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RESEARCH ARTICLE

Survival of the greenest: evolutionary economics and policies for energy innovation

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Abstract
This paper aims to explore the possible contribution of evolutionary economics to environmental policy-making, in particular with respect to innovations in energy technology. Evolutionary economics offers insights into the mechanisms that underlie innovations, structural changes and transitions, therefore making it of great value in framing policies aimed at stimulating environmental innovations and transitions to sustainable development. The paper identifies 'bounded rationality', 'diversity', 'innovation', 'selection', 'path dependency and lock-in', and 'co-evolution' as the main concepts in evolutionary economics. These concepts are subsequently used to formulate guidelines for designing energy innovation policies. We evaluate current Dutch policies related to energy technologies against this background and examine the development of three particular energy technologies within the adopted evolutionary economics framework, namely fuel cells, nuclear fusion, and photovoltaic cells. We conclude that in order to incorporate the core concepts of evolutionary economics, governmental technology policies should focus more on the *diversity* of technologies, strategies and businesses, rather than on economic efficiency as the key goal. It is further found that evolutionary concepts conflicting with traditional growth objectives are rarely incorporated in Dutch energy innovation policies.

Keywords: *Evolutionary economics, energy, environmental policy, innovation policy, sustainability, transition management*

1. Introduction

Evolutionary economics was hinted at as early as 1898 in the question posed by Veblen (1898): "Why is economics not an evolutionary science?". Some decades later, Schumpeter and the Austrian school laid a fertile basis for the development of economics as an

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evolutionary science, notably by focusing on innovations. Schumpeter introduced the concepts of 'entrepreneur' and 'creative destruction' (Schumpeter 1934, 1939, 1942), which came to have enormous influence in later economic policy-making. Evolutionary economics gained full momentum from the 1970s onwards, when Nelson and Winter (1982) built their theoretical framework on the evolutionary ideas laid down by Schumpeter. A number of evolutionary schools have emerged since, such as evolutionary game theory, neo-Schumpeterian technology analysis and evolutionary multi-agent modelling.

Environmental policy, with its focus on innovations and system change, could greatly benefit from insights taken from evolutionary economics. One reason why evolutionary economics is now more relevant to economic and environmental policy theories is the rapid development of evolutionary economics since the 1970s. As opposed, in Schumpeter's time evolutionary thinking—in biology and certainly economics—still lacked a coherent perspective on microevolution, coevolution, group selection, macroevolution and other issues relevant to social science.

In this paper, we offer a theoretical evolutionary framework based on six central concepts: diversity, innovation, selection, bounded rationality, path dependency and lock-in, and co-evolution (Section 2). The evolutionary framework is applied to assess Dutch energy innovation policies, for which environmental policy provides an important context (Section 3). Testing for the presence of evolutionary elements in policy documents allows current energy innovation policies in The Netherlands to be evaluated from an evolutionary economics perspective (Section 4). The evolutionary concepts are applied to the technology level, with three main energy technologies being examined: fuel cells, nuclear fusion and photovoltaic cells (Section 5). Section 6 draws conclusions and makes a number of policy-relevant suggestions.

2. The evolutionary economic framework in six basic concepts

2.1. Bounded rationality

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 experience. 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 (Vermeij 2004). This concept of bounded rationality may take the form of routines, habits, imitation and a limited horizon in time and scale.

2.2. Diversity

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, which usually involves a homogeneous population of economic agents or strategies based on rational optimalisation. 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.[1]

2.3. Innovation

Over time, system diversity will change as a result of the processes 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.

Future visions and utopias may be useful for enhancing the effectivenes and focus in searching for profitable innovations. Innovations can be classified in various ways, for example, by distinguishing products, production and services. A common distinction is made 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. Even in isolation, it should be noted that innovations are always developed within an institutional setting or innovation system and almost never in a linear fashion.

2.4. Selection

Diversity is reduced by processes of *selection*. Selection refers to the survival and reproduction of successful 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 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.

2.5. Path dependency and lock-in

Repeated selection can result in *path dependencies.* This concept relates to increasing returns because of scale advantages, 'learning-by-using', imitation, network externalities, information effects (what is sold most is best known and thus sells more) and technical complementarity (Arthur 1989). Increasing returns are often the result of and lead to positive feedback mechanisms. This process may end in the dominance of a particular technological or economic regime and may, in turn, be reinforced by incremental innovations based on previous innovations within that same regime. The situation where technologies become dominant due to positive feedback mechanisms is often referred to as *lock-in.*

A topical example of a locked-in technology is the Windows operating system. Microsoft Windows is ubiquitous on PCs worldwide and its dominance is reinforced through positive feedbacks and network advantages: users without Windows are disabled or limited in exchanging information with others, as well as in using certain software programs. Although favourably evaluated alternatives like Linux have existed for some time now, the technological and market monopoly of Windows remains unchallenged due to its increasing returns to scale on the demand and supply side.

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 can return to an optimal configuration, thus often neglecting technologically or institutionally irreversible developments. 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 Section 3).

2.6. Co-evolution

A final core evolutionary concept is co-evolution. 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. Co-evolution is thus a particular concept of dynamic interaction between two populations with internal diversity. Norgaard (1984) first applied the concept of co-evolution to socio-economic systems, introducing 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, but also an increase in resistance of the pests to the pesticides. Another example is the co-evolution 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 co-evolution of human diseases and bacteria and viruses derived from animals (Diamond 1997).

An example of co-evolution 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 led to a large and inexpensive supply of olefins as a by-product in the refining process. By the end of World War II, 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.

3. Evolutionary concepts and environmental policy

The evolutionary economic framework and its concepts give rise to new insights in the framing of environmental policy, particularly where this policy focuses on innovative solutions within the existing economic system or on system changes to sustainable development (also known as ‘transitions’ or ‘industrial restructuring’). The neoclassical economic perspective on environmental policy theory emphasises the efficiency of regulation, interpreted as welfare maximisation or cost minimisation. This theory aims to remove market failures that reduce social welfare, notably those relating to public goods (‘bads’ in the case of environmental pollution) and negative (environmental) externalities. Evolutionary economic theory distinguishes fundamentally from general economic theory on several features (see also Boschma et al. 2002):

- The central focus of evolutionary policy is on economic dynamics resulting from innovation, selection and accumulation, while general neoclassical economic policy is very much concerned with static equilibria (however, this does not hold for growth theory as applied to environmental and resource issues).
- Although evolutionary processes are fundamentally without a goal or target, normative elements can be added by policy-makers. In neoclassical policy the main goal is maximum social welfare or minimum cost of regulation.
- In the neoclassical economic theory of policy the governmental role is restricted to removing market failures. Public policy from an evolutionary angle is more focused on influencing the selection environment and the effectiveness of innovation.

As a result, ‘evolutionary policy’ will refrain from ‘picking winners’. The reason is that it can never be known beforehand who will be the winners in terms of economic, environmental or social benefits, given that the complexity and uncertainty of evolutionary dynamics are very large. Policy-makers could put evolutionary economics into practise by creating conditions under which evolutionary processes will lead to socially desirable outcomes. An evolutionary-based policy will focus on influencing the conditions of the selection environment, promote innovative strength, and make advantageous use of co-evolution. An important element of an evolution-inspired policy is to promote diversity as a goal in itself. The six concepts we identified in Section 2 can help us to describe an environmental policy based on evolutionary economic theory.

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. Therefore, care is needed to foster new technologies and experiments in the early phases, although it will still be important to keep an eye on all phases of an innovation or technology development. This is to maintain sufficient diversity of 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.

Unlocking of existing, undesirable (fossil fuel) technologies requires an 'extended level playing field', where alternative technologies, organisations and institutions can compete with more dominant elements. A number of conditions need 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. Second, 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 relatively unsustainable technologies should therefore be avoided, as it will go along with an early decrease of potentially attractive more sustainable technologies. This might take the form of preventing or compensating (coincidental) increasing returns (see the Box text 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.

Stimulating unlocking requires in addition that all explicit and implicit stimuli of the dominant technology are removed, and that preferential treatment (e.g. in public choices and purchases) be given to desirable alternatives. Unlocking can also be enhanced by setting a clear, ambitious environmental goal with a time horizon, like the zero-emissions vehicles' regulatory goal set by California. Selection pressure will then be clear, consistent over time and thus effective.

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 *co-evolution*. 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.

Box. 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) decreasing the demand for useful energy (e.g. insulating homes or decreasing the air resistance of cars) and (2) 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 Figure 1.

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 point pits 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.

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 for evolutionary theory is that pricing instruments will not even realise efficiency at the level of individual agents. The efficiency—and effectiveness—of such instruments is therefore overestimated in traditional economic analysis and policy-making.

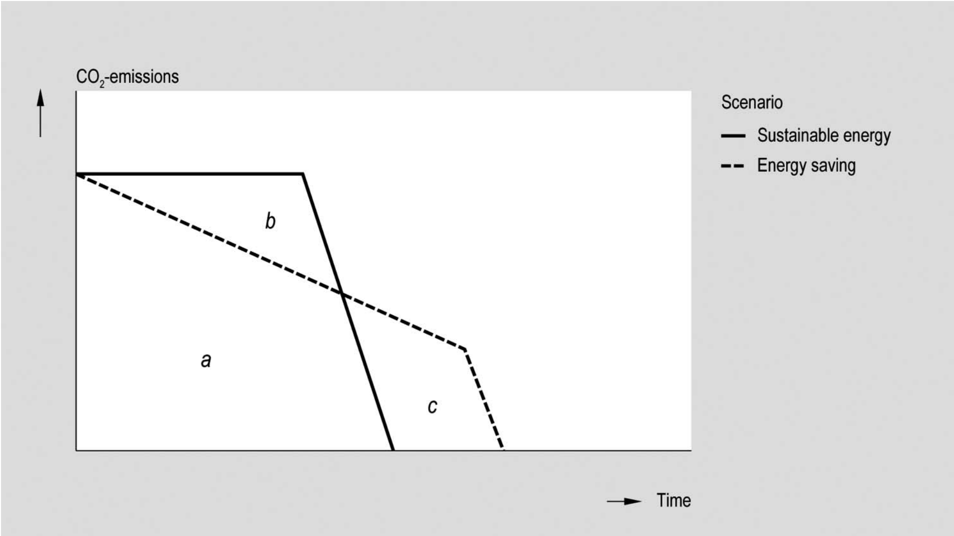

Figure 1. CO_2 emissions under a 'sustainable energy' scenario (solid line) and under an 'energy saving' scenario (dashed line).

4. Assessment of Dutch energy innovation policy from an evolutionary perspective

4.1. Design of the Dutch energy innovation policy

Dutch policies concerning the stimulation of energy innovations are embedded in several policy fields with different co-ordinating ministerial departments. The Ministry of Economic Affairs is responsible for energy policy and innovation policy. Climate policy, transition policy and the stimulation of environmentally sound technologies are co-ordinated by the Department of the Environment within the Ministry of Housing, Spatial Planning and the Environment. Consequently, recent policies on the stimulation of energy innovation are based on many different memoranda and reports formulated by different ministries and advisory bodies. The evolutionary economic assessment of energy innovation policy in The Netherlands is based on an analysis of the objectives and mechanisms identified in these reports. In the present paper we will only refer to the dominant reports for current policies: 'Energy Research Strategy' (Ministry of Economic Affairs 2001) and 'Action for Innovation' (Ministry of Economic Affairs 2004a).

Policies to stimulate energy innovations relate to the overall objectives of energy policy, which are largely inspired by the Kyoto Protocol objectives. The Dutch CO_2 emission-reduction goals are translated into objectives to stimulate energy savings and the use of sustainable ('green') energy resources. An important point of departure for the Energy Research Strategy is the changing position of the government: "The government's role is shifting from a player in the field to a conductor. The character of policy instruments is also changing: demand is influenced by instruments such as norms, standards and fiscal investment incentives. Furthermore, a more generic approach is more consistent with contemporary thinking. New approaches, such as the use of technology roadmaps, have become established. The focus of existing instruments is shifting, for example, towards dissemination of knowledge and issues such as public acceptance" (Ministry of Economic Affairs 2001).

'Action for innovation' (Ministry of Economic Affairs 2004a) elaborates the policy focus for improving a sustainable economic growth through innovation. It presents the plans by the Dutch government to 'tackle the Lisbon ambition'. This ambition was formulated at the European Council in Lisbon (2000) where the member states agreed that the European Union should develop into the most competitive and dynamic knowledge-based economy in the world within ten years.[2] 'Action for innovation' was preceded by a number of reports and memoranda which agreed on the perceived problems: (1) the Dutch innovation climate is not attractive enough; (2) this climate lacks innovative companies; and (3) research lacks sufficient focus and quantity. Current Dutch innovation policy is based on the concept of a dynamic innovation system: the connection between the development, application and introduction of innovations to the market. It focuses on improving the weak spots in the system: the knowledge infrastructure and the introduction of innovations on the market. Current innovation policy proposes the development of generic instruments to deal with these problems. Specific attention is also paid to focusing on the economic sectors that are frontrunners, so as to make full use of the advantages of the cutting-edge industries (Ministry of Economic Affairs 2004a). Thus the Dutch innovation policy has two main goals: to improve the *focus* on the strengths of the innovation system and to increase the *mass* of the innovation system as a whole.

4.2. Evolutionary assessment of Dutch energy innovation policy

The identified evolutionary economic concepts of diversity, innovation, selection, bounded rationality, path dependency (and lock-in), and co-evolution can be used for a policy assessment, as seen in our analysis of a number of key documents of Dutch energy innovation policy.[3]

Although the point of departure of current Dutch innovation policies is a systems approach, which is in line with evolutionary economic thinking, the practical implementation of these policies still focuses on traditional policy instruments, such as subsidies, fiscal measures and negotiated agreements.[4] Only very recently an increase comes forth in focus on and tentative application of system instruments, such as innovation networks and thematic innovation programmes. Specifically, thematic public–private partnerships in R&D based at the large Dutch technological institutes are generally conceived to be very well organised (OECD 2003).

Many of the central evolutionary concepts can be traced in energy innovation policy, although practical application is, in many instances, limited. For example, strategic documents signal the importance of diversity and diversity management, but this management is more applicable to technologies than strategies, sectors or companies. A central point in innovation policy is the dilemma between focus and momentum, on the one hand, and diversity, on the other. This is much in line with the theoretical dilemma introduced in the previous section.

The elaboration of evolutionary principles behind the concept of innovation shows a somewhat mixed assessment. Much attention is paid to interaction and technology transfer, which is often regarded as one of the main shortcomings in the Dutch innovation system. On the other hand, elements like cross-fertilisation, serendipity, isolation and niche markets do not receive any attention in energy innovation policy. Increase in the fundamental body of knowledge is largely dependent on training and education, both of which receive considerable attention in policy issues. Niche markets are not present as a strategic tool, but some experiments on innovative, sustainable energy alternatives are stimulated through subsidies or other instruments. Finally, we discern a large focus on technologies, or rather, organisational or institutional innovations, which may be just as important for goals of productivity.

The evolutionary concept of *selection environment* is lacking. In Dutch energy innovation policy the market is implicitly considered to be the dominant selection factor, to which government should maintain a sound distance so as not to disturb the mechanisms of the free market. Relatively much attention is reserved for the removal of innovation barriers. Much policy is focused on the inclusion of external costs, which should, to a large extent, be sufficient for making market mechanisms work properly. "A new selection mechanism for innovations in the free market can thus be applied; government does not need to interfere, as the winners will come forward automatically" (Ministry of Economic Affairs 2004b).

With regard to the concept of *bounded rationality,* much attention is given to the elements of time horizon and imitation. A limited time horizon can be associated with many private entrepreneurs. Government itself often applies more distant time horizons, for example, by making use of scenario studies and strategic planning tools. On the other hand, a level of routine can often be distinguished in the application of traditional policy instruments focused on direct economic incentives, such as subsidies and taxes. Imitation increasingly plays a role in the framing of innovation policies, especially for SMEs following frontrunning enterprises.

The concepts of *path dependency* and *lock-in* have found their way in strategic policy, including the concept of the level playing field. Elaboration of the strategic concepts into operational policy instruments seems to be turned toward prevention of barriers, rather than stimulation of driving forces. The prevention of lock-in—which is very clearly incorporated in policy—is thus mainly framed in postponing selection, rather than full-hearted support for flexible solutions. A discussion on more strategic choices for the prevention of lock-in may be useful in energy policy, for example, in large-scale versus small-scale energy production. The dense energy network in The Netherlands is only tentatively mentioned, supporting a policy choice for large-scale and centralised options rather than small-scale solutions. Finally, the element of level playing field is very often mentioned, but usually in the context of competitive relations with other countries with a much more limited meaning than proposed in the previous section. Different positions on the learning curve are not recognised as an important point of attention. Transition management would require a stronger focus on the development of sustainable energy technologies through early investments and learning-by-doing. The concept of level playing field is not usually regarded in its extended version, i.e. where alternative technologies, organisations and institutions can compete with more dominant elements.

Finally, the concept of *co-evolution* is not generally used as an important element in Dutch innovation policies. Although different memoranda on the subject of energy innovation note the importance of developments in non-energy-related technologies, there is hardly any connection between energy policy and innovation policy. Co-evolution is, moreover, seen as an advantageous or unpleasant coincidence but not as something policy could consciously try to make use of. An example of potential co-evolution based on complementarity is hydrogen transport in a hypothetical hydrogen economy that would make use of gas pipelines already in place.

From this assessment, we may conclude that the evolutionary economic concepts adopted in Dutch energy innovation policy are in accordance with traditional notions of efficiency and effectiveness: diversity of technologies, co-operation in public–private partnerships, application of future visions for roadmapping, market as a selective mechanism, several elements of bounded rationality and the consciousness of scale advantages. The concepts that are applied most thus satisfy both evolutionary and traditional perspectives. Practical elaboration of policy strategies usually still relies on traditional command-and-control and some market instruments, which do not necessarily collide with the evolutionary perspective. However, we can see a tendency towards the application of system instruments, which align well with evolutionary policy-making.

5. Evolutionary assessment of three specific energy technologies

5.1. 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'. In this concept, hydrogen is the central energy carrier and fuel cells are an important element of the system. In fuel cell technology we can find a high level of diversity in techniques, applications and companies involved. 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.[5] 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 manufacturers, 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 co-evolution, 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. Government may play a role here, both as legislator and large customer.

5.2. 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 projects on application 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. The very centralised energy technology 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 rather steep, even when compared to the well-known Moore's Law for the evolution of computer processors (Figure 2).

The high costs involved in nuclear fusion allow for only one type of fusion technology, that 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 former

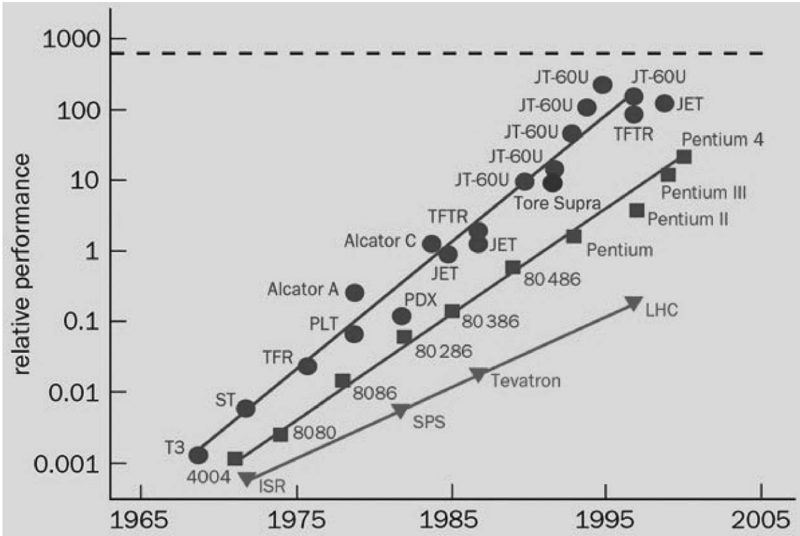

Figure 2. Relative performance of fusion experiments and other hi-tech developments over the last 30 years. *Explanation*: Since the early Russian T3 tokamak, the performance of fusion plasmas has doubled every 1.8 years (circles). The performance of fusion plasmas is defined in terms of the triple product (density × temperature × time). The progress in this triple product compares favourably with the doubling of the energy of particle accelerators every 3 years (triangles), and the doubling of the number of transistors on a chip every 2 years ('Moore's law'; squares). The dashed line at the top shows the performance expected with the planned ITER fusion reactor (*Source*: Hoang and Jacquinot 2004).

Soviet Union even during the Cold War period. Finally, the vision of the future is very utopian in attractiveness: large-scale application of nuclear fusion requires a cheap, unlimited and widely availabe fuel (water) and causes hardly any environmentally harmful emissions.

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, the viability of which 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 path 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 co-evolution, 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).

5.3. Photovoltaic cells (PV)

Photovoltaic (PV) or solar cells are seen in sharp contrast to nuclear fusion in the sense that the former type of energy conversion 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 PV 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 quite steep, largely 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, therefore 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, we saw that 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.[6] 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. In terms of path-dependency and lock-in, we can mention that 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

Evolutionary economics offers clear insights into the mechanisms that underlie innovations, structural changes and system transitions, therefore making it highly valuable for the framing of policies aimed at fostering environmental innovations and a transition to sustainable development. On the basis of major literature sources in this field, we have drawn up a list of core concepts which can be helpful in putting the evolutionary economic theory into policy practice. The central evolutionary concepts include 'diversity', 'innovation', 'selection environment', 'bounded rationality', 'path dependency and lock-in', and 'co-evolution'.

We have presented an evolutionary economics assessment of current Dutch policies on energy innovations, showing that some evolutionary economic notions have found their way into the policy discourse. Nevertheless, when it comes to concrete actions, only those aspects of evolutionary economic theory that do not conflict with notions of efficiency are put into practise. Current policies concentrate on cooperation, education, future perspectives and demonstration projects. Evolutionary aspects such as innovative combinations, cross-fertilisation and serendipity, however, are not stimulated and sometimes even hampered by current policies. Moreover, the idea of an extended level playing field receives hardly any attention.

The case studies of three specific energy technologies—fuel cells, nuclear fusion and photovoltaic cells (PV)—show how useful evolutionary economic notions are in understanding the development of new technologies. The development of fuel cells has been stimulated by a high degree of diversity of economic agents, techniques and products, by the cooperation between different parties, and by the niche market (e.g. for zero-emission cars). The case of nuclear fusion shows the importance of having an appealing perspective of a clean and inexhaustible energy source. However, in spite of this positive future perspective, it is not enough to overcome the bounded rationality (short time horizon) of private investors. Photovoltaic cell technology, on the other hand, has developed well in The Netherlands despite the drawback of a pessimistic future perspective. This case study showed both the important role of serendipity and cross-fertilisation, and of niche markets, for the development of this technology.

Our study does not offer instant policy solutions such as in terms of specific levels of diversity required. Nevertheless, this paper has shown that many useful policy lessons can be learned. Although a central concept of evolutionary processes is the inherent absence of a purpose or goal, this does not mean that it is impossible to influence these processes. Since it is impossible to predict which technologies will be the 'greenest' or 'best' in any other way, policy-makers should refrain from 'picking winners'. Instead, policy aimed at stimulating the development of sustainable technologies should emphasise the creation of conditions under which only the greenest technologies will survive.

Notes

1. In addition, it is good to notice that in-group diversity is relevant to co-evolution. History shows that human societies perform better—in terms of economic productivity—when a variety of complementary types of behaviour, such as selfish behaviour, cooperative behaviour, and altruistic punishment, is present. This is consistent with the notions of specialisation and labour division that are at the core of market liberalisation and free-trade thinking in economics in general and international trade theory in particular.
2. See Presidency Conclusions of the Lisbon European Council (2000): http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/ec/00100-r1.en0.htm
3. A list of these documents (all of them in Dutch) is available from the authors upon request.
4. Although negotiated agreements (also called voluntary agreements or covenants) are not common in all countries, they have flourished in The Netherlands since the 1980s. These are agreements between government and private parties for reaching targets on the reduction of environmental pressure. They often act as an alternative to direct regulation. Negotiated agreements are based on trust between the parties involved, but have no foundation in public law. Part of the arrangement is usually that legislative measures are either not imposed or imposed at a later stage (Hofman and Schrama 2003).
5. With regard to the impact of energy market liberalisation on the transition to sustainable energy opinions seem to diverge. Some believe that liberalisation of energy and electricity markets will hamper such a transition because firms will be focusing on short-term competition and profits, as well as strategic innovations with short payback periods. Others feel that market liberalisation will lead to more diversity in characteristics like size, technology and strategy of firms, which in turn will contribute to an unlocking of outdated technologies as well as stimulate innovations in general. Given the short and imperfect history of liberalisation of energy markets it is still too early to arrive at a definite judgement on this issue.

6. 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

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