replaced in time by hydroelectricity and feed for working animals is replaced by motor fuels. Despite the simultaneous competition

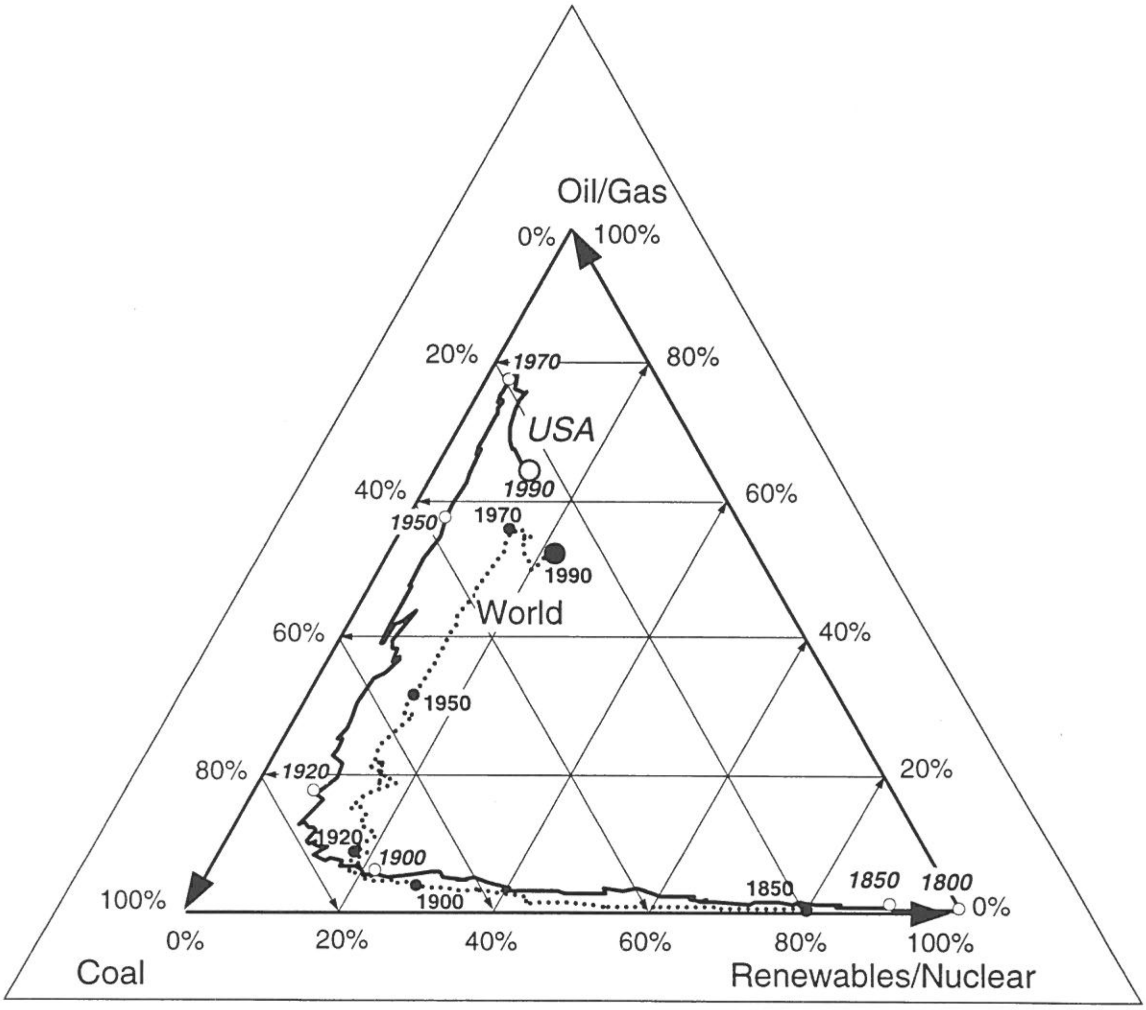


Figure 3: Evolution of primary energy consumption in the USA and the world expressed in form of a triangle. Three edges show shares in primary energy consumption of coal, oil and natural gas, and nuclear and renewable (including) traditional energy sources.

and interaction among many different sources of energy, each of the historical periods is characterized by a clear dominance of one single energy source as indicated by the triangle from Figure 3. Coal was by far the most important source energy for almost a century, followed by the age of oil. The replacement process extends over 50-100 years; energy infrastructures do not rise and fall rapidly.

This evolutionary competition among technologies is not limited to the primary energy system alone. Figure 5 illustrates the evolution of passenger transport technologies in France. This example is used because the data are among the best, but is indicative of similar technological change in other parts of the world including the USA. There is a close relationship between the sources of primary energy and transportation technologies. When fuel wood and animal feed were the prime sources of energy, people traveled mainly by foot (walking and horses) and boat (canals). Most energy was consumed at the point of gathering rather than transported. During the age of coal, railways provided most of the mobility; today, in the age of oil, automobiles provide an unprecedented level of individual mobility in the industrialized countries of the world. Today, most energy is

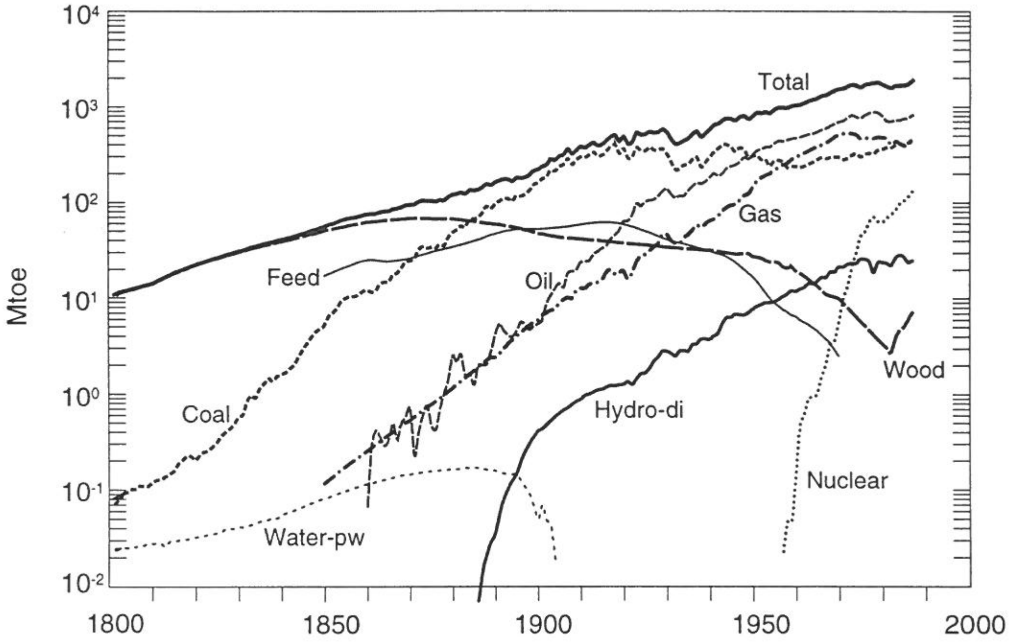


Figure 4: Primary energy consumption by major energy sources in the USA expressed in million tons of oil equivalent (Mtoe).

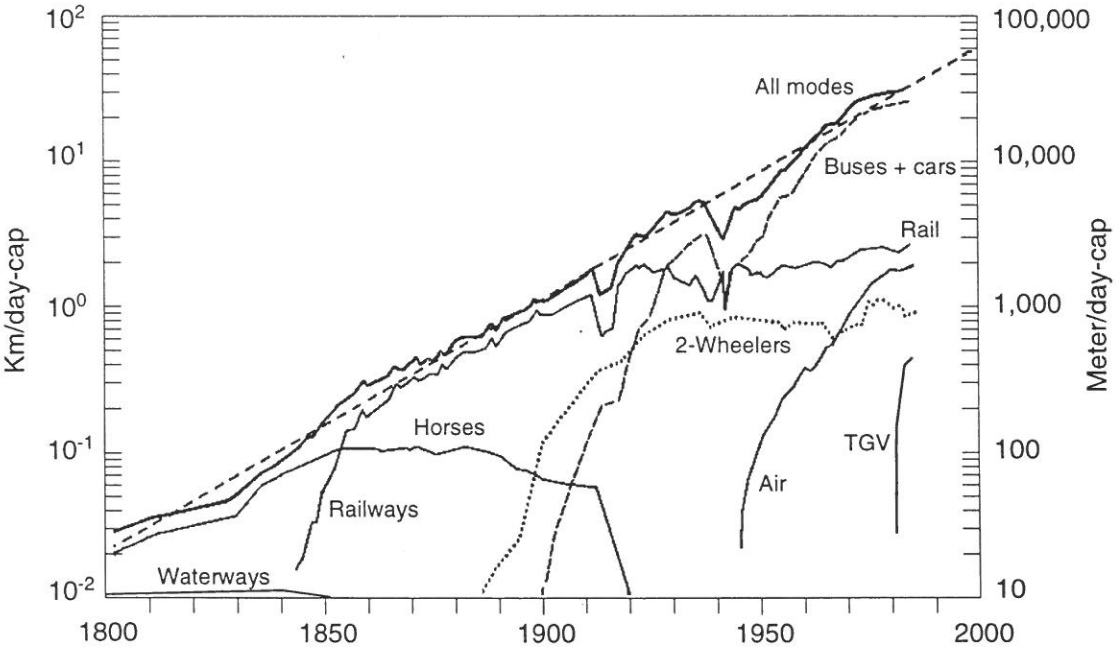


Figure 5: Mobility increase by major transport mode in France expressed in passenger-kilometers per day per capita.

itself transported.

Figures 4 and 5 also illustrate that technologies co-evolve -- innovations, diffusion and replacements occur in clusters. For example, the age of coal was marked not only by the dominance of coal as a source of energy but also by railways as the means of transport and steel as the prime material. Each, co-evolved and cross enhanced each other to create the age of coal. Technological changes occur in many areas of human activity simultaneously and are related. Successful technologies are mainly built to work within existing infrastructures; radical change is difficult and takes a long time.

# From Inventions to Innovations

It is becoming widely accepted among economists and historians of technology that technological change is a fundamental determinant of social progress and economic development. This is well illustrated by the above examples of technological change in energy and transport systems that expanded more than an order of magnitude in two centuries, growing at a typical long-term rate of three to four percent per year.

Yet the dynamics of technological change is external to most models of economic development be it for a whole country, or energy, transport or agriculture sectors alone. Moreover, at present technological change is treated as an exogenous determinant of growth in practically all models of economic and environmental interactions. Drawing on the historical examples of technological change and development, we will show that technological learning and clustering are endogenous driving force of social and economic change.

Every new technology has its roots in an invention, but it is through innovation, commercialization in niche markets and pervasive diffusion that technologies affect the daily lives of people. In a highly stylized manner each technology undergoes a number of development phases starting with basic invention and early development, commercialization in niche markets, followed by pervasive diffusion of the (few) successful technologies in the market place, and ending with a period of maturity and eventually also senescence. This simplified life cycle model of technological development is borrowed from analogies with biological growth and development. The actual processes of technological change - for example, as illustrated for energy and transport systems in Figures 4 and 5 - is more complex, and we will return to that after briefly discussing the case of a single technology.

Each technology starts with some kind of invention, and its economic significance starts with innovation. According to Freeman (1986) the extremely important distinction between invention and innovation goes back to Schumpeter and has since been generally incorporated into economic theory. An *invention* is an idea, a sketch or model for a new or improved device, product, process or system. Inventions are often patented but they do not necessarily lead to technological innovations. In fact, the majority do not. An *innovation* is the first practical application of an invention, sometimes meaning the first commercial transaction involving the new product, process, system or device, although the word is more often used to describe the whole process of going from invention to the market.

Table 1 summarizes the different phases in the technology life cycle. Today, invention

**Table 1.** Phases of technological life cycle.

| Phase | Measure/Mechanism |
|---|---|
| Invention | Basic research and development, breakthrough |
| Innovation | Applied research, pilot and demonstration plants |
| Niche markets | Investment, learning-by-doing and using |
| Pervasive diffusion | Standardization, mass production, economies of scale |

usually refers to *basic* research and development. Inventions can be marginal changes to existing systems, or a completely new idea or unexpected breakthrough. Both of these two phases, invention and innovation, are usually resource intensive; they take a lot of time, and have relatively low success rate. Like in biology, the selection mechanisms are stringent; only a few are chosen. The history of technology is full of examples of wrong choices and promotions of new technologies. The track record of picking the winners is notoriously bad. Thus, diversity and richness of technological alternatives is generally desirable during the early, pre-commercial research and development phase of new technologies.

The distinction between invention and innovation is important for policy. Efforts to generate discoveries and inventions have been increasingly promoted by specialized public and private programs generally referred to as R&D efforts. This reflects the increasing recognition by public and private institutions that R&D are intrinsic prerequisites for economic development. However, today the innovation process is an equally important element of public and private technology polices. Usually it is based on applied research often with an explicit objective to achieve practical demonstration or a pilot project with a promise of commercialization. Invention without innovation does not yield products that diffuse through the market and contribute to economic growth.

# Technological Change and Learning

Neither invention nor innovation have any direct economic importance; rather they are a precondition for a technology to move from the laboratory (basic and applied R&D) to the market. The shift to the market typically occurs in two phases (Table 1); early deployment of the technology in niche markets that leads to commercialization of (few) successful technologies, pervasive diffusion and substitution of older technologies, and eventually market saturation and senescence. Figure 6 gives a stylized illustration of the three phases in the development of a technology.

The economic significance of a technology begins with its introduction in a market place and onset of competition with its alternatives. Initially, this usually occurs in niche markets. New technologies are generally more expensive and in many ways inferior compared to their more mature alternatives. But often they provide a new service of function not possible with the old technologies; e.g., precision of a digital clock compared to the best analog counterpart or speed of a jet airplane compared to the best piston engine powered model.

An attractive feature of new technologies is that they hold the promise of improving

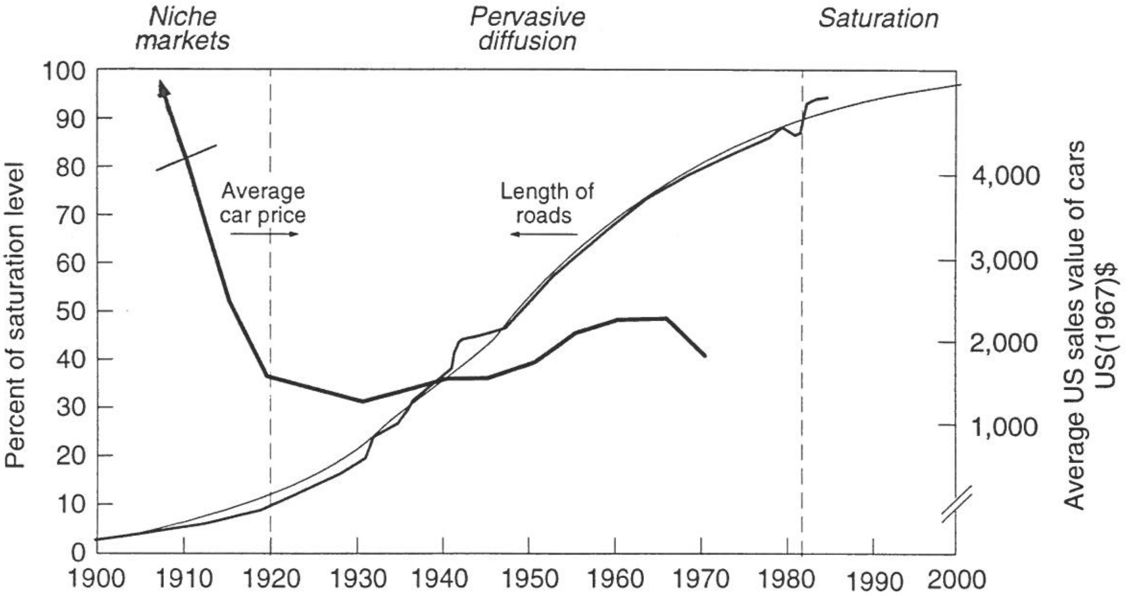


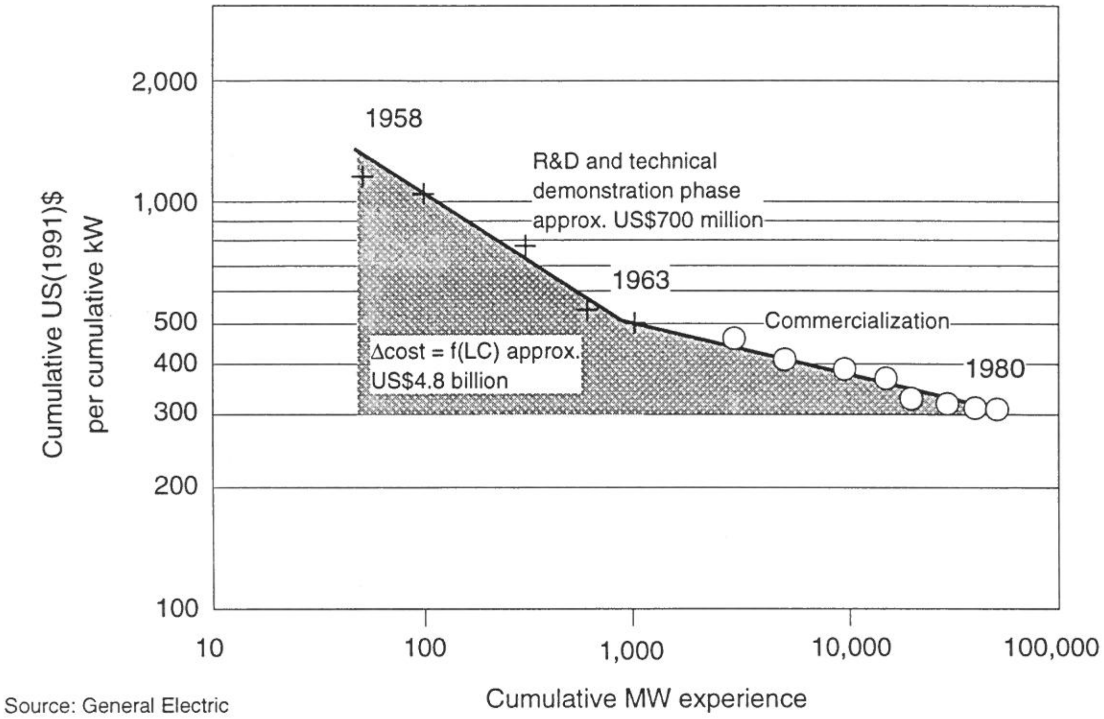
Figure 6: Stylized illustration of three phases in the development of a technology; including commercialization in niche markets, pervasive diffusion and saturation.

market competitiveness in time. The expectation is of declining costs and improving performance with accumulated knowledge. Figure 6 shows declining costs of new technology starting with the introduction phase and accelerating during the growth phase, ending with only incremental improvements with onset of maturity. Figure 6 shows declining costs of automobiles and growth of paved roads in the USA. The rates of improvement of new technologies are typically more rapid than that of their more mature counterparts and this leads to substitution and replacement of older technologies.

Innovation continues throughout the life cycle of a technology - even after a technology has entered the markets. The basic innovation that creates a new technology is followed by incremental innovations which accrete around the basic innovation, which leads to improved performance and reduced costs. This requires investments in innovations even when a technology is already competing in the market, often well before it becomes really competitive and profitable. With successful commercialization and pervasive diffusion, innovation continues in order to achieve even lower costs and better performance. Standardization, mass production,and economies of scale characterize the shift from niche to mass markets.

Common to all of these phases in a life cycle of a technology is accumulated knowledge, often called technological learning - a process of acquiring new knowledge through experience, through doing and using. It is a process of experimentation, competitive selection of a few among many inventions and innovations. Such experimentation and selection are often the most efficient ways to improve performance and lower costs. Some of what is learned is embodied in physical capital; some is much less tangible.

The rates of technological learning can be illustrated for many different technologies by so-called experience or learning curves. The first examples came from the aircraft manufacturing where it was observed that production costs decline in proportion to cumulative output. With every doubling of production, costs decline a fraction. A typical learning



Source: General Electric

Figure 7: Reduction of investment costs for gas turbines for electricity generation as a leaning process expressed in specific investment costs [US(1991)$/kW] versus cumulative installed capacity [MW] on double logarithmic scale.

curve is shown in Figure 7 for gas turbines for electricity generation. The literature is full of numerous other examples (adapted from IIASA-WEC, 1995).

The learning curve in Figure 7 consists of two segments. The first corresponds with the entry into niche markets which led to early commercialization. The second segment is the competitive phase, which led directly to pervasive diffusion of gas turbines; today, gas turbines are the preferred technology for electricity generation. The marginal cost per new unit of capacity has declined dramatically with the cumulative increase in installations. For much of this period, the new technology was costlier than its alternatives and represented an investment activity rather than profit taking. Our estimate is that, together with R&D effort, the total investment approaches some $5 billion before the new technology became competitive on cost basis. This figure does not include any of the original investment in aircraft jet engines before their first derivatives were adapted for electricity generation.

Figure 8 contrasts the learning curve of the gas turbines with two new renewable electricity generation technologies - wind and photovoltaics. Both technologies display rapid learning albeit at high costs. Wind can be competitive under special conditions already today - at sites with steady strong breezes and often with subsidies. Photovoltaics are competitive only in very specialized (and small) market niches such as power sources for remote mountain huts. The question is whether these two new technologies will become economically competitive with more conventional alternatives as installed capacity rises – in other words, whether the learning curves can be extended, as shown, by public and private investors willing to speculate that further (costly) investments will sufficiently

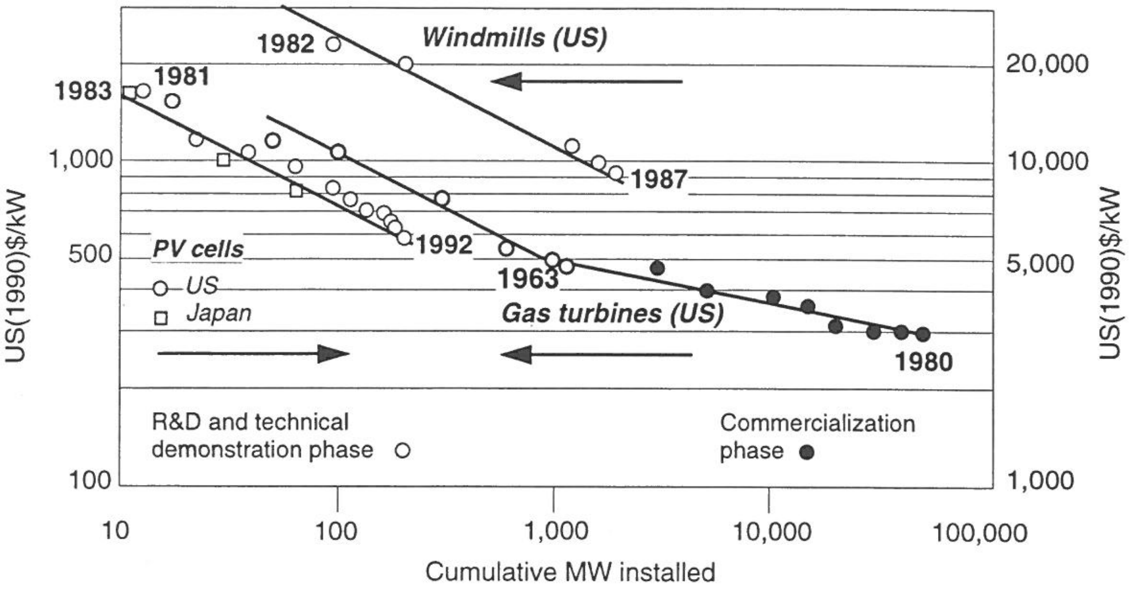


Figure 8: Reductions of investment of costs for three representative new and advanced technologies as a learning process expressed in US dollars at constant 1990 prices per unit installed capacity [US(1990)$/kW] versus cumulative installed capacity [MW] on double logarithmic axis.

reduce costs in the future.

In other words, improvement of performance and reduction of costs of new technologies are not "autonomous" processes; rather, they are an outcome of accumulated knowledge mainly by learning-by-doing. The process of competition in niche and then in wider markets is, indeed, marked by continuous marginal innovations that improve the performance and lower the costs of a basic, core technology. Continuous improvement of technologies beyond the research phase is an important prerequisite for their future competitiveness in the market place.

# Dynamics of Technological Change

There are many examples in the literature of single technologies following the simple S-shaped diffusion curve (shown in Figure 6, each starting with an early exponential growth phase followed by decline of growth rates with the onset of maturity and eventual saturation (and, in some cases, decline). The development of canals in the early nineteenth century offers a reasonable case of simple diffusion. Figure 9 shows that the actual data on the growth of canal networks in the USA (as in many other countries) are approximated very well by a simple S-shaped growth curve - the logistic function. The estimated upper limit of the diffusion process, some 4,000 miles of canals, matches the historical maximum of 4,053 miles of canals in operation in 1851. The characteristic duration of diffusion (or $\Delta$t), defined as the time required for the process to unfold from 10 to 90 percent of its extent, is 31 years.

In some cases, the sequence of technological changes can be shown as a series of S-shaped

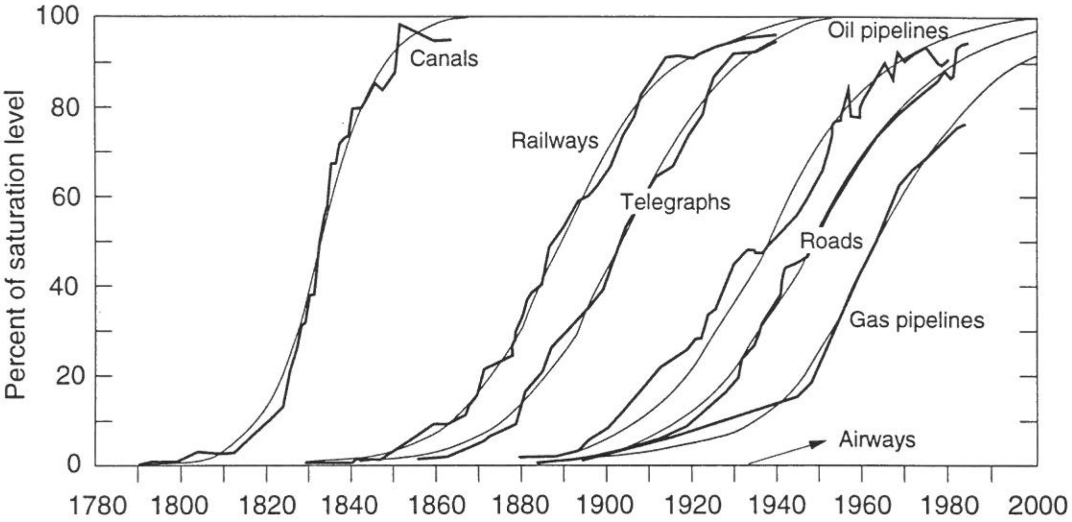


Figure 9: Growth of infrastructures in the USA expressed as a percentage of their maximum network size. Source: Grübler and Nakićenović, 1991.

logistic diffusion curves – one technology follows the next, with each following an S-shaped curve. As Figure 9 illustrates, rails and roads evolved along a dynamic pattern similar to canals. In the figure the sizes of individual networks have been normalized to allow easy comparisons; in absolute values, railways were one order of magnitude larger than the maximum length of the canal network and surfaced roads were, in turn, an order of magnitude greater than the rail network. The duration of growth is somewhat longer. In time, the three infrastructures are spaced rhythmically apart by a half-century or so.

Figure 10 indicates the degree of technological learning achieved especially during the early commercialization phase in niche markets before the widespread diffusion of the transport infrastructures by showing the cost reductions per unit service, e.g., average costs per passenger kilometer transported. Continuous cost reductions and improvement of performance made pervasive diffusion possible. The continuous technological improvement and development are thus an inherent part of technological diffusion and continue even after a technology has already saturated. For example, in railway networks, traffic management systems are improving load factors and average rail speeds, sustaining competition with roads and airways for passengers and freight. A dying competitor – railroads – does not exit without a fight. This is sometimes called the "sailing ship" effect in the literature (see Montroll, 1978).

Like individual technologies, infrastructures often evolve in symbolic clusters. Figure 9 suggests, the railway and the telegraph evolved together – rails and telegraph wires used the same strips of land (rights of way). The road network and the oil pipelines delivering fuel for cars, trucks and buses have also evolved together. This synchronization illustrates interdependence and cross-enhancement of the infrastructures and the particular technologies that infrastructures serve.

Moreover, new technologies do not evolve in a vacuum but rather emerge from existing practices and technologies. One technology replaces or substitutes for another, with varying degrees of direct one-to-one competition and complementary interaction. For example, after reaching its maximum size, the canal network declined rapidly because

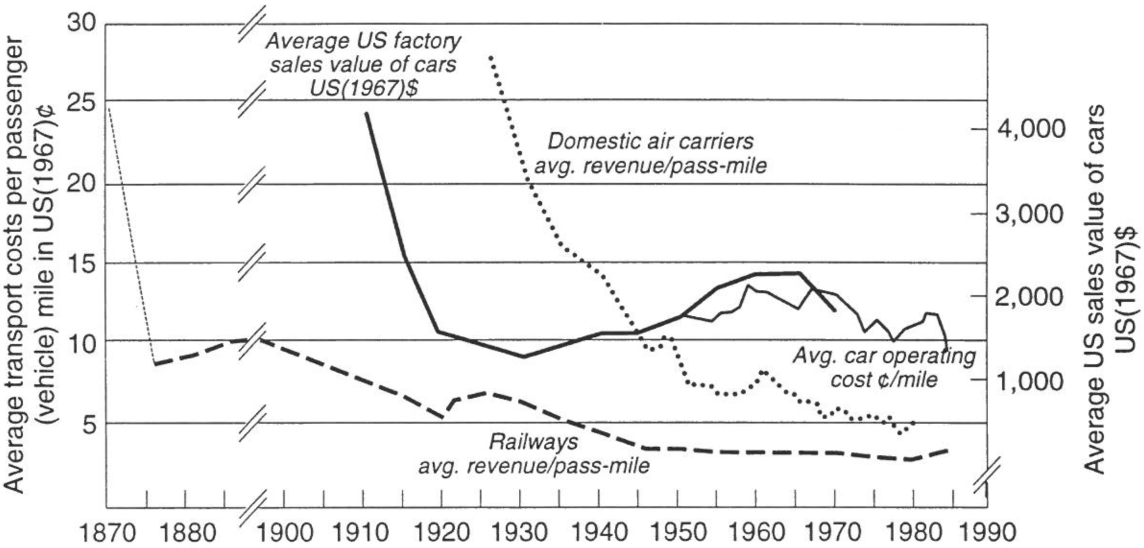


Figure 10: Average costs of passenger transport in the USA [US(1967) ¢/passenger-mile]. Source: Grübler, 1990).

of vicious competition from railways. Looking at relative "market shares" of competing alternatives rather than at absolute volumes makes the interaction visible. First, we will consider direct one-to-one competition among two technologies that substitute each other; the new replacing the old. Then, we will consider more complex cases of multiple technological substitution involving simultaneous replacement of more than two competing technologies.

Probably the most famous case of technological substitution is motor cars for horses. In this case, the diffusion of one technological artifact, the passenger car, began simply by replacing another, the riding horse and the carriage. Looking at the absolute numbers of draft animals and cars in the USA in Figure 11, we see that the millions of horses and mules used for transport practically disappeared from the roads within fewer than three decades. Figure 12 shows the logistic substitution process in terms of relative market shares. The time constant ($\Delta t$) of the replacement process was only 12 years, fast enough to traumatize the oat growers, coachmen, blacksmiths and (fatally) the horses. Interestingly, the diffusion of modern low-emissions vehicles, the regulated catalytic converter cars, also occurred with the time constant of 12 years in the USA (Grübler, 1997, Nakićenović, 1986). Replacement of railway rolling stock and substitution of steam by diesel-electric locomotives are among the many examples with similar decade-long time constants - they are cases of single technologies competing in a common infrastructure constants in the same range across many examples for different countries.

The competitive sequence of horses, trains, and cars brings us to consider the most general and frequent process of technological change: multiple competing technologies. Figure 13 gives such an example for the evolution of domestic intercity passenger traffic in the USA. The fraction of total intercity traffic "market share" is shown together with smooth lines representing the model estimates of the substitution process. Cars contribute about 90 percent to total domestic mobility while the role of public transport systems by rail and road is rapidly declining. Airways are expanding, which partially reflects the long distances and low population densities across the country.

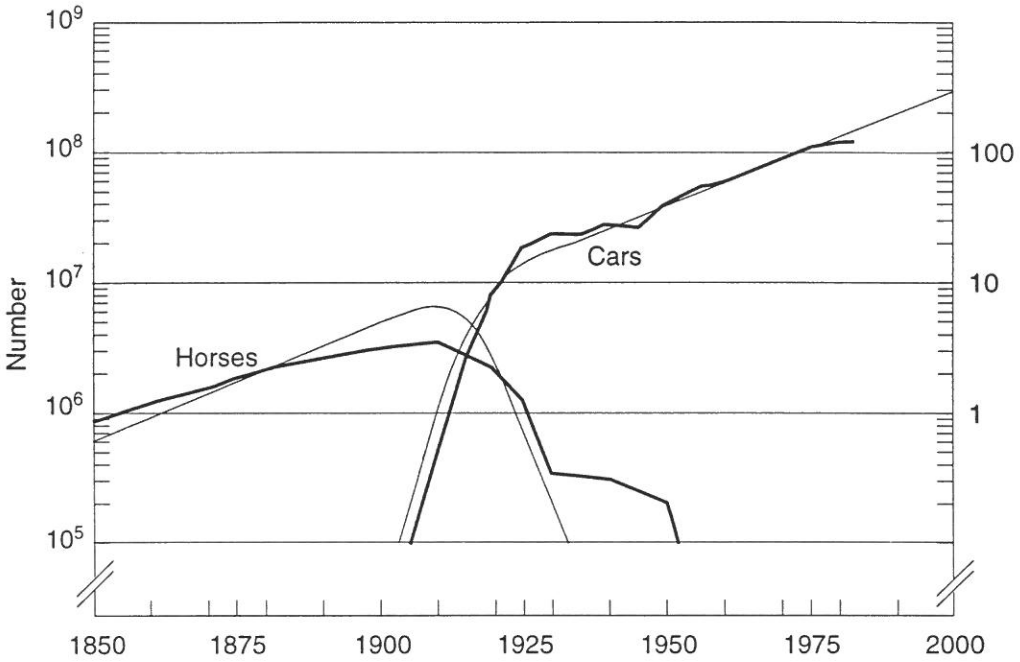


Figure 11: Number of non-farm draft horses and automobiles in the USA. Source: Nakićenović, 1986.

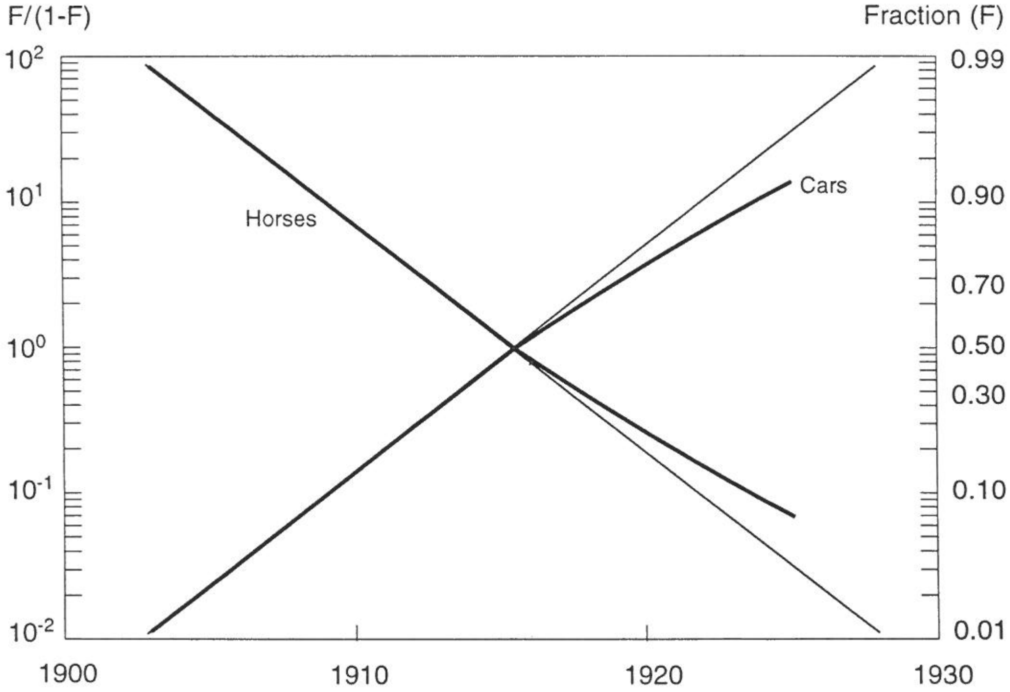


Figure 12: Logistic substitution of draft horses by cars in the USA expressed as fractional market shares (F) and transformed as F/(1-F) on logarithmic axis.

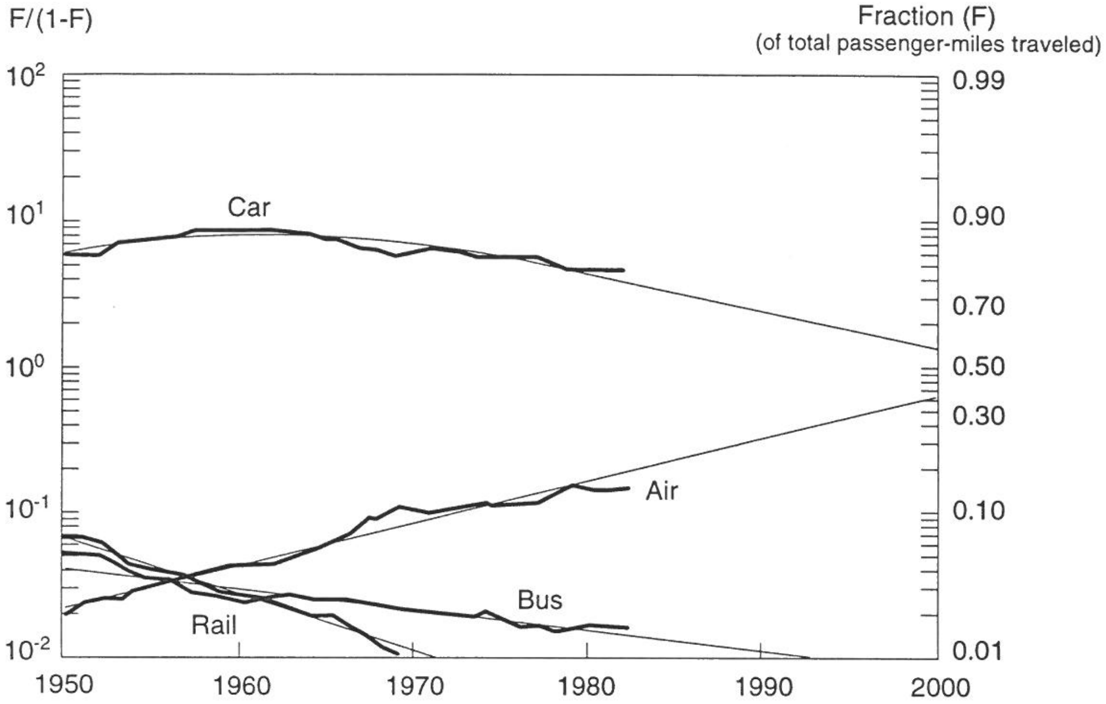


Figure 13: Logistic substitution of passenger intercity transport modes in the USA expressed as fractional market shares in total travel (F) and transformed as F/(1-F) on logarithmic axis.

Going back to the case of transport infrastructures from Figure 9, their competitive struggle can also be represented as a substitution process as is shown in Figure 14. Also shown is the equivalent substitution process of transport infrastructures in the USSR. Time constants of this substitution process are long and increasing in time. While the decline in the relative importance of canals proceeded with a time constant of about 45 years, that of the railways and roads took about 80 years, and the diffusion of airways may take even longer. The main difference between the USA and the USSR is the slowly diminishing lag in the substitution process leading to the USSR catch-up.

These examples underscore that the dynamics of technological substitution are slower for infrastructures and other systems associated with high investments and longevity, while they are swifter for equipment and processes with shorter life-times such as vehicle fleets or household machines. It is the long time constants of infrastructures that determine in a fundamental way the pace and direction of technological change as more dynamic processes compete at lower hierarchical levels within the system. Urban structures condense along transport infrastructures; work patterns evolve in response to changing commuting possibilities. Many features of infrastructures thus become frozen by human activities. Consequently, it takes many decades before a fundamental change in the technological systems can occur despite rapid change in many of its component parts.

The evolution of primary energy consumption from Figure 4 can also be represented as a technological substitution process as shown in Figure 15. Time constants are long and remarkably invariant for the seven sources of primary energy in the USA. The characteristic duration is about 80 years indicating a strong infrastructural dimension of the energy system. Similar diffusion patterns prevail in many other countries and at the

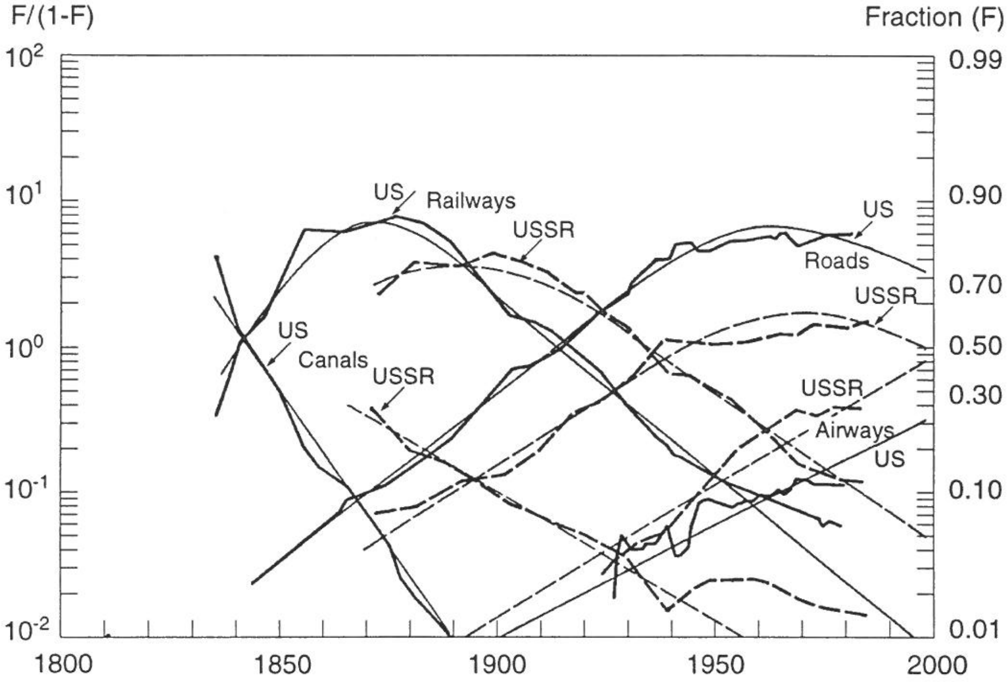


Figure 14: Logistic substitution of transport infrastructures in the USA and the USSR expressed as fractional market shares in total infrastructure length (F) and transformed as F/(1-F) on logarithmic axis.

global level. Consequently, if historical dynamics are used as a guide, more than fifty years are required to achieve a fundamental transition in the energy system. Projecting the substitution process into the future implies that fossil sources would continue to be the dominant form of energy during the next decades with an increasing share of natural gas. Alternative sources of energy, such as the new generation nuclear and renewable forms, are unlikely to achieve large market penetrations during this period. The development of alternative forms of energy, however, needs to proceed swiftly if they are going to fulfill the promise of more environmentally compatible energy patterns in the next century. A radically different energy system by the end of the 21st century will require substantial penetration of such new technologies and infrastructures in the next few decades.

Other technological systems can be analyzed from the same perspective of dynamics in time and space. For example, in steel manufacturing as many as four technologies have competed simultaneously with decreasing and increasing market shares. Figure 16 shows that the diffusion trajectories of the processes are diverse, with the time constants ranging from less than two decades for the replacement of crucible process to nearly seven decades for the diffusion of electric arc steel in the USA. The substitution processes are not so regular as was the case for energy and transport, the dynamics change but the patterns are the same as in the other two examples. This means that technological change portrays invariant patterns across a large and diverse set of historical examples.

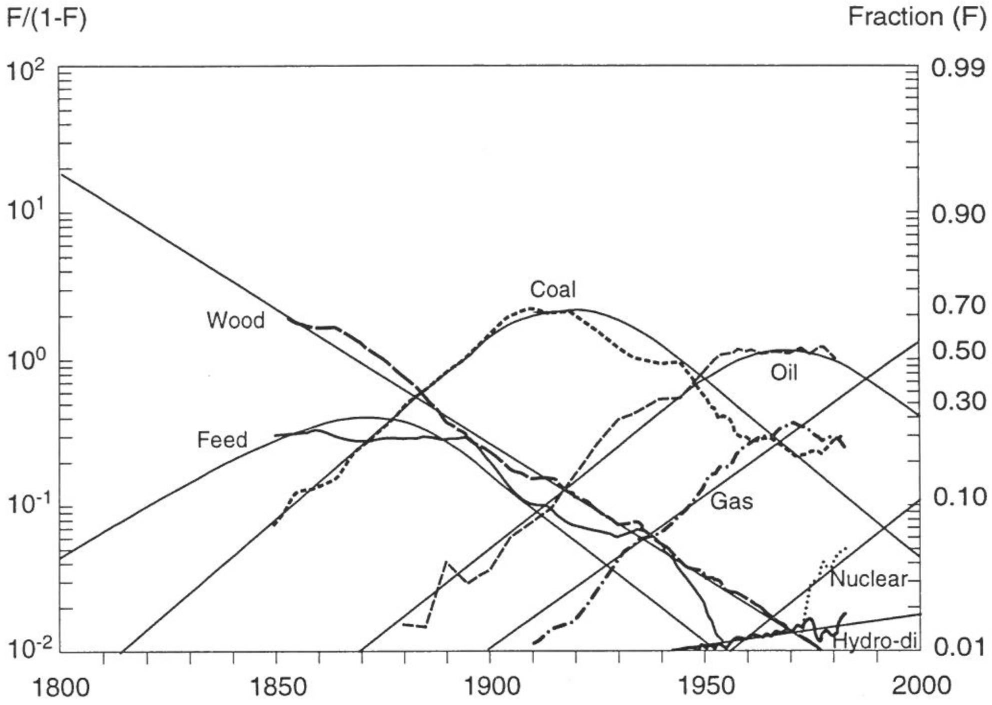


Figure 15: Logistic substitution of primary energy in the USA expressed in fractional market shares (F) and transformed as F/(1-F) on logarithmic axis. Source: Nakićenovicć, 1987.

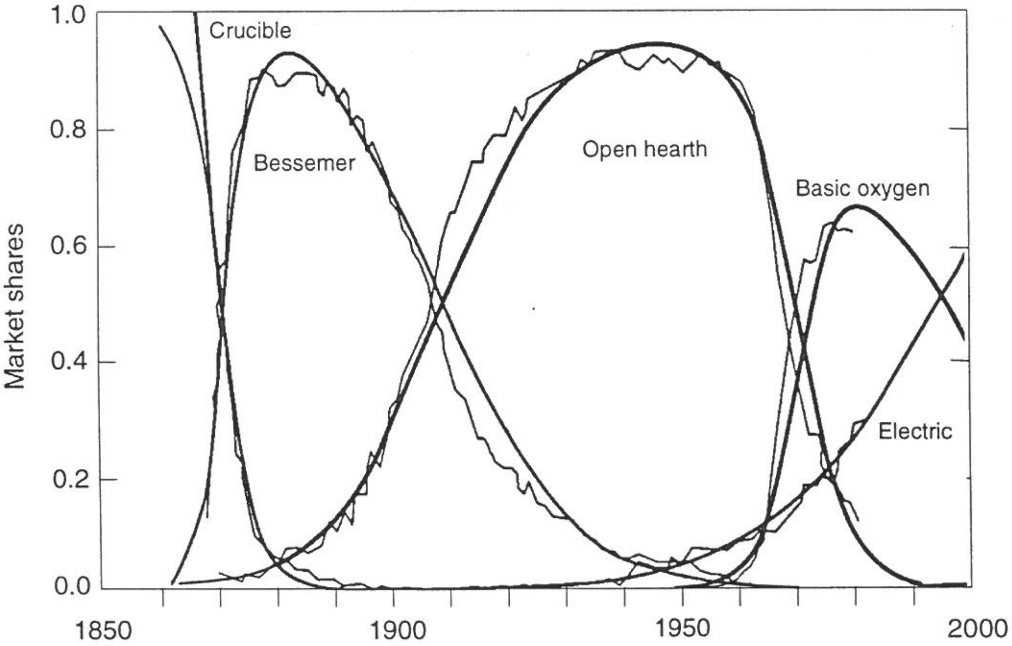


Figure 16: Process technology change in steel manufacturing in the USA expressed as fractional shares (F) of raw steel tonnage produced. Source Nakićenović, 1987.

# Technological Diffusion Clusters

We have noted the close relationship between the successive systems of technologies – in the case of energy and transport systems: first, between fuel wood, draft animals and canals; followed, second, by coal and railways, and, finally, oil and automobiles. Each of these three development phases is characterized by a cluster of basic innovations that gave rise to respective technology systems. In fact, each cluster develops through a whole family of new, interdependent and mutually cross-enhancing, technologies with associated new institutional and organizational settings. For example, the development of the automobile and the automotive industry was contingent on developments in materials (high-quality and wide steel sheets), the chemical industries (oil refining, in particular catalytic cracking and octane enhancing additives), production and supply infrastructures (exploration and oil production, pipelines, gasoline and service stations), and development of public infrastructures (roads, bridges, and parking areas).

The growth of the industry was based on a new production organization (Fordist mass production combined with Taylorist scientific management principles), yielding significant real-term cost reductions that made the car affordable to more social strata, thus changing settlement patterns, consumption habits of the population, leisure activities, and many institutional arrangements such as insurance and traffic regulation. Of particular significance are the enormous reductions in the costs of producing automobiles and the related goods and services (fuel, steel, plastics, electronics) through technological learning. The automobile is just one artifact of the automobile age.

These linkages multiply the effects of such technological diffusion clusters on the economy and society and account for their pervasive impacts (Grübler, 1997). The technologies are connected by web-type structures at many hierarchical levels. They can share related subcomponents such as internal combustion engines, electric motors or digital processors, and they can share in the provision of services such as transport. They compete directly or indirectly, but they can also have symbiotic character. It is for these reasons that many related technologies diffuse in unison; they may be characterized by different time constants, some may be introduced earlier and others later, but they tend to cluster to form technological diffusion clusters. A large number of technologies needs to mesh with each other for a cluster to form. By themselves individual technologies have little direct economic impact, but together they are linked into whole growth sectors creating productivity increases, new goods and services, new human activities and affluence.

These technology diffusion clusters can be documented internationally. Although we have focused on examples from the USA in this paper. The same phenomena occur in different countries and sectors. It is the pervasiveness of these clusters that leads to the labeling of the whole economic development phases by phrases such as the age of "railways" or "coal". Figure 17 summarizes the empirical evidence of these technology clusters based on numerous examples studied to date (e.g., see Grübler, 1997; Grübler and Nakićenović, 1991). For example, we have shown the diffusion of canals, railways, automobiles in the USA, and they are also reproduced in Figure 17 together with the equivalent technology clusters in several other countries. Given below each era denoting a diffusion cluster is a list of the various technologies belonging to it.

As mentioned earlier, there is a considerable heterogeneity in the dynamics of individual

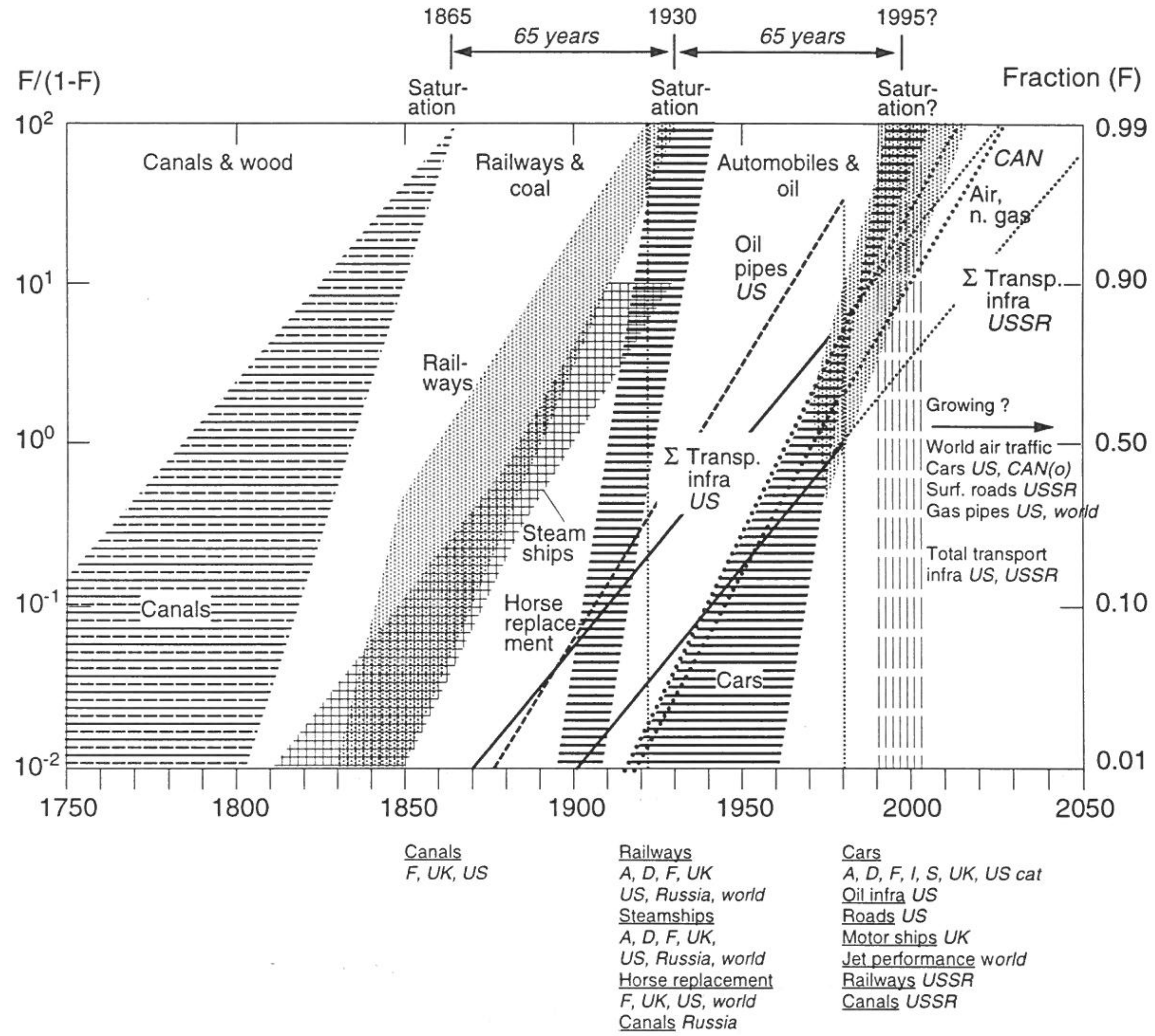


Figure 17: Three technological diffusion clusters - wood and canals, coal and railways, and oil and automobiles. Examples are from many countries. Diffusion processes are expressed as percentages of their saturation level (F) and transformed as F/(1-F) on logarithmic axis. Source: Grübler and Nakićenović, 1991.

technologies within a cluster; thus the "focusing" of the three clusters is not very pronounced. Individual technologies diffuse with different time constants and starting dates; some technologies overlap between clusters. Nevertheless, three rather clear clusters can be distinguished. The first saturates around 1865, the second around 1930, and the third saturated two years ago in 1995. Due to the overlap of technologies between clusters, one might speculate that the fourth cluster of technologies has been already launched, but is not yet clearly perceivable due to the insignificant degree of diffusion achieved to date by the key technologies that might constitute this new cluster. For example, the new emerging cluster might be one day characterized by decarbonization and dematerialization. It could be based on interaction among natural gas, hydropower, fuel cells and advanced turbines in the energy area, among new approaches to miniature production and conversion processes, such as micro- and nanotechnologies, and among bioengineering and advanced communication systems.

Each of the three historical clusters converges toward its respective saturation period. The "focusing" of each diffusion cluster increases as it matures. This is partially due to the increasing interdependence among the technologies that constitute a cluster as they achieve widespread adoption. It is partially also due to the more rapid diffusion into geographical areas or markets where technology is adopted late. This compensates for the lags in introduction of innovations between the early and late adopters – between the core and the periphery in spatial technology diffusion. The increasing focus of the clusters is partially enhanced by the increasing lag of latecomers to introduce the new technology as diffusion progresses internationally but in conjunction with faster diffusion rates once the technology is introduced. This catch-up effect is especially pronounced near the saturation of a technology cluster. This phenomenon has been documented for many technologies that have diffused throughout core and new periphery markets.

There is some more limited evidence suggesting that the absolute adoption level of a technology is lower for the latecomers compared with the early innovators. For example, historically the saturation density of railroad networks in many countries has been lower if the country was a latecomer, though the diffusion rate was higher. In other words, the ultimately achieved railroad density is in general higher the earlier the railroads are introduced – leaders achieve the highest diffusion levels. The same phenomenon can be observed in the adoption of the automobile in different countries. Early adopters, such as the USA, have the highest per capita diffusion of automobiles; the level of automobile penetration achieved in other countries has decreased in proportion to the automobile introduction lag.

Figure 18 illustrates in a highly stylized and perhaps oversimplistic manner the diffusion of a technology in time and space according to the paradigm of S-shaped adoption path, shorter time constants for latecomers together with lower absolute adoption level by the time saturation occurs simultaneously in time and space. It also illustrates the "focusing" of diffusion clusters. This schematic diagram refers to the diffusion of only one hypothetical technology and not to the evolution of the whole technology cluster. Nevertheless, the illustration shows that the diffusion of each technology portrays a characteristic space-time structure.

It would be difficult to portray a whole cluster as a system of space-time structures of individual diffusion processes, but as long as the technologies that constitute an individual cluster constitute families of interrelated processes that enhance each other, together they would tend to promote the pervasiveness of each of the three successive diffusion clusters and their increasing "focus" toward saturation period. In other words, each diffusion cluster is a network of interrelated technologies that reinforce and build upon each other. Classification of technologies that constitute a cluster would probably reveal a hierarchical system with one successful diffusion yielding a positive externality and a catalytic effect on the development of many other within the same cluster. In this sense, the clustering of technological diffusion processes is an *endogenous* phenomenon resulting from the interdependent network structure. Clusters are not coincidental.

One further evidence for the emergence of technology clusters is the empirical distribution of diffusion time constants ($\Delta t$'s) for two samples of technologies in the USA (Grübler, 1997). The histogram of the time constants for the two samples is shown in Figure 19. Sample A is based on 117 case studies performed at IIASA and sample B includes 265

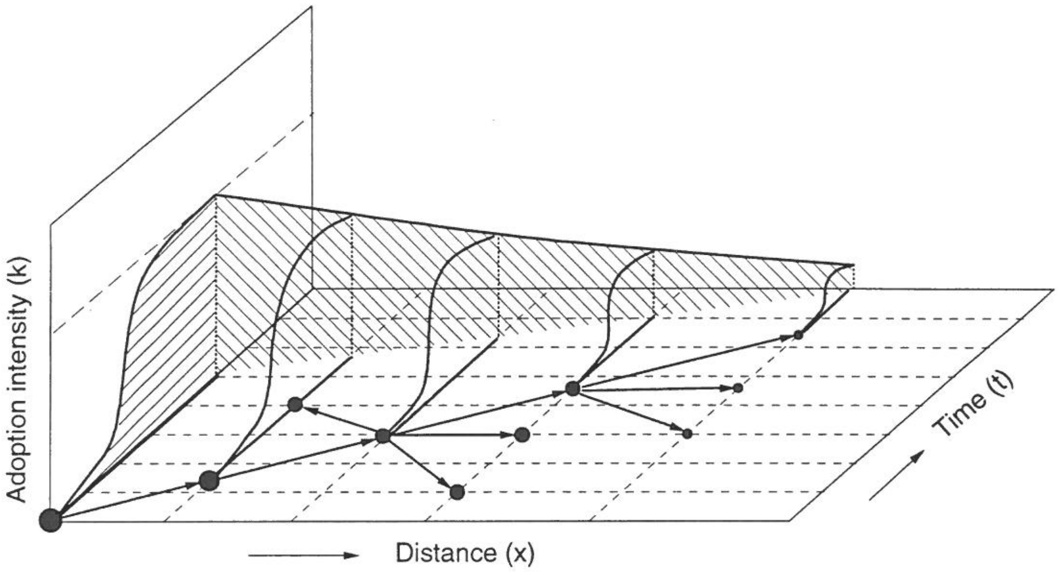


Figure 18: Stylized illustration of technology diffusion in time and space according to the paradigm of S-shaped adoption path, showing shorter time constants for latecomers together with lower absolute adoption level by the time saturation occurs, simultaneously in time and space.

additional, well-documented diffusion cases with quantification of time constants from the literature (Grübler and Nakićenović, 1991). The case studies include diffusion of energy, transport, manufacturing, agriculture, consumer durables, communication, and military technologies, as well as diffusion of economic and social processes, such as literacy, reduction of infant mortality, and changes in job classes.

The distribution of diffusion time constants ($\Delta t$'s) is quite similar for the two samples. In general, the histogram portrays long-tails similar to Pareto or rank-size distributions. The diffusion time constants range from very short-term processes of only a few years to processes that extend over two to three centuries.

The mean value of the time constants is in the range of between forty and sixty years, with a standard deviation of about equal size. This is in a very good agreement with the mean duration of diffusion clusters shown in Figure 17 indicating that the majority of technologies shown on the figure diffuse and saturate within the duration of a single cluster. The largest number of diffusion processes have characteristic time constants of between fifteen and thirty years. There are very few diffusion processes that span more than one cluster by extending over a century. A good example for long diffusion time are energy and transport infrastructures.

This empirical distribution implies that most of the technologies and artifacts can be replaced within a few decades, but also that some key technologies and socio-economic processes have demonstrably long durations. Pervasive transformations and changes take a long time and span more than one technology diffusion cluster.

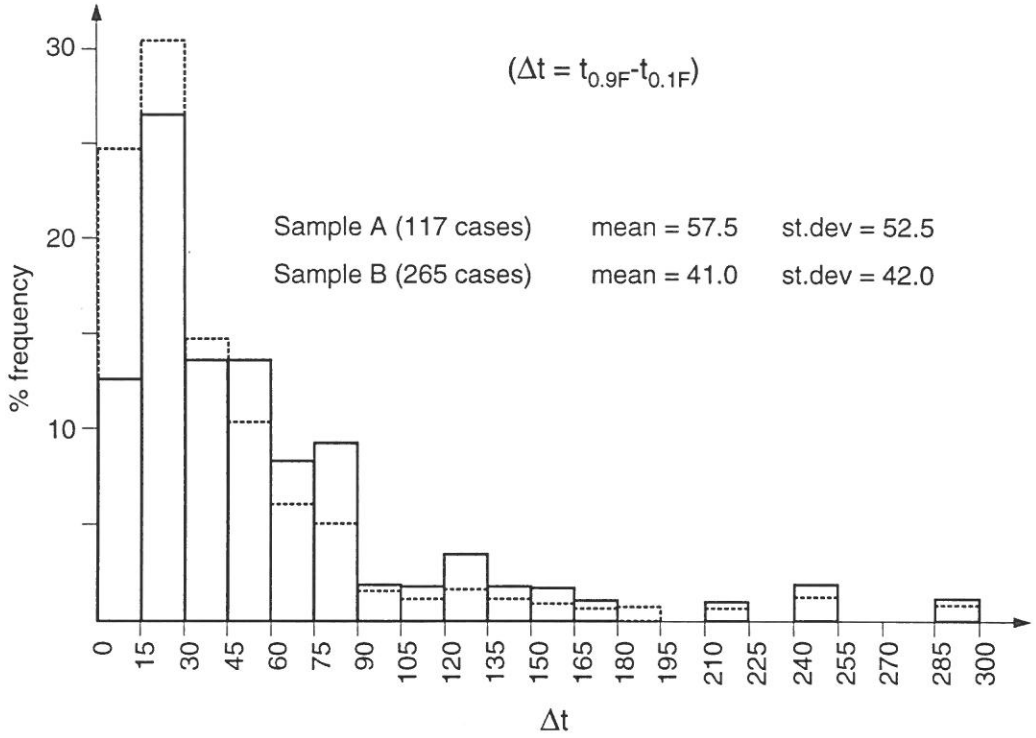


Figure 19: Histogram of diffusion time constants (Δt) for two different samples in the USA expressed as relative frequency of occurrence of different Δt's in the two samples. Source: Grübler, 1997.

# Conclusions

Technological change in the energy sector is characterized by long time constants. It takes anywhere between 20 to more than 50 years before much of the energy-related capital stock turns over. This means that during the next century the energy systems would be replaced on average at least once. At the same time this also means that about 50 years will pass before a fundamental change and a transition to new energy technologies can occur. Premature replacements would be very costly.

Technological change can be viewed as a social learning process. Typically it takes a long time and investment before technologies are brought to markets from the occurrence of the initial innovation. Still more time and investment is required for pervasive diffusion of successful technologies. In other words, improvement of performance and reduction of costs of new technologies are not "autonomous" processes, they are an outcome of accumulated knowledge from learning-by-doing. Development of technologies beyond the research phase is an important prerequisite for their future competitiveness in the market place.

In order to achieve a transition toward less carbon intensive and zero-carbon technologies during the next 50 years or so, the development of these technologies needs to be underway now. This requires the development of a whole cluster of new technologies and not just energy supply systems. Technological innovation and diffusion is generally easy and rapid for incremental improvements of current technologies, such as efficiency improvements of heat pumps or gas turbines. But careful attention to all phases of technological development – not just invention – is a central issue for successful diffusion of more radical innovations that could form the next technology cluster. For example, the wider deployment of new renewable technologies would generally also require different energy transformation and end-use systems compared with the present infrastructure. In transportation, an example of incremental innovation is intercity fast train that generally does not require new infrastructure for its deployment, while the magnetic levitation (Maglev) train certainly represents a radical innovation and a radical departure from the current concept of railways.

Perhaps the most crucial issue is how to promote increased technological learning at minimal costs. Clearly, improvements of fossil energy technologies will occur; thus future alternatives to fossil fuels must improve at higher rates to become economically attractive and competitive in a market place. New technologies are generally more expensive and in many ways inferior compared to their more mature alternatives. However, the learning rates of new technologies are more rapid provided that niche markets exist or are created and provided that this is a continuous process.

The history of technology is full of examples of wrong choices and promotions of new technologies. The track record of picking the winners is notoriously bad. Thus, diversity and richness of technological alternatives is generally desirable during the early, pre-commercial research and development phase of new technologies. After that comes a long phase of market introduction and promotion. This phase is generally characterized by high investment and financial risk. The new technology is usually costlier than its alternatives, but holds a promise to provide a new or improved service.

The tentative conclusion concerning energy futures is that it would be very costly to prematurely replace energy capital stock with new technologies. However, it is crucial to make early investments in creating niche markets for these new technologies so that their performance and costs can decrease sufficiently during the next decades to become more attractive alternatives in the market place. If successful, these technologies could comprise the next diffusion cluster.

Further decarbonization of energy system is unlikely to occur with current fossil fuel-based technologies. A prerequisite is new cluster of innovative technologies to promote enhanced energy productivity, efficiency and environmental quality. Decarbonization is not an autonomous process and thus should not be looked at apart from how it is achieved. In fact, many coal-rich countries plan on further carbonization of their energy systems. In general, the shift from coal to oil was achieved for both economic and environmental reasons. If natural gas becomes an energy bridge to the future, significant decarbonization will occur, regadless of the political fate of the climate change.

It is useful to view decarbonization as a learning process. Figure 20 recaptures the historical decarbonization trend in the USA from Figure 1 as a learning process. The progress ratio is relatively high compared with other technology learning curves analyzed so far in this paper. For every doubling of economic output, the specific carbon dioxide emissions per unit economic activity decrease by about one third. This learning process spans two centuries; for it to continue, a new cluster of innovative technologies is required.

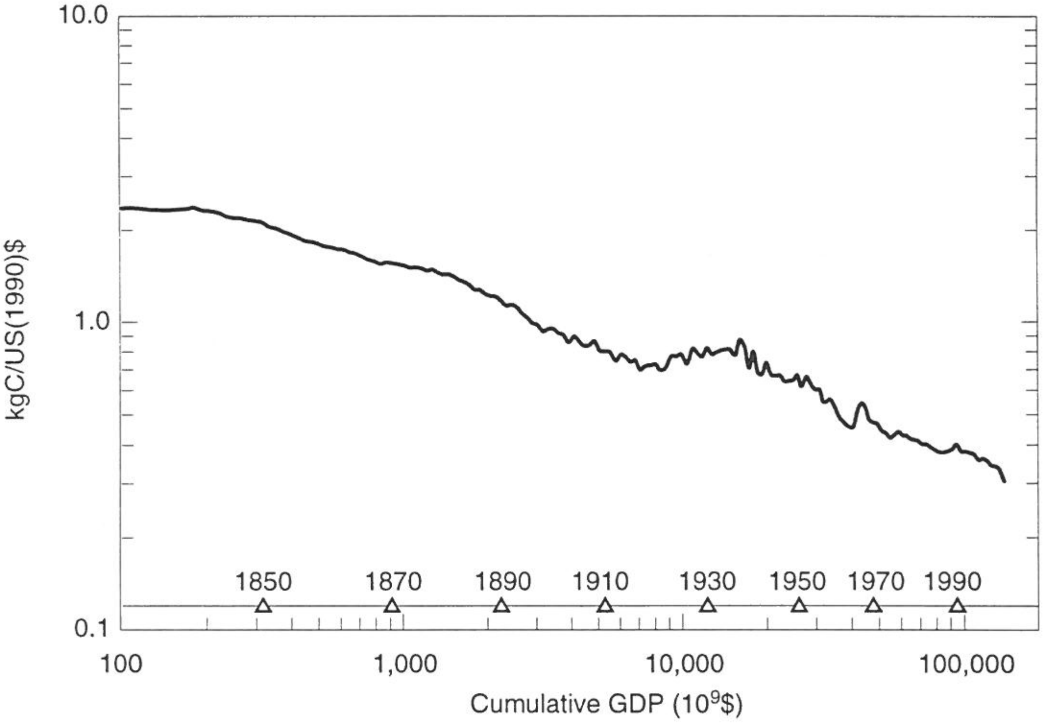


Figure 20: Decarbonization of economic activities as a learning process in the USA expressed in kilograms of elementary carbon per unit of GDP at constant 1990 prices [kgC/US(1990)$] against cumulative GDP [$10^9$US(1990)$] on double logarithmic scale.

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