An Evolutionary Economic Analysis of Energy Transitions

Jeroen C.J.M. van den Bergh[*]
Department of Spatial Economics, Faculty of Economics and Business Administration
& Institute for Environmental Studies
Free University
Amsterdam

and

Frans H. Oosterhuis
Institute for Environmental Studies
Free University
Amsterdam
Frans.oosterhuis@ivm.vu.nl

[*] Corresponding author; address:
De Boelelaan 1105
1081 HV Amsterdam
The Netherlands
jbergh@feweb.vu.nl
phone: 31-20-5986164
fax: 31-20-5986004

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Abstract

Evolutionary economics offers clear insights into the mechanisms that underlie innovations, structural change and transitions. It is therefore of great value for the framing of policies aimed at fostering a transition to a sustainable development. This paper offers an overview of the main insights of evolutionary economics and derives core concepts, namely 'diversity', 'innovation', 'selection environment', 'bounded rationality', 'path dependence and lock-in', and 'coevolution'. These concepts are subsequently used to formulate guidelines for the role of the government and the design of public policies, such as the learning from historical technological pathways and the creation of an extended level playing field. In addition, the developments of certain energy technologies are examined in detail within the adopted evolutionary economics framework. Three particular technologies receive attention, namely fuel cells, nuclear fusion, and photovoltaic cells.

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1. Introduction

In this paper the recent attention for transitions with a particular focus on energy provision is linked to the older tradition of evolutionary thinking with regard to economic and technological change. The notion of transition has its origin in population dynamics and therefore relates well to evolutionary theory (Kemp, 1997; Rotmans et al., 2001; Geels, 2002a; Geels, 2002b; van den Bergh, 2004; AER/VROMraad, 2004). A transition denotes a society-wide system innovation with a focus on basic or fundamental activities, such as energy provision, transport and agriculture (Rotmans et al., 2000). Alternative terms are employed in the literature, notably system innovation in the technological literature, industrial transformation in the environmental science literature, and structural change in both environmental and development economics. A main motivation for using the notion of transition is that while it links up with the notion of sustainable development, it has the advantage that it shift the attention from a vague end goal to stimulating transition processes as a more concrete step. Note, however, that both concepts are part of systems thinking, as a result of which they cannot avoid complex system analyses.

Different perspectives are possible on transitions. In fact, inspiration can be drawn from a wide range of disciplines and fields of study. For example:

- Innovation studies – innovation systems and long waves (Kondratiev, Schumpeter, Freeman).
- Organisation studies - radical innovations, organisational change (Nelson/Winter, Hannan/Freeman/Caroll).
- History of technology.
- Sociology – multilevel institutions and networks.
- Development studies, including economic development theories (Rostow).
- Catastrophe studies – by anthropologists and others (Tainter, Diamond).
- Administrative and political sciences - political revolutions.
- Complex systems, including chaos theory (catastrophes, fractals en hysteresis) and evolutionary modelling.

Transitions can be characterised in various ways. Four important dimensions of transitions can be identified. First, one may focus on aspects of hierarchy, aggregation and space. A multilevel perspective has been proposed in this respect, covering the niche, regime and landscape levels. Economists would refer to micro, meso and macro. Second, different temporal phases of a transition have been identified. In this respect a life cycle or multi-stage development framework – consistent with insights from both marketing and development economics (Rostow) – has been used, distinguishing between pre-development or conception, take-off, acceleration and growth, stabilisation or saturation (including standardisation), and senescence. Third, the literature on transitions emphasises that we are dealing with complex systems and complex changes, due to simultaneous and interactive structural changes in resources/inputs, sectors (supply), demand (life-styles), institutions/policy (legislation), culture (values). Finally, from a traditional technological perspective, notably long wave theories, clustering of innovations is stressed. The idea here is that major, basic innovations are followed by derived and complementary innovations.

Next, a typology of transitions can proceed along two lines. First, a distinction can be made between spontaneous or autonomous and steered or goal-oriented transitions. Most known, historical transitions are of the first type, which suggests that there is little to learn from history. The second type includes, for example, the Green Revolution in agriculture, and the shift from coal to gas in post-war Netherlands. A second typology is based on identifying the degree of complexity of a transition. One can distinguish between relatively simple (minor) versus complex (major) transitions, and even intermediate types. Examples of major transitions are the invention and use of fire, the rise of agriculture, and the Industrial Revolution. All of these have changed human society in the most fundamental way. Electrification and various transitions in transport (e.g. from horse and wagon to car) can be considered as intermediate types. Minor transitions include the already mentioned Green Revolution and shift from coal to gas. Perhaps it is not a coincidence that these minor transitions are the only steered transitions mentioned here. This may hint at major transitions being out of reach of (public) regulation by humans, and that transitions aimed at attaining a sustainable development need to be of ‘medium’ complexity. Finally, some foreseen transitions or transitions in an early phase are uncertain in terms of impact. This holds for information and communication technology, genetic modification technology and energy related technologies like hydrogen, solar PV and nuclear fusion. The latter will receive specific attention later on in this paper.

The neoclassical economics perspective on transitions has been formulated by den Butter and Hofkes (2004). Two main sub-perspectives are relevant, namely based on general and partial equilibrium theories (micro and static) and on (endogenous) growth theories (macro and dynamic). The critical assumption of this perspective is rational, optimizing agents, both at the level of households and firms, and at that of regulators. From this perspective a number of suggestions can be derived. First, exogenous or endogenous changes in technology or resource availability stimulate responses. Price mechanisms play a central role here and are neglected in most other perspectives. They imply a market response to increased scarcity, taking the form of substitution in consumption and production, and (increased) R&D efforts. The neoclassical theory regards innovation as involving market failures due to positive externalities of R&D or innovation, and advises to make sure that behaviour of innovators and users of innovations is appropriately informed (correcting prices to reflect positive externalities) or constrained (e.g., patent systems rewarding innovators and limiting or pricing any use of their innovations). The neoclassical economic theory suggests trends (growth theory) and smooth changes (equilibrium theory) rather than breaks, and allows both sectoral shifts and gradual replacement of old, obsolete by new, more profitable techniques within sectors.

In the remainder of this chapter we will present an evolutionary economics perspective. The starting point for this is the intuitive feeling that evolution (as a general theory) is our best bet to understand and manage dynamic complexity. Evolution is a rising star in many fields, including chemistry, computer science (evolutionary computation), psychology, sociology, economics and philosophy. Evolution is often misunderstood: it is not an easy theory. For this reason, we will spend some time explaining core aspects of evolutionary theory in economics. Section 2 provides a short introduction to evolutionary economics. Section 3 presents an evolutionary economics framework around six core concepts. Section 4 examines the characteristics of transition policy within the evolutionary economics framework. Section 5 offers an evolutionary economics evaluation of three potentially sustainable energy technologies, namely fuel cells, solar PV and nuclear fusion. Section 6 concludes.

2. Evolutionary economics

Despite the fact that Veblen (1898) had already called economics an evolutionary science, a coherent development of this idea had to await the work of Nelson and Winter in the 1960s and 1970s, which blended with the earlier work by Schumpeter to give an impetus to the neo-Schumpeterian school of evolutionary economics. Any evolutionary theory has to start from a population approach. This immediately clarifies an essential difference with traditional microeconomics, where the assumption of a representative agent is crucial. Contrary to common belief, such a microeconomics is not really as micro as is possible. In fact, evolutionary theories are 'more micro', because they describe populations with behavioural or technical diversity among individuals or firms.

Joseph Schumpeter was without any doubt the most influential of all early evolutionary economists. This is due to his general standing in economics, in Europe and the USA, as well as to the many important concepts and ideas that sprang from his mind. Schumpeter questioned the static approach of standard economics, and showed a great interest in the dynamics of economies, in particular the capitalist system, in all of his major works (Schumpeter, 1934, 1939, 1942). He considered qualitative economic and technological change in a wider context of social change, focusing on the impact of the innovative ‘entrepreneur’ (Schumpeter, 1934: first published in German in 1911). Schumpeter regarded economic (capitalistic) change as the result of revolutionary forces from within the economy, which destroy old processes and create new ones: “creative destruction”. This allows for discrete or non-gradual changes, through clusters of derived innovations following a major invention. These themes were elaborated in his studies of business cycles (long waves). Although Schumpeter realized that discontinuities play a role, he did not assign to them the critical role that they have in Marx’s theory. Instead, he believed that political responses would lead to a gradual transition. Another important notion derived within his dynamic perspective is that of (what was called later) Schumpeterian versus equilibrium (neoclassical) competition, where Schumpeterian competition denotes a competitive advantage that is brought about by process or product innovation.

Since the 1950s, there has been a slow increase of publications on economic evolution. This can be partly explained by the success of evolutionary biology, the limits of neoclassical economics, and the search for evolutionary underpinnings of optimizing behavior as assumed by neoclassical economics (Alchian, 1950; Friedman, 1953). The most cited work since the 1950s has been that of Richard Nelson and Sidney Winter, which culminated in their book “An evolutionary theory of economic change” (1982). Not only has this work influenced evolutionary economists in the neo-Schumpeterian tradition, but it has also been regarded as the most important evolutionary text by mainstream economics. The reason is that a formal, axiomatic approach to evolutionary economics is proposed, involving theoretical models and empirical, statistical applications. Nelson and Winter focus on firms and gradual change, assuming that firms are “…motivated by profit and engaged in search for ways to improve their profits, but their actions will not be assumed to be profit maximizing over well-defined and exogenously given choice sets” (p.4). Moreover, regarding their analysis, they state “… we do not focus our analysis on hypothetical states of ‘industry equilibrium’, in which all the unprofitable firms no longer are in the industry and the profitable ones are at their desired size.” Nelson and Winter argue that their theory can do most of what neoclassical theory can do, and much more. The three building blocks of Nelson and Winter’s theory of microevolution are organization routines, search behavior and selection environment. A routine can be considered as the equivalent of the gene in biological evolution, having some durability and being subject to change due to selection.

Various other, authentically evolutionary approaches have been proposed — perhaps with less impact (so far), but not necessarily less relevant. A diversity of approaches addresses the interface between evolutionary economics and organization theory. The most important recent proposal concerning the direction evolutionary economics should follow is perhaps Potts (2000). He presents a view of economic systems being like complex "hyperstructures", i.e. nested sets of connections among components. Against this background, economic change and growth of knowledge are in essence a process of changes in connections. Potts suggests that connections and their changes have a spatial dimension as well, implying the relevance of the 'geometry of space'. In line with the idea of changing connections, Potts calls for a new microeconomics based on the technique of discrete, combinatorial mathematics, such as graph theory, to study the change of microeconomic connections. This can be seen as a fundamental discussion of the need for multi-agent or population models.

The two main current schools of economic evolutionary thought include the neo-Schumpeterian theories of technical change and evolutionary game theory. The first study phenomena at the firm level (technological innovation), the market and sector level (competition and diffusion, structural change), and at the macro-level (growth, long waves and international trade) (Dosi et al., 1988). It is recognized that the impacts of firm-level innovations are multifold. Innovation causes asymmetry in technology among firms, sectors and countries, leading to exchange and trade. Comparative advantages are not fixed but change due to innovation and diffusion. Trade itself stimulates diffusion of knowledge. In addition, technological change affects the division of labor, the organization of intra-firm and inter-firm relationships, and thus the industrial structure and patterns of intermediate deliveries. Moreover, some firms try to broaden their range of activities and products (maintain variety), not just to realize economies of scope, but to be resilient in the face of market and competitive selection. User-producer interactions may be important as well, such as geographical and cultural proximity, which can give rise to national or regional systems of innovation.

Within the neo-Schumpeterian literature on technological evolution, the notion of path dependence has received much attention. This is based on the idea that changes in population systems are characterized by increasing returns. These can be based on various phenomena, such as learning by using, bandwagon demand side effects (imitation), network externalities (e.g. telecommunication), informational increasing returns (if more adopted, then better known), and technological interrelatedness or complementarity (Arthur, 1989). Increasing returns are important in competition among alternative technologies. Who gets a larger market share, by coincidence, has an advantage and can grow relatively quickly and at the cost of others. In standard economic terminology, one can translate this as “the existence of multiple equilibria”. The paths towards them are important, which is typically the study area of evolutionary economics. Consequences and characteristics of increasing returns are that inefficient equilibria can arise and a certain (inefficient) technology can be locked-in. With increasing returns, the process towards the final or equilibrium state of the system is path-dependent (non-ergodic or historical), as it depends on the way ‘adoptions’ or ‘adaptations’ are cumulated. Non-ergodic systems look irregular, and have been linked to the notion of chaos in (temporal) data, which means that regularity and repetition are lacking. Evolutionary systems in general are non-ergodic because they consist of so much internal variety that the probability of a system revisiting an earlier state is negligible. Moreover, the specific diversity encountered in a particular state is critical for – i.e. limits – potential future paths of the system. A consequence of path-dependence is that the adoption process is very unstable and sensitive to initial events (historical coincidences or accidents). Ample empirical support exists for lock-in and path-dependence due to increasing returns. Well-known examples of locked-in and suboptimal technologies are the QWERTY keyboard, the VHS video system, the fossil fuel engine, and the Windows operating system.

A second current ‘school’, which is becoming more influential, is evolutionary game theory. It has three roots, although this is not often acknowledged. The first is formed by the writings of Alchian and Friedman, who attempted to found equilibrium theory on evolutionary theory. Indeed, evolutionary game theory is also known as equilibrium selection theory, because it solves the problem of multiple Nash equilibria common in nonlinear economic equilibrium models. The second root is the group of Chicago economists of the 1970s who studied selection, took ideas from sociobiology, and developed theory around the notion of utilitarian altruism. The third root is the method of evolutionary game analysis based on populations and selection, which was developed in biology (Maynard Smith, 1982). This method was originally used to support insights of sociobiology. Evolutionary game theory focuses on the existence of asymptotic equilibria. These are possible because no attention is given to a structural process of diversity generation, as a result of which selection completely dominates system dynamics. In other words, the interaction between innovation and selection, typical of evolution in reality, is missing. A more suitable name for evolutionary game theory is thus “selection game theory”.

With regard to transitions two further issues are important, namely long waves and lessons from evolutionary biology. Long waves can be defined as cycles of prices, wages, and outputs of specific commodities (e.g. coal, iron), foreign trade, interest rates, and various other economic variables. The notion of waves or cycles suggests up and downswing, or rise and decline, or boom and depression. Many different opinions have been expressed regarding the nature of waves as well as their causes (see the marvellous collection of classic articles in Freeman, 1996). Long waves are often regarded as being caused by major shifts in technology, due to fundamental advances in science. Freeman points out that various writers do not believe in the existence of long waves, even if they — evidently — recognize fluctuations in economic variables over time. The problem arises from the combination of the complexity of long-term history, and the difficulty of empirically assessing the precise causality behind the composition of long-waves phenomena. Reconstruction of historical data and statistical problems related to 'de-trending' cause additional problems. Nevertheless, various types of cycles or waves have been identified (cf. Freeman, 1996):

- Kitchin cycle: forty months: related to keeping inventories; nowadays, similar short cycles may be due to political (election) cycles;
- Juglar or business cycle: 7-11 years: related to adjustment of investment in fixed assets responding with delays to price changes, i.e. inequality of demand and supply;
- Kuznets cycle: 15-30 years: this has been noted especially in the US and has been explained by waves of migration (possibly self-generating or endogenous through pull forces exerted by an upswing in the wave) and weather (exogenous 'luni-solar tides' affecting rainfall and, in turn, crop production); and
- Kondratieff cycle: 40-60 years: Different particular explanations of long Kondratieff waves have been suggested. From an evolutionary angle, the most important explanation is that the source of new paradigms (e.g. fossil fuel-based industry, electricity) are radical innovations supported by fundamental advances in science, which run through particular sectors and firms that have a direct link between fundamental innovations and their processes and products, and which are most direct and influential in early stages of new technological paradigms. These advances are supportive of many processes and products, directly, or indirectly through process and product innovations. As a result, the innovative key factor or technology generates many related innovations (processes and products), causing a clustering in time of innovations. Together with a phenomenon similar to the product-life-cycle over time, characterised by an end phase of saturation, senescence and diminishing returns, to further investments

> and marginal improvements in the dominant technology, this clustering of innovations gives rise to patterns that can be interpreted as long waves.

Finally, it should be noted that transitions are not restricted to the context of socio-economic systems. Transitions are also prominent in evolutionary biology, as witnessed by the subsequent emergence of chemical cycles, protocells, cells, multicellular organisms, sex, animal groups, human societies (Maynard Smith and Szathmáry, 1995). This sequence suggests various trends: more complex specialisation, labour division, cooperation and emergence (= arising of new levels or meanings of reality). These biological transitions are the result of self-organisation – not regulation: similar to how humans organize themselves in groups, firms, clubs and associations. This suggests that we can learn much from evolutionary biology, in terms of conceptualisation, methods and insights.

3. An evolutionary economics framework

Evolutionary economics is increasingly regarded as a useful approach for assessing processes of structural change, including developments in technology, innovation, organisations, economic structure and institutions. The evolutionary perspective on economics replaces the traditional neoclassical assumption of rational and optimising behaviour with the more realistic assumption of bounded rationality of economic agents. The concept of *bounded rationality* implies that agents are not fully informed and will not include all possibilities in their considerations for performing any behavioural or economic act. Much more often, agents rely on routines, heuristics and imitation (van den Bergh et al., 2000). Bounded rationality is largely based on the idea that gathering full information is constrained by time and energy: it is simply impossible to collect all this information. Neither is it always useful to make a fully informed economic decision, since actions based on limited information usually offer a very satisfactory solution. Thus, a satisfactory outcome is often as good as or better than a perfect one, and it may be very rational in terms of costs related to achieving that solution. This concept of bounded rationality may take the form of routines, habits, imitation and a limited horizon in time and scale.

An important consequence of bounded rationality is heterogeneity in strategies of economic agents. This heterogeneity based on bounded rationality is contrary to the neoclassical economic approach with representative or average (rational) behaviour. Heterogeneity translates into *diversity* of economic strategies, technologies, agents and structure. Diversity is a central concept in the evolutionary framework, as it is regarded as a measure for the fitness of an economic or ecological system. Fitness is in itself a measure of survival and reproduction in a system. Diversity relates to fitness through Fisher's Theorem:

‘The greater the genetic variability upon which selection for fitness may act, the greater the expected improvement in fitness’ (Fisher, 1930). The concept of diversity can be elaborated with three properties (Stirling, 2004): variety (the number of options in a portfolio), balance (the evenness of representation of the different options in the portfolio), and disparity (the degree to which the options in the portfolio are different from one another). All three dimensions will affect the outcomes of both innovation and selection.

System diversity will change over time as a result of the combined effect of innovation and selection. *Innovation* increases diversity in economic systems, analogous to mutation and re-combination in ecological systems. An increase in diversity implies an increase in opportunities for creative combinations contributing to the system’s survival and fitness. Innovation is often the result of serendipity: an outcome that results from combining insight and expertise with chance (Fine and Deegan, 1996). Knowledge is thus crucial for processes of innovation, as these often involve re-combinations of existing techniques or concepts. Systematic search (R&D, science) is a method to increase the chance of useful innovative combinations.

Innovations can be classified in various ways. One relates to the distinction between products, production and services. Another is between radical and incremental innovations. Incremental innovations are in line with the prevailing technological paradigm and often improve the performance of existing technologies. Incremental innovations usually reinforce the technological system they align with. Radical innovations, on the other hand, fall outside the prevailing technological paradigm and usually involve combinations of very different concepts and technologies. The 12th century windmill can be seen as a combination of waterwheel milling technology and sailing technology aimed at the use of wind energy (Mokyr, 1990: p. 44). Incremental innovations are far more common than radical innovations, but the influence of the latter can be enormous. A certain level of geographical or institutional isolation may be useful for harbouring radical innovations, that is, to allow for technological niches apart from the dominant technological regime. Iceland has recently put this notion into practice by developing a technological niche regime aimed at enhancing the concept of a hydrogen economy.

Diversity is reduced by processes of *selection*. Selection refers to the survival and reproduction of succesful agents or strategies in a system. A selection environment involves physical, physiological and geographical constraints, and in economic systems also technological, organisational, economic or institutional dimensions. Selection should not be simplified as ‘survival of the fittest’, but rather as the survival of the sufficiently fit – sufficiently adapted – species in a changing selection environment. In a natural system, different species choose different survival strategies. A similar specialisation process applies to economic systems, where agents adapt their economic activities to the extent to which they can occupy their own niche in the economic system.

Repeated selection can result in a *path dependent* development. This depends on increasing returns that result from demand and supply side factors like scale advantages, ‘learning-by-using’, imitation, network externalities and information effects (what is sold most is best known and thus sells more) and technical complementarity (Arthur, 1989). Increasing returns are a type of positive feedback or self-reinforcing mechanisms. These mechanisms can easily end in the dominance of a particular technological or economic regime. Moreover, this process may be reinforced by incremental innovations based on previous innovations within the dominant regime. The situation where technologies become dominant due to positive feedback mechanisms is often referred to as *lock-in*. An often used example of a locked-in technology is the QWERTY keyboard. This keyboard is sometimes seen as lacking the efficiency of the ‘Dvořák keyboard’, but due to institutional and organisational embedding it is still dominant, even though the original technological advantages based on the setting of the type bars in the typewriter are no longer relevant in computer keyboards. Processes of path dependency introduce history into economic dynamics, since technological developments tend to follow irreversible pathways. This is an important distinction from neoclassical economic theory, which suggests that a system is reversible, that is, it can return to an optimal configuration. It should be noted that lock-in and path dependency make it particularly difficult to introduce and proliferate technologies outside the dominant technological regime. Reducing the chances of lock-in requires maintenance of diversity, and more generally, an extended level playing field (see the next section).

A final core evolutionary concept is *coevolution*. This concept refers to the mutual influence and interference between two or more systems or populations: one system may exert selection pressure upon another system and vice versa, leading to related evolutionary developments in both systems. Coevolution is thus a particular concept of dynamic interaction between two populations with internal diversity (van den Bergh and Stagl, 2003; Winder et al., 2005). An early application of this concept to socio-economic systems was done by Norgaard (1984). He introduced feedbacks between five partial systems of knowledge, values, organisation, technology and environment. Variations in each of these systems are strongly influenced by the other systems and vice versa. An example is the introduction of pesticides, which not only triggered higher crop yields and a policy effect, but also an increase in resistance of the pest to the vermin. Another example is the coevolution following the domestication of animals, which triggered not only large-scale cultural and economic changes in early societies, but also led to artificial selection of plants and animals (Campbell, 1996: p. 569). Later this was followed by a coevolution of human diseases and bacteria and viruses derived from animals (Diamond, 1997). An example of coevolution between economic systems is provided by the heavy organic chemical industry in the United States, which was coal-based in the beginning of the last century. In the 1920s, the rapid growth in demand for petrol (gas) for automobiles in the United States supplied a large and inexpensive supply of olefins as a by-product in the refining process. By the end of WWII, the US chemical industry had fully changed to petroleum-based feedstocks (Ruttan, 2002). It is interesting to see that present-day sustainability policies sometimes refer to a new transition in the chemical sector, which should be based on biomass feedstocks. It may well be that changes in other economic systems are required in order to be able to make such changes in the chemical industry.

When these concepts and their interactions are taken together, a picture arises as shown in Figure 1. Note that even if this seems complex, it understates the complexity of the real world economy.

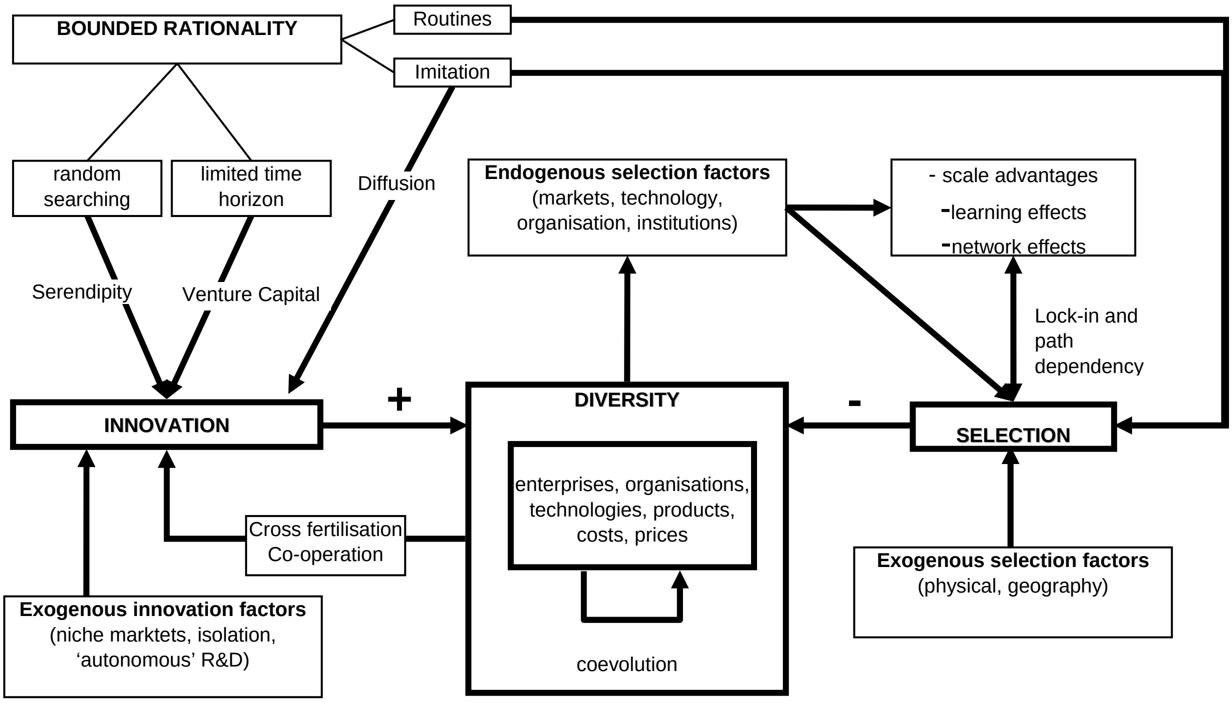


Figure 1. A simplified picture of the evolutionary economy

4. Transition policy within the evolutionary economics framework

The evolutionary economic framework and its concepts give rise to a number of insights regarding transition policy and management. Although evolutionary processes are fundamentally without a goal or target, normative elements can be added by policy-makers. An important lesson of evolutionary economics is, however, that policy-makers should refrain from 'picking winners', since it can never be known beforehand what the winners will be in terms of economic, environmental or social benefits. Policy-makers could put evolutionary economics into practice by creating conditions under which evolutionary processes will lead to socially desirable outcomes. An evolutionary-based policy will focus on influencing the selection environment, promoting innovative strength, and making advantageous use of coevolution. An important element of an evolution-inspired policy is to promote diversity as a goal in itself. Evolutionary economics as inspiriation for environmental policy has received some attention (e.g., Faber and Proops, 1990; Norgaard, 1994; Kemp, 1997; Gowdy, 1999; van den Bergh and Gowdy, 2000).

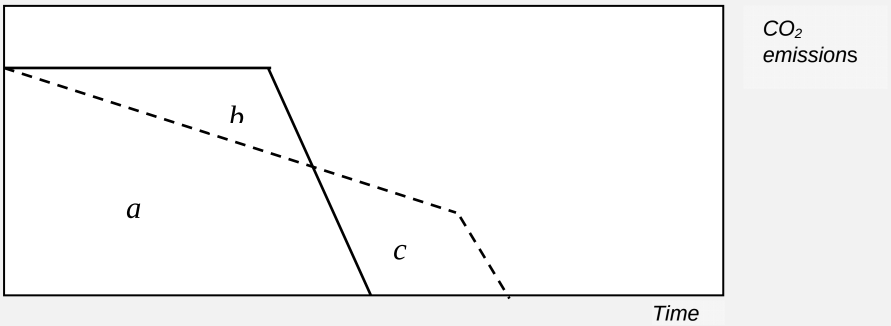
A starting point for an evolutionary environmental policy lies in the concept of *path dependency*. It is of key importance to realise that most developments are decided in their early phases, and care is needed to foster new technologies and experiments in the early phases. It will still be important to keep an eye on all phases of an innovation or technology development. This is to maintain sufficient diversity in technologies, from both the innovation (potential for combinations) and selection (acting upon diversity) perspectives. *Diversity management* should focus on stimulating a wide range of technologies and strategies in terms of variety, disparity and balance. Diversity of technologies and strategies introduces resilience and robustness in environmental policy, which goes beyond the concepts of efficiency and unilinear (economic) growth.

Diversity management requires an *'extended level playing field'*, where alternative technologies, organisations and institutions can compete with more dominant elements. A number of conditions needs to be met if a credible extended level playing field is to be realised. First, prices need to reflect all the external costs generated by activities and products. Secondly, technologies that are low on the learning curve, but at the same time may be expected to have large sustainability potential in the long run, need to receive special support, either by creating niches or by providing subsidies. Exposing such technologies to free market competition where short-term cost-effectiveness dominates is not a good strategy in trying to make a transition to long-term sustainability. An early lock-in of unsustainable technologies should therefore be avoided, as it will go along with an early decease of potentially attractive technologies (see Box 1 for a theoretical example of this due to energy saving). A third condition for an extended level playing field is to try to expose different technological options to similar selection mechanisms.

Box 1: Evolutionary assessment of energy saving

The notions of lock-in and environmental policy may be illustrated by experiences from energy-saving policy. Energy-saving strategies often imply an increased efficiency of the use of fossil fuels. There are two different types of energy-saving strategies: **(1)** one decreasing the demand for useful energy (e.g. insulating homes or decreasing the air resistance of cars) and **(2)** the other increasing the efficiency of converting fossil fuels into useful energy. A decreased demand for useful energy will not alter the economic advantage of one fuel over the other. An increased conversion efficiency of fossil fuels, however, will decrease the costs per unit of useful energy based on fossil fuel, and thereby strengthen the economic advantage and lock-in of these fuels. Consequently, the increased conversion efficiency of fossil fuels could hamper the transition towards an energy system based on more sustainable energy resources.

This point is illustrated in the following graph:



The solid line shows CO_2 emissions due to a large-scale transition to sustainable energy production, while the broken line shows CO_2 emission in an energy-savings scenario. Cumulative emissions in the transition scenario are $a+b$. Cumulative emissions in the energy-saving scenario are $a+c$. The most attractive scenario (in terms of reductions) depends on whether $b>c$ or $b<c$. Now, if time before the point of transition increases, b increases compared to c, thus making energy savings more attractive. On the other hand, since the saving of energy is progressing well (especially in the initial stages of this scenario), policies for rendering a transition may become less interesting. Energy-saving may hamper the sense of urgency that is often considered necessary for a transition to sustainable energy production.

This raises a theoretical argument against energy-saving policies. In practice, however, it is conceivable to elaborate a more diverse and sophisticated policy strategy, aimed at a sustainability transition in the longer term, but to maintain energy-saving policies in the shorter term. This may not be the most cost-effective approach, but it does line up with the theoretical perspectives from the evolutionary economic theory and thus yields a more diverse and robust economy.

Diversity increases through *innovation*. Innovation in evolutionary policy-making can be reinforced by increasing the chance of realising creative combinations, by stimulating attractive future perspectives, and by supplying capital and facilitation, through a level of niche management (i.e. increased isolation) and by increasing insight and knowledge. The concept of serendipity could become operational through the creation of innovative networks, with a focus on cross-fertilisation and stimulation. Such cross-fertilisation from different institutional systems may also lead to fruitful *coevolution*. An example is applying our experience from natural gas systems to set up distribution systems in the hydrogen economy. Isolated experiments and initiatives on the other hand may yield unique and surprising technological pathways outside the dominant regime. Such initiatives may be useful in small-scale incubator settings, where experiments are fostered as possible contributors for future solutions.

It is crucial for evolutionary policy-makers to balance between diversity and selection, so as to prevent a system ending up in either deadlock or inefficiency. Here, it is important to balance the cost of diversity in the short term against the benefits of diversity in the longer term. This trade-off can never be made on the basis of full information, but relies on expert estimation of chances, barriers and opportunities. On a larger scale – e.g. Europe as compared to any one of its countries – it may be easier to balance between diversity and efficiency, since relatively minor technologies may also reach a minimal scale advantage at this level. With this insight, policy-makers should be invited to align trajectories for sustainable development in large-scale co-operation, such as in the EU Framework programmes.

It is important to note that evolutionary theory does not offer an ‘optimal policy’. *Bounded rationality* prevents economic agents from optimising their economic behaviour. An implication of evolutionary theory is that pricing instruments will not even realize efficiency at the level of individual agents (van den Bergh et al., 2000). The efficiency – and effectiveness – of such instruments is therefore overestimated in traditional economic analysis and policy-making.

5. Evolutionary economics assessment of three specific energy technologies

In this section, the role of the evolutionary economic concepts that were discussed above will be explored in three concrete examples of new energy technologies that might play a role in the development of a sustainable energy supply. These are: fuel cells, nuclear fusion and photovoltaic cells. The section concludes with some general observations based on the three cases.

Fuel cells

Fuel cells are clean and efficient energy transformation appliances, which convert a fuel (usually hydrogen) into electricity (and heat). In general discussions, fuel cells are often related to the ‘hydrogen economy’. Within such a perspective, hydrogen is regarded as the central energy carrier while fuel cells are considered as important mechanisms of energy transformation. Thanks to fuel cells there is a high level of *diversity* in techniques, applications and companies. With regard to the *innovation* aspects, fuel cells can be considered a radical innovation, characterised by strong interactions between different industries (*inter alia* the chemical industry, energy companies and car manufacturers). Niche markets can be found in aeronautics and ('zero emission') motor vehicles. Liberalisation of energy markets (provided that there is a level playing field) and stringent environmental policy might be conducive to creating a favourable *selection* environment for fuel cells. *Bounded rationality* could hamper the introduction of fuel cells, as it requires a clean break with existing routines and long-term, risky investments. Nevertheless, if one sheep leaps over the ditch, the rest will follow (we can already observe this imitative behaviour among car manufactureres, many of whom are now working on fuel-cell cars). *Path dependency and lock-in* in existing technologies (such as the internal combustion engine and batteries) imply an important barrier for fuel cells. On the other hand, economies of scale in the application of fuel cells are limited, which means that they would fit very well into small-scale, decentralised energy systems. In terms of *coevolution,* a strong interdependence between fuel cells and other components of the energy system can be noted (such as the fuel supply infrastructure).

The Dutch as well as the larger European fuel-cell arena is still very much focused on the R&D phase, since large-scale commercial application is still beyond the horizon. Many technical and economic barriers remain to be overcome. However, small niche markets are already in place, often in hybrid applications. Increasing demand for fuel cells may now be at the turning point of opportunity: further new applications will be increasingly important, so as to allow the technology to move forward on the learning curve. The government may play a role here, both as legislator and large customer.

Nuclear fusion

The path of nuclear fusion to commercial application has long been said to be about 50 years and remains so to date. Much research is still very fundamental and even application-oriented projects are very much focused on experimenting with fundamental principles. The high costs involved and the still distant benefits largely exclude private partners from the research. A very centralised energy technology like nuclear fusion only allows for very large-scale units. Present-day experimental units are thus very expensive. Even though commercial application may still be beyond the horizon, the learning curve is passing very fast, even when compared to the well-known Moore's Law for the evolution of computer processors (Figure 1).

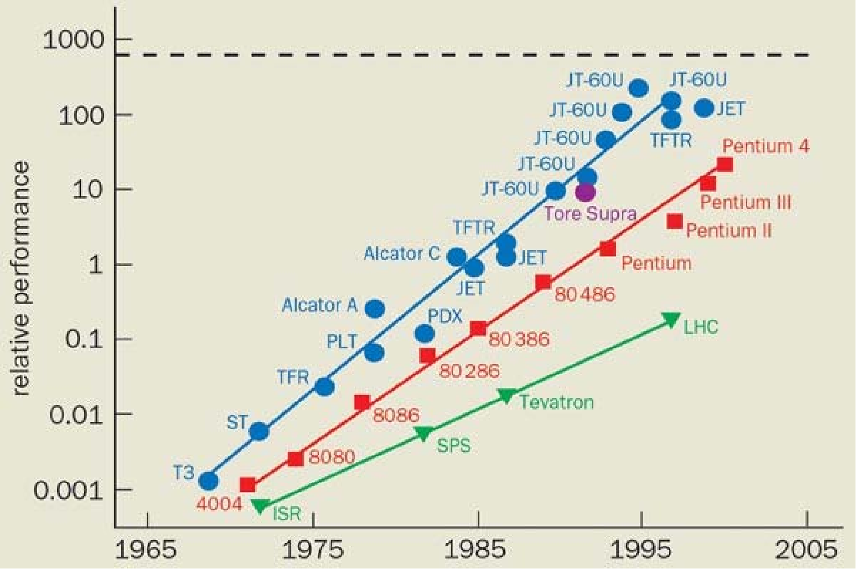


Figure 1. Fusion experiments have kept pace with other hi-tech developments over the last 30 years.

Note: Since the early Russian T3 tokamak, the performance of fusion plasmas has doubled every 1.8 years (blue line). The performance of fusion plasmas is defined in terms of the triple product (density × temperature × time). This triple product compares favourably with the doubling of the energy of particle accelerators every 3 years (green line), and the doubling of the number of transistors on a chip every 2 years (red line). The dashed line at the top shows the performance expected with ITER (Source: Hoang and Jacquinot, 2004).

The high costs involved in nuclear fusion allow for only one type of fusion technology, the one based on Tokomak installations. A second important element is the high level of co-operation, illustrated by the continuous interaction between the United States and the Soviet Union even during the Cold War period. Finally, the vision on the future is very utopian in attractiveness: large-scale application of nuclear fusion requires cheap, unlimited and widely availabe fuel (water) and causes hardly any environmentally harmful emissions. All these features allow for a fast learning curve for nuclear fusion.

When assessing nuclear fusion for the six evolutionary economic aspects that we have distinguished, it is obvious that the degree of *diversity* in this technology is very low. The main observation concerning the factors relating to *innovation*, is that there is a lot of (worldwide) co-operation within a relatively small network of experts, whose interactions with other sectors are limited. There are, as yet, no (niche) markets for the technology, of which the viability will be strongly dependent on a favourable *selection* environment, in which stringent CO_2 policies will have to play an important role. With respect to *bounded* *rationality,* it can be said that there is a lack of interest among private investors (due to the long time horizon involved) and an absence of established routines on which to base the technology's application. With respect to p*ath dependency and lock-in,* the huge investments in fusion technology would clearly seem to have an irreversible character and economies of scale are extremely important. This implies that nuclear fusion will fit in well to the existing large scale electricity supply regime, but it is incompatible with a decentralised energy supply system. Regarding *coevolution,* there is very little exchange to be noted with other areas of energy technology, but some complementarity between areas of expertise relevant for nuclear fusion can be observed (e.g. plasma physics and materials science).

Photovoltaic cells (PV)

Photovoltaic (PV) or solar cells are seen in sharp contrast to nuclear fusion in the sense that the first type of energy production is conceptually very de-centralised. The silicon-based PV cell was discovered more or less by accident in the electronics industry, making it a good example of serendipity. The concept of applying thin film cells originated in photography, providing a good example of cross-fertilisation. Niche markets for PV applications, first developed in aerospace technology, were later extended to off-grid applications such as marine light beacons. PV applications may be grid-coupled, although there is no fundamental need to do so. Scale advantages in application are very limited. Many off-grid applications in remote areas, for example, are conceivable or already in place. Investment costs are, however, still very high, even though the learning curve is proving to be rapid, very much due to learning-by-doing experiences. Large-scale application opportunities in the Netherlands are seen as being limited, since the Dutch electricity network is very dense, thus not allowing for many off-grid niche markets. Large-scale application in other parts of the world will certainly require a break in the technological regime, as the PV production units can be applied in a much more decentralised context than present power production units.

In addressing PV in terms of the six evolutionary-economic aspects, we can make the following observations. *Diversity* is high in several respects: companies dealing with PV-technology display a large variety (both in size and type of industry); a number of different technologies are in existence, in addition to the 'traditional' monocrystalline silicon cells, and there is a wide range of (potential) areas of application. With respect to *innovation*, serendipity, cross-fertilisation and niche markets have played an important role in the development of PV. On the other hand, the lack of an authoritative, coherent future perspective on the role of PV may have been a restraining factor.[1] In the *selection* environment for PV, government policies form an essential factor. PV is still an expensive technology and will remain dependent on subsidies and other preferential policy measures for quite some time. Among the elements of *bounded rationality*, it is the short-time horizons of private investors that stand out. PV is capital intensive, with a long lifetime and low operational costs. Its financial performance is therefore highly dependent on the discount rate or payback period applied by the investor. As far as *path-dependency and lock-in* are concerned,, we can mention that because PV can hardly benefit from economies of scale in application, it is therefore particularly suitable for systems of decentralised electricity supply. Finally, with respect to *co-evolution* a relevant feature of PV is its intermittent character (due to the fluctuations in solar energy influx). This implies that application of PV application will have implications for other components of the energy system (such as energy storage devices).

6. Conclusions

Transitions are being studied in many ways, including various theoretical perspectives. Here it has been suggested that an evolutionary economics angle provides clear insight into the mechanisms that underlie transitions to a sustainable development. After a discussion of the meaning of transitions and evolutionary economics, a framework was presented around six central evolutionary concepts. These are 'diversity', 'innovation', 'selection environment', 'bounded rationality', 'path dependence and lock-in', and 'coevolution'. Next transition policy and management were discussed. Here the notion of an extended level playing field was emphasized which requires in addition to perfect market competition three other conditions, namely charging of negative environmental externalities in prices, resisting early lock-in, and striving for alternative, competing options to be on equal positions on their learning curves. It was further argued that energy conservation does not only have beneficial effects but may also delay an energy transition, suggesting a limit to (optimum level of) this option.

The case studies reveal some features that may also be relevant for other cases where the implications of evolutionary economic insights for the development and application of new (energy) technology are at stake. First of all, government policies have been mainly directed towards stimulating R&D. This has contributed to the progress made in creating better, cleaner and more efficient technologies. However, in order to ensure that these technologies

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[1] To some extent, the publication in September 2004 by the European Commission of 'A Vision for Photovoltaic Technology for 2030 and Beyond' may have filled this gap. See: http://europa.eu.int/comm/research/energy/photovoltaics/introduction_en.html

continue to advance on their learning curve, policies should (in addition) be directed more towards application and diffusion. The independent variable of the learning curve is cumulative production/application of the technology, and this variable has to increase exponentially in order to achieve an (also exponential) reduction in production cost (or price).

Stimulating the market is also of particular relevance in order to break out of the ‘chicken-and-egg’ problem that potential investors in a new technology take a wait-and-see attitude, hoping for lower prices and better quality, which are in turn dependent on growth in cumulative investment volumes. Creating a favorable selection environment (e.g. by creating or stimulating niche markets) can be conducive to this break-out.

Stimulating specific technologies should not be seen as a way of ‘picking the winners’, but rather as a matter of promoting diversity, preventing lock-in and providing fair chances to competing technologies.

Creating a favorable selection environment seems to be at odds with the current trends of privatisation and government retreat from areas with traditionally strong public involvement (such as energy, housing and public transport). A reconsideration of the government’s role in these areas would therefore be advisable, as these are sectors where economies of scale and long term investments are paramount, and the risks of lock-in and suboptimal results are therefore high if everything is left to the market.

A dilemma facing the policymaker could be: should investments in improving ‘traditional technologies’ and in ‘hybrid’ technologies be encouraged or not? On the one hand, this could contribute to the ‘lock in’ of the ‘old’ system; on the other hand, experience shows that a hybrid technology can be an intermediate step towards a technological breakthrough. A final solution for this dilemma cannot be given on the basis of our case studies.

Future visions can play a useful role as a source of inspiration. Recently, initial steps have been made to sketch such visions at EU level for fuel cells and for PV. It seems worthwile to continue working on these (and other) energy future visions.

Finally, the importance of exchange, co-operation and cross-fertilisation should be emphasised. The case studies confirm that technological breakthroughs often find their origin in applying knowledge from a totally different industry or discipline. One might therefore advise policy makers to bring together people from very divergent areas, so that they can exchange ideas and find unexpected solutions.

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