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Socio-cognitive evolution and co-evolution in competing technical trajectories: Biogas development in Denmark (1970–2002)

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SUMMARY

This article makes two fundamental contributions to evolutionary theories of technological changes. First, a socio-cognitive evolutionary perspective is developed that conceptualises the emergence of new technologies in the pre-market phase. This topic is underdeveloped in evolutionary economics, because of its emphasis on market selection. Second, the article addresses co-evolution between two competing technical trajectories. In the pre-market phase, this interaction occurs via expectations and social networks. The perspective is illustrated with a longitudinal case study of biogas plants in Denmark. This sustainability innovation exists in two forms: farm-scale plants and centralised plants. Both forms are carried by different populations and based on different cognitive rules.

INTRODUCTION

How can we understand the dynamics and interaction of emerging technological trajectories in the pre-market phase? This question is difficult to answer for evolutionary economics because of the prominence it gives to market selection. Hence, this article proposes a socio-cognitive evolutionary perspective that can explain the origins of technical novelty. The emergence of novelty has received little attention in evolutionary economics. Arch father Schumpeter was more interested in innovation than in invention, warning that 'It is, therefore, not advisable, and it may be downright misleading, to stress the element of invention as much as many writers do' (Schumpeter 1934: 89). Evolutionary economists often pay most attention to the selection process, assuming that variety exists, paying more attention to the selection process. Nelson and Winter (1982: 257), for instance, write that 'the history of many technologies seems to be characterised by occasional major inventions,' but do not really address their origins. Other scholars assume that novelty emerges through blind, stochastic events or that 'technological breakthroughs are relatively rare and tend to be driven by individual genius' (Tushman and Anderson 1986: 440). In the punctuated equilibrium model of technological evolution such breakthroughs are assumed to trigger an era of ferment with competing designs and much uncertainty. The

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selection of a dominant design then ushers in a period of incremental change, characterised by retention periods, enhanced competence and increased interdependence within the community of practitioners (Figure 1).

This punctuated equilibrium model leaves the origin of technological discontinuities unexplained *and* conceptualises variation, selection and retention as *sequential* processes. To that end, evolutionary processes are better viewed as 'cumulative progression of interrelated acts of variation, selection, and retention over an extended period of time' (Van de Ven and Garud 1994: 427). Innovation scholars and historians of technology have shown that new technologies do not emerge suddenly, but incrementally through sequences of steps (Rosenberg 1982; Hughes 1983; Basalla 1990). Novelties start as small mutations, and develop gradually into new technologies, which ex-post may be labelled as discontinuous. The small steps in the innovation process form variations. These variations are discussed and evaluated in technical communities, and selected if actors find them useful. Their subsequent institutionalisation in technical models, design approaches and other cognitive rules signals retention. Figure 2 provides a heuristic representation of this evolutionary process as parallel micro-events.

This article links up with this evolutionary debate by further developing the latter line of thought. The conceptual perspective is described below, taking on board insights about the role of niches in emerging technologies. This is then illustrated using a case study of a sustainability innovation, biogas production in Denmark in the last three decades. This innovation involved two competing trajectories: small farm-scale plants and big centralised plants. These trajectories differed in design rules and were carried out by different technical communities.

SOCIO-COGNITIVE EVOLUTION AND CO-EVOLUTION IN NICHE DEVELOPMENT TRAJECTORIES

We will develop our argument in several steps. The first step is to broaden the discussion from bounded rationality to constructed reality. While evolutionary economists accept the bounded rationality of human beings, this concept remains wedded to rationality and the idea of information processing. We go one step further and argue that human

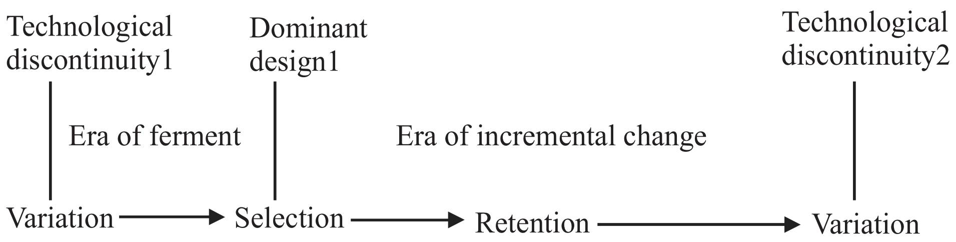

Figure 1 Technology cycle in punctuated equilbrium model (adapted from Anderson and Tushman, 1990; Van de Ven and Garud, 1994)

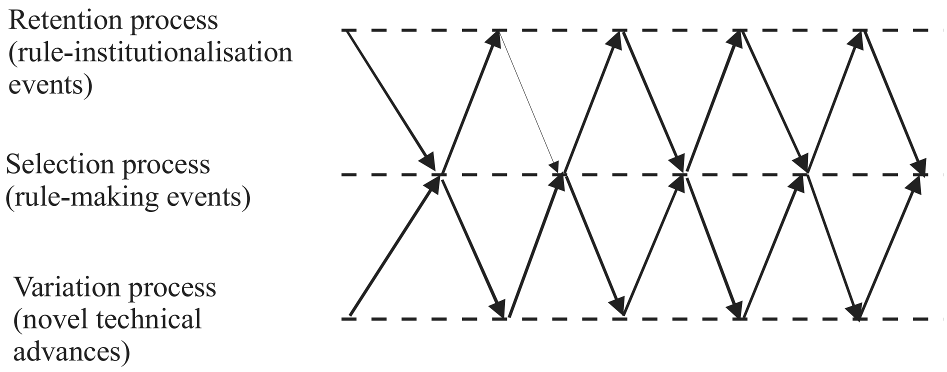

Figure 2 Parallel, interacting processes of variation, selection and retention (Van de Ven and Garud 1994: 428)

cognition *constructs* mental frames and maps of reality (Simon 1957). These cognitive frames select bits and pieces from the wide variety of signals that enter the brain, and help to construct meaning. In this view, sense-making is a crucial aspect of cognition (Weick 1979). Cognitive frames assist in sense-making, but are also altered in the process.

This basic view gave rise to cognitive evolutionary perspectives, emphasising cycles of action, learning and adjustment of cognitions. With a small modification of the common variation-selection-retention model, the social psychologist Weick (1979) proposed an 'enactment-selection-retention model.' On the basis of existing cognitive frames, actors *do* something in the world, because they expect it to be fruitful. The world reacts, and selection then takes place as individuals impose meaning upon, and make sense out of, the returning signals. Those patterns of data that fit their cognitive frames are selected in, while the rest is edited out. In this cognitive view, selection criteria are not embodied in the external environment, but in people themselves. Retention occurs as meaningful data are embedded in the cognitive frame, which may lead to some alterations. In this view, learning is not the accumulation of information or data, but changes in cognitive frames. This has similarities with the experiential learning theory, although this is not explicitly expressed in evolutionary terms (Kolb 1984). This theory argues that learning is an ongoing process that consists of four elements: concrete experience, observation and reflection, the formation of abstract concepts and testing in new situations (Figure 3).

Douthwaite *et al.* (2002) explicitly combined both views in an evolutionary framework, focusing on cognitions and learning. The framework is useful for this article because it is co-evolutionary, specifying how different evolutionary cycles interact (Figure 4). Although Douthwaite *et al.* draw an analogy with natural selection, they note an obvious difference, namely that natural selection is 'mindless' and blind (genetic mutations), while learning selection is guided by perceptions and expectations. People do not act blindly, but have particular reasons. Building on this, we will argue below that expectations and visions need to be added to the framework. Another characteristic is that this framework is very general and applies to all human action. Further specification for technology is required. And the framework is about individuals, less about technical communities.

This last point forms the basis for the second step in our argument, moving from individual construction to social construction. The SCOT theory (social construction of theory) broadens the analysis to shared cognitive frames at the level of inter-organizational field or innovation community (Pinch and Bijker 1984; Bijker 1995). When new technologies emerge, there is much uncertainty about the final form and function. Many directions are open for exploration. Because technical laws and material constraints under-determine the shape of artefacts, there is 'interpretative flexibility', which creates possibilities for actors to make design choices. These choices are not only made inside the firm, but also in interaction with other 'relevant social groups'. Different social groups initially have different problem definitions, different interpretations and hence different solutions. This variety of meanings is eventually reduced through 'closure', an inter-group process in which some problems and solutions are placed on the agenda of a technical community for further attention while others are not. Closure means that one interpretation of an artefact eventually becomes dominant and others cease to exist. During this process, a shared cognitive frame is build up, which guides (inter)actions and includes elements such as 'goals, key problems, problem-solving strategies

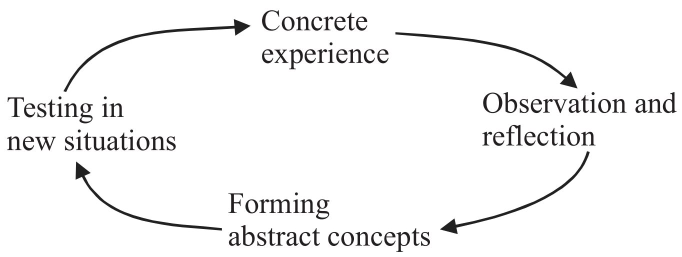

Figure 3 Experiential learning curve (Kolb 1984)

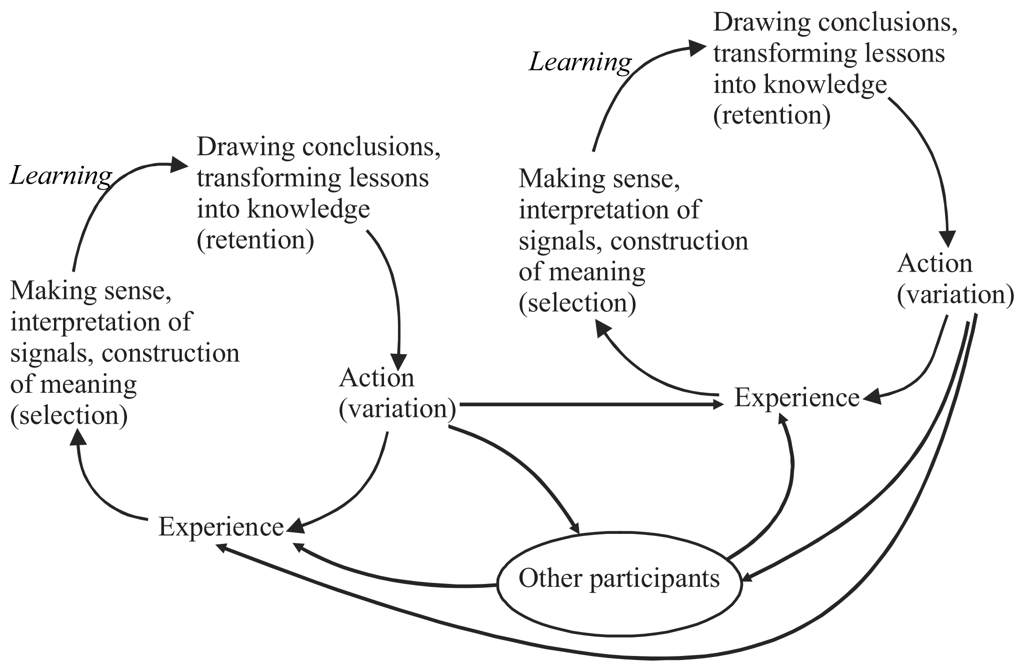

Figure 4 The learning selection algorithm, analogous to natural selection (Douthwaite *et al.* 2002: 115)

(heuristics), requirements to be met by problem solutions, current theories, tacit knowledge, testing procedures, and design methods and criteria' (Bijker 1995: 123). These frames form repositories of knowledge, sediments of previous learning. In that sense, cognitive frames function as retention mechanism at the community level, as 'carriers of history' (David 1994). For the content of frames, we use the general concept of 'rules', linking up with recent discussions in evolutionary economics (e.g. Hodgson 1997; Loasby 2002). Rules are connected into rule systems, including knowledge:

> 'Knowledge therefore consists of rules that exist as connections between ideas. Rules may exist in a number of places. Rules that are internal to the mind are, in effect, heuristics as cognitive mechanisms. When these become behaviours with a measurable frequency in a population of agents, they are institutions. (. . .) When they are directive, they are organizational rules and when they are constraining they are laws. All are rules and all represent knowledge as a connected system of elements' (Potts 2001: 419).

So rules can be private, but also collective. Furthermore, rules can be cognitive, formal and normative (Geels 2004). People are not seen as passive rule followers, but as active rule makers and rule users (Dopfer 2004). While rules function as a retention mechanism, they also guide actions and variations (Weick's 'enactment').

The third step in our argument is to define the elements of the population. Coming from the sociology of technology, we see artefacts, actors and rules as interrelated (Geels 2004). Artefacts do not exist without human action, actors are embedded in social networks and communities, actions and perceptions are guided by shared rules (Figure 5). Given our aim to understand *technical* evolution, artefacts form the phenotype, while the 'rules-actors couple' forms the genotype. Rules and actors form an intrinsic couple, constituting each other. This is in line with sociological structuration theory (Giddens 1984), in which structures are both context and outcome of action. This 'rules-actors' couple also provides a criterion to demarcate populations. A population consists of a social network of actors (individuals, organizations) who share rules that are related to the development and use of a particular technology. In the case study, we have a population related to farm-scale biogas plants and a population related to centralised plants. This demarcation is non-essentialist and partly constructed by actors themselves. A population may split, if actors differentiate themselves, specialize and group around different rules (e.g. goals, technical design principles). Boundaries can be reinforced through official membership, inclusion-exclusion mechanisms, etc.

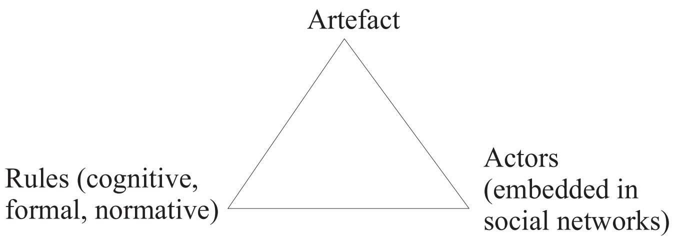

Figure 5 Interrelated analytical dimensions

The fourth step is to combine evolutionary mechanisms into a perspective on the emergence of new technologies. To that end, we use the literature on the role of niches in *technological* evolution (Schot 1998; Kemp *et al.* 1998, 2001; Hoogma *et al.* 2002; Raven 2005). For *biological* evolution, the allopatric theory also emphasises separation, arguing that new species emerge in geographically isolated niches or in niches operating at the periphery of a dominant existing ecosystem. When these niches provide distinct selection pressures, they lead to divergent evolutionary paths (Mayr 1963; Schot and Geels 2007).

For radical technical novelties, niches act as 'incubation rooms', shielding them from mainstream market selection, and providing space for nurturing and development processes. Such protection is needed, because new technologies emerge as 'hopeful monstrosities' (Mokyr 1990: 291). They are 'hopeful' because product champions believe in a promising future. But they are 'monstrous', because price/performance characteristics are low so they cannot survive on mainstream markets. Niches may have the form of *small market niches*, where selection criteria are different from the existing regime. Or they may have the form of *technological niches*, where resources are provided by public subsidies. These niches provide protection and separation from the incumbent, dominant technological regime. For electricity production, this regime is organised around steam and gas turbines, using cheap coal and gas. Niches provide some protection from this regime for renewable technologies, such as biogas plants.

The niche approach emphasises the importance of experimental projects, pilot projects and demonstration projects with new technologies. Three processes are important. First, projects provide space for the *building of social networks*, allowing users, policy-makers and special interest groups to give feedback to firms, engineers and researchers. Second, local projects provide space for *learning processes* with regard to technical design, user preferences, regulation, infrastructure requirements, etc. The third process is the articulation of expectations and visions. Expectations are important to attract attention and resources from the social network. And expectations provide direction to learning processes and activities in projects.

Insights from the previous steps can be introduced into the niche approach. The emergence of a new technical trajectory is located at the field/community level, but carried through projects in concrete locations. These technical projects are variations that build on shared rules, but also try something new (e.g. particular design changes). The projects lead to experiences from which important lessons and data are selected. These lessons are then incorporated in shared rules (retention). Initially there are only a few small projects and the rules are unspecific and unstable (high interpretative flexibility). If results and experiences are promising, more projects may be formulated, creating more space for learning processes. As experiences and lessons accumulate, rules become more specific and stable, gradually leading to a recognisable technical trajectory (Figure 6).

Using the above perspective, we can give evolutionary meaning to the internal processes in the niche approach, how they interact and how they relate to the three basic elements (Figure 7). Actors, embedded in networks, are willing to invest resources (money, people) in projects if they have a positive expectation of a new technology. This shared expectation, which is based on cognitive rules from previous learning processes, provides direction to the projects. Projects with concrete artefacts provide space to try out new things (variation). Actors negotiate the outcomes of projects, trying to give sense to the experiences (selection). Through learning processes the outcomes may be aggregated into generic lessons and rules (retention). Positive outcomes facilitate enrolment of more actors, expansion of the social network, more resources and continuation of the search in similar directions. Negative outcomes require 'repair work' to keep actors supporting the technology. Expectations need to be adjusted, leading to new promises of better results.

The fifth step is towards co-evolution. The perspective described above is an internally coherent evolutionary cycle, which fits well with the parallel evolutionary micro-processes described by Van de Ven and Garud (Figure 2). But reality is more complex because new technologies emerge in a wider environment. This wider environment consists of other technological niches, an incumbent socio-technical regime, and an external socio-technical landscape. The regime refers to exsting systems in particular societal domains (e.g. energy systems, agricultural systems), while the socio-technical landscape refers to broad societal changes (e.g. macro-economics, -politics, cultural values). Elsewhere a multi-level perspective has been developed which describes how these three levels interact in transitions from one socio-technical system to another (Rip and Kemp 1998; Kemp *et al*. 1998; 2001; Geels 2002, 2005). In this article, we will focus on the co-evolution between two competing

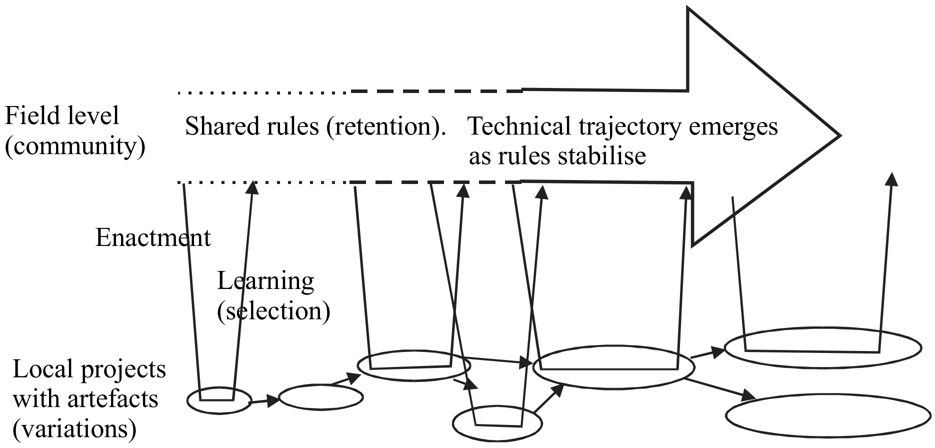

Figure 6 Socio-cognitive evolutionary perspective on emerging technical trajectory

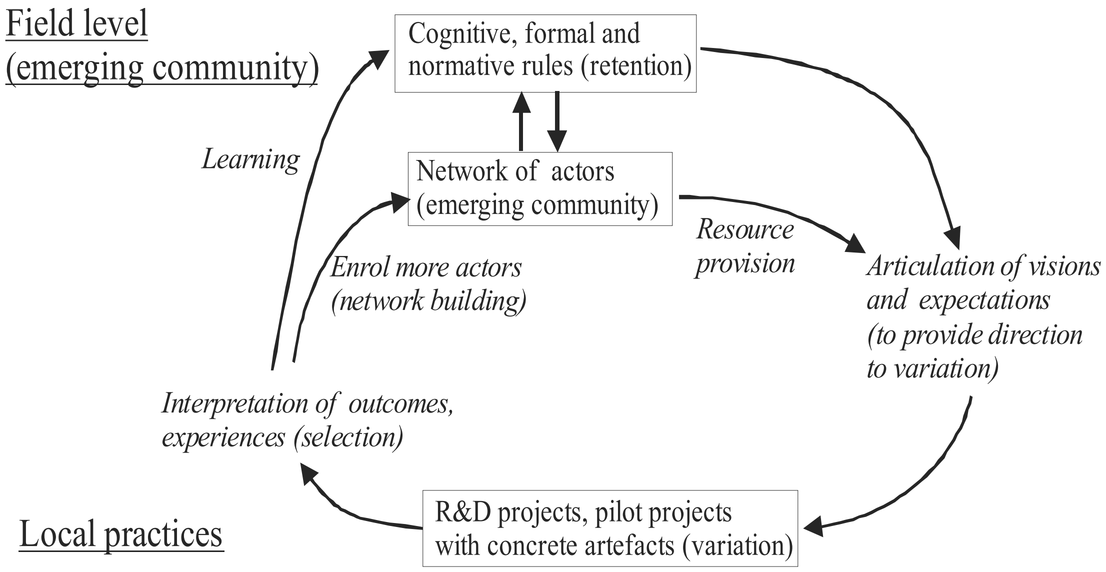

Figure 7 Socio-cognitive evolutionary dynamics of niche development trajectories (elements in boxes and crucial processes in italics)

niche-trajectories, in the context of regime and landscape changes. We will first present the case study, and then address this topic in the conclusions.

CASE STUDY: THE DEVELOPMENT OF BIOGAS IN DENMARK (1970–2002)

The evolutionary cycle of emerging technologies will be illustrated with a case study on biogas production in Denmark, an emerging sustainability innovation. The case study leans heavily on Raven (2005). While the case study also shows the influence of regime and landscape developments on niches, the focus is on the socio-cognitive evolutionary cycle. The case is suited to explore the topic of co-evolution because biogas exists in two technical designs: farm-scale plants and centralised plants.

In general, a biogas plant produces a mixture of methane and carbon dioxide (biogas) from organic sources like manure. The heart of a biogas plant is the anaerobic digester (Figure 8). Inside the digester, manure is stored for about three weeks. In the absence of oxygen, anaerobic microbes convert part of the manure into methane and carbon dioxide. Before manure enters the digester, it is preprocessed to increase homogeneity. The digestion process has two end products. The first is biogas. This gas often has small contaminations and needs cleaning before it can be used as an energy source. Biogas is often used in combined heat and power units (CHP), in district heating plants, or for injection into a natural gas grid. The second product is processed manure that can be used for fertilizer purposes. In some biogas plants, organic waste sources like fish oil or corn are added to the digestion process (up to 25% of total volume). This increases the biogas production, and reduces the amount of waste that is otherwise dumped at landfill sites. About 3% of Danish renewable energy is produced from biogas, which is high compared to other European countries (only Germany scores higher). This was the result of positive niche internal processes and beneficial circumstances on the regime and landscape level.

Farm-scale plants process manure from a single farm. The resulting biogas is used on-site to heat stables, while processed manure is used on the land. *Centralised biogas plants* are larger and process manure from multiple farms, something that has design consequences for transport and storage. Furthermore, centralised plants are operated by dedicated firms with chemical competencies. The emphasis tends to be less on biogas and more on manure processing, producing and selling fertilizer granules.

Figure 9 plots the development of farm-scale and centralised plants. Between 1974 and 1984 there were only farm-scale plants. Between 1984 and 1994 farm-scale plants declined, and the focus shifted towards centralised plants. After 1998 the number of centralised plants stabilised, while farm-scale plants witnessed a revival. The case study will explain the processes 'behind' this pattern.

Farm-scale biogas plants (1974–1984)

In the early 1970s, 80% of Danish electricity came from oil; 40% of household heat also depended on (heavy) oil, produced in district heating systems. Remaining heat came from individual heating systems (also often using oil) and surplus heat from large-scale electricity production. The 1973 energy crisis was a shock to the energy regime. Danish energy policy responded by stimulating nuclear power and renewable energy. Biogas was one of the options. Following the rise in oil prices, farmers, research centres and technology companies articulated visions of a bright future for biogas plants.

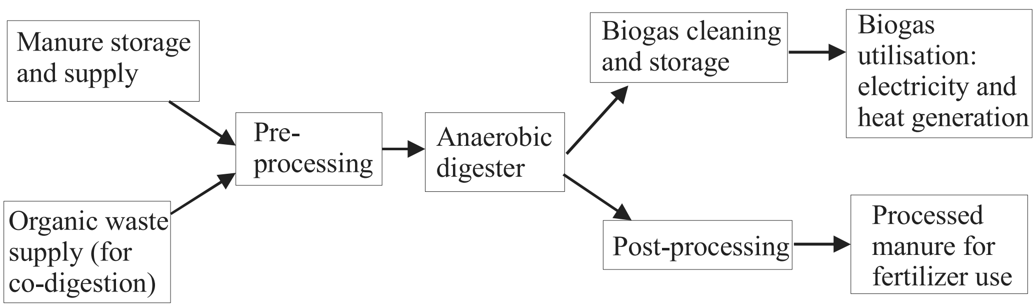

Figure 8 Basic layout of a biogas plant

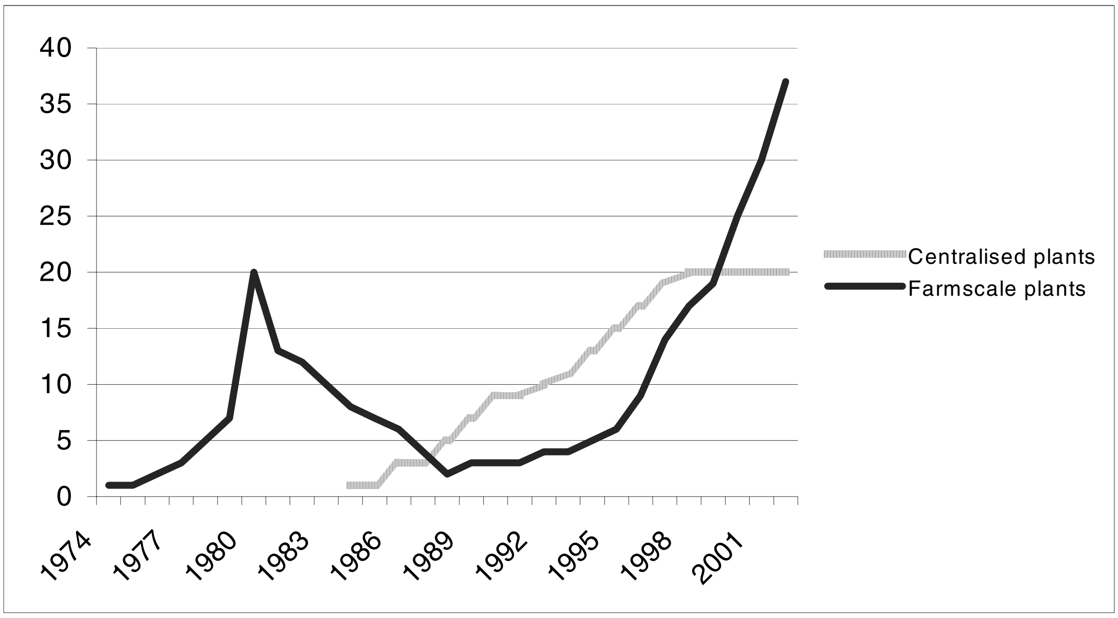

Figure 9 Number of Danish farm-scale and centralised biogas plants (compiled from Energigruppen 1979; Operations Analysis Centre 1982; Elmose 2002; Seadi 2000)

Hans Aage Jespersen constructed the first pilot plant, in cooperation with a local blacksmith, to demonstrate basic digestion principles (Beuse *et al.* 2000). His initiative was embedded in the Danish grassroots movement, which included Folke High Schools, several scientists, local energy offices and farmers.

In 1978 the Ministry of Trade facilitated the creation of the Cooperation for Technological Development of Biogas Plants (STUB). This Cooperation mobilised expertise from the Danish Technological Institute, agricultural specialists and engineering firms such as Carls Bro A/S. So a social network was formed to support and develop farm-scale plants. The Ministry of Trade gave a 3.6 million DKK grant (about half a million Euros) to the Cooperation to assist farm-scale plant construction (Groen 1981). Projects focussed on energy generation and high biogas yields. Within the programme, seven plants were constructed to advance technical and economic information. STUB engineers visited the projects to collect information, which was published in a magazine *Biogas Nyt*. So knowledge was explicitly aggregated and circulated within the emerging community. But there were also tensions. Some farmers criticised the STUB programme, because researchers looked only at *new* plants with innovative designs, not at *existing* plants constructed by local farmers and the grassroots movement.

The oil crisis of 1979 led to new discussions that involved the Danish government, the two Danish power producers ELSAM and ELKRAFT and the grassroots movement. The latter protested against nuclear energy. Furthermore, environmental concerns (e.g. acid rain) rose on the agenda, creating more support for renewable energy. In this context, the Ministry of Energy donated 3.2 million DKK to expand the biogas programme in 1981.

In 1982 an inventory was made of the 21 registered biogas plants (ten were in the STUB programme). Experiences showed technical problems in all plants (Operations Analysis Centre 1982). Manure digestion was found to be an unstable process, of which the actors involved had no established experience. For instance, there were no specialised producers. Biogas plants were often constructed by farmers in cooperation with local craftsmen. But farmers had no experience in operating a biochemical plant. Biogas yields in the programme were below initial expectations (Table 1) and farmers began to lose interest. In subsequent years the number of farm-scale biogas plants declined. Disappointing outcomes led to lower expectations, shrinking networks and fewer resources. But the niche did not die, because grassroots movements kept it alive (in particular the Danish Folkecenter). They continued technical development and some implementation at neighbouring farms, although at a small scale.

Table 1 Expected and realised biogas production of projects in STUB programme (Operations Analysis Centre 1982)

Location	*Digester size (m^3)*	*Calculated/expected production in 1981 (m^3/day)*	*Real production in 1982 (m^3/day)*	*Real production/calculated production*
Stenderup	45	63	45	71.4%
Elsted	4 × 220	1232	17	1.3%
Vilstrup	2 × 150	435	160	36.4%
Sjoulundgård	6 × 60	504	180	35.7%
Hjelmerup	100	140	80	57.1%
Brested	100	140	85	60.7%
Assendrup	2 × 200	560	150–200	26.3–35.7%
Grasten	2 × 180	504	350	69.4%
Gadebjergård	360	504	200	39.7%
Lejre	20	28	6	21.4%

Centralised biogas plants (1984–1994)

Negative farm-scale experiences stimulated the emergence of new expectations about *centralised* biogas plants. Researchers suggested that bigger plants could reduce production costs and increase biogas yields. Centralised plants would also move operational responsibilities from individual farmers to professional firms. These new expectations formed the start of a new technical trajectory.

Inspired by the new visions, a Danish county in the North of Jutland implemented the 'Village Energy Project', which initially included the construction of three biogas plants throughout North Jutland. The first plant was built in 1984 in Vester Hjermitslev with the aim to make the town self-supporting regarding energy (Seadi 2000). Almost all costs were covered through a four million DKK grant from the government and an 8.4 million DKK loan (about 1.2 million Euros) from the North Jutland County Council. In 1985, a second centralised plant was constructed in Vegger. The design was similar to the first plant, but operating temperatures were higher (55°C instead of 35°C). This variation meant that an extra pasteurisation step could be left out. A third plant was constructed in Skovsgård.

Experiences with the plants were disappointing. The first plant encountered problems with the gas transport system, heat pump (used for recovering waste heat) and the pre-sanitation step (to kill pathogens). The plant was reconstructed in 1988–89, improving performance substantially. The other two plants encountered less problems, but biogas production remained below expectations. Hence, the North Jutland county withdrew support for biogas technology (Maeng *et al.* 1999). The social network that carried the niche threatened to fall apart.

But landscape developments and changes in the energy and agricultural regimes, revitalized the niche after 1985. In the energy regime, the government rejected nuclear power and expanded domestic fossil fuels (mainly natural gas from the North Sea), wind power and biomass applications. Natural gas was to be used for decentralised combined heat and power units (CHP). But some regions were not connected to the natural gas infrastructure (about a quarter of Denmark). In these regions, the government expanded support for biomass, including biogas plants. After 1985, a landscape change, decreasing global oil prices, threatened to frustrate this energy strategy. To prevent reintroduction of oil, the government decided to raise taxes on oil products, coal and electricity. Renewables (including biogas) and natural gas were tax-exempted. For households the net effect was that the electricity price remained the same (IEA 1998). The tax changes in the electricity and heating regime made energy from biogas more competitive in Denmark than in other European countries.

Around the same time, the agricultural regime faced increasing criticisms about nitrate leaching and water pollution. A 1984 report from the Danish Environmental Protection Agency (EPA) triggered a societal debate, which led to stricter agro-environmental rules (Miljøstyrelsen 1984). Farmers were only allowed to distribute manure on the land in periods when the risk of nitrate leaching was low. They had to store manure for the rest of the year. Farmers were required to build storage capacity sufficient for six to nine months manure production. In 1987, the EPA published the Water Environment Action Plan I, which included a major reduction goal for nitrate leaching in agriculture. This plan regulated the number of animals per hectare as well as the maximum input of nitrogen per hectare. In several Danish regions, farmers produced more manure than they were allowed to spread. One of the options was to participate in centralised biogas plant organisations. These organisations could collect, transport, store and redistribute manure for farmers.

These regime changes created a window of opportunity for centralised biogas plants. New actors joined the niche, expecting that biogas could address the new problems. In 1988 the Danish Energy Agency (DEA), the EPA and the Ministry of Agriculture established a framework to stimulate centralised biogas plants: the Biogas Action Programme. This programme focussed on research and development, construction and monitoring, and information activities. Also included were an investment grant for centralised biogas plants (up to 40% of costs) and a loan scheme with long-term low interest rates. Initially the programme ran between 1988 and 1991. But it was renewed several times until 2002.

In the Biogas Action Programme, one or two centralised biogas plants were constructed annually, constituting a learning trajectory. The programme was implemented through a bottom-up approach, allowing it to build on local learning experiences. There were also many interactions in the social network, involving policy-makers, farmers, researchers, biogas plant suppliers (often non-specialised large contractors) and biogas plant operators. Regular meetings and workshops stimulated the emergence of a biogas community and rapid diffusion of experiences and innovations. For example, an improved gas cleaning system (based on adding a little air), elaborated at a plant in Fangel in 1993, quickly diffused to other plants. Also, social and behavioural changes occurred. Centralised biogas plants led farmers to change their routines with regard to manure distribution on the land, using less artificial fertilizer. Furthermore, scientific analysis of manure composition improved insights about crop absorption of minerals and nutrients. Using these insights, scientists recommended changes in agricultural practice that enabled lower fertiliser expenditures. Centralised manure storage also lowered investment costs for individual farmers (who did not have to construct storage capacity). The Ministry of Agriculture implemented several sanitation research projects on sanitation and pathogens to investigate risks of spreading animal diseases. Researchers developed a measurement method to determine the presence of pathogens in digested manure. This method was applied in biogas plants in 1994 and improved operating conditions. Research also produced detailed knowledge about relationships between temperature, residence time and pathogen kill-off in biogas plants. This knowledge allowed specification of regulations about sanitation requirements for waste products. The new regulations were more flexible, tailored to different operating characteristics, lowering sanitation costs. In sum, the projects in the Biogas Action Programme provided space for learning processes on technical, scientific, user, regulatory and environmental dimensions.

A crucial outcome in the technical learning processes was co-digestion, i.e. addition of small amounts of organic waste (in particular fatty waste and fishery waste) to manure. Co-digestion substantially increased biogas production and energy sales. Furthermore, biogas plants received a gate fee for processing waste that was otherwise dumped at landfill sites. Co-digestion enabled biogas plants to link up with three regimes: 1) it produced renewable energy, which was interesting for the DEA; 2) it helped organic waste recycling, which was interesting for the EPA; and 3) it helped to distribute, control and process manure streams, which was interesting for the Ministry of Agriculture. So, through co-digestion centralised biogas plants secured support from three ministries.

The niche of centralised plants was also characterised by well-functioning social networks, in the form of farmers' cooperatives (5–100 farmers). The cooperative organisation was the dominant organisational structure after 1987, fitting well with the general Danish preference for bottom-up collectives. These cooperatives transported and distributed manure, and constructed local storage facilities near farmer's fields. The non-profit cooperatives were financed with loans and grants from the government. They also earned money from energy sales and gate fees for industrial waste. This organisational form enabled farmers to process manure without paying. In other European countries farmers had to pay processing fees.

The cycle of internal niche processes functioned positively and created internal momentum. Performance of centralised biogas plants improved in the 1990s, resulting in higher biogas yields and better economic feasibility (Figures 10 and 11).

Slowdown of centralised biogas plants and revival of farm-scale plants (1994–2002)

By the mid-1990s, the niche of centralised biogas plants was ready for take-off. This did not occur, however, because of regime changes that created new barriers and uncertainties. The emergence of neo-liberal pro-market values (a landscape development) led to changes in the energy regime as part of liberalisation processes. In 1996, the government passed an amendment to the Danish Electricity Supply Act to permit private companies and distribution companies to buy power from third parties (IEA 1998). In 1999, parliament confirmed a new energy act, the Danish Energy Reform, to further transform the energy regime after 2003. This included changes in the way renewable energy was stimulated. Traditionally, the long-term fixed price paid per kWh for renewable electricity was between €0.06–0.075. The new act would replace this fixed price scheme with 'green certificates',

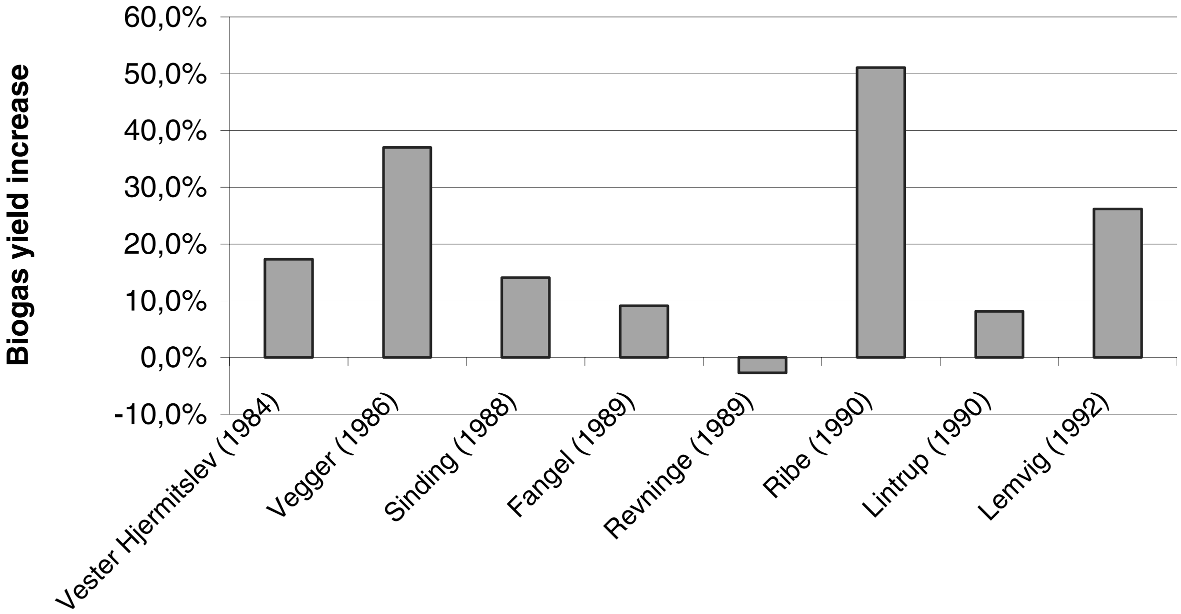

Figure 10 Increase in biogas yields per plant between 1991 and 1998 (Danish Energy Agency 1992; Hjort-Gregersen 1999)

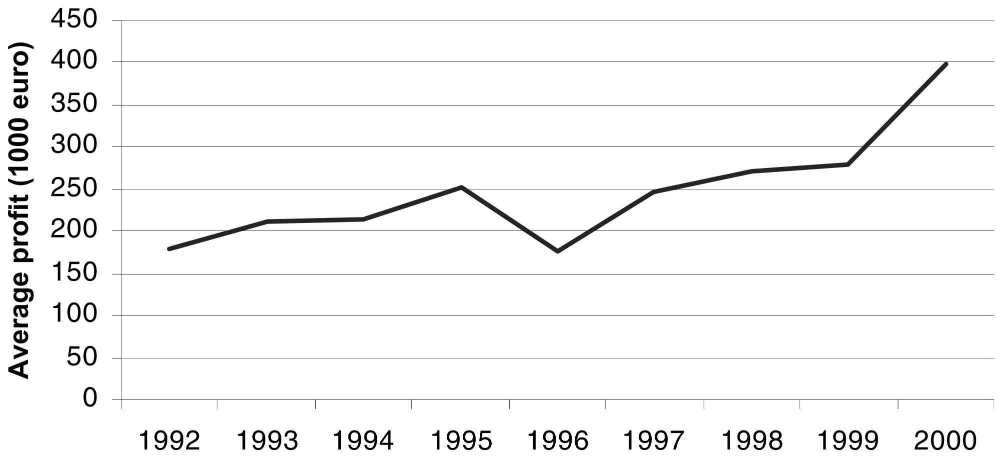

Figure 11 Average profit of centralised biogas plants (not including payment of loans)

which price depended on supply and demand. This introduced uncertainty about the price of renewable energy (Meyer 2003). Furthermore, there was uncertainty about how these new rules would be introduced because a green certificate market would not be fully operational until 2005.

In this changing context, the diffusion of centralised plants slowed down after 1995, despite major improvements in technological and economic performance in preceding years. The last centralised biogas plant was constructed in 1998. From then on, the ongoing regulatory changes created uncertainties that halted investments in new centralised biogas plants (Christensen 2000).

Also, other developments frustrated new centralised plants. As more biogas plants used organic waste for co-digestion, it became scarcer and more expensive. Another macro-change was the election of a new government in 2001. With regard to energy production, the new liberal/conservative government was less interested in environmental issues and more concerned with cost efficiency. Many grants, funds and support schemes for renewable energy were cancelled and replaced by more generic and market-oriented Joint Implementation and Clean Development Mechanisms (see Table 2). These changes reduced support for renewable energy in general, and stopped the Biogas Action Programme in 2002 (Evald and Jakobsen 2003).

Meanwhile, farm-scale plants, which had been kept alive by the Folkecenter for Renewable Energy, experienced a revival for three reasons. First, the Folkecenter had made technical changes which improved the farm-scale concept. The Folkecenter was a grassroots actor with a strong vision on decentralised energy generation. The Folkecenter's engineers improved farm-scale designs through cooperation with experts from the German biogas industry and through local testing in their own facilities. In 1995 an employer of the Folkecenter established a new company 'Dansk Bioenergy A/S' to commercialise improved farm-scale plants (Hjort-Gregersen 1998). Second, the average size of Danish farms had increased in the 1990s, resulting in more animals per farm (Boon 2000). These structural changes in the agricultural regime made farm-scale plants economically more attractive because of economies of scale. Third, new government regulations created more support for farm-scale plants. The 1997 Kyoto Protocol drew attention to methane as important climate forcing gas, next to CO_2. The agricultural sector was the main producer of this gas (from manure). To tighten methane emissions from agriculture, the Danish government implemented the second Action Plan on the Aquatic Environment in 1998. Subsequently, the government made grants available for construction of farm-scale plants. The assessment was that farm-scale plant performance had increased sufficiently, but that high investment costs hindered diffusion (Hjort-Gregersen 1999a). With the help of investment grants (up to 40%) farm-scale plants in Denmark rapidly diffused after 1998.

CONCLUSIONS

The research question was: How can we understand the dynamics and interaction of emerging technological trajectories in the pre-market phase? To answer that question, we articulated a socio-cognitive evolutionary perspective on emerging technologies. This involved a cyclic process, with projects forming variation mechanisms. These variations are not blind, but guided by expectations and visions. Attractive expectations are important to convince sponsors to provide resources for the projects. Projects deliver outcomes and experiences, which are interpreted. This sense-making and learning process forms a selection mechanism.

Table 2 Programme reductions after new government (Evald and Jakobsen 2003)

Programme	*Old government support (million Euro)*	*New government support (million Euro)*
Development and information of renewable energy	20	0
Energy research	14	5
Utilities energy research	10	10
Energy savings and fuels switch in industry	19	0
Investment grants for biomass CHP	4	0
Joint Implementation and Clean Development Mechanism	0	17

The institutionalisation of lessons as formal, normative and cognitive rules provides a retention mechanism. Outcomes are also used to attract new actors, expand the social support network and augment available resources. This evolutionary perspective combined socio-cognitive insights with the technological niche approach, which emphasises learning processes, network building and articulation of expectations. The resulting perspective explains the evolution of technologies in the pre-market phase.

The case study demonstrated the usefulness of this perspective, showing the importance of local projects as spaces to try out new designs (e.g. reactor temperatures, co-digestion, gas cleaning systems). If innovations worked in particular projects, they were selected by the broader community and incorporated in design rules (retention). We made a distinction between two competing evolutionary trajectories: farm-scale and centralised biogas plants. Both trajectories were carried by different social networks (populations). *Farm-scale* plants were carried by individual farmers, the grassroots movement, and (small) technology suppliers (individual farmers and craftsmen in the 1980s; spinoffs from Folkecenter in the 1990s). In the late 1970s the government was also involved through the STUB programme, which brought in agricultural and engineering expertise. But this withered away in the early 1980s. *Centralised* plants were carried by farmers' cooperatives and biogas plant suppliers (non-specialised contractors), and supported by three ministeries (environment, energy, agriculture). The Biogas Action Programme provided financial support and brought in academic expertise. So each trajectory was embedded in a separate process of variation in local projects and learning and selection in two populations.

However, the two evolutionary trajectories also influenced each other. To address co-evolution, we build on Douthwaite *et al.* (2002), who conceptualised how evolutionary cycles of individual cognition influence each other (see Figure 4). We can rephrase their ideas in a less individualistic manner and with our socio-cognitive concepts. The crucial mechanism for co-evolution is the link between expectations that guide variations and outcomes of projects in other trajectories. Expectations for new projects are, of course, based on internal technical considerations and experiences from previous projects. But these expectations also take into account the wider world, e.g. regulations, market dynamics and competing technical trajectories. Product champions, when searching resources for new

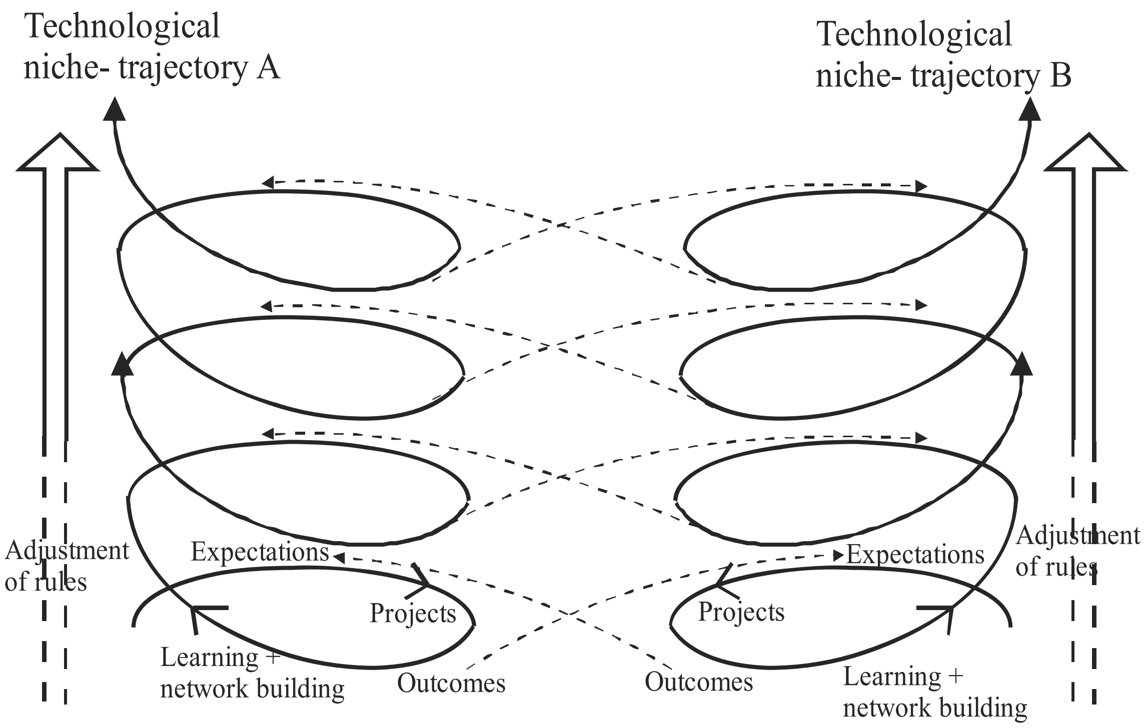

Figure 12 Co-evolution mechanisms between competing niche trajectories

projects, sketch 'diffuse scenarios' about future worlds in which the innovation would work (Rip and Kemp 1998). So the formulation of (new) expectations in niche A is influenced by experiences in niche B. If experiences in niche B are negative, it becomes easier to formulate positive visions for niche A, and attract people and funding (Figure 12). In the case study these interactions were quite clear. The negative experiences with farm-scale plants in the early 1980s formed the main reason for the start of centralised biogas plants. It was expected that scale increases would improve performance and lead to economies of scale. Although this new expectation was based on farm-scale plant experiences, it was supported by a different population of actors. As another example, the stagnation of centralised plants in the late 1990s led to renewed positive expectations regarding farm-scale plants (as a way to reduce methane emissions in agriculture).

Expectations also form the mechanism through which broader regime and landscape developments influence niche dynamics. The case study showed several instances of such positive and negative influences. Oil crises and high prices in the energy regime led to positive expectations for farm-scale plants in the late 1970s. In the mid-1980s problems in the agricultural regime (nitrate leaching) boosted expectations about centralised biogas plants. In the late 1990s, liberalisation in the energy regime created uncertainty, which negatively influenced expectations about centralised plants. So we conclude that the case study demonstrates the importance of multi-level interactions on socio-cognitive evolutionary processes in technological niches.

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