Technology and the Transition to Environmental Sustainability:

The Problem of Technological Regime Shifts[1]

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The present environmental problems call for more environmentally benign technology. This article examines the possibilities of achieving radical change in technology like a shift away from hydrocarbon-based energy technologies. We provide an explanation as to why such a change is likely to be a gradual and slow process. Radical technologies often have long lead-times and require for their operation special skills, infrastructure and all kinds of institutional changes (organizational changes, regulation, new ideas and values etc.). Furthermore, the short-term costs are likely to be high as the new technologies have not yet benefitted from dynamic scale and learning effects (that result in cost reductions per unit of output and evolutionary improvements in the technology). The article also provides some answers as to how it is possible for firms with restricted technological capabilities to bring about a shift into a new technological regime – emphasizing the importance of early market niches, available knowledge that may be used, institutional support, and the role of expectations. And finally, we look at niche management as a way to manage the transition towards a more environmentally sustainable energy system.

1.Introduction

The past two decades witnessed a heightened concern over environmental degradation. Of the various options open to society to reduce the environmental burden, technology is widely considered as the most attractive option. Whether technology alone will be sufficient to achieve an

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environmentally sustainable future is unclear. This will depend on public and private support for environmentally beneficial technologies and the extent to which further growth in world population and economic output will compromise per capita emissions reductions and a more efficient use of natural resources.

This article examines the technology dimension in achieving a sustainable economy and analyzes the possibilities of inducing large-scale technological transitions – that is a change in our basic technologies of production, transport and consumption rather than modifications of existing products and processes or the adoption of end-of-pipe technologies. Certainly, the installation of pollution control devices and re-use systems, the introduction of environmental care systems, and the modification of existing technologies are necessary if we are to achieve a sustainable economy. However, such changes alone will be largely insufficient for achieving the ultimate goal of sustainable development. To achieve that, more fundamental changes in technology are needed such as a switch away from hydrocarbon-based energy supply, conversion and end-use technologies (towards the use of renewables or electric vehicles powered by batteries or fuel cells) or the replacement of car commuter traffic by interactive telecommunication systems allowing for activities like telework and teleshopping.

The problem of inducing such shifts in complex technological systems poses a formidable task for policy makers, as it involves not only a change in technology, but also quite fundamental changes in production, organisation and the way in which people live their lives. The aim of this article is to examine some of the general issues involved in the change in complex technological systems, with a general focus on environmentally sustainable technologies. Rather than examining the specific technical, economic and social aspects of a transition to more environmentally benign technologies (like photovoltaics or intermodal shifts within the transport system), we are exploring the broader question of how technological systems evolve and change.

The article is organized as follows. Section 2 looks at the various technology concepts employed by different writers to account for the ordering and structuring of technology. While acknowledging the importance of shared engineering beliefs and expectations in the direction of technological change, this section stresses the socio-economic dimension in the stability of a technological regime. Section 3 discusses shifts in technological regimes as opposed to changes *within* a technological regime or system. Key factors in inducing and sustaining shifts in technological regimes are identified and discussed, using historical examples to illustrate theoretical arguments. Section 4 deals with the relation between shifts in technological regimes and firm behaviour. It asks the following questions: How do new technological systems come about in a world of specialization and decentralized decision-making? How are ideas of radically new technologies that require a different knowledge base and production capabilities, translated into tradeable products? Section 5, finally, explores some of the policy issues in achieving a shift towards a more sustainable energy system, away from hydrocarbon-based energy technologies.

2.Technological Patterns

That technical change is not a haphazard process but proceeds in certain directions is by now widely recognized. Examples of persistent patterns of technical change, given by Donald MacKenzie, are the increasing mechanization of manual operations, the growing miniaturization of microelectronic components, the increasing speed and computer operations.[i] Other examples of patterns in technological change are: reductions in material requirements in products, the trend towards the use of lighter materials (in automobiles and aircraft), the use of electronic components in consumer products and equipment etc. There also exist relatively stable patterns in the usage of products and processes. In the western world, cars only gradually came to dominate other modes of transport (horse-drawn carriages and later on trains) in the last 100 years. Oil and natural gas became dominant energy sources over a period of half a century. It even took almost a whole decade for a simple product such as the ballpoint to become widely used.

Economists, historians and more recently sociologists have studied these regularities in technological change and have come up with concepts to account for the ordering and structuring of technology. We will describe some of these concepts. Richard Nelson and Sidney Winter use the concept of a "technological regime" which defines certain boundaries for technological progress and indicates directions in which progress is possible and worth doing.[ii] The concept of a technological regime relates to technicians' beliefs about what is feasible or at least worth attempting – implying that cognitive aspects are considered important. Nelson and Winter give the example of the DC3 aircraft in the 1930s which defined a particular technological regime: metal skin, low wing, piston powered planes. As they write: "Engineers had some strong notions regarding the potential of this regime. For more than two decades innovation in aircraft design essentially involved better exploitation of this potential; improving the engines, enlargening the planes, making them more efficient".[iii] In a study by Georghiou *et al* on post-innovation improvements and competition the concept of a "technological regime" is further developed and defined as:

> a set of design parameters which embody the principles which will generate both the physical configuration of the product and the process and materials from which it is to be constructed. The basic design parameters are the heart of the technological regime, and they constitute a framework of knowledge which is shared by the firms in the industry.[iv]

The concept of a technological regime is illustrated by the example of a plastic-bodied, electrically powered car, being part of a new technological regime as the material properties of plastics, the functioning of electric motors and the manufacturing of such a car requires a different knowledge base, different types of engineering skills, linkages with information networks and interactions with different supply industries.[v] Such a technological regime does not imply a unique design. A technological regime usually consists of a set of design configurations, which forms the basis for competition, research activities and agenda of development of individual firms or business units.[vi]

Technological advance may also extend particular technologies, in which case Nelson and Winter speak of general trajectories. Four types of such general trajectories are identified: latent scale economies, mechanization of operations, electrification (and the use of electronic components) and the development of chemical technologies. The search heuristics underlying these types of trajectories offered "natural" ways to reduce costs, increase reliability and precision of production, and achieve products improvements.

The idea of a common technological framework guiding research activities is also the central element of the concept of a *technological paradigm* developed by Giovanni Dosi, which has been highly influential in the field of the economics of technical change. The concept of technological paradigm refers to Kuhn's concept of a scientific paradigm and Lakatos' theory of scientific research programmes from the philosophy of science. It is chosen by Dosi because the procedures and the nature of technologies are believed to be broadly similar to those which characterize science. Just as scientific research is aimed at solving particular problems or puzzles (while neglecting others) on the basis of a certain body of knowledge and the application of search heuristics, so are problem-solving activities by engineers employed in organizations to develop or improve products that may be sold in the market place. Whereas a scientific paradigm may be defined as an "outlook" which defines the relevant problems, a "model" and a pattern of inquiry, a technological paradigm is defined by Dosi as a "model" and "pattern" of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies.[vii] Elsewhere Dosi writes:

A technological paradigm defines contextually the needs that are meant to be fulfilled, the scientific principles utilized for the task, and the material technology to be used. (...) A technological paradigm is both an *exemplar* – an artifact that is to be developed and improved (such as a car, an integrated circuit, a lathe, each with its particular techno-economic characteristics) – and a *set of heuristics* (e.g. Where do we go from here? Where should we search? What sort of knowledge should we draw on?).[viii]

Examples of technological paradigms are the internal combustion engine, the oil-based chemistry, and semi-conductors.

An important characteristic of a technological paradigm, and the concept of a technological regime, is that there exists a core technological framework which is shared by the entire community of technological and economic actors as the basis upon which one looks for improvements in process efficiency and product performances. As Dosi writes:

a technological paradigm has a powerful exclusion effect: the efforts and the technological imagination of engineers and of the organizations they are in are focused in rather precise directions while they are, so the speak, "blind" with respect of other technological possibilities".[ix]

To describe the dynamics of technological change many students of technology use the concept of a "technological trajectory". The use of the metaphor "trajectory" suggests that a pathway may be defined on the basis of the characteristics of technical advances. Examples of technological trajectories are: in aircraft technology, the loglinear improvements in the tradeoffs between horsepower, gross takeoff weight, cruise speed, wing loading, and cruise range; and, in microelectronics, the exponential trajectory of improvement in the relationship between density of the electronic chips, speed of computation, and cost per bit of information.[x]

According to Dosi, his model may be used to account for both continuous changes and discontinuities in technological innovation. Continuous changes are related to progress along a technological trajectory defined by a technological paradigm, while discontinuities are associated with the emergence of a new paradigm.[xi]

The above studies rightly corrected the simple view that most economists held about technology, as being fine-tuned to demand and cost conditions, or, as Donald MacKenzie puts it, "an entirely plastic entity shaped at will by the all-knowing hands of market forces".[xii] However, they suffer from "deterministic overtones", as pointed out by technology sociologists like Donald MacKenzie.[xiii] In the above models, engineering imagination causes technology to proceed a certain trajectory, more or less in the same way as a stone or rocket follows a trajectory once it has been launched.

In our view, there is a clear *socio-economic* dimension involved in the stability of search activities and the patterns of technological change. One of the key reasons why technological progress often proceeds along certain trajectories (defined by a technological regime or paradigm) is that the prevailing technology and design has already benefitted from all kinds of evolutionary improvements, in terms of costs and performance characteristics, from a better understanding at the user side, and from the adaptation of socio-economic environment to a certain type of technology in terms of accumulated knowledge, capital outlays, infrastructure, available skills, production routines, social norms, regulations and life styles.[xiv]

For example, the dominance of the internal combustion engine in motor vehicles is strongly related to the improvements in the design of the engine (leading to important improvements in speed, durability, fuel consumption), the cost savings in manufacturing due to large scale production and learning by doing, advances in material technology, technical advances in machinery and equipment, organizational adaptations in order to produce more efficiently, low fuel prices due to economies of scale and technical progress in petrol production, and the whole network build-up around the internal combustion engine: the distribution of petrol, a road and service infrastructure, training of mechanics, etc.

To give another example, the costs of producing a 64 megabyte chip would be much too high for any chip-producing firm or indeed the computer industry as a whole had they not been involved in producing a 4 megabyte chip and gained experience in solving complex problems in design and production of micro-chips. Similarly, the revenues from selling a 64 megabyte chip depend on the size of the market for computers and other applications for chips. But this market is shaped by the stock of computers already in use, available computer software, computer knowledge and skills in using computers, the existing infrastructure in telecommunication and so on.

These two examples are merely used as illustrations of a more general story. Below we will explain more systematically how the dominance of particular trajectories is related to the "dynamic scale and learning effects" prevailing technologies have benefitted from and the adaptation of the "selection environment" to the old technological regime. The concepts of dynamic scale and learning effects and selection environment also help explain why the diffusion process of radical products and processes (such as alternative energy technologies) is likely to be slow and why the short-term costs of large-scale technological transitions are likely to be large.

The term "dynamic scale and learning effects" denotes the evolutionary improvements in the performance characteristics of a technology and the cost savings in the manufacturing (allowing for price reductions). These dynamic scale and learning effects are related to the establishment and growth of the manufacturing industry, technological progress in related industries, and network externalities due to the growth of the system (for example, the growth of the petrol distribution system, the telecommunication network). An important part of these dynamic scale and learning effects are so-called learning curve effects that allow for cost reductions in the manufacturing of a product.

Technology features in the stability of technological regimes

In the world of engineering, learning curves are a well-known phenomenon. With the increase of production, per unit costs tend to fall. Such cost reductions per unit of output are related to economies of scale in production (lower costs per unit of production related to higher production scales), standardization of products, process improvements, and learning-by-doing in manufacturing. Learning curve effects are particularly important in processing industries (such as the chemical industry, the food industry) and in industries involved in the mass production of consumer durables (cars, television sets, etc.).

The learning curve, or the experience curve, may be described by the following function: Install Equation Editor and double-click here to view equation. 1 with C per unit costs (or labour input per unit of output) and N the cumulative production Q over time.[xv] The parameter b is called the learning index or learning elasticity. In economic terms, b is the cost elasticity with respect to cumulative production. Parameter b defines the "slope", S_L, of the learning curve, the level at which costs fall each time the cumulated output doubles.[xvi] The cost reduction with doubled experience is described by the following expression: Install Equation Editor and double-click here to view equation. 2.

Figure 1 depicts a typical learning curve. With increasing production, per unit costs fall. (Sometimes the unit costs are expressed as a decreasing function of time). If the learning curve is of the loglinear type – being the most common type of learning curve – the relationship between the natural logarithm of per unit costs and the natural logarithm of cumulative production is depicted by a straight (downward-sloping) line.

Figure 1. The learning curve

To illustrate the importance of learning curves, price reductions (in percentages) with doubled experience for a number of consumer durables are given in Table 1.

Table 1. Price reductions over time and related to experience for consumer durables. Source: Frank Bass (1980, S61).[xvii]

As a further illustration, Figure 2 gives estimates for parameter *b*, the learning elasticity, and *a*, the cost reduction with doubled experience, found in a number of industries (the chemical industry, the computer industry, electric power generation industry and the automobile industry).

Figure 2. Parameters of the experience curve for various industries. Source: Robert Ayres (1985, p.379).

Table 1 and Figure 2 clearly show that learning curves exist and that they are an important phenomenon. In the case of consumer durables, such as electric refrigerators, air conditioners, dishwashers, television sets and electric clothes dryers, price reductions between 5 and 22 per cent were connected with a doubling of cumulated production in different post-war periods. In the semi-conductor industry, in the 1964-1977 period, even cost reductions per unit of output of as much as 40 percent were associated with a doubling of cumulated output. In steel production, pvc production, aircraft assembly, petroleum cracking and refining, cost reduction between 15 and 25 per cent were realized with each doubling of cumulated production, whereas for the famous T-ford automobile this was "only" 14 per cent. These figures are even more impressive when compared with the growth of real disposable income in the same period. Of course, the increases in real disposable income and the price reductions in several product categories are correlated with each other: price reductions and productivity gains led to increases in real income which in turn stimulated demand and helped producing industries in achieving further cost reductions.

In all these cases, important cost savings were realized that led to lower prices and higher sales. Price reductions, however, were not the only factor in stimulating product sales. Other factors include post-innovation improvements in design, performance, functions, user-friendliness, and durability. The redesign of products opened up new markets and helped firms to expand in early markets. Although there does not exist an analytical parameter describing these kinds of post-innovation product improvements, historical studies show that they were numerous and important for the expansion and opening up of markets. Many historical studies show that, at the time of their introduction, new technologies were often ill-developed in terms of performance characteristics and offered only few advantages over existing technologies. They needed to be improved, in terms of both prices and technical characteristics, in order to be diffused more widely. As Nathan Rosenberg notices:

> most inventions are relatively crude and inefficient at the date when they are first recognized as constituting a new innovation. They are, of necessity, badly adapted to many of the ultimate uses to which they will eventually be put; therefore, they may offer only very small advantages, or perhaps none at all, over previously existing techniques. Diffusion under these circumstances will necessarily be slow (...).[xviii]

Network externalities may reinforce the entrenchment of technologies in the economic system. With the growth of the network of users, a network technology becomes more attractive to its users. An example is the fax machine. The more people or firms adopt the fax machine, the more valuable it becomes to the individual users. Network externalities that result from the growth of the system are a special kind of increasing returns with adoption, which are being analyzed in Brian Arthur.[xix] Five sources of increasing returns with adoption are identified by Arthur: learning by using, network externalities, scale economies in production, informational increasing returns and technological interrelatedness. With increasing returns of adoption, a technology becomes more attractive the more it is adopted, which further stimulates its adoption. Thus, in a situation where two network technologies are competing, a technology that gets ahead early may for that reason end up dominating the market. As Brian Arthur writes:

If one technology gets ahead by good fortune, it gains an advantage. It can then attract further adopters who might otherwise have gone along with one of its rivals, with the result that the adoption market may 'tip' in its favour and may end up dominated by it. Given other circumstances, of course, a different technology might have been favoured early on, and it might have come to dominate the market.[xx]

When there exist increasing returns with adoption it is entirely possible that society becomes locked into a suboptimal technology. Well-known examples of suboptimal technologies which came to dominate the market are the VHS-video system and the QWERTY typewriter keyboard.[xxi] There may also be an element of self-fulfilling prophecy involved in persistent patterns of technological change, as noted by MacKenzie.

The problem of compatibility

This brings us to the role of institutions and technical interrelationships in the selection of technologies and the ways in which they shape technological trajectories. As a theoretical organizer we use the term "selection environment", stemming from the evolutionary theory in biology, and introduced into the economic literature by Nelson and Winter. It is chosen as a more general term than "market" (or market demand) to emphasize the institutions involved and the mechanisms behind the selection of an innovation. The selection environment is defined by the capital outlays, physical infrastructure, supplier-user linkages, production routines, skills, technical standards, government rules, norms, people's preferences and beliefs.

The term "selection environment" is used to illustrate the importance of the historical socio-economic context in the selection of innovations. Whereas economists use the concept of a demand curve, describing the relationship between quantities demanded and purchase price, we prefer the term "selection environment", which brings out the systematic nature of technology and economy, the transfer of knowledge and information that are necessary for exchange to take place, social processes of habituation and taste formation, and political factors in the selection of an innovation. The important point here is that a technology needs to be incorporated into a larger technical and socio-economic system which has evolved in the process of development.

Between firms, but also inside firms, all kinds of technical, economic and institutional interrelationships have developed that may hinder the adoption and use of a new technology. Within an economic system, activities are coordinated and were optimized in the past. Patterns of exchange and information transfer are established through supplier-user relationships and intra-organizational linkages. What we have is economic actors dealing with each other, using materials with specific physico-chemical properties, using special-purpose machinery and equipment, employing workers with certain skills and knowledge, and operating within a broader socio-economic context. A new process or product must be embedded in the existing production processes of potential users and must comply with a diversity of qualitative demands (in terms of performance norms, durability, user-friendliness, etc.).

In such circumstances, the introduction of new technologies may require the replacement of large parts of the production system, creating an unusual heavy obsolescence problem. A special kind of technical interrelationships are technical standards that create well-known problems of compatibility and raise complex issues of strategic behaviour and government intervention. [xxii] Institutional rigidities usually aggravate the problem of technical interrelationships. The use of new technologies may require new labour skills, management styles, and other kinds of institutional changes (for instance new legislation). Vested interests (firms, industries, workers associations, etc.) may also hinder the adoption of new technologies and the growth of new technological systems.

Consumer tastes, life styles and habits are also an important part of the selection environment. But consumer tastes, preferences and the ways in which people live their lives are not autonomous factors: they are shaped by the adoption and use of past technologies. Technological progress in food distribution, together with the widespread diffusion of the automobile, have changed shopping habits dramatically. Also the movement towards living in suburbs and the countryside is related to the availability of the automobile as a convenient means of individual transport. These two examples illustrate that technology is an important factor in shaping people's lives, either directly through the services provided by the technology or indirectly by increasing real disposable income. Of course, we do not want to suggest that social changes are the result of antecedent changes in technology only. Technological change and socio-economic trends co-evolve and interact.

Besides social adaptations in response to technological change there may also be mechanisms of habituation and endogenous taste formation at work.[xxiii] People have gained experience with certain goods and have become habituated to them. An important implication of this is that new technologies are evaluated in terms of the characteristics and services of the old technologies. This may explain the trajectory of ever more powerful cars in a world where speed limits are becoming more and more tight. The fact that people are used to having a car with a certain mileage and speed may obstruct the development of a car with totally different characteristics (for instance, an electric vehicle with a relatively low speed and range and long recharging times). In the process of consumer taste formation there are also complex social aspects involved such as status, appeal, emulation, social acceptance, etc. These social aspects are still not well understood, but they may have important implications for the ultimate choice of technologies. New ideas about social behaviour and different values may be needed for new technologies to be adopted and used.

Government is also an important actor within the selection environment. Through its science and technology policy, the government is involved in the generation of knowledge and through its education policy in education and skill formation. Public authorities are often heavily involved in the provision of infrastructures (roads, telecommunication, etc.) which are so important for the growth of new technological systems. As a last point, the government's tax policy, industrial policy, procurement and regulation all affect the economic process in important ways.

But just as firms and consumers are adapted to the old technological regimes, so are governments. Environmental and safety standards are usually based on well-proved compliance technologies, which hinders the adoption and development of more advanced technologies. Industrial policy is often aimed at the protection of old industries that are challenged by new firms and technological advances. Time is needed for new skills and ideas to penetrate in the education system, and so on. The key problem for new technologies to become incorporated into the socio-economic system is that of compatibility. Within the process of economic development, technical interrelationships and institutional rigidities have developed that may hinder technological shifts. New technologies that can be easily embedded in the production system and people's ways of life will diffuse more rapidly than technologies which require the replacement of capital goods, a new infrastructure, different skills, new ideas about production and consumption, and regulatory changes. Not only do the characteristics of the selection environment determine the relative use of technologies over time but these characteristics also have implications for the kind of search activities that are likely to be undertaken by for-profit organizations.

The above helps to explain why manufacturers often strive to develop so-called "drop-in" innovations which can be easily embedded in existing production processes and require few changes in the selection environment. For example, in the case of chlorofluorocarbons (CFCs), research efforts are directed towards the development of CFC substitutes (e.g. as cooling medium in refrigerators) that can be easily embedded in the economic and social environment rather than towards the development of totally different production techniques and products (e.g. a refrigerator with a totally different cooling system). Not only do the manufacturers of CFCs have an interest in developing these innovations that belong to the old CFC trajectory but so do the users of CFCs. The idea of a selection environment shaped by the application of past technologies also explains the dominance of "end-of-pipe" techniques over "process-integrated" changes because the former can simply be added to the existing production processes.

In conclusion, contrary to popular public perceptions of revolutionary technical change and heroic inventors, modern historical studies find that technological change is much more a cumulative and gradual process, proceeding in quite specific directions. Underlying these technical advances are engineering ideas and beliefs of technical opportunities for improvements. These engineering beliefs and expectations of where to go to, what problems to solve, and what sort of knowledge to use, are often shared among communities of technologists. The reason why such beliefs are shared is believed to be related to economic supply and demand factors (past capital formation, accumulated knowledge and experience, cost efficiencies and product improvements achieved with the old technologies, social habituation and adaptation, etc.) rather than to cognitive limitations of imagination, although the two explanations are strongly related since they reinforce each other.

Of course, the argument should not be carried too far. Although there are some powerful mechanisms that reinforce the embedment of technologies in the economic and social system, there have been major technological regime shifts in the past. How such transitions come about, and particularly what economic factors are involved in large-scale technological shifts will be discussed in the next section.

3.The Conditions for Radical Technological Change

When taking a long-term historical perspective, we see that at certain times technological paradigms and systems become outdated and are replaced by new ones, despite the self-sustaining elements involved in the development of technological paradigms and regimes. At certain historical moments, radical innovations are produced challenging the old paradigm and gradually replacing it (although the two may co-exist for a long time). Despite the importance of such events, our knowledge of how radical innovations come into being and how they come to replace the old regime is rather limited. There do exist, however, certain clues about what induces technological breakthroughs and some ideas of the factors that govern the diffusion of radical innovations and the evolution of large technological systems.

It is frequently stated that radical innovations depend on new scientific insights opening up new technological and economic opportunities.[xxiv] For example, Maxwell's theory of electromagnetism in the 1860 was instrumental to the development of radio technology, although the understanding of the phenomenon of electromagnetism did not lead directly to the radio as a new consumer product; several decades of applied research and experimentation were needed to turn it into a tradeable product. Radical innovations sometimes also critically depended on breakthroughs and advances in engineering and material technology. Perhaps the best example is James Watt's steam engine with its separate condensing chamber, which depended for its production and success on Wilkingson's boring mill.

This raises the question what other factors are conducive to the development of radical innovations. So far, we have discussed the importance of new scientific insights to the development of radically original products. They provided essential knowledge and guidance to engineers in achieving technological breakthroughs. Pressing technological needs that could not be met with available technologies and required fundamentally different solutions are another factor. These technological needs may stem from bottlenecks or reverse salients that arise in the growth of technological systems, or stem from pervasive shifts in consumer preferences. Many technological breakthroughs are also achieved in war times, when demand for new and better military technology is especially high as is the need to develop substitute products and materials when nations are cut off from critical supplies. To these technological needs, we may add the demand for more environmentally benign technologies to arrest environmental degradation.

It may also be that old trajectories have reached certain technical limits or that further advances along the same trajectory run into increasing marginal costs.[xxv] In terms of the modern philosophy of science, engineers may confront an "anomaly" which leads them to search into a new direction of technological advance, based on a different knowledge base and engineering principles. Such anomalies need not constitute acute and pressing problems. Also the perception of theoretical limits for advancement may induce firms and technologists to shift towards a different technological regime. Edward Constant uses the term "presumptive anomaly" for such a situation.[xxvi] A presumptive anomaly emerged in the late 1920s when insights from aerodynamics indicated that the conventional piston engine-propeller system would not function at the near-sonic speeds foreseen for airplanes.[xxvii] This led to the invention of the turbojet engine.

Often, radical innovations are produced by newly established firms or by industries diversifying into a new market. There are several possible explanations as to why radical innovations are developed and supplied by outsiders. First, a radical innovation may require a different knowledge base which may not be available in the manufacturing industry. In relation to this, "community practice may define a cognitive universe that inhibits recognition of a radical alternative to convention practice".[xxviii] Second, vested interests may obstruct the development of a different technological system or paradigm. According to Thomas Hughes, this was the reason why so many technological breakthroughs in the late nineteenth and early twentieth centuries were achieved by independent inventors who had distanced themselves from large organizations:

They [the independents] rightly sensed that the large organization vested in existing technology rarely nurtured inventions that by their nature contributed nothing to the momentum of the organization and even challenged the status quo in the technological world of which the organization was a leading member. Radical inventions often deskill workers, engineers, and managers, wipe out financial investments, and generally stimulate anxiety in large organizations. Large organizations sometimes reject the inventive proposals of the radicals as technically crude and economically risky, but in so doing they are simply acknowledging the character of the new and radical.[xxix]

This same argument applies to modern firms, although such resistance may be less fierce now technological competition is becoming more and more important to the survival of the firm. Radical inventions may still endanger current activities of firms and for that reason be rejected or delayed. On the other hand, new technological developments may be nurtured by industries or organizations having an interest in the development of the new product. The development of clean coal-burning technologies is strongly supported by the coal industry in an attempt to secure the usage of coal in a world where environmental regulation is getting tighter. Electricity producers have supported the development of the electric car, as have producers of plastics. Customer firms may also actively support the development of new technologies, by providing information about product requirements and their involvement in tests. Even consumers may be involved directly in the support of new technologies. As an interesting example, the German branch of Greenpeace has provided financial means for the development of a CFC-free refrigerator by an East German firm. They also took care of the marketing of the product through their magazine.

The propensity to take risk may also be an important factor in the development of radical innovations. Risk-taking entrepreneurs are often identified with the development of radically new products. They may be inventor-entrepreneurs such as Thomas Edison, venture capitalists that financially support an innovation, or managers that lead their firm into a new technology field. Schumpeter even based his theory of economic development on these entrepreneurs, picturing them as heroic men of great will, vision and persistence.

It should be emphasized that the importance of entrepreneurship and pioneering firms lies not so much in the market share they are able to achieve, for that is likely to be small (at least in the early years), but much more in inducing other firms to take risks and change their strategies. For the development of an alternative trajectory it is important that the traditional firms possessing great market power, specialized knowledge and large financial means commit themselves to the development of this trajectory. It is only through the commitment of other firms that a dynamic learning process may emerge, resulting in a wide array of post-innovation product improvements, complementary innovations and cost reductions, which gives the new regime enough "momentum" so as to replace the old one.

As a last general point, also non-market mechanisms were often important in the establishment of a new technological regime or paradigm. As noted by Chris Freeman, universities and public laboratories often played an important role in the generation of the original radical innovations, as did government procurement in their early applications. Each new paradigm requires a modification to infrastructure which can only occur as a result of institutional and regulatory changes in each country. Particularly important in the evolution of the Information and Communication Technology (ICT) paradigm were public programmes for computer technology and public policies for the telecommunications infrastructure.[xxx]

Competing designs

So far we have discussed the emergence of radical innovations which came to replace old technological paradigms and technological systems. The importance of fundamental breakthroughs in science and technology, particular technological needs, the economic context (and wider social and political context), and the presence of entrepreneurs in such events has been noted. From the above one may get the impression that the replacement of old technological regimes was a relatively straightforward process. It would be a mistake to think so. In many cases it was not a straightforward event to the people living in those ages, not even to those who were actively involved in the development of the new regime. At times in which a radical invention was developed which later came to dominate the market, there were usually different technologies and different designs to satisfy a particular need. The fact that different technologies were produced and supported by various organizations implies that the later dominance of one particular technology and design was not at all obvious.[xxxi]

Some examples of different technologies competing for a market of adopters are given by Brian Arthur:

In the 1890s the motor carriage could be powered by steam, or by gasoline, or by electric batteries. In more modern times nuclear power can be generated by light-water, or gas-cooled, or heavy-water, or sodium-cooled reactors. Solar energy can be generated by crystalline-silicon or amorphous-silicon technologies. An AIDS vaccine may eventually become possible by cell-type modification methods, or by chemical synthesis, or by anti-idiotype methods. Video-recording can be carried out by Sony Betamax or by VHS technologies.[xxxii]

The reason why various technologies with different designs based on different engineering principles are developed at about the same time is related to the following factors. First, the opening up of technological and economic opportunities by new scientific knowledge (as in the case of nuclear power). Second, the emergence of particular technological needs (as in the case of an AIDS vaccine). Third, the discovery of a new market (as for bicycles). Fourth, uncertainty as to the "best technical solution" for meeting certain market needs (which is related to uncertainty about the future rate of technological progress). Fifth, uncertainty about market demand and the evolution thereof. Sixth, the fact that the technologies are produced by organizations with different technological capabilities and interests.

Since all these factors usually operate at the same time, it is difficult to assess their relative importance. Of these factors, however, uncertainty about technological opportunities and user needs are known to constitute two fundamental problems. The long-run success of a product strongly depends on the rate of technological advance that may be realized in a certain product and design. The technical advances to be realized depend on the potential for improving performance characteristics and achieving cost efficiencies and on the ability of innovating firms to solve certain critical problems. It also depends on the rate of technical progress in other industries and scientific advances at universities. All types of advances are difficult to predict.

Uncertainty about user needs and requirements (and the evolution thereof) is another serious problem. Although engineers and marketers may have certain notions about what "the market" wants, market demand for a new product does not articulate itself in an unambiguous and quantitative way. As Morris Teubal writes:

> Technological innovation, like the activity of production, may be regarded as induced by human needs, but unlike it these needs are frequently not represented by an unambiguous and well-defined market or demand curve. Innovations generally involve a new product component and in so far as this is so they *precede* the generation of markets and demand curves. They should accordingly be regarded as responses to more general, less-defined needs than those expressible in terms of well-defined markets or demands (original italics).[xxxiii]

It should be noted that the problem of user needs is not so much whether people or firms would like to *have* the innovation but about how much they are actually prepared to pay for it (their "willingness-to-pay") – which depends on their conception of the product and their valuation of the service characteristics. This problem of user needs and market demand is particularly large for radical innovations (a computer, an automobile, a radio or even a bicycle) that constitute a radical departure from past practices. For radical innovations, the problem of user needs is not only a problem of preferences which are not revealed in the market place but also a problem of needs and wants which are not yet determined. What we may have, in the words of Teubal, is consumers who learn about what they want or need.[xxxiv]

It furthermore implies that innovating firms involved in the commercialization of a radically new product must not only engage in developing and producing the artefact, but must also engage in shaping the market: to organize the product's distribution, to inform customers about its existence and performance characteristics, to persuade them to purchase the new product, and to educate them in using it.[xxxv] They may also need to go into scientific and public debates about the efficacy and desirability of the new product or to persuade policy makers to change the legal framework (the definition of property rights, the setting of more strict environmental standards, etc.).

The shift into a new technological regime

Up until now we have not discussed how it is possible for a radical innovation to establish itself as a dominant technology in the market place. In section 2, we noted that there exist powerful mechanisms that reinforce the entrenchment of a technology in the socioeconomic system. As we saw, radical technologies are relatively crude at the time of their invention and need to be improved and better adapted to user needs. They are only able to compete in specialized markets. These early market niches are important for the further development of the new technology. Besides providing necessary financial means, the experiences of users are an important source of information in helping firms further to improve the product.

Radical technologies may also benefit from accumulated experience in other sectors, and from the presence of a network in which it can be easily introduced. It is perhaps not well-known that the automobile owed much of its success to the bicycle. Experience accumulated in bicycle production was put in good use in the automobile industry and an improved road infrastructure was already present. Existing components and products could often be incorporated in, or combined with, new technologies. Photographs of the first automobiles clearly show that the automobile originally was nothing else than a carriage powered by an engine instead of being drawn by a horse (the early expression of a "horseless-carriage" thus described the first automobiles rather well). Only in a few respects did radically new products constitute a radical break with the past, which suggests that the term "radical" is somewhat misleading. Radical innovations often combined the new with the old (or even combined older technologies) and often rightly so because this helped the product to survive the initial harsh market selection and establish itself in the market place. A good example of an intermediate technology were the first steamships. According to Joel Mokyr, "the first steamships were really sailing ships with auxiliary engines, with steam only helping out against unfavourable winds and tides".[xxxvi]

As noted by Chris Freeman, in every change of a techno-economic paradigm which has so far occurred, the new paradigm already emerged and developed within the previous one. Steam power (the second techno-economic paradigm) was based on a technology already well established. Electric power (the third techno-economic paradigm) was developing over half a century before the generation and transmission of electricity became widespread towards the end of the nineteenth century. Mass production (the fourth techno-economic paradigm) was already established in such industries as meat-packing and automobiles decades before it became the dominant system. The fifth information and communication technology paradigm has been developing since the Second World War to the point where it is achieving dominance today.[xxxvii]

The transition to sustainable technologies

What now are the implications of the above for the transition to a sustainable economy? The concept of technological regimes is believed to be highly relevant to the problem of achieving sustainable development. For its operation, the economic system depends on an energy system which is almost totally based on fossil fuels – coal, oil and natural gas. Worldwide, these three energy sources supply about 90 per cent of the energy which is being purchased and put into use in the economic system.[xxxviii] Together with these energy sources, we have conversion and end-use technologies in which energy is converted into useful energy forms and energy services. The energy sources and technologies even extend well beyond industry: into consumption patterns and people's ways of life. Although alternative energy supply technologies are available, the move towards an energy system based on renewables and other non-hydrocarbon energy technologies is hindered by the small-scale production and the fact that so far they have benefitted insufficiently from dynamic learning effects which are so important for energy technologies. Furthermore, the capital-intensive petro-chemical firms vested in the fossil fuels-based energy system have no interest in developing non-hydrocarbon energy technologies. They will only move into the business of alternative energy technologies when fossil fuels are depleted or when the costs of extracting fossil-fuels are becoming too high.

A similar story applies to the internal combustion engine, being the dominant conversion technology in transport. Motor vehicle engines are an essential part of a highly complex technology – the automobile is probably the most advanced consumer product, being able to drive over 100,000 km at speeds well over 100 km/h – which has benefitted over the last century from a wide array of product improvements in terms of reliability, durability, speed, range, fuel efficiency, etc. Furthermore, the automobile depends for its manufacturing on a production system and organisational structure which is complex and capital-intensive. This makes it extremely difficult for new firms to successfully enter the automobile business. The automobile is also part of a larger technological system involving gas stations, automobile repair shops, an extensive road infrastructure, etc. As a last point, the automobile is deeply entrenched in the social system and people's ways of life.[xxxix] This also explains why technological shifts in the transport system (away from private transport and aircraft) will be slow and why tax policies that change the marginal costs of using specific transport technologies will be largely insufficient for achieving radical shifts in the transport system.

Finally, in the transition to a sustainable economy, we have competing technologies of which it is impossible to foretell which technology or design will eventually dominate the market or will be able to capture a large market share. Again, the success of different technology options depends on the technical advances that may be realized in certain designs, future cost efficiencies in the production and usage and the evolution of market demand. To these factors we must add government policy, which is particularly important for the development and adoption of sustainable technologies. Government policy (in the form of R&D subsidies, special science and technology programs, infrastructure provision, tax policies, environmental standards) may exercise a decisive influence on the selection of the various technology options. The policy implications of inducing a shift in energy technologies will be taken up and further examined in the final policy section. Before we go into this we will say more on the relationship between firm behaviour and technological regime shifts.

4.Firm Behaviour and Technological Regime Shifts

In the previous sections we paid attention to the direction of technological change without explicitly discussing firm behaviour. This is a clear shortcoming since firms are central institutions in the shaping of trajectories of technological advance: user needs are translated in economic goods by firms and production of these goods is organized in firms. Unfortunately, the relationship between firm behaviour and technological regime shifts is a relatively under-researched area. It involves the integration of studies which have been carried out separately from each other: evolutionary theories of technical change, corporate decision making and strategy, and organisation theory. It raises a number of questions which are highly pertinent to a better understanding of this important relationship. For instance: How do new technological regimes come about in a world of specialization and decentralized and myopic decision making? How are innovating firms able to appropriate the economic benefits from systemic innovations? What are the implications of economic organization for the development of new technological systems? What visions of the world underlie the decisions of firms to develop radically new technologies and how are those visions being translated in firm behaviour?

To answer the above questions it is important to see that firms have a restricted knowledge base and a field of competence that is related to the products they have produced and the markets they have operated in.[xl] This knowledge base of firms involves technological know-how of the product (its functions, components and materials, etc.), understanding of customer needs and user valuation of performance characteristics, financial and accounting knowledge, marketing knowledge, engineering knowledge (both codified and tacit), and management skills. This knowledge base, together with its organization and stock of capital equipment determines a firm's production capabilities and ability to generate profits. These technological capabilities at any point in time are shaped by their history and by the niches which they have been able to occupy. Typically, they have a limited range of product and processes which they understand well, and where they can compete. Martin Fransman speaks of a "bounded vision":

the field of vision of for-profit corporations is determined largely by their existing activities in factor and product markets, in production, and in R&D and by their need in the short to medium term to generate satisfactory profits. The resulting bounded vision implies that new technologies emerging from neighbouring areas where the corporation does not have current activities are likely to take some time to penetrate the corporation's field of vision. ... The need to generate satisfactory profits in the short to medium term therefore further bounds the vision of the corporation, contributing in some cases to a degree of "short-sightedness". One example is the creation of technologies for "the day after tomorrow" where the degree of commercial uncertainty is frequently great. In view of their bounded vision, corporations often tend to underinvest in the creation of such technologies.[xli]

This knowledge base is often shared by firms in the same industry. Such a shared framework of knowledge may be considered a technological regime. The reason why such a framework is shared by other firms is not so much because it constitutes the only way or the natural way of doing things but critically depends on the accumulated knowledge, realized cost efficiencies, the past investments in plant and infrastructure, established supplier-user relationships within a regime, as explained earlier.

Against this background we may ask ourselves the following question: how is it possible for firms with a restricted knowledge base and highly specific technological capabilities to engage in developing a radical technology which requires different knowledges, skills, machines and performs different functions? Perhaps there does not exist a good answer to this problem. Perhaps firms underestimate the problems involved in the development and commercialization of a radically original product. Maybe it is overoptimism in the commercial viability of radically original technologies that induces firms to develop and introduce a radically new product or process. In this connection, Ian Miles notices that, just as in the establishment of a new scientific paradigm, there may be an element of "hype" in the emergence of a new technological regime:

This hype involves overstatement of the speed of change and rapidity of realisation of benefits, it creates heroes and exemplars, and it serves to cement together the networks of agents whose semi-coordinated action is necessary to bring about substantial shift in interconnected technologies and practices.[xlii]

Although this may be an important element in the transition in techno-economic regimes, there are other explanations. One such explanation is that radical innovations are produced by firms with a knowledge base which is highly relevant to the new product. For example, firms in the dye and organic chemicals industry with special knowledge in synthetic chemistry moved into pharmaceutics (a field traditionally based on analytical and extractive chemistry), and oil companies moved into the new business of producing plastics.[xliii] New firms may also be created by inventor-entrepreneurs, as done by people like Edison, Perkin, Baekeland and more recently (with less success so far) by bioscientists with the help of venture capital.

Firms may also decide to collaborate with other firms in order to develop a new innovation. They may engage in joint R&D projects, or involve users in experiments with the new product. When learning curve effects are believed to exist, they may decide to sell the product initially at a loss, as some kind of investment, in order to benefit from user experience and achieve cost efficiencies in manufacturing through accumulated experience. Such a strategy, however, has the danger of running into vast financial losses and will only be undertaken by large organizations with sufficient financial means. Another possible strategy is to involve potential beneficiaries from the new product in its development, although uncertainty about the likely economic gains may prevent potential beneficiaries from taking part in the development (both technically and financially). Such firms may also be unwilling to share economic benefits with the innovator, which brings us to the issue of appropriability.

The appropriability conditions are about the ability of the original innovator to capture the benefits from the innovation and "hold off other firms from eating too much and too rapidly into these returns".[xliv] As noted by David Teece, it may be more difficult for suppliers of *systemic* innovations that often require complementary assets (special materials, machinery, skills) to appropriate the benefits from innovation. Control over complementary assets may be necessary to capture the benefits from innovation when the appropriation regime is weak.[xlv] Elsewhere, Teece discusses the vertical integration of General Motors into electrical equipment supply and its implications for the development of the diesel electric locomotive. In the case of General Motors it is found that this integration reduced costs by "internalizing market exchange under circumstances (uncertainty, technological interdependence) which generated significant contractual difficulties".[xlvi] Furthermore, the pace of product development was stimulated by a more harmonious information exchange. Teece concludes that "the experience with vertical integration in the diesel electric locomotive building industry suggests that technological innovation displaying interdependencies among the parts is greatly facilitated by common ownership of the parts".[xlvii]

This does not imply that vertical integration is always conducive to the development of systemic innovations, a point taken on board by Teece, when he writes that "older, vertically integrated firms may have a greater commitment to older technology because of the large technology-specific investments they have made upstream and downstream".[xlviii] This leaves the issue whether vertical integration is favourable to the development of radical innovations rather inconclusive (although Teece is of the opinion that the favourable appropriability conditions under common ownership outweigh the unwillingness of firms to "cannibalize the value of past investments"). Of course, the whole issue of appropriation is much more complex. The appropriability conditions also depend on the market power of the firm and the existence of entry barriers preventing other firms from entering the industry and challenging incumbent firms.

Important as the issue of appropriability of economic benefits may be, to us, a greater problem seems to be that there are few or no benefits to reap, at least not in the early stage, as the new technology has to compete with well-developed, existing technologies, depends for its success on technical advances (in material technology, complementary technologies) outside the innovating firm, may need the construction of physical infrastructure, and must find ways of persuading potential customers into buying the new product. Probably more important for the take-off of the new regime is that an early market niche may be found for some applications. Besides providing financial means, it helps to build "a wide constituency behind the product" as Ian Miles calls it, finding support from other actors in the selection environment (firms, government agencies, beneficiaries).[xlix]

5.The Transition to an Environmentally Sustainable Energy Future

After having described – in rather general terms – changes in complex technological systems, we will now examine in more detail the policy problem of inducing and sustaining a shift to an environmentally sustainable energy future, away from fossil fuels. As we noted, there exists a symbiotic relationship between energy sources, technology and consumption patterns. Energy technologies are part of an energy system that have been developed over time, that consists of capital outlays and physical infrastructures, involves particular inter-industry relationships, and extends into consumption patterns and forms of every day life which are quite fundamental to the operation of advanced economies. A shift towards a different energy system not only involves different energy sources and energy supply technologies but also changes in science, education, manufacturing, transport and consumption patterns. What we have is a change in technological regime or techno-economic paradigm as Chris Freeman calls it.

Alternative energy technologies like renewables and other non-hydrocarbon energy technologies are available but so far have not made an impact (except for hydropower and nuclear power). The move towards renewables and other non-hydrocarbon energy technologies technologies (like fuel cells) is hindered by small-scale production (which prevents cost reductions from scale economies), the fact that they have not much benefitted from learning effects (despite the progress made in the past) and the lack of institutional support for these technologies. The lack of institutional support is partly explained by vested interests that have an input into public policies. However, this is not the only factor. It is also related to engineering scepticism as to the viability of such an energy system (a common phenomenon in technological regime shifts) and to legitimate public concerns whether the high costs of a transition away from fossil fuels will not outweigh the possible benefits.

This brings us to the following question: How to achieve a swift and smooth transition away from the old hydro-carbon regime into the new regime of non-carbon or low-carbon energy sources and more energy-efficient technologies? This question raises further questions as to which technologies should be used, for what purposes, and within what time frame. Should one opt for incremental efficiency improvements of existing supply, conversion and end-use technologies, of which the costs are relatively low and which do not require major change in the production system and people's way of life? Or should one opt for more fundamental changes in energy technologies which yield higher environmental benefits but which bring high costs, especially in the short-term? This is the fundamental technology issue that policy makers face.

Of course, the choice of particular technology options should not be decided at the central level by public authorities but be made at a decentralized level by firms, organizations and consumers which are in a far better position to weigh the individual costs and benefits of using different technologies for highly specific purposes. However, since the economic viability of environmentally preferable technological solutions strongly depends on government policy, public policy actions indirectly determine which technologies will be developed and successfully applied in the coming decades. Public authorities therefore should be careful not to foreclose some of the more radical technology options that yield significant environmental and welfare benefits in the longer term.

What now does this imply for public policy? First of all it implies that policy makers should initiate a thorough scientific assessment of the near-term and long-run environmental benefits, economic costs and social acceptance of the various technology options. Such an assessment should be the basis for any sensible tax policy and standard-setting policy to limit fossil-based emissions. Second, promising technology options for the longer-term should be nurtured by special technology programs, R&D subsidies to stimulate further development of these options. So far, this is nothing new. A somewhat new element in the policy debate which follows from the earlier-described system's model of technical change is the creation, through public policy, of market niches for some technology options with potentially high environmental benefits. These market niches may be an important stepping stone for the further evolution of radically new energy technologies. It helps suppliers to better understand user needs, to identify and overcome critical problems, to achieve cost reductions in mass production, and, perhaps most important, to "create a constituency behind the new product" as Ian Miles calls it, finding support from other actors (firms, research institutes, public agencies, users).

The creation of a market niche for radically new technologies with a low environmental impact should be considered as a learning experiment, not just for suppliers and potential users of these technologies but also for public authorities that want to achieve a smooth transition towards a more environmentally sustainable energy future. It helps to remove some of the uncertainty about the viability of radical technical solutions that may otherwise be forclosed or seriously delayed.

What does the creation of market niche for particular environmentally beneficial energy technologies imply in more practical terms for public policy? First, part of such a policy is a good understanding of the barriers that prevent the environmentally benign technology from being introduced into the market place. These barriers may be economic (when the new technology is unable to compete with conventional technologies given the prevailing cost structure), they may be technical (lack of complementary technologies, infrastructure facilities, appropriate skills or problems of integration in the existing technical infrastructure), and they may be social and institutional (related to laws, attitudes, perceptions, habits). To successfully deal with these barriers, an integrated and coordinated policy is required, which involves not only the implementation of taxes and subsidies that change the marginal costs of using particular technologies or the setting of emission reduction standards but also the formulation of long-term goals and the creation of an actor network to sustain a new technological trajectory.

niche management

A good example of such a policy is the so-called "Los Angeles initiative" to promote electric vehicles. Although the Californian policy is primarily aimed at reducing photochemical smog, a notorious problem in the Los Angeles basin, it vividly illustrates how "strategic niche management" (as Arie Rip and Johan Schot call it) may be used to induce radical changes in the hydrocarbon-based energy system. By requiring car manufacturers to mass-produce zero-emission vehicles, it surpasses a technological stalemate in which car manufacturers were reluctant to introduce electric vehicles for fears that consumers would not want to purchase alternative-fuel cars whereas demand for electrically-powered vehicles could not develop since electric vehicles were not for sale. According to California rules, zero-emissions cars must account for 2% to 10% of new-car production in the 1998-2003 period, while strict standards regarding hydrocarbon and nitrogen oxide emissions are being set for all new motor cars to be sold in the 1994-2003 period.[l]

Part of the program is a competition under which the three winning manufacturers are to build a variety of small cars, passenger vans and light commercial trucks to create the 10,000 zero-emission vehicle fleet by the year 1995.[li] The whole initiative is jointly sponsored and overseen by the city council, its Department of Water and Power and the private sector utility, Southern California Edison. The Department, and Southern California Edison are providing development funds to the chosen companies. In addition, they are devising with both state and federal authorities fiscal incentives to make the use of such cars attractive. This program could pave the way for alternative-fuel vehicles, not only in the Los Angeles metropolitarian area but also in other parts of the world.

To give another, more speculative example: hydrogen (H_2) is often considered as the ideal transportation fuel from an environmental point of view. Hydrogen has a high energy efficiency and does not emit carbon dioxide (if non-carbon energy technologies like renewables or nuclear power are used in the production of hydrogen). Hydrogen may be used in internal combustion engines or in fuel cells to supply power. Again, although technically feasible, the high costs of using hydrogen pose an enormous barrier. According to Tim Jackson, using estimates from various authors, the economic costs of a hydrogen-fuelled car using electrolysis and photovoltaics to produce hydrogen are in the range of 100 and 500 US cents per kilometre whereas the economic costs of a conventional car are between 5 and 10 c/kilometre.[lii] These figures are for 1990, and further cost reductions and efficiency improvements are to be expected from future advances in fuel cells, photovoltaics and other technology fields. However, to achieve or accelerate the transition to an integrated hydrogen economy, the creation of a market niche could make an important contribution.

At this moment, aircrafts are possibly a good candidate for the introduction of hydrogen in the transport sector. Within the aircraft industry, hydrogen is already considered as a potential commercial aviation fuel. Over the last three years, 15 German and Russian firms, under the leadership of Deutsche Aerospace Airbus Gmbh (DASA), have investigated the possibility of using hydrogen.[liii] They are now involved in the design of a large passenger airplane fuelled by liquid hydrogen, the cryoplane, of which they hope a prototype is ready by the year 2005. Whether a hydrogen-fuelled airplane will be mass-produced and will find its way into the market within the next 15 or 25 years is unclear. There are several barriers which hinder the introduction of the cryoplane in the commercial market: First of all, the high costs of hydrogen as compared to kerosine (so far the only fossil fuel which is not taxed), the build-up of an infrastructure to mass-produce hydrogen, the distribution of hydrogen in various parts of the world, and a number of safety and environmental problems (for example, although it does not emit CO_2 it emits water vapour which at high altitudes contributes to global warming). A carefully designed and coordinated policy could help realize the potential of the hydrogen option and exercise a decisive influence on the future course of events, leading up to an energy future which is more environmentally sustainable.

i. Donald MacKenzie, 'Economic and Sociological Explanations of Technical Change', in Rod Coombs, Paolo Saviotti and Vivien Walsh (eds.) *Technological Change and Company Strategies* (London, Academic Press, 1992), page 30.

ii. Richard R. Nelson and Sidney G. Winter, 'In Search of Useful Theory of Innovation', *Research Policy*, 6, 1977, page 57.

iii. *Ibid*, page 57.

iv. Luke Georghiou, J.Stanley Metcalfe, Michael Gibbons, Tim Ray, and Janet Evans, *Post-Innovation Performance: Technological Development and Competition*, (London, MacMillan, 1986), page 32.

v. *Ibid*, page 34.

vi. *Ibid*, page 35.

vii. Giovanni Dosi, 'Technological Paradigms and Technological trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change', *Research Policy*, 6, 1982, page 152 (original italics).

viii. Giovanni Dosi, 'Sources, Procedures and Micro-Economic Effects of Innovation', *Journal of Economic Literature*, 26(3), 1988, page 1127.

ix. Dosi, *op cit*, reference 7, page 153.

x. *Ibid*, page 1128-1129.

xi. Dosi, *op cit*, reference 7, page 147.

xii. MacKenzie, *op cit*, reference 1, page 34.

xiii. According to MacKenzie, "a technological trajectory is an "institution" which like any institution is sustained not through any internal logic but because of the interests that develop in its continuance and the belief that it will continue" (MacKenzie, *op cit*, reference 1, page 34).

xiv. The ideas described in this section are earlier described in René Kemp and Luc Soete, 'The Greening of Technological Progress: An Evolutionary Perspective', *Futures*, 24(5), 1992, pages 437-57, and René Kemp, 'An Economic Analysis of Cleaner Technologies: Theory and Evidence' in Kurt Fisher and Johan Schot (editors), *Environmental Business Strategies: International Perspectives on Research and Policy Implications*, (Washington, Island Press, 1993), pages 79-113.

xv. Taken from Robert U. Ayres, 'A Schumpeterian Model of Technological Substitution', *Technological Forecasting and Social Change*, 27, 1985, page 375-83.

xvi. That is, Install Equation Editor and double-click here to view equation. **Error! Main Document Only.**

xvii. Frank M. Bass, 'The Relationship between Diffusion Rates, Experience Curves, and Demand Elasticities for Consumer Durable Technological Innovations', *Journal of Business*, 53, 1980, pages S51-S67.

xviii. Nathan Rosenberg, 'Factors Affecting the Diffusion of Technology'. in his book *Perspectives on Technology*, (Cambridge, Cambridge University Press, 1976), page 195.

xix. W. Brian Arthur, 'Competing Technologies: An Overview." in Giovanni Dosi, Chris Freeman, Richard R. Nelson, Gerald Silverberg and Luc Soete (editors), *Technical Change and Economic Theory*, (London, Pinter Publishers, 1988), pages 590-607.

xx. *Ibid*, page 591.

xxi. The story of the QWERTY typewriter keyboard which became the dominant standard for keyboards despite the superiority of the later developed Dvorak keyboard is described in Paul A. David, 'Clio and the Economics of QWERTY', *American Economic Review* AEA Papers and proceedings, 75, 1985, pages 332-37.

xxii. For a good overview of these issues, see Paul A. David and Susan Greenstein, 'The Economics of Compatibility Standards: An Introduction to Recent Research', *Economics of Innovations and New Technology*, 1, 1990, pages 3-41.

xxiii. The terms "habituation" and "endogenous taste formation" are used by Paul David in *Technical Choice, Innovation and Economic Growth. Essays on American and British Experience in the Nineteenth Century* (Cambridge, Cambridge University Press, 1975). A recurrent theme in Paul David's work is the importance of historical factors in the rate and direction of technological change.

xxiv. The importance of scientific discoveries to the development of several radical innovations (synthetic dyes, plastics, drugs) in the chemical industry has been analyzed empirically in Vivien Walsh, 'Invention and Innovation in the Chemical Industry: Demand-Pull or Discovery-Push?', *Research Policy* 13, 1984, pages 211-34.

xxv. Paolo Saviotti and J. Stanley Metcalfe, 'A Theoretical Approach to the Construction of Technological Output Indicators', *Research Policy*, 13, 1984, page 149.

xxvi. Edward E. Constant, *The Origins of the Turbojet Revolution*, (Baltimore, John Hopkins University Press, 1980), page 75.

xxvii. Thomas Hughes, The Evolution of Large Technological Systems." in Wiebe E. Bijker, Thomas P. Hughes and Trevor J. Pinch (editors) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, (Cambridge (Mass.), MIT Press, 1987), page 75, who based himself on Edward W. Constant, op cit, reference 26, pages 194-207 and 242.

xxviii. Edward E. Constant, 'Communities and Hierarchies: Structure in the Practice of Science and Technology', in Rachel Laudan (editor), *The Nature of Technological Knowledge: Are Models of Scientific Change Relevant*?, (Dordrecht, D. Reidel, 1984), pages 27-46.

xxix. Hughes, *op cit*, reference 27, page 59.

xxx. Chris Freeman, 'A Green Techno-Economic Paradigm for the World Economy', in his book *The Economics of Hope*, (London, Pinter Publishers, 1992), page 202.

xxxi. To illustrate this: in 1893, a group of 74 prominent Americans were asked to write an essay about what the world would look like in 1993. These predictions were recently published in the book *Today Then: America's Best Minds Look 100 Years into the Future on the Occasion of the 1893 World's Columbian Exposition*, compiled by Dave Walter (American & World Geographic Publishing, 1993). Almost all forecasts turned out to be wrong, in fact most predictions were completely wrong. For example, the common opinion in 1893 was that in 1993 the railroad would still be the fastest means of transport. Air travel was considered to be an alternative way of transport, but only in balloons. None of the 1893 forecasters anticipated the future dominance of the automobile, a product which at that time had already found its way in the street (based on Edward Cornish, '1993 as Predicted in 1893: If They Could See Us Now', *The Futurist*, May-June, 1993).

xxxii. Arthur, *op cit*, reference 19, page 590.

xxxiii. Morris Teubal, 'On User Needs and Need Determination: Aspects of the Theory of Technological Innovation' in M.J. Baker (editor), *Industrial Innovation: Theory, Policy, Diffusion*, (London, MacMillan, 1979), page 266.

xxxiv. *Ibid*, page 275.

xxxv. Kenneth Green, 'Creating Demand for Biotechnology: Shaping Technologies and Markets', in Rod Coombs *et al*, *op cit*, reference, pages 169-170.

xxxvi. Joel Mokyr, *Twenty-Five Centuries of Technological Change: An Historical Survey*, (London, Harwood Academic Publishers, 1989), page 84.

xxxvii. Freeman, *op cit*, reference 30, page 207.

xxxviii. Paul E. Gray, Jefferson W. Tester, and David O. Wood, 'Energy Technology: Problems and Solutions', in Jefferson W. Tester, David O. Wood and Nancy A. Ferrari (editors), *Energy and the Environment in the 21st Century*, (Cambridge (MA), MIT Press, 1991), page 122.

xxxix. In a COST project memo about the motor car and the environment, the motor car is described as "a backbone of high mobility and suburbanization as well as a vehicle of self-expression and identity" (Knut H. Sørensen, 'The Car and its Environments. Proposal for an International Study of the Past, Present and Future of the Motorcar in Europe', Centre for Technology and Society, University of Trondheim, Norway, 1992, page 3.

xl. This part is based on the writings of Keith Smith in the joint research project "Technological Paradigms and Transition Paths: the Case of Energy Technologies" for the Commission of the European Communities.

xli. Martin Fransman, *The Market and Beyond. Cooperation and Competition in Information Technology in the Japanese System*, (Cambridge, Cambridge University Press, 1990), page 3.

xlii. Ian Miles, 'Shifting Paradigms: How are Transition Paths Constructed?', internal discussion paper EC-project Technological Paradigms and Transition Paths: The Case of Energy Technologies, PREST, Manchester. This corresponds to the idea of self-fulfilling prophecies in technology development expressed by Donald MacKenzie, referred to previously.

xliii. Walsh, *op cit*, reference 24, pages 227-232.

xliv. Richard R. Nelson, *Understanding Technological Change as an Evolutionary Process*, (Amsterdam, North-Holland, 1987), page 52.

xlv. David J. Teece, 'Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy', *Research Policy* 15, 1986, pages 285-305.

xlvi. David J. Teece, 'Technological Change and the Nature of the Firm', in Giovannni Dosi *et al*, *op cit*, reference 19, page 274.

xlvii. *Ibid*, page 274.

xlviii. *Ibid*, page 274. This argument is not new. Thomas Hughes made the very same point and Teece himself refers to James Utterback as one of the writers using this argument.

xlix. Johan Schot refers to this as the creation and utilisation of the technological nexus (Johan Schot, 'The Policy Relevance of the Quasi-Evolutionary Model: The Case of Stimulating Clean Technologies', in Rod Coombs *et al*, *op cit*, reference 1, page 193-196).

l. Neal Templin, 'California Rules Push Car Makers To Clean Up Act', *Wall Street Journal Europe*, March 27, 1991.

li. This part stems for a Financial Times Survey "Vehicles and the Environment", july 27, 1990.

lii. Tim Jackson, 'Renewable Energy. Summary Paper for the Renewables Series', *Energy Policy*, 1992, page 869.

liii. This part is based on René Raaymakers, 'De Zeppelin van de volgende eeuw' (The Zeppelin of the Next Century), *Intermediair*, 1992.